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A-Priori Travel Time Predictor for Long Term Roadworks on Motorways

Simeon C. Calvert

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Final Report

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Summary

Road users have never had as much travel information as is available today. However the extent of congestion on major roads has also never been as critical as it is now. For this reason road authorities, including Rijkswaterstaat[1], aim to inform road users as best they can in an effort to allow the road user to make a more educated decision on travel and to increase the confidence they have in travel times.

In a bid to improve traffic flow on motorways, many roadworks are carried out yearly with a large number planned for the coming years. This contributes to congestion and delays in the short term however and leads to a greater uncertainty in travel times. Many techniques and models already exist to predict travel times under 'irregular' traffic conditions. For situations where roadworks are due to be carried out in the future however, no models or methods explicitly exist which allow travel times to be predicted in advance. It is this problem that this research project attempts to tackle.

The main objective for this research is to develop a methodology incorporated in a model, which is capable of predicting travel times on motorway corridors for situations during roadworks that are to be carried out in the future.

To achieve this objective the research question is posed: How can a-priori travel times be predicted on motorway corridors for situations during roadworks, prior to the commencement of the roadworks?

The objective is achieved by firstly consulting external research on the topics of travel time estimation with models and the influence of roadworks on travel times. Using the acquired knowledge a modelling approach is developed which makes use of the basic principles of traffic flow based on the conservation of vehicles and first order traffic flow theory.

The developed model makes use of traffic flow profiles and capacity profiles, which are processed by an LWR-model using a Godunov scheme. Traffic is numerically fed through the model and where it exceeds capacity, congestion occurs and propagates backwards in space according to first order traffic flow theory and in keeping with the general characteristics of real traffic flow. From the modelled data, speeds are derived for each iterated section. This allows for travel times per section and total travel times along a certain trajectory starting at a specific time of day to be calculated. These travel times form the prediction for the corresponding motorway corridor.

The effects of roadworks are incorporated in the model through a reduction of the road capacity in the capacity profile. This is performed by applying a capacity reduction factor to the available capacity. This reduction factor is

[1] Executive arm of the Ministry of Transport, Public Works & Water Management in the Netherlands

determined using characteristics of the roadworks which correspond to certain reduction values taken from extensive research preformed externally.

The traffic flow profile is also adjusted for the effects of mobility management, which is commonly applied during roadworks in the Netherlands. Mobility management is an organised attempt to reduce the level of traffic demand on routes where road capacity is not expected to be able to cope with traffic demand, such as during roadworks. A mobility management factor is therefore applied to the traffic demand profile to reduce demand as a consequence of this.

The model is evaluated using a roadworks study case on the A12 between The Hague and Gouda. The results of the model, in which a base capacity[2] of 2100 veh/hr/ln is applied, show a good likeness to the recorded travel times during the performed roadworks. An absolute relative error of less than 5% is recorded for the travel times during the main peak periods. These results are produced with the application of a mobility management factor of 6-7%, which corresponds to the expected values for this specific case. The performance requirement for the error of travel times during the entire day is also achieved in the case study.

The research shows that predicting travel times for future roadworks is possible and moreover can be performed in a relatively accurate fashion without the necessity of an overcomplicated model. Producing traffic flow demands is achievable, however estimating the extent of mobility management and the indirect reduction of traffic demand is more complicated. Road capacity during roadworks is affected and estimates are made of the reduced workzone capacity. The capacities found show a good likeness to recorded data, however small adjustments in the capacity reduction have the potential for large travel times variations. For this reason the application of confidence bandwidths, as applied, is valuable. Further difficulties in determining capacities stem from the inability to produce operational capacity estimations where no congestion occurs. The application of a base capacity solves this, however the applied value cannot be generically validated with great ease.

The application of the model is most suited to implementation for road user information through a website or incorporated in a route planner. The use of the model in roadwork planning is also possible, but will require alterations to model.

The case study results are encouraging, however the model requires further validation over a wider range of roadworks as varying locations and roadwork characteristics may lead to differing results. Further research is recommended into a simple capacity reduction method for roadworks. Research on the effect of mobility management and an effective method to estimate the effect of it is also recommended. The implementation of these as well a generic manner of determining a base capacity in the model are further recommended as possible adjustments to improve the model.

[2] The base capacity is the nominal capacity presumed, when an operational capacity cannot be determined

Preface

This report is the documentation of the research carried out as part of my final thesis project for my Postgraduate Master degree in Civil Engineering at the Delft University of Technology. The research was performed in conjunction with, and at, the ITS Edulab, which is a cooperation between the Rijkswaterstaat Centre for Transport & Navigation and the Department of Transport & Planning of the faculty of Civil Engineering & Geosciences at the Delft University of Technology.

During the process of this research there were a number of people whose assistance made it possible for me to develop the research into the product that lies before you now. First and foremost I would like to thank my examination committee for their input and feedback during the past seven months. From the University, these were Serge Hoogendoorn and my daily supervisor Hans van Lint. From Rijkswaterstaat, these were my daily supervisor Ydo de Vries and Michel Kusters. Especially Hans and Ydo as my daily supervisors, I would like to thank you for your constructive input and expertise in assisting me.

Thank you to my father Robert Calvert for taking the time to read through the extensive report and offer corrections. And off course to both my parents for their continuous support in many ways during my studies.

I would also like to say a word of thanks to my colleagues at the ITS Edulab, who succeeded greatly in providing a fun and relaxed atmosphere in which I could work. Your friendship and support is truly valued.

I must also thank my dear wife Els for her overall support during the research and also the studies before that. And finally I must praise God for the chance to study and the abilities and love given to me to excel where I am, to which I dedicate this research.

Simeon Calvert
Delft, December 2009.

Table of contents

1.Introduction

1.1 Introduction

The time at which one must depart from a certain location to arrive at the desired destination at a certain time is a question that is as old as travelling itself. In today's society this question takes on great importance, as most activities are bound by a desired or compulsory starting time. With the majority of trips performed by car, a large number of people make trips simultaneously and therefore influence each others travel time on their journeys. Modern day traffic research has led to many predictive tools for estimating travel times prior to a journey. This has led to a greater confidence in the travel times expected by road users and therefore improved departure time predictions for road users. Prediction of travel times under irregular circumstances however is harder than for everyday situations. For many of these situations, predictors already exist and give good estimates, but not for all. This research will focus on one of these situations for which no (accurate) travel time predictor exists, namely for future roadworks.

1.2 Problem definition

Most road users on motorways find themselves on ever increasingly congested roads. The process of improving road layouts and expanding roads to counteract the increase in congestion actually cause further capacity reduction on motorways and lead to further congestion. Roadworks for periodical maintenance further reduce the available capacity. The consequences are increasing travel times, leading to increasing costs to road users, companies and the environment.

In an attempt to improve the traffic conditions on motorways and to inform road users to a better extent on what to expect, travel information has been widely incorporated into travelling over the past decades. Travel information in advance has the advantage of improving journeys through improved route and/or departure time choices by road users, but can also increase travel comfort through fewer unexpected situations, such as delays or detours.

Travel time prediction, as part of this range of travel information, is arguably one of the more important pieces of information available, as this allows a road user to determine when a journey should be undertaken and which route might be chosen (normally the route with the shortest travel time). Current travel time predictors have been developed to cope with a wide range of variables and thus not only take a nominal speed over a route into account, but also congestion and delays resulting from congestion.

This presumes that the road is clear of blockages. With many roadworks planned for the coming years in the Netherlands, many of which are extensive, travel times experienced by road users are going to become increasingly hard to predict when considering the consequences of the roadworks. Recording realised travel times and duplicating the results for future journeys cannot be performed before such travel times have been realised. This means that at the moment roadworks are due to commence, no recorded travel times are available, leading to poor route and departure time choices and frustration at unexpected delays on the side of road users. This leads to the conclusion that a-priori estimation methods must be used.

During the spring of 2009 Rijkswaterstaat[3] recognised the need to develop a methodology to allow travel time predictions to be made for future roadworks. The main goal was to provide a greater quality and accuracy of travel information to the road users making use of stretches of motorway where major roadworks are planned. In the original plan a predictor, with the power to predict future delays due to uncommenced roadworks days or weeks in advance was proposed. It was however deemed necessary for further research to take place before implementation could be considered. It is in addressing this problem that this research is undertaken.

Problem definition:

The problem definition for the project is defined as the necessity to have more accurate travel time predictions as part of the available travel information for road users prior to the start of roadworks. This is the consequence of expected roadworks on Dutch motorways in the coming years and decades and the wish from road users to be well informed of travel restrictions leading to delays.

[3] The proposal was made by Rijkswaterstaats Division of Noord-Brabant.

1.3 Research Objectives

The main objective for this research work, based on the problem definition is as follows:

Main research objective:

The main objective is to develop a methodology incorporated in a model, which is capable of predicting travel times on motorway corridors for situations during roadworks that are to be carried out in the future.

Taking the main objective into account, the result of this research is:

- This report explaining the details of the model methodology and the underlying theories, arguments and deliberations, which led to it.
- A software tool based on the developed theory showing the workings of the model as a demonstration, which has the capability to be expanded for use in real life.

1.4 Research Questions

The mentioned research objective is achieved by finding answers to a set of main and secondary research questions. These questions form the basis of which each section of research is founded and lead to an answer for the main research question.

The main research question resulting in the completion of the main objective is:

Main research question:

How can a-priori travel times be predicted on motorway corridors for situations during roadworks, prior to the commencement of the roadworks?

To help answer the main research question and complete the objective of this research, a set of secondary research questions are formulated. The answers to these questions form the step-wise approach for the construction of the model methodology presented in this report.

The secondary research questions are formulated as such:

1. How can travel times be predicted for future scenarios without knowledge of the future traffic conditions?
2. Which factors influence workzone capacity and what are their relations to travel time?
3. Which modelling methods are applicable in travel time prediction for traffic demand profiling?
4. Are travel time predictions using the developed model reliable and sufficiently accurate?

1.5 Research Relevance

This research has a real relevance on both a scientific as a practical level.

On an scientific level this research contributes to a deeper understanding into the possibilities of a-priori travel time predictions. Greater insight is gained in the process of travel time predicting and it's opportunities and applications, including capacity estimation during roadworks. Besides this, a new methodology is proposed for a-priori travel time predicting during roadworks, which offers a valuable addition to current predictors.

The research also holds relevance on a practical level. The resulting methodology/model offers the building blocks for the development of a relatively simple though accurate roadworks travel time predictor for use prior to the commencement of the roadworks. Furthermore, tools are given to further develop and implement additional roadworks information for road users in the form of (personalised) travel time estimations. Finally the research opens up the possibility for increased accuracy for route and travel planners with an additional algorithm for planned long-term roadworks.

1.6 Research Approach

With the research objectives and questions set out, a clearer picture is gained of the scope of the research and the envisaged results. To achieve these results a specific approach has been used in the research as described here.

The first step (**Chapter 2**) is a comprehensive literature review of the relevant areas of interest for this research. A general overview of the current workings of roadworks in the Netherlands is of interest, as this gives insight into the work field in relation to roadworks and communication with road-users at present. Furthermore a general overview of traffic flow theory, especially in relation to travel times and the underlying components that influence it and finally a look at current models and modelling approaches for travel time predicting and the estimation of its underlying components, are considered.

The specific approach and methodology used in the research and the development of the model are then explained in **Chapter 3**. This includes the main decisions concerning the set-up of the model, the main data sources used to develop and evaluate the model, and the final evaluation method.

Following this an analysis of factors that influence one of the main travel time components: the capacity, is performed which results in a relation between these factors and the capacity. Similarly the other main components affecting travel time are analysed and a modelling approach is proposed. This is performed in **Chapter 4**.

Thereafter the development of the model using the previously developed approach (**Chapter 5**) is explained. The model makes use of predefined parameters for roadworks configurations and historical traffic flow data as input, among others, to determine delays and consequently the travel times along the corresponding motorway corridor. The calibration of the model is further discussed in this phase of research.

Finally the model is evaluated by means of testing with independent roadworks data other than with which the model was developed (**Chapter 6**). The results give a good indication of the accuracy and workings of the model. An analysis is then given of the possible applications for the model (**Chapter 7**). Following this the main conclusions and recommendations are given including the final outcome to the research questions posed (**Chapters 8**).

1.7 Report Outline

The structure of this report follows that of the research as it was performed. A graphical overview of the report structure is given in figure 1.1.

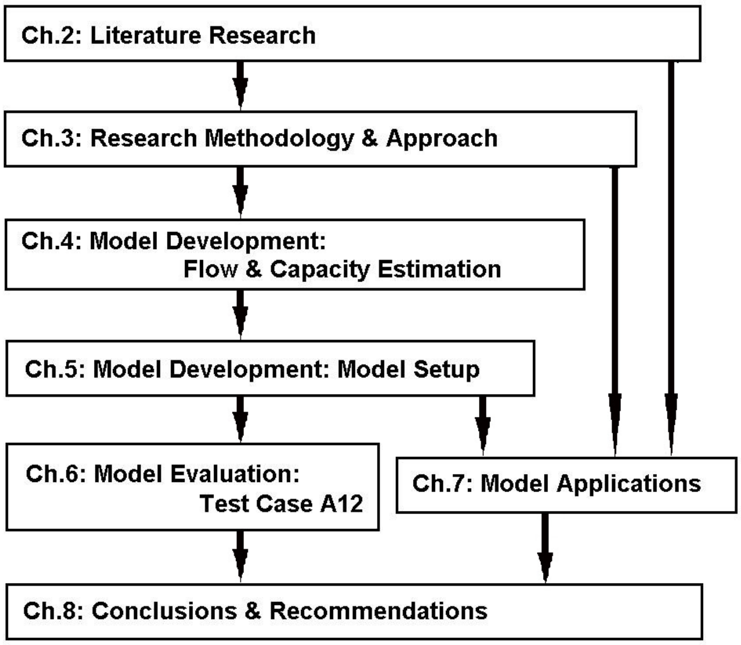

Figure 1.1: The structure of the thesis

2. Literature Research

Before explaining the development of a new method for travel time predictions for roadworks, an extensive literature research is performed. The main results of this are presented in this chapter. As part of this research work, a deeper understanding of the way roadworks are organised in the Netherlands is strongly desired. The literature research starts with this and looks at the general methodology from the planning side of roadworks and the way that nuisance and delays are communicated with road users (2.1).

Determining travel times in road traffic can be performed in many fashions. The basics of road traffic theory are researched and explained to gain a deeper understanding of the dynamics behind this (2.2). Finally an overview is given of modelling approaches that are available for road traffic modelling (2.3). In this overview a number of different approaches are presented for a wide selection of applications. From the knowledge gained by researching the various models, certain strengths and weaknesses can be obtained, which help the decision making process for the developed model presented in this research work.

2.1 Roadworks methodology

Before a literature analysis of the effects of roadworks on travel time is performed, a look at the current policy for roadworks in the Netherlands is taken. It is necessary to be aware of the way these roadworks are organised to aid the communication with road users. This is necessary because the proposed model to evolve from this research is aimed at travel time information for road users as determined by the road authority, which is in the case of the Netherlands: Rijkswaterstaat. The relevance of this research becomes more apparent with foreknowledge of these processes.
As mobility management holds a key part in roadwork planning, the description of roadwork methodology will be given from this viewpoint.

2.1.1. Methodology for roadworks and communication with road users

When a decision is made that work is needed on a motorway, a whole cascade of steps are put into motion. From the perspective of mobility management these steps are published in the Handbook Mobility Management for Roadworks[4], however these steps are generic for the planning of roadworks as a whole and correspond to the Rijkswaterstaat directives for roadworks[5]. In the mobility policy document the main path starting from the decision to perform work through to the project evaluation are described. Determining the severity of nuisance and mitigating measures for the road users, as well as the methods of communication with the road users hold the most relevance in relation to this research. These will therefore be elaborated on.

Mobility management is defined in the document as *"Organising smart travel".* This definition of Mobility Management is generally accepted as the norm in the Netherlands. Although other definitions are used in practice, in this research the definition held by Rijkswaterstaat ("Organising smart travel") will be used.

The generic project approach for planning roadworks follows the steps:

1. Initiation and initial planning of works
2. Preparation and scenario-planning
3. Works preparation
4. Implementation of roadworks
5. Project evaluation

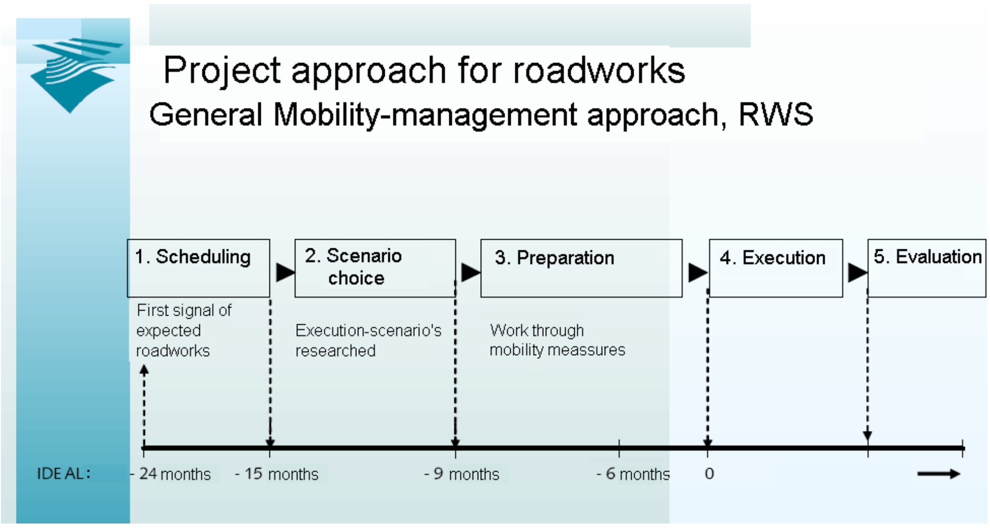

Figure 2.1: Roadwork planning approach (Rijkswaterstaat, 2007)

[4] In Dutch: 'Het Handboek Mobiliteitsmanagement bij Wegwerkzaamheden'

[5] In Dutch: 'RWS-richtlijn voor verkeersmaatregelen bij wegwerkzaamheden op rijkswegen'

The main phases for determining the levels of nuisance and communication with road users, take place in phases 1 through 3. In the first two phases initial calculations are made of the expected capacity drop due to the works and initial mitigating measures are drawn up. These calculations are rough estimates of changes to the capacity of a road, using official directives and software tools, and estimates of possible changes to the traffic demand. At an early stage, and often up to a year before the commencement of the works, the public is informed along with an indication of the expected nuisance. As the commencement of works nears, the accuracy of the delay predictions may change as specifics in the works planning are adjusted.

2.1.2. Determination of Nuisance- levels

In internal communication as well as communication with road users, *the level of nuisance* for road users is taken as the quantity to determine the extent of roadworks and severity of possible delays. There are five *nuisance categories* defined (see table 2.1). A nuisance category (A-E) gives a description of the extent of the roadworks and is determined by the expected delay caused either by congestion or detours and is displayed in a nuisance class (0-4) along with the number of road users affected by the roadworks.

Table 2.1: Nuisance Classes and Categories (Rijkswaterstaat)

		Road users affected				
Nuisance Class	Delay/Divertion	<1.000	<10.000	<100.000	<1M	>1M
0 no nuisance	–	–	–	–	–	–
1 small nuisance	< 5 min. / no traffic jam	E	E	D	C	B/C
2 some nuisance	5-10 min. congestion / divertion	D	D	C	C	B
3 much nuisance	10-30 min. congestion / divertion	C	C	B	A	A
4 extreme nuisance	>30 min. congestion / divertion	B/C	B	B	A	A

Category	Description
A	Extremely large works
B	Large works, non-national scale
C	Medium works, regional scale
D	Small works
E	Small closures

The *nuisance classes* are used by the road authorities to help determine the level of action that is needed to counteract the effect of delays and is further used to communicate with road users. Within the process of works planning, traffic management is given a prominent place in reducing the levels of nuisance for road users. The amount of traffic expected on a route where roadworks are to take place can be influenced resulting in a lower extent of nuisance for road users, through a wide range of measures from cheap or free public transport passes to extra travel information.

2.1.3. Communication with Road-users

Currently Rijkswaterstaat publishes general nuisance information as a result of roadworks on their website[6] and on a collective roadworks information website[7]. There the indication of delays is given in rough bandwidths. Road users can access information on the types of works to be performed and the type of alterations to the physical infrastructure, such as narrower lanes and reduced maximum speeds. The nuisance categories that are given however indicate to a road user merely if they can expect delays of a few minutes, of more than 10 minutes or more than 30 minutes. This is in conjunction with the nuisance categories and classes used in planning as was seen in the previous section. These levels of delays depend heavily on the traffic flows, which often in turn depend on the time of day and the day of the week. A road user gains an impression of the length and type of delay, without being able to more accurately plan their journey. Delays also depend on the time of day, the day of week as well as a large number of other factors. When the road is quiet in the evening for example, a road user may hardly experience any delays at all, while the same delay recommendation stands. Taking this into consideration, the availability of personalised travel advice is desired.

According to the Rijkswaterstaats Directive for traffic management with roadworks (2007), the main goal of information for road users is "*to achieve understanding for the necessity of the roadworks and to allow road users to anticipate for delays*". This is primarily performed through the nuisance indicators. For larger construction works extra information must be made available. This task is generally delegated to regional authorities, while at national level the extent of information is usually limited to descriptive information of the types of works and the nuisance classes. In 2006 the system *MELINDA* was set-up to coordinate information flows about roadworks between the road

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[6] This can be accessed at *http://www.rijkswaterstaat.nl/geotool/geotool_weg.aspx*

[7] This can be accessed at *http://www.vananaarbeter.nl*

authorities and service providers. This means information is collectively gathered and forwarded to the service providers. This allows for a better information service, however the quality of information remains of the same level of accuracy (Rijkswaterstaat: Handboek Communicatie bij wegwerkzaamheden: Categorie A).

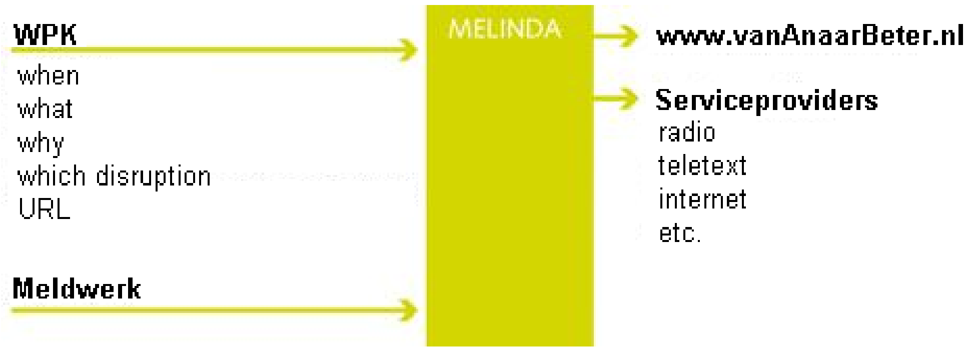


Figure 2.2: Information flow for major roadworks on highways in the Netherlands (Rijkswaterstaat)

Through the current methods, a road user gains an impression of the length and type of delay without being able to accurately plan their journey. Moreover when the levels of congestion are taken into account and therefore the delay shows a very large variance, it seems almost impossible for a road user to accurately determine their travel time with the current level of information. For this reason a necessity to offer more detailed and individual information about delays arises. This offers a huge opportunity for Rijkswaterstaat, as road authority, to give more accurate delay predictions and in doing so allow road users to plan their journeys more effectively. This also complies with Rijkswaterstaats wishes to reduce nuisance for road users by means of better information and travel advice. In such a manner Rijkswaterstaats definition of Traffic Nuisance[8]: "Nuisance as experienced by the road user", is taken into account.

2.1.4. Demand manipulation

The main focus for the explanation of the methodologies used in roadwork planning is taken from *mobility management*. One of the main goals of mobility management in roadwork situations is the reduction of the traffic demand on the motorways where roadworks are carried out. As will be explained later on in the literature review, the demand of traffic has an enormous influence on traffic conditions and especially during roadworks.

Rijkswaterstaat has made deliberate efforts to reduce the demand of traffic through the use of mobility management. On relevant motorway corridors, road users are encouraged to make use of alternative travel

[8] Taken from: *Kader: Werken met hinderbeleving – Rijkswaterstaat (2007)*

modes, to stagger their journeys outside of the peak hours or to avoid travelling at all (Rijkswaterstaat, 2007). To achieve this, various advice is given to both individuals and companies along the section of highway where works are due to take place. The actions include using public transport instead of car transport, use of bicycles or scooters, carpooling, travelling outside the peak hour (coupled with improved traffic information) and teleworking to mention just a few. It is also interesting to highlight that road users who choose or are bound to car transport, benefit from improved and more detailed travel information. It is deemed to have a positive effect on avoiding congestion or at the very least creating understanding and a larger predictability for travelling.

Evaluations of the use of mobility management in long-term roadworks in the Netherlands have shown a positive effect. In the summer of 2001 large-scale roadworks on the A10-West, which is part of the Amsterdam ring road, took place. The works began in May and lasted until August of the same year. During this period mobility management was used to encourage road users to use alternative options to driving in the rush hours. In the evaluation of the effects of mobility management during these works, a reduction was shown of some 10% in traffic demand along the relevant section of highway (Taale et al., 2002). A large part of this was attributed to the use of various mobility management initiatives during the works. Another large-scale roadworks evaluated for the effect of mobility management were those carried out on the A4 and A10-South from July until the end of August in 2006. During this period the capacity of the motorway was severely limited and the use of mobility management was deemed necessary. The evaluation study showed that a staggering 30% reduction in car use was achieved (Taale et al., 2002). According to the Handbook for Mobility Management (Rijkswaterstaat, 2007) a reduction of 40% in extreme cases is possible[9], however it is noted that this is optimistic and that a lower reduction in traffic demand should be considered. This is also backed up by the evaluations of other large-scale roadworks that showed very positive results, but nowhere near the 40%.

[9] Major roadworks on the A9 in 2006 is a good example of this (approx. 35%)

2.1.5. Conclusions

During the process of planning roadworks extensive attention is paid to informing the public about which works are planned and the consequences of these works. This is incorporated in the general planning for roadworks and is essential.

Although information is given to road users and updated at set intervals when more information is available, the quality of the information must also be considered. It is understandable that details may be sketchy months or even years before the works are due to commence, however shortly (weeks or days) before the commencement of the roadworks more detailed information is desired. Despite this road users are given global delays that are both not specific to time of day or phase of works. Road users are informed that delays are possible, but with uncertainty to the extent of the delays and also the probability that these delays will actually occur is not known, more specific and personalised (i.e. for specific departure time) information is recommended.

While travel time delays are given globally, great efforts are being made behind the scenes to reduce delays with the deployment of mobility management. Over the last decade various mobility management projects have managed to reduce traffic demand where roadworks are carried out by tens of percent. Theoretically according to the norm, reductions of 40% can be achieved in extreme cases. The reduction in traffic demand reduces the chance of congestion and therefore also the extent of delays.

> Information is widely available during the process of roadwork planning. However near the commencement of the works, travel times (delays) remain rough and offer little more than a global indication of delays. Furthermore mobility management has had great success in demand reduction during roadworks and must therefore not be discarded.

2.2 Basic Traffic Theory

Informing road users of the expected road conditions as well as the delays that can be expected is valuable information especially when travel times show great variance over the duration of a day. It is not a straightforward task to say something about travel times under varying traffic conditions and for varying roadwork types, as many factors influence this. It takes a deeper understanding of the basic governing traffic theories to understand how travel times and therefore also delays are measured, calculated and predicted. These and their influence on travel times are explained in this paragraph. Publications by Hoogendoorn (2007) and Maerivoet & de Moerde (2008) explain the underlying theory and are used as the main sources in describing it here.

2.2.1. Fundamental Traffic theory

To be able to understand the influence that roadworks have on travel times, it is first necessary to outline the basic principles of traffic theory. Traffic theory framework is based upon a principle of demand and supply. Figure 2.3 gives a schematic overview of the framework.

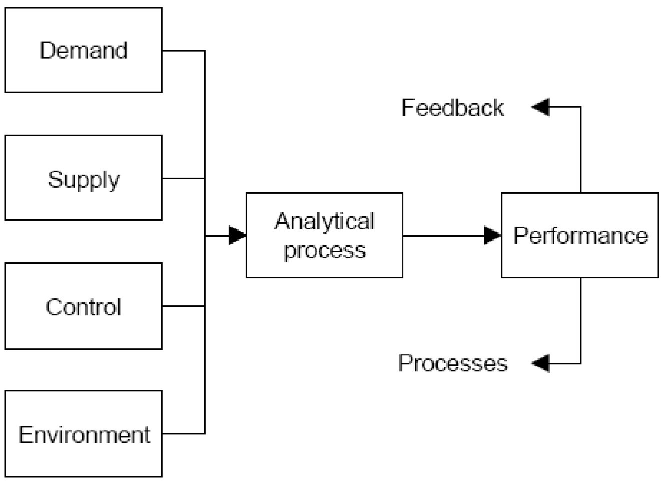


Figure 2.3: Analytical framework for demand-supply analysis of traffic systems (Hoogendoorn, 1990)

The principle dictates that a demand, in the case of traffic this is the number of vehicles, can be met with a certain supply, the capacity of a road. As long as the demand is lower than the supply or capacity traffic can flow without congestion. At the point that the demand exceeds the capacity however, various phenomena occur. These phenomena are explained further in the following paragraphs.

Traffic Flow Theory
While the theoretical capacity of a road has a set value, the real operational capacity has not and changes depending on the ruling traffic conditions. To understand this, the fundamental traffic flow relations must be explained.

In traffic flow theory a distinction is made between *microscopic* and *macroscopic* traffic flow. Microscopic traffic flow theory focuses on the characteristics of an individual road user, while macroscopic flow theory focuses on a large number of vehicles simultaneously. This can be described by taking a look at the time-space in figure 2.4.

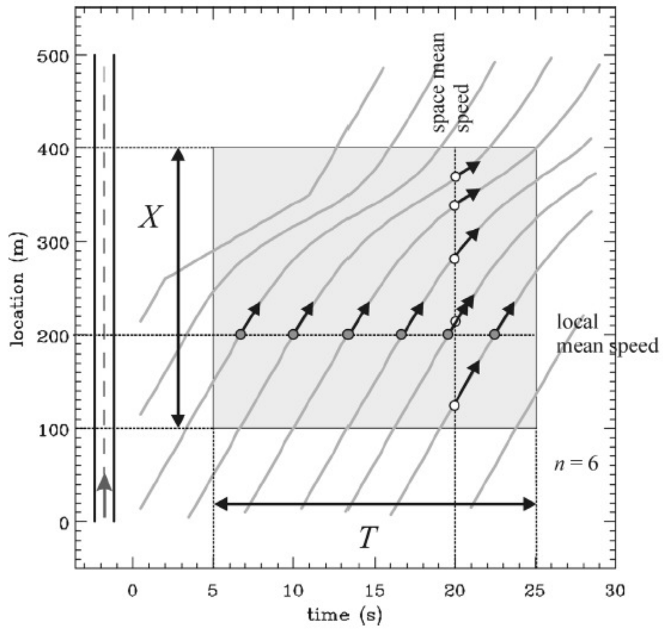


Figure 2.4: Location-time diagram for vehicle trajectories (Hoogendoorn, 2007)

Travel time
The time-space trajectories of each vehicle are given microscopically, because the specific characteristics of each road user can be followed and with that the various parameters of their journey (such as speed, acceleration, travel-time, etc.). However when all road users on a specific stretch of road or at a specific time are taken collectively, one refers to this as macroscopic traffic theory.

In traffic, travel time is broadly defined as '*the time necessary to transverse a route between any two points of interest' (HCM, 2000)*. When determining an individuals travel time between two points, the mathematical definition held is the total distance travelled divided by the dynamic speed of space-mean speed over that distance. This formulation is known as the *instantaneous travel time*:

$$T(t_0) = \int_0^x \frac{1}{v_s(t_0, x)} dx \tag{2.1}$$

However when working with macroscopic traffic flow it is a collective travel time that is calculated. This is performed by taking the total distance travelled by all vehicles and dividing this by their space mean speed:

$$T(t_0) = \frac{\sum x}{\bar{v}_s(t_0)} \tag{2.2}$$

As this research focuses on producing a model that yields overall travel times and therefore values that represent all vehicles, a macroscopic model is preferred. This is furthermore confirmed when considering the calculation times of microscopic and macroscopic model, wherein microscopic models need longer simulation times as each vehicle is individually modelled.

Main traffic parameters

To this extent there are a number of main parameters, which can be identified in the macroscopic traffic theory. The governing parameters are the *flow (q), density (k)* and *mean speed (v).*

Flow (q) is defined as the number of vehicles that pass a certain place on a road (often denoted as detection point) divided by the time over which the count takes place. This results in an intensity of traffic, a quantity that is often used to describe how busy a road is. The flow is expressed by the following equation:

$$q = \frac{n}{T} \tag{2.3}$$

Where: N = number of vehicles
T = length of time

The *density* (k) in traffic theory indicates the how crowded a certain section of road is and is defined by the number of vehicles occupying the set section of road. Because it is often complicated or expensive to determine the density directly, indirect estimations of the density are usually made. The reason for this is that the density is an instantaneous quantity and therefore cannot be easily measured from a single location. The general equation for the density is:

$$k = \frac{n}{X} \tag{2.4}$$

Where: n = number of vehicles
X = set distance

When it comes to describing the speed, it is important to keep in mind that there are different ways to determine an average speed. For macroscopic traffic theory, the *space mean speed* is most commonly used, as it has a direct relation to other fundamental quantities. However often it is the *time mean speed* that is more readily available, therefore care should be taken when analysing mean speed data. The fundamental difference is the way they are calculated. The *space mean speed* is the average speed measured by the time travelled between two points along a set section of road. The *time mean speed* is the average speed of all road vehicles over a period of time at a set point. The mean speeds are expressed as follows:

$$v_s = \sum \frac{T_i}{X} = \frac{1}{X} \cdot \sum v_{si} \tag{2.5}$$

$$v_t = \frac{1}{X} \cdot \sum v_{ti} \tag{2.6}$$

Where: T = travel time for vehicle i
X = set distance
v_i = speed of vehicle i at a set point

Between the three mentioned parameters exists a unique relation known as the *continuity relation*, which is expressed as such:

$$q = k \cdot v \tag{2.7}$$

Fundamental diagrams

Equation 2.7 is an important equation in explaining the relations between the three basic parameters in traffic flow theory, as it allows one to easily calculate other variables from the measured data. Measured data may also be shown in statistical relations between the fundamental parameters in the three *fundamental diagrams.* These diagrams are proven to be generic for traffic flow and are an essential part of traffic flow theory. The relations between the parameters are expressed in the fundamental diagrams as shown here in the following figure:

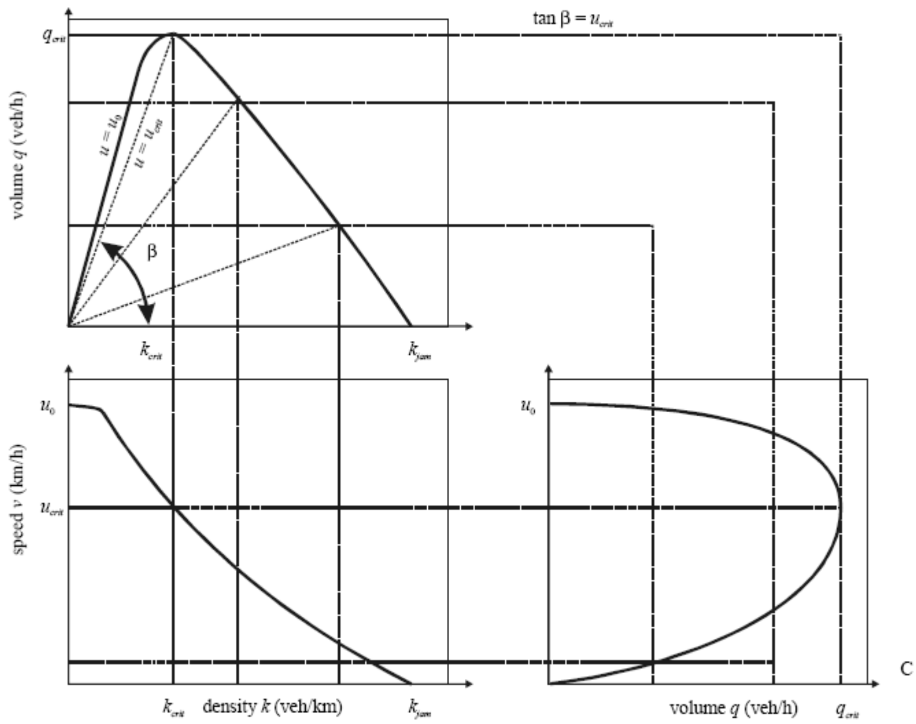
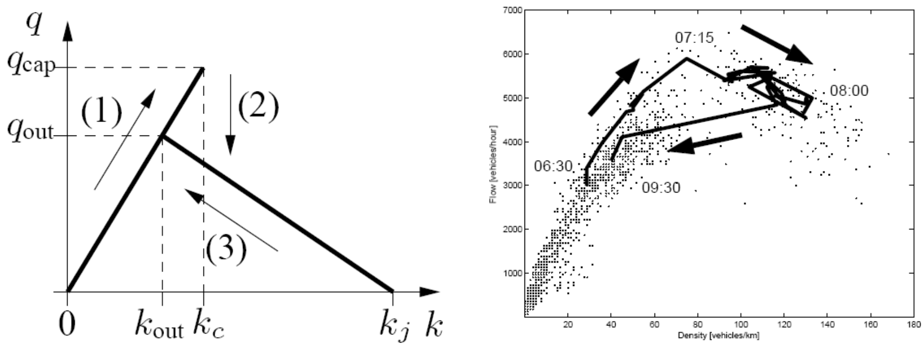


Figure 2.5: Fundamental diagrams and their interrelations (Hoogendoorn, 2007)

Each diagram in figure 2.5 shows the relation between two of the three basic parameters and has further advantages. One of these main advantages is the ability to calculate the capacity of a road section using empirical data to construct the fundamental diagram. The operational capacity of a road will generally be the point at which traffic flow is critical and congestion is likely. This can be seen in the fundamental diagrams. At this point, denoted by the subscript 'crit', the addition of further traffic will cause congestion and the throughput, or simply flow, will start to decrease. Using this the capacity speed, density and flow can be calculated. Fig. 2.6 shows this for real data.

Figure 2.6: Flow-density fundamental diagrams (Maerivoet & de Moerde, 2008):

a) Theoretical b) Operational



When viewing the real data points in the fundamental diagram, it is necessary to point out that the flow can take on two different values for a single density depending on the traffic conditions. The diagram is said to demonstrate *hysteretic* behaviour. This basically means that for a certain value of the density multiple values for the traffic flow can be viewed and that multiple states can be present due to the fact that the path to the extreme state (qcap) is different than the path leading back from this state (Maerivoet & de Moerde, 2008). Figure 2.6 further shows at (2) a sharp reduction in the capable flow of capacity of the road. This is known as the *capacity drop*. When traffic flow breaks down, a drop in capacity results which is generic for all traffic flows in this situation. In a system with hysteresis it is not easy to accurately predict the output without knowing the system's current state. To learn what the system's current state is, it is necessary to know the history of the input. This means that knowledge is needed of the path that the input followed before it reached its current value. This is particularly relevant for real-time applications, but also for predictive ones too. An estimate is made of the expected current conditions based on historic data. This allows for a pattern to be derived and applied in forecasting.

The relation this has to the capacity flows, on the supply side, and the consequences of roadworks on the capacity is given in the following paragraph.

2.2.2. Traffic flow characteristics (normal and reduced capacity)

Onset of congestion and queuing

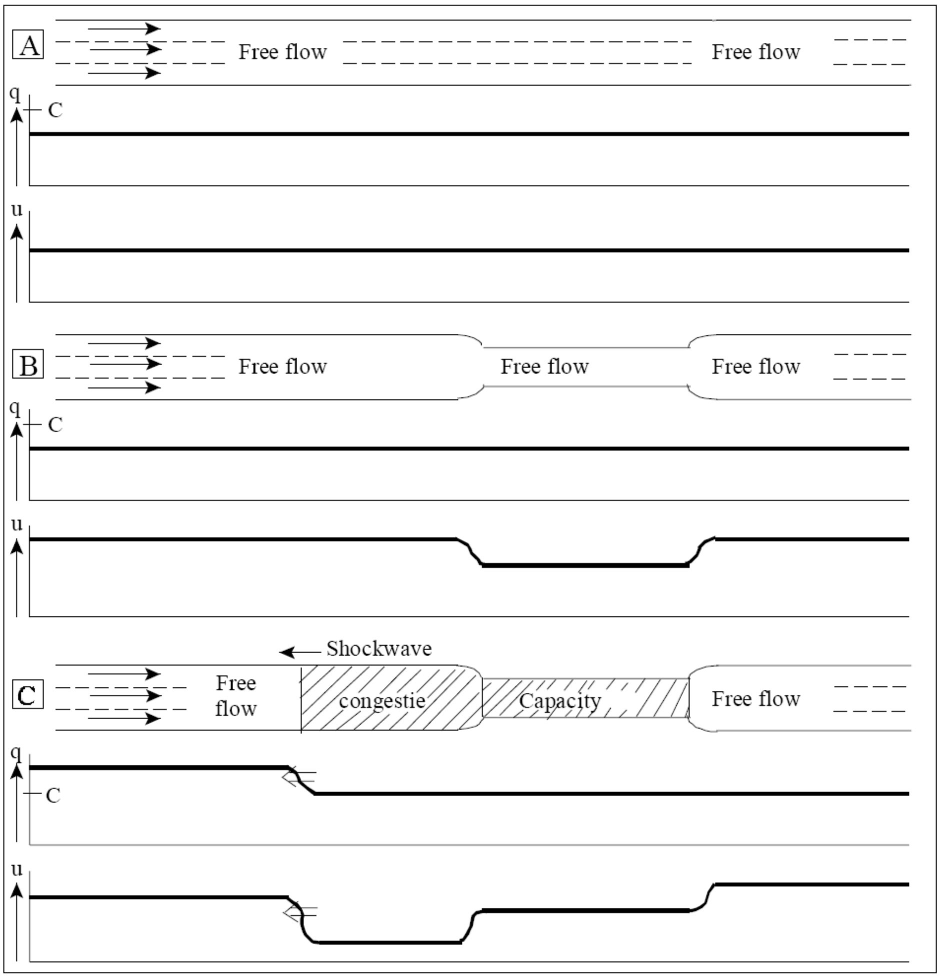
Explaining the theoretical phenomena that take place in a real life situation during the onset of congestion can best be undertaken by means of a graphical example. In figure 2.7 three scenario's on the same stretch of road are shown.

Figure 2.7: Traffic flow at bottleneck (Adapted from Hoogendoorn, 2007):

a) Bottleneck capacity > flow

b) Bottleneck capacity = flow

c) Bottleneck capacity < flow



Scenario A shows the road under normal conditions with the capacity (6000) of the road being higher than the traffic flow demand (4000). Under these circumstances the traffic is in a state known as *free flow* along the road without experiencing congestion or extensive delays. When roadworks take place, as shown in scenario B, we see the capacity of the road drop along the location of the roadworks. The capacity here is at 4000 veh/hr and therefore is equal to the traffic flow demand. As the demand does not exceed the capacity, congestion will not occur (in this non-stochastic example). However capacity flow will occur, which will influence the speed at which traffic will be able to travel. This is due to the fact that vehicles drive at close approximation to each other and therefore affect the possibilities to travel freely. This can also be easily viewed in the speed-flow fundamental diagram, for the point at qcap.

In scenario C the same roadworks situation is taken as for scenario B, however the traffic flow demand (5000) is now at a level that represents a busier part of the day, such as a rush hour. In this scenario the demand is lower than the capacity both before and after the roadworks section, The capacity along the workzone is lower than the traffic demand and therefore congestion occurs. As the congestion forms it leads to queues stream upwards of the roadworks location. The formation of congestion corresponds to a high density of vehicles driving at a relatively low speed. This can be equally viewed in the fundamental diagrams. The speed not only decreases, but also the traffic flow decreases. This means in turn that fewer vehicles can pass the roadworks per hour and congestion has the chance to worsen. This is known as the *capacity drop* as a result of the congestion, as previously seen.

As a result of the lower speeds due to congestion caused by the roadworks as demonstrated in scenario C (which otherwise would not have occurred), it becomes obvious that roadworks can have a large effect on the travel times on a section of road. Even when congestion does not occur, scenario B shows that vehicles can encounter a lower speed along an area where roadworks are present. This will in turn affect the travel times of road users and this effect will be magnified especially for longer sections of works, as the travel time depends on the distance travelled at a certain speed as seen in equation 2.2. The manner in which queues and the corresponding delays are calculated is described in the following section.

2.2.3. Traffic queuing & shockwave theory

We have seen that bottlenecks caused by roadworks can lead to congestion. The resulting queues and delays from this congestion can be calculated using a different methods. The *deterministic queuing model* is commonly used as it can give a correct and accurate delay due to a queue (Hoogendoorn, 2007). Shockwave theory is also commonly applied to explain traffic queuing phenomena. Deterministic queuing models are best explained using figure 2.8.

Figure 2.8: Graphical depiction of queuing in time (Hoogendoorn, 2007)

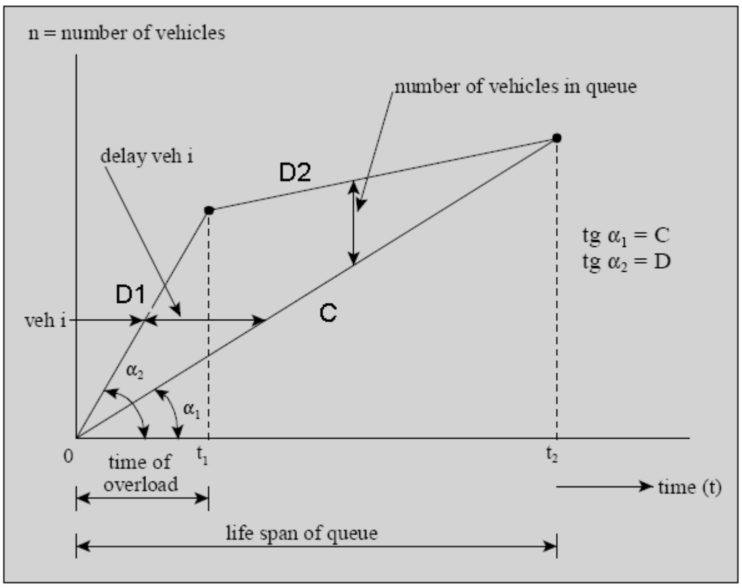


Fig. 2.8 shows a flow-time diagram in which the capacity is given by C and the traffic flow demand is given by D. At a certain point the demand D1 exceeds the capacity C and a queue starts to grow along the time axis. At another point in time the demand changes (decreases) to demand D2 which is lower than that of capacity C (this can be seen by the gradient) and the queue begins to disperse.

Because the model is based on the principle of conservation of flow (Karim & Adeli, 2003) and therefore only requires the knowledge of the capacity and traffic flow demand, while producing accurate results, it is seen as a dominant method for queue and delay calculation.

The queuing model however does have a shortcoming in the fact that it queues vehicles vertically. This means that the queue is measured from a single point and may not propagate from its original location. In the case of a bottleneck queue, this is not unrealistic as this type of queue will generally remain at the same location until demand has reached a low enough level. Other queuing models may make use of *shockwave theory* (Karim & Adeli, 2003) or will be of dynamic nature. In such models multiple consecutive sections are used to model the traffic flow, with the previous sections passing on traffic flow and queue information onto the next. In this way the verticality of the model is (partially) eliminated. Such an approach is especially useful when using the queuing model in a network situation.

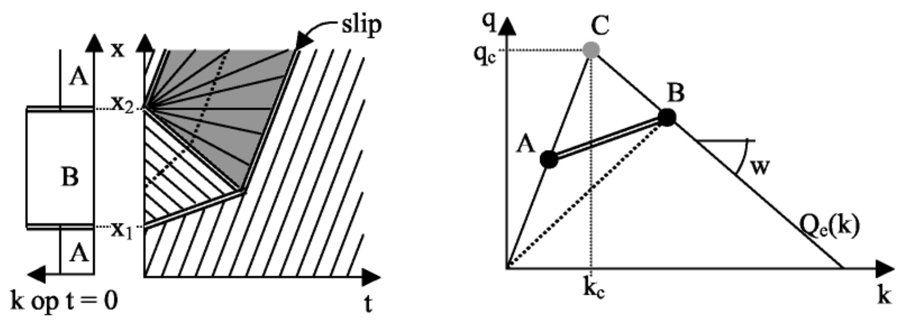


Figure 2.9: Graphical representation of first order traffic theory (Maerivoet & de Moerde, 2008)

The modelling of shockwaves is made possible by use of *first order traffic flow theory*. A simplification of this is shown in figure 2.9. This basically entails making use of a simplified fundamental diagram and from deriving the macroscopic movement of these 'congestion' shockwaves. These waves will move at a rate corresponding to the lines from the fundamental diagram, which is almost always recorded between 15 and 20 km/hr in an upstream direction. This means congestion will propagate upstream at a speed that can be calculated making use of this simplified graphical relation. Being able to determine the location of congestion helps to more accurately determine travel times.

A method which has been widely used for the modelling of traffic flows and includes congestion modelling according to first order traffic flow theory is the LWR (Lighthill-Whitman-Richards) method. The method is deemed to be relatively simple and at the same time robust (Chiabaut & Durlin). The method is based in essence on a scalar conservation law using the variables density and flow (Eq. 2.8). Combining the conservation equation with the flow definition (Eq.2.9) and the equilibrium fundamental relation (Eq.2.10), the main set of equations are given which allows the model to produce a representation of traffic using capacity and flow data.

$$\frac{\partial k(x,t)}{\partial t} + \frac{\partial q(x,t)}{\partial x} = 0 \tag{2.8}$$

$$q(x,t) = k(x,t) \cdot v(x,t) \tag{2.9}$$

$$q(x,t) = Q_E(k(x,t)) \tag{2.10}$$

Where:
k = density
q = flow
v = average speed
Q_E = fundamental diagram
x = space step
t = time step

As the method makes use of flows that influence both upstream and downstream conditions, the model is generally solved numerically by using the Godunov scheme. The scheme iteratively determines the allowed flows for each space and time step as well as the traffic density for each section by solving the corresponding Riemann problems making use of the equations from the LWR-model.

2.2.4. Conclusions

In this paragraph the basic theories on traffic flow have been discussed to explain what the underlying theory in traffic flow entails and the position these accommodate for travel time predicting. This showed that the process of determining travel time is based on the principle of supply and demand. In the case of traffic this is the supply of capacity and the traffic flow demand.

Distinction is made between microscopic and macroscopic traffic flow. The earlier taking the movement and characteristics of each individual road user into account while the latter looks at traffic from a collective point of view.

We have further seen that the main parameters – speed, flow and density – combined in the continuity equations, as well as the empirically based fundamental diagrams form a powerful basis for traffic flow theory. These factors lie at the heart of traffic flow and therefore also at the heart of predicting travel times and for this reason cannot be ignored.

Travel times are obviously susceptible to congestion and delay caused thereby. The onset of congestion, although fundamentally basic, is closely connected to a high level of stochasticity in traffic flows stemming from the actions of individual drivers. It is therefore important to take this effect into account.

Not only the onset of congestion, but also the manner in which congestion propagates requires attention. A basic queuing method is generally easy to implement and harbours sound theory. The theory is incomplete however when considering the dynamics of congestion. Shockwave theory has the capability to consider this movement of congestion in space and time and offers an excellent addition to the basic theory. For this reason a combination of queuing and shockwave theory is sought that makes use of the LWR-method in which a reliable and robust representation are given, while not unnecessarily complicating the model and adhering to traffic flow theory.

How these theories are implemented in the developed model is shown in later chapters.

2.3 Model-driven approach

As explained in the previous paragraphs, travel times in traffic flow theory are dependent on an interaction between demand (traffic flow) and supply (road capacity). This forms the basis for traffic theory and therefore often also the modelling of traffic flows and related quantities. In this paragraph an overview of the types of traffic models for determining the behaviour of the fundamental traffic conditions will be given. For the relevant model types, some specific methods will be further elaborated on, which have potential use in this research. An evaluation of the methods is performed in the following chapter.

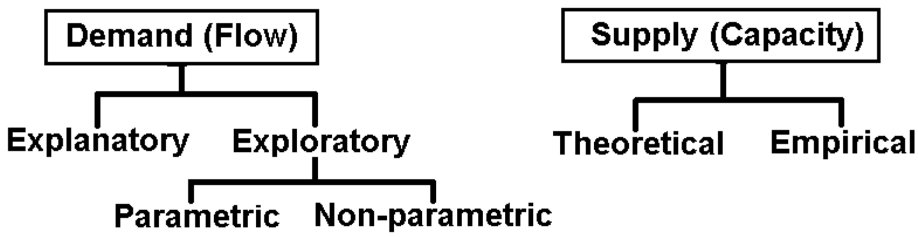
For the analysis of the different types of modelling methods, a distinction will be made between methods which deal with the demand (flow) side (2.3.1), methods which deal with the supply (capacity) side (2.3.2) and methods which combine the outcome of the these two (2.3.3) to produce travel time predictions.

The considered methods in this chapter are:

Table 2.2: Considered methods

Flow Methods	Capacity Methods
ARIMA	Factor Method
Kalman Filter	Headway Distribution
Data Fusion	Fundamental Diagram
Neural Network	Queue Discharge Distribution
	Product Limit Method
	Neural Network

Figure 2.10: Traffic modelling types (Derived from Versteegt & Tampére, 2003)



2.3.1. Flow modelling

Modelling of the traffic flows for a specific section of road can be performed on the basis of two main modelling types: the explanatory and exploratory methods (Versteegt & Tampére, Vlahogianni et al, 2003 & 2004). Explanative methods are based on the principles of traffic flow theory and therefore are derived from the basic governing principles of traffic flow theory as described in the previous paragraph using the fundamentals of traffic flow theory. Explorative methods are based on statistical analyses of real data and do not rely on a strong theoretical bases for the modelling of processes. In the statistical analysis a relation is determined from the input data in an effort to describe these processes.

Explanative

Explanative methods take set parameters and variables in an explicit form as input for the theoretical modelling of traffic demand on certain roads (Versteegt & Tampére, 2003). To accomplish this, a large amount of information is needed about both the physical traffic infrastructure and more importantly all road users (or at least a representation of this). This information is used to assess and then assign road users to a specific route and in doing so modelling the traffic flows along certain roads. There are two main types of explanative methods: *Traffic assignment* and *traffic state based methods* (Versteegt & Tampére, 2003).

The first type, traffic assignment, works along the principles of an analytical method using an origin-destination matrix and assigning traffic along specific routes depending on a cost function. In this research, this type of explanative method will not be considered for three main reasons. Firstly, the type and amount of information needed to determine route-choice and assignment under the irregular conditions of roadworks are deemed too extensive to make easy predictions in the developed model. Secondly, the envisaged road layout considered for use in the model is a single stretch of road and does not allow for multiple routes.

The second type, the traffic state based methods, makes use of knowledge of the traffic state, such as intensities and speeds, to determine future traffic conditions. These methods have a main advantage that they are based on traffic theory, while being allowed to take non-theoretical influences into account for making predictions. Kinematic traffic flow theory is a main type of this kind of model. This will be considered for the main modelling part of the model, but not for creating a demand profile, as this is a step further than is necessary.

Finally, this type of modelling relies on simulations and therefore omits many parameters of real life travel. Simulated results do not directly take real life data into account except for calibrating and validation. This can yield good results, but is not as suited for the creation of a demand profile in our case and can also be very time consuming for a single location making it also less suitable for in this model.

Explorative

Although explorative methods do not directly take the governing traffic flow theories into account, they have proven to be very accurate in analysing and producing reliable results. This is largely down to the fact that these methods can determine the daily and weekly patterns that are present in real life traffic flows along a set road section with relative accurately (Verhaeghe, 2007). In doing this they have the capability to be more accurate in predicting ex-ante flows, because the recurrent immeasurable interferences that cannot be measured by explanative methods are included in explorative methods.

As categorised by (Vlahogianni et al, 2004) explorative methods can be further separated into parametric and non-parametric methods. The term parametric refers to the assumption of a specific functional form for the dependent and independent variables used in the model. Depending on the type of parametric explorative method a certain type of function will be used to approximate a relation from the data. Contrary to parametric methods, non-parametric methods do not assume a specific function and approximate the governing functions by extensive iteration using the principles of pattern recognition and chaotic systems (Smith, Williams & Oswald, 2002). This has a number of advantages and disadvantages in comparison to a parametric approach. The main advantages arise from the fact that the non-parametric methods are not bound by a certain function and therefore have a greater opportunity to self-select an approximation of function type that is most suited to accurately solving the problem. This can often lead to large improvements in accuracy and reliability in comparison to parametric methods as proved by (Van Lint, 2005). However allowing these non-parametric methods to approximate a solution without a specific starting function demands a large amount of data. This data is required to *train* the model to allow it to give accurate outputs. That these methods not only require large amounts of data, but that the process of determining results is implicit and means they cannot be easily ratified. The data intensive character of the non-parametric methods and the black-box character are seen as the largest disadvantages. The increasing computational and algorithmic power of these non-parametric methods nevertheless continue to produce better results (Vlahogianni et al, 2004).

Types of explorative methods

Examples of currently used parametric methods are ARIMA, Kalman filters and Data fusion. Besides these, simple regression methods such as various non-linear regression methods, Bayesian linear regression, logit/probit estimation and data fusion also exist. Furthermore neural networks are available as a powerful alternative.

ARIMA

The *ARIMA* method is a statistical method, which is not uncommon in predicting travel times in the past. The method is seen to yield good results, while not being too complicated or data intensive in use. The method makes use of an autoregressive part and a moving average part. The autoregressive part analyses the data and derives relations from it, while the moving average part integrates multiple data inputs and forms an average value from the data and computed relations. This allows for a more powerful predictive and regressive use, while maintaining a good representation of the available data. A disadvantage often mentioned in literature however is the difficulty that the method has processing outliers (Vlahogianni et al, 2004). For this reason it is imperative to process the data for these outlying values before using this method to process the data.

Kalman Filter

A *Kalman filter* is a recursive filter based method, which estimates a certain value, i.e. the traffic flow (Van Lint & Hoogendoorn, 2006). The estimation is made by introducing data input and combining this with governing system dynamics, such as traffic theory. The prediction is compared with real data and is corrected in the following iteration. The more real life data that is available allows for more corrective steps and iterations and therefore should lead to a more accurate result. A Kalman Filter is probably more suited for use in real-time applications as it has the capacity to correct the outcome based on new information. Off-line use is possible, but it may be more effective to make use of other techniques, as these can more effectively calculate output hence it is not possible to update real-time.

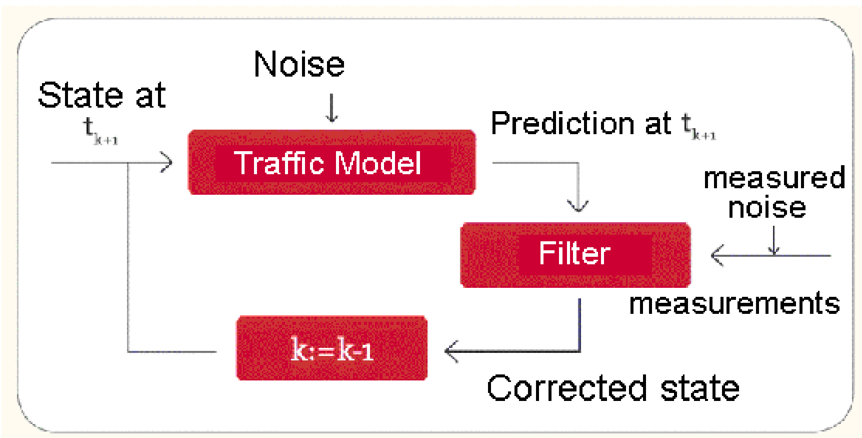


Figure 2.11: Flow diagram of a Kalman Filter (Van Lint & Hoogendoorn, 2006)

Data Fusion

Data Fusion is a method used to combine various input data to produce a completer and more accurate output of the required quantity. In traffic the use of speed and flow data can be used to gain a more comprehensive overview of traffic conditions on a stretch of road. Furthermore raw traffic data can be corrected for various errors, allowing for more reliable dataset. Hoogendoorn & Van Lint (2008) developed such a filter in which a combination of smoothing and data fusion are incorporated in space and time. This form of data smoothing is generally less demanding for calculation time and in complexity, and generally yields good results. Using this filter, data is processed in a relatively accurate manner and gives a good representation of the governing patterns by filtering out extreme unrealistic values and correcting for missing and corrupted data. Figure 2.12 shows some results of this filter, with the filtered data showing fewer unexplainable outliers and corrected data for under performing detectors.

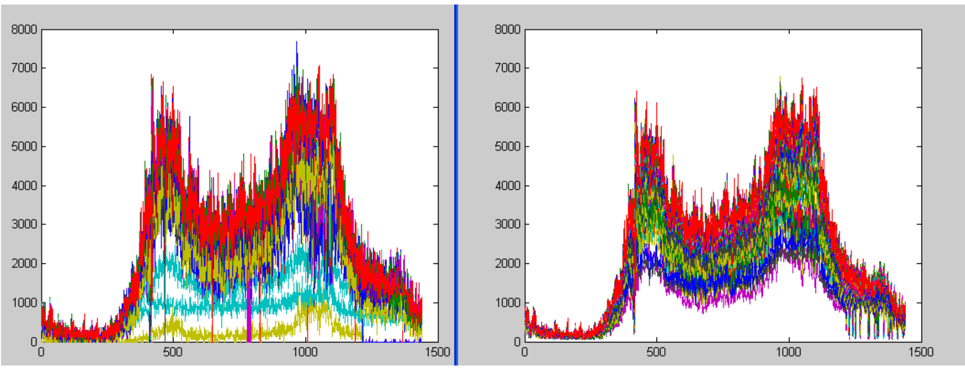


Figure 2.12: Comparison between raw (left) and filtered data (right) using the filter developed by Van Lint & Hoogendoorn

It should be noted that although the filter eliminates errors or/and missing data, it often does this in a manner that introduces a bias at and near the locations where the corrupted or missing data was present. For this reason it remains advisable to use raw data with no or a very low level of corruption and/or missing data when available.

Neural Network

The main and most advanced type of non-parametric method is the neural network. Although there are various types of neural networks developed and in development, the general workings of a neural network are pretty generic.

A *neural network* consists of three parts: the input, the neural layer(s) and the output layer as described in many publications. Data is fed into the input layer and sent through to one or more neural layers, which in turn will consists of a varying number of neurons. Each input from the input layer has a designated strength or weight and a threshold value. Each neuron also has a threshold value. The weighted sum of the inputs composes the activation of the neuron after subtraction of the neuron threshold value. This activation signal is then passed through an activation function to produce the output of the neuron. This process is repeated many hundreds or thousands of times with different sets of data to train the neural network to any relations in the data. Typically neural networks will be *feed forward* in structure (known as Feed forward Neural Networks: FNN). This basically means that the neural iteration is processed from the input layer, through the hidden neural layers to the output layer. Other types of neural networks with feedback algorithms or other adjustments to gain better results also exist, such as state space neural networks (SSNN) or time delayed neural networks (TDNN). By the use of additional manipulation in the hidden layers, more accurate results are achieved, possibility with fewer iterations or with a smaller data set. These will not be discussed in detail here.

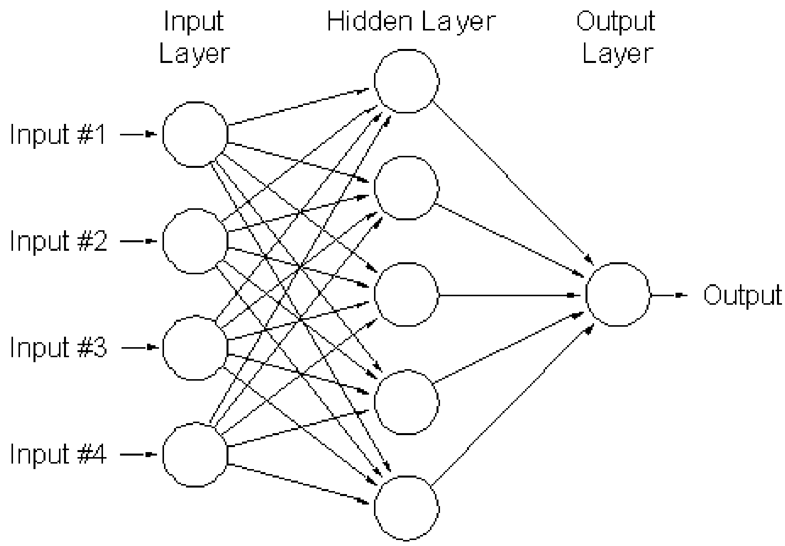


Figure 2.13: General layers in a simple Neural Network (Stagg, 2007)

It should be noted that certain methods eliminate the necessity of supply and demand comparison by directly determining the patterns in travel time. This often returns good results, however the use of explorative methods in this way are not possible for this research as there is no real travel time data available. This is due to the fact that research question states that the model is to be able to predict travel time a-priori, or in other words for situations where no roadworks are in place yet. Therefore no travel times have been realised. This tactic can be used in this research to determine base travel times without roadworks for the case that factors are used on the current travel times to determine the future travel times. The neural networks can also be used to generate the predicted *traffic flow demand profile*.

2.3.2. Capacity modelling

On the supply side of the equation is the capacity of a road. The *capacity* of a road is defined as *"the maximum hourly rate at which vehicles can reasonably be expected to transverse a point or uniform section of a lane or roadway during a given time period under prevailing roadway, traffic and control conditions"* (HCM, 2000). As explained in the previous paragraph, a road has a theoretical capacity and an operational capacity. The theoretical capacity of a road is the capacity that the road should be able to achieve under ideal traffic conditions (as conditions are never 100% ideal this value is never reached!). We have also seen that traffic is a stochastic entity however and that fluctuations in traffic flow can lead to the premature onset of congestion, which was shown by means of the fundamental diagram. These fluctuations do not always have to be connected to pure stochasticity and can often be initiated by certain (unmeasured) characteristics of a road.

Road capacity may also be seen as a *static quantity* or a *dynamic quantity*. With the onset of congestion we have seen that the capacity of a road will drop, leading to a lower capacity post-queue in comparison to pre-queue which can reach levels of up to -15%, accredited to the *capacity drop* (Hoogendoorn, 2007). There are basic traffic models, which do not take this capacity drop into account, however most are in some way dynamic in nature. As seen from fundamental diagrams and also shown in fig. 2.5, traffic flow will at a certain density breakdown and a drop in capacity and flow will be visible. At the point where traffic is slowed, or in other words at the bottleneck, traffic flows at capacity. This is due to the fact that traffic flows through a bottleneck at a steady speed, while congestion is found upstream of the bottleneck. In the bottleneck a near maximum flow can be measured with a high density while vehicles propagate at a reasonable speed. This is measured and gives an accurate estimate of the lane/road capacity. Three commonly use types of theoretical based methods and three empirically based methods are discussed. The considered methods are:

Table 2.3: Capacity estimation methods

Theoretical methods	Empirical methods
Basic Capacity Estimation method	Queue Discharge method
Headway Distribution method	Product-Limit Method (PLM)
Fundamental Diagram method	Neural Networks (RBFNN)

These are each discussed in the following subsections of this paragraph.

a) Theoretical Methods

Three types of theoretical methods will be discussed: those that use a basic capacity estimation method, those that make use of a headway distribution method and those, which use the fundamental diagram method.

A **basic capacity estimation** can be made by taking the theoretical design capacity of a road and applying a number of factors in an attempt to derive an acceptable capacity estimation. An example of such a method is the use of the following relation as described in the Highway Capacity Manual (2000)[10]:

$$c = c_j \cdot N \cdot f_w \cdot f_{HV} \cdot f_p \qquad (2.11)$$

Where:	c_j	=	lane capacity under ideal conditions
	N	=	number of lanes
	f_w	=	lane width and lateral clearance factor
	f_{HV}	=	HGV factor
	f_p	=	driver population factor

This method presumes that the capacity under ideal circumstances is effected by various factors that reduce the capacity. By using these factors in the equation, an estimation is made of the capacity. This method does not automatically take a capacity drop into account and is therefore not dynamic to changes in traffic conditions.

The **headway distribution method** makes use of the average headways between vehicles (Verhaeghe, 2007). This value is in most cases a generic value for certain roads at specific speeds and can therefore be applied. The relation used is the following:

$$q_{cap} = \frac{k}{h} \qquad (2.12)$$

Where:	q_{cap}	=	capacity flow
	k	=	critical density
	h	=	headway

It is clear that the chosen values are susceptible to subjectivity and choosing the right values is not a trivial task. Furthermore there is no consideration of a capacity drop.

[10] The HCM also provides equations for capacities in workzones: see chapter 4

The third theoretical method is the **Fundamental diagram method**. This approach makes use of the traffic flow theory worked out in the fundamental diagrams without using measured data points. As seen previously the capacity of a road can be derived from the fundamental diagram. With this method a choice of diagram form must be made and estimates must be made of the critical density of the road. These can be performed in relation to the expected vehicle behaviour and physical characteristic of the road.

b) Operational-Empirical Methods

There are many methods for determining road capacity from real traffic data. Most make use of relations between measured flow and (empirically determined) fundamental diagrams. The main methods used for traffic flow determination of the capacity and an alternative method will be discussed.

The **queue discharge distribution method** is a method that makes use of observations of the discharge flow out of bottlenecks on a stretch of road to construct a capacity distribution or obtain a value for the capacity. It is generally accepted that a capacity flow can be measured at a short distance downstream of a bottleneck[11]. By measuring the discharge flow out of such a bottleneck an estimation of the capacity of the road for the section in which the bottleneck is present can be made.

Another empirical method is the **Product-limit method (PLM)**. This method makes use of observations of both flows below capacity and at capacity flows to determine a more complete capacity distribution over a section of road. The method relies on the construction of a distribution in which a number of measurements are admitted. The method makes use of a likelihood function:

$$L = \prod_{i=1}^{n} f(q_i)^{1-\delta_i} S(q_i)^{\delta_i} \tag{2.13}$$

The capacity is estimated in this function with the help of a capacity survival function S(q) and partial differential equation: f(q). There are two types of PLM's: parametric and non-parametric. The parametric type uses the natural logarithm of the likelihood function to fit the distribution and determine the capacity. The non-parametric type uses

[11] Bottleneck: a point or section of road where the flow is at it's lowest and therefore at a critical level.

cumulative estimations of the survival function to determine the capacity. A detailed working of this method will not be discussed at this point.

In a study on capacity and queue estimation in workzones, Karim & Adeli (2003) make use of a **Radial Basis Function Neural Network (RBFNN)** to make predictions of the capacity in a work zone. Previously we saw that neural networks can be very powerful in estimating values for chaotic systems where many variables can be considered. The use of a neural network to estimate capacity in workzones was not directly considered. To make estimations a neural network needs to be fed a large amount of data with which it is able to train itself and produce a prediction. For the case of roadworks there are a wide range of different factors that can influence the capacity, which are partially interconnected. In his research Awad (2003) made use of 40 roadwork scenarios and derived 11 input parameters from them. The roadworks varied greatly in character and parameter values. The resulting predictions were compared with the real capacities from the same data and showed a wide range of accuracy. The authors did not show a error analysis in their paper, but did mention a few figures of error. As might be expected the results gained from this method showed that a quarter of the outcomes showed an error of between 20 and 70%, while the remaining sample scenario's showed capacity estimation errors of 1 to 11%. Such errors are too high, as an error of just a few percent of the capacity will give vastly different outcomes when predicting the onset of congestion and travel times. As mentioned in the paper and the reason for expecting a considerable error is the fact that there was only data used from 40 roadwork scenarios, while there are 11 parameters. To train a neural network with this number of parameters a much larger data set is necessary. Such a data set would exist of at least a few hundred roadwork locations. It is primarily for this reason that the use of a neural network to estimate roadwork capacity is not considered a real option. Also the physical character of each works zone is different. Capturing these variations in such a model would also lead to further uncompensatable errors.

2.3.3. Workzone Capacity Modelling

Most existing methods for the estimation of the road capacity in a workzone make use of capacity reduction factors. This is mainly due to the ease of calculation and the relatively accurate manner in which the influence of the various factors can be brought into account. Other methods lean more towards explorative methods and make use of regression and neural networks to derive relations between factors. A short explanation of the main types of existing methods will be given here, making use of example studies in which these methods are considered. The three considered methods are the *Capacity Reduction factor method*, the *Speed reduction factor method* and *Regression & neural networks methods*.

a) Capacity reduction factor method

In literature one will find that a large amount of effort is put into determining the influence of various factors on the capacity of roads in workzones. These factors will often be gathered and unified in capacity estimation equations. This method is used in the Highway Capacity Manual (HCM), which is widely used throughout the world as a main guideline for traffic planning. The equation used in the HCM is deliberately kept simple in order for it to remain generic and understandable. Due to its generic character accuracy is often lacking. For this reason the values that the HCM equation gives tend to be conservative and will yield lower capacity values than might be the case in real life. Despite this the general formulation is well regarded and is often used:

$$C_{adj} = (1600 + I - R) \cdot f_{HV} \cdot N \qquad (2.14)$$

Where:	Cadj	=	Adjusted capacity
	I	=	Adjustment factor for type, intensity and location of work activity
	R	=	Onramp factor
	f_{HV}	=	HGV factor
	N	=	Number of lanes open

As can be seen from the equation itself, the number of factors that are taken into consideration are limited. It is generally accepted, however, that the factors used are the main factors that influence capacity.

Heaslip et al. (2008) in their research methodology for the estimation of capacity in work zones also made use of a factor based approach.

The function proposed from the research gives the *adjusted capacity* C_{adj} in which various factors are taken into account:

$$C_{adj} = f_l \cdot f_d \cdot f_r \cdot (C_{unadj} - V_R) \qquad (2.15)$$

Where:	Cadj	=	Adjusted capacity
	f_l	=	Lighting conditions factor
	f_d	=	Driver population factor
	f_r	=	Weather factor
	C_{unadj}	=	Unadjusted capacity
	V_R	=	Onramp traffic volume

Although at first sight it may seem that the equation does not take that many factors into account, it must be noted that before this function is used, the C_{unadj} is determined making use of a number of other factors. In this C_{unadj} a factor for HGV, for rubbernecking (as a consequent of work activity), for roadworks configuration and for the width of lanes is taken into account. Therefore the C_{unadj} has actually been adjusted for the physical infrastructural factors. The term 'unadjusted' refers to external influences.

b) Speed reduction factor method

In a similar way to the previous factor based approach, a factor based approach using the estimated reduction in speed rather than capacity can be used. Because a relation can be found between speed and the capacity, good results can be found in this manner. In Benekohal et al., (2003) such a method is developed with the goal to determine the cost for road users of congestion. Only in the last step does a cost factor enter the equation and therefore an estimation of just the capacity can also be made using this method.

In this method the first three steps consider the effect of a narrow lane, the lateral clearance and the work intensity. These are expressed in a reduction in speed measured in miles per hour. Using the estimated free flow speed and applying these factors, an operating speed is calculated followed by the operational capacity. The operational capacity is found by making use of a speed flow curve developed through empirical observations. Once this unadjusted operating capacity is found, it is further adjusted for a HGV factor to give an *adjusted capacity* C_{adj} in the work zone. Following these steps the delay and costs for road users are calculated.

c) Regression and Neural Network methods

A multiple regression model was developed by Kim et al. (2000) to describe the relationship between various roadwork factors and the carriageway lane capacity. The authors considered a number of factors and rested on a set number of significant factors combined in the following equation:

$$C = 1857 - 168.1 \cdot NCL - 37 \cdot LCL - 9 \cdot HV + 92.7 \cdot LD \\ - 34.3 \cdot WZL - 106.1 \cdot WI_H - 2.3 \cdot WZG \cdot HV \quad (2.16)$$

Where:			
	C	=	Capacity in work zone
	NCL	=	Number of closed lanes
	LCL	=	Location of closed lanes
	HV	=	Proportion of HGV's
	LD	=	Lateral distance to open lanes
	WZL	=	Work zone length
	WI	=	Work activity intensity
	WZG	=	Work zone grade

As the factor values determined in this regression analysis are dependant on the considered locations and characteristics, it is understandable that the values seem to be overly precise. The authors nevertheless managed to show that this equation yields a much higher level of accuracy than many other models including that of the HCM. The respective Root Mean Square (RMS) errors were calculated at 145.3 and 226.9 for the proposed method and the standard HCM equation respectively.

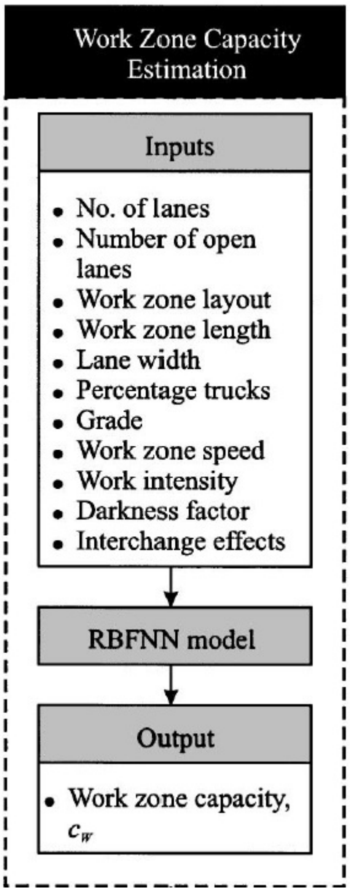


Figure 2.14: Radial Based Function neural Network Factors and flow diagram

Another type of explorative method found in literature makes use of a neural network to determine relationships between the factors and the work zone capacity. While the previously mentioned regression makes use of set functions, the neural network is non-parametric in character and determines relations through more intense data mining. The neural network used by Karim & Adeli (2003) is of the Radial Basis Function type and used 40 roadwork locations to train the network. Eleven factors were considered for the roadwork locations as can be seen in figure 2.14. The results, although showing similarity to the real data, had a large relative inaccuracy of well above 20% in a lot of cases. The inaccuracy was primarily attributed to the lack of good training data.

2.3.4. Other direct travel-time estimation methods

In traffic modelling there are a number methods that do not need to make use of comparisons between traffic flow and capacity. These methods are mostly explorative methods that estimate travel times using historic travel time data. We have already seen a few of these methods among the flow modelling methods. When estimating travel times, these methods work in exactly the same way except that the input and output are not traffic flows but travel times. Other methods in this category are the PLSB (Piece-wise Linear Space Based) method and MTS method.

Both the PLSB and MTS methods are methods that construct trajectories using data from certain detection points along a road. These trajectories are analysed and an average trajectory per unit of time is given from which travel times can easily be calculated. A study by Van Lint (2006) showed that the PLSB method, as used by Rijkswaterstaat to derive information from induction loops, has a much higher accuracy than the MTS method. The MTS method uses mobile devices to detect vehicle movements and characteristics. Both methods are capable of giving good predictions of travel times based on past data, but are not able to give results based on a road section without historical traffic data. This eliminates them from consideration for use in this research.

2.3.5. Conclusions

In this paragraph we have seen that there are a large number of different approaches and methods for the estimation of travel times through modelling. The overview given in this paragraph is merely an introduction into the main types and methods and it must be noted that the overview is far from exhausted. The focus in this literature study has mainly been on the use of traffic demand (flow) and supply (capacity) as separate modelling steps. It must be mentioned that although these are two different quantities, the one does have a certain influence on the other that should not be ignored. This focus is primarily inherited directly from the estimation of travel times, because of the non-existence of historic travel times for the locations where roadworks are to be carried out.

Methods for determining traffic flow can be exploratory or explanatory. The explanative methods are not being considered for use in this research, because of the magnitude of information required and the usefulness in application in the developed method. Explorative methods on the based of historical data give real options for use when determining the expected traffic flow. With their use however it should be taken into account that the current traffic flows will be influenced by the initiation of roadworks.

Models for capacity estimation are split into theoretical and empirical methods. The theoretical methods rely on theories and formula that have been derived for the estimation of road capacity. Using these a relation may be made with the fundamental equations and diagrams, however taking different inputs into account such as headways, presumed densities or maximum traffic flows. As headways are not measurable and fundamental diagram methods rely on real input, the basic capacity estimation method remains as the most suited. The empirical methods derive capacity estimations along similar lines, though make use of empirical data to form the input for the derivation of the capacity values. Both methods have their advantages. Often empirical methods will be preferred as these limit imperfections on the theory and road conditions into account. As we have already seen however, there is no empirical data available for the actual roadworks situation before roadworks start.

The specific configurations of the used methods are elaborated on in later chapters.

3. Research Methodology & Approach

The basic dynamics involved in this research as well as the main theories were presented in the literature research. Making use of the gathered information, the approach used to develop the model is constructed.

In this chapter the general modelling approaches available and the approach used in this research will be discussed (3.1). The selection for a specific model type at the heart of the developed model will also be explained and underlined (3.2). The main data sources, which are used to develop the model will be shown, along with the chosen locations of roadworks to be used in the calibration and validation of the developed model (3.3). The chapter concludes with the evaluation criteria (3.4) with which the model is later evaluated for performance and accuracy.

3.1 Modelling Approach

The overall modelling approach used to produce predicted travel times in this research is dependent on a number of decisions related to the type of methods to be used in the model. The deliberation between methods is given in the below table 3.1 along with the considered methods and models as described in the literature research.

Table 3.1: Considered modelling options

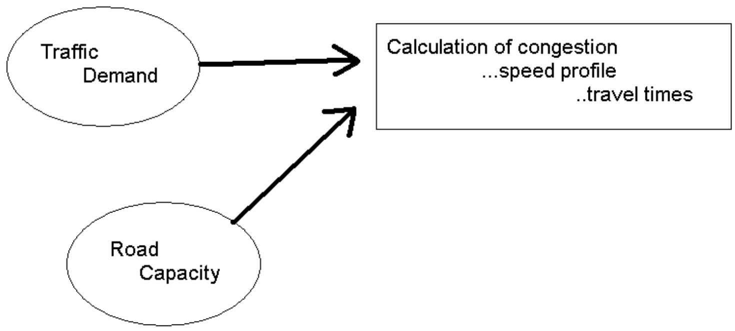
Modelling choice	**Considered Options**
Approach:	Complete solution, **Defragmented approach**
Model type:	**Macroscopic**, Microscopic
Data Processing:	Unprocessed, Filtered, Smoothed

3.1.1. Approach

When predicting travel times, it is possible to make use of an approach, which calculates travel times in one step directly from the input data and form a *complete solution*. Such methods are, for example, the neural networks, which take the raw data and analyse this for specific patterns. In doing this, the network is trained to recognise similar patterns in other data. Another approach is to separate the various influencing parts of the traffic process and calculate a few or all of these individually to produce the desired outcome. This *defragmented approach* allows for input and the exertion of influence on variables in the entire model and also allows for a theoretical basis, contrary to a complete approach.

Often statistical methods, such as neural networks, will be preferred as these limit imperfections in the theory and observed road characteristics. This research does not allow by definition for empirical data for the actual roadworks travel times before roadworks start however. A capacity estimation based on theoretical methods will therefore be used and form a defragmented approach. As shown in the literature research, travel times are dependent on traffic flows, which in turn are affected by the traffic flow demand and the available capacity of a road. This propagates from basic traffic theory and is used in this research. Figure 3.1 gives a basic representation of the chosen approach.

Figure 3.1: General model approach



3.1.2. Model type

A distinction is made between a *microscopic* and *macroscopic* representation of traffic flow. The earlier takes the movement and characteristics of each individual road user into account while the latter looks at traffic from a collective point of view. When making travel times predictions, it is not necessary or even advisable to consider fictive individual drivers, as this will generally lead to a higher complexity for the application of the chosen method and increase calculation times. An exception to this is obviously the case in which the influence of individual drivers must be considered, which is not the case here. Furthermore the option to include a variation in the road capacity, per location, linked to the operational capacity is realistically only possible for a macroscopic case. In this research, the developed model will focus on macroscopic traffic flows, as this offers the greatest potential for modelling the desired conditions and does not lead to unnecessary complication of the model as a whole.

3.1.3. Data processing

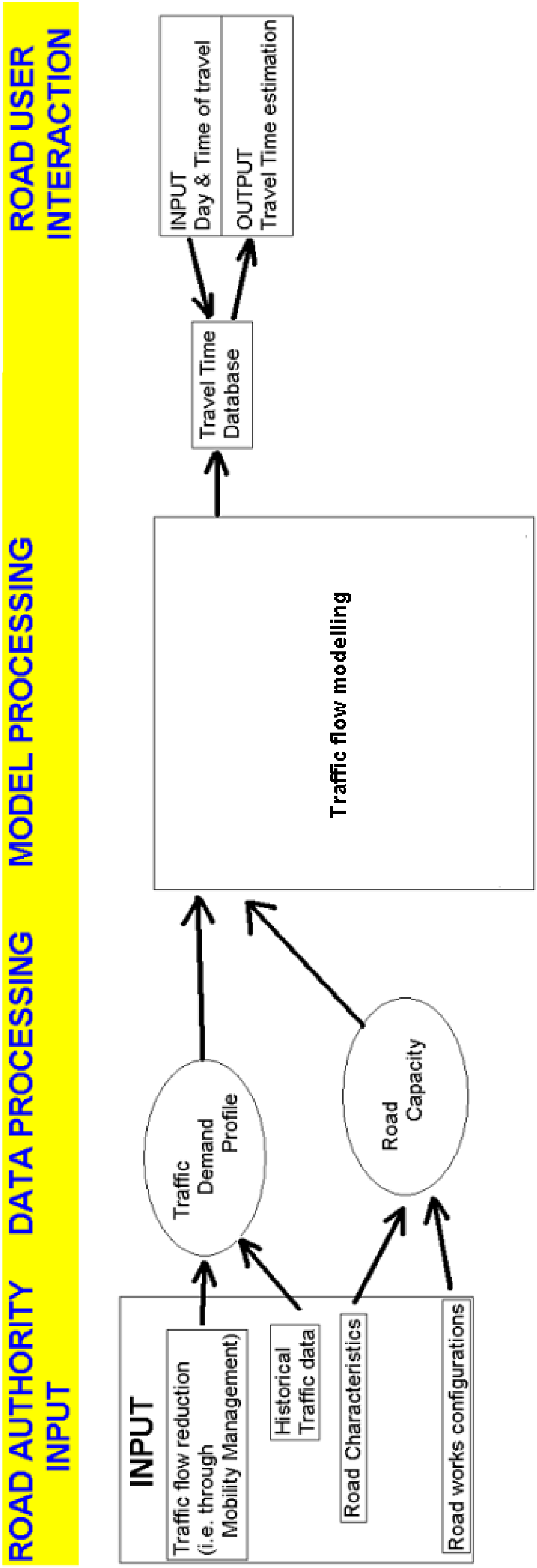
The manner in which the developed model processes the input data is obviously important as it influences the output of the model.

The model is developed to produce travel times after considering the general traffic conditions gained from information using both historical traffic data and the proposed roadworks characteristics. The manner in which the travel times are to be gained is through the processing of a traffic demand profile and a road capacity profile. The use of historical traffic information and the future roadworks configurations gives the best combination between reliable traffic flow and a good estimate of capacity through operational capacities adjusted for the influence of roadworks.

The general algorithm of the model, shown schematically in figure 3.2 on the next page, has its basic shape. The manner in which the traffic demand profile and the capacity during roadworks are calculated are yet to be specified. The elaboration on these parts of the model is discussed in the following chapter (chapter 4). The necessary inputs required depend on the manner in which these profiles are determined. A general consideration leads to the conclusion that historic traffic information and potential traffic flow influencing measures are needed. For the capacity estimation: the road characteristics and configurations of the roadworks are required.

Once a traffic demand profile and capacity profile are created, these must be processed to gain travel times. The specific manner in which this is to be performed is explained in chapter 5, however the choice for the desired modelling approach is made in the following paragraph.

Figure 3.2: General model algorithm



3.2 Selected Model

3.2.1. Model selection

In general there are three main types of macroscopic methods for modelling traffic flows. These are the *explanative deductive models* based purely on a theoretical of traffic flow theory, the *explorative inductive models* which make use of traffic flow patterns from empirical data, and the *intermediate models* combining both approaches (Papageorgiou, 1997). These models were explained in the literature research. The decision was made not to make use of explorative methods, such as neural networks. These require a large amount of training data that cannot be guaranteed in the considered situations and their implementation in the model is not validable. Therefore the considered methods considered are explanative.

In macroscopic traffic flow modelling there are two main types of explanative models, namely the *first order* and *the second order traffic flow models* (Hoogendoorn, 2007). The basics of the first order traffic flow models were explained on the basis of the LWR- model in paragraph 2.3.3. Second order models differ from first order models by attempting to more accurately describe and model the behaviour of specifics in traffic flow, which are not considered in first order models. The main areas in which the second order models attempt to offer an improvement is in:

1. The manner in which speeds are represented are dynamic mean speeds, while first order models use a static mean speed for each road section.
2. The higher headways as vehicles approach a jam, which are not included in first order models.
3. Traffic instability is considered, while this is not the case in first order models. This instability refers to small disturbances at certain traffic densities, which have the capability to result in a larger breakdown of traffic flow.

While second order models offer a more detailed and therefore a higher expected accuracy in traffic flow, they are not without their drawbacks. Papageorgiou (1997) states that the greater complexity of these models makes solving them a real challenge. While there are developed methods that can perform these tasks, a certain level of robustness cannot be guaranteed. The greater complexity also makes completely understanding the mathematical properties a yet unachievable task (Hoogendoorn, 2007) and therefore other impurities in the modelling method may occur (Daganzo, 1995).

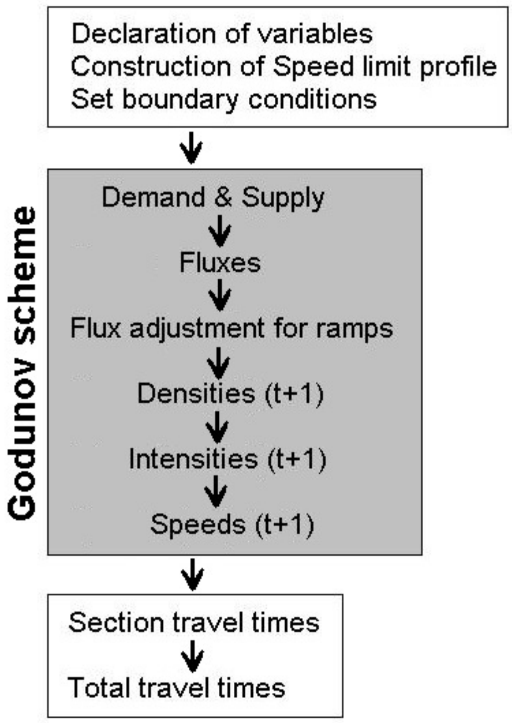
Although it would seem that the use of a second order model would yield better results, its main advantages lie at the heart of its main inadequacy: namely in its detail and complexity. It must be questioned furthermore if such a level of complexity is required for the considered problem. The potential improvements in travel time predictions over the considered sections of motorway (most will be less than a few tens of kilometers) are not deemed to be sufficient to make the choice for a second order model.

The choice is therefore made to use the first order traffic flow model (LWR model). Using a Godunov scheme to solve the model has proved to give a good representation of traffic flow during congestion and also take into account the main governing traffic flow characteristics. In many cases the performance of the first order model will not be significantly inferior to a second order model (Blandin e.a., 2009). Although not considering detailed phenomena, as in a second order model, the overall performance of the simpler first order model is deemed sufficient.

3.2.2. Model Explanation

The main section of the model in which the travel times are calculated with the Godunov scheme, is modelled using the scientific programming tool: MatLab. The manner in which this is performed is shown in figure 3.3 and explained thereafter. A diagram of the modelling scheme is given in appendix C along with the MatLab code.

Figure 3.3: Godunov scheme in the model



Firstly the necessary variables are declared and the time steps for the flow demand are adjusted from one-minute values to six-second values to meet the celerity condition. This is achieved by assigning the value of the one-minute values over ten six-second observations, creating ten identical and consecutive flow demands (The section distances are 200 metres corresponding to the average loop distance on main motorways). Secondly the maximum speed profile is constructed, using the maximum speeds for each section of road, with the workzone sections obviously being assigned the workzone speed limit. Finally the boundary conditions needed to ensure the correct processing of the model are set. The main boundary conditions are the *initial flow demand*, which is the flow demand at the start of the motorway corridor; the *initial densities* for each road section, set at an infinitely small number; and the *outflow densities*, which allow vehicles to flow out of the model without hindrance.

Once the necessary variables are set up, the Godunov scheme is applied. The steps involved in the scheme are repeated for each of the 14400 time-iterations needed to model a whole day:

1. The **traffic demand and supply** of each section are collected, which are basically the demand profile and the capacity profile.
2. The **flux** between each motorway section is determined.
3. The **flux is adjusted** for inflowing and outflowing vehicles from **ramps** at the relevant locations. A distinction is made between morning and afternoon ramp activity, as these are significantly different.
4. The **densities** for the following iteration steps are determined using the calculated fluxes and the flow definition equation.
5. The corresponding **traffic intensities** for the following iteration are derived using the equilibrium fundamental relation and the calculated densities.
6. The average space mean **speeds** per section are calculated from the determined intensities and densities using the flow definition equation.

From the section speeds calculated in the Godunov scheme, the trajectories of vehicles are determined, resulting in the travel times per motorway section. The section travel times are combined to give the overall travel time over the entire motorway corridor.

The calculations performed in the Godunov scheme are done so using the three relevant equations: the conservation equation, the flow definition equations and the equilibrium fundamental relation. The manner in which the in- and outflow of vehicles at ramps is considered, is through an adjustment of the calculated fluxes at the ramp locations by the values of the net difference of the in- and outflow. Because these differences are not constant values over the whole day, a separate value for morning and afternoon traffic is applied. This value is determined as a percentage of the traffic flow rather than a set value, as this gives a better representation of the traffic flows on the ramps.

3.3 Data Sources

3.3.1. Historical traffic data

Historical traffic data can be collected from the Dutch motorway monitoring system known as MoniCa (Monitoring Casco). This system, which is managed by Rijkswaterstaat, records the presence of vehicles at various points on a motorway and processes the data to give average speeds and flow intensities on a minute-by-minute basis. The detection is performed using induction loops, which detect the presence of a vehicle and, for the double loop configuration, also the individual speeds of vehicles. The loops are generally placed at an approximate distance of 200 to 500 meters apart, though this varies per motorway. The accuracy of the data produced has been shown to be higher than 95%[12] and therefore sufficiently accurate for determining traffic characteristics and values.

Besides the use of induction loops, there are a small number of locations on Dutch motorways that are (temporarily) fitted with vehicle detection camera's. During large-scale roadworks, it is known that this camera technology is often used for the duration of the roadworks. The travel times recorded from this method are individual travel times for each road user and are therefore very accurate. As the availability of data from cameras is scarce however, this method will not be used as the main method for collecting traffic data. The near 100% accuracy of the recorded data means that where the cameras are available the data will be used as a further source for calibration and validation of the model.

12 Polman, Voertuigdetectie: wensen en mogelijkheden, Goudappel Coffeng in opdracht van het ministerie van Verkeer en Waterstaat/Rijkswaterstaat Adviesdienst Verkeer en Vervoer, november 2001

3.3.2. Roadworks Selection

With thousands of roadworks and maintenance requests handed in each year to the road authorities in the Netherlands, a wide range of roadworks are available for analysis. In this research, databases held by Rijkswaterstaat from *Meldwerk* and *WPK*[13] are accessed. These databases hold vast amounts of information on planned and contracted roadworks. The vast majority (>97% (source: Meldwerk)) of these works however are for minor repairs or maintenance. A distinction is made between major roadworks and minor works, thereby allowing relevant roadworks to be selected.

Four roadworks locations are chosen which meet the requirements and are deemed suitable for use in this research. The roadworks selected are:

- Major road reconstruction on the **A2** in **2008 & 2009**
- Major resurfacing works on the **A9** in **2007**
- Construction of additional peak hour lanes on the **A12** in **2008**
- Major bridge repairs on the **A16** in **2006 & 2007**.

Among these roadworks are a mixture of different types of works. This allows for a more elaborate analysis of different capacity reduction factors and with this improved prediction power for the model. Of these, the works on the **A2, A9 and A16** are used for **calibration** and the works on the **A12** are used for the **validation** of the model. Specific details of each roadworks location are given in appendix A.

[13] These are databases held by RWS for the registration of roadworks.

Figure 3.4: Motorway corridors selected for calibration & validation of the developed model (A2,A9 ,A16 & A12)

3.3.3. Selected Data

From each of the works locations, data is collected for specific days and along specific locations in order to compare the differences in traffic flow between works and non-works situations. To this extent and in keeping with the requirements constructed for the roadworks, motorway corridors are of at least ten kilometres and are selected between two easily measurable locations. In appendix A the precise hectometre locations are given for each motorway. These are generally chosen between two major interchanges. Along each motorway corridor there are 24 to 52 induction loops present, depending on which motorway. These register the speed and flow intensity of the traffic.

The comparison between the works and non-works traffic is performed using data taken from **Thursdays**. On Thursdays a representative amount of traffic for a working day can be measured and therefore an accurate estimation can be made from the data. Obviously other days, such as Fridays, will show different traffic patterns. However for the purpose of testing the model, the use of a busy weekday such as Thursday is essential. For each motorway (A2, A9 and A16) data from at least three separate days are selected for both works and non-works conditions. This allows extreme traffic situations that might have occurred on a specific day to be detected and the stochastic character of traffic to be reduced. The non-works days are chosen on the corresponding day of the year a year earlier, as this should eliminate bias due to seasonal differences. An overview of which days are chosen can be viewed in appendix A.

3.3.4. Bias due to Mobility Management

From the collected data during roadworks, it can be expected that a certain 'bias' is present as a result of deliberate flow reduction measures in the form of *mobility management*. This basically entails that the collected data from and around workzones will show a lower total traffic demand due to demand reducing efforts from mobility management and indirect traffic demand effects. To allow the effect of this bias to be considered when measuring the traffic flow for calibration of the model, the reduction in traffic flow as a result of this between the works days and the reference days is recorded.

For all three of the roadworks locations mobility management was applied. For the works on the A16 the focus is mainly concentrated on widespread communication via the mass media. For both the A2 and the A9, this included a broader range of measures including cheap public transport passes and collaboration with local businesses. This was especially the case for the A9 works[14].

The extent to which mobility management managed to reduce the traffic flow has been calculated by comparison of travel demand for the corresponding data and shows a reduction in traffic (either directly caused by mobility management or otherwise) of **9%** for both the A2 & A16 respectively, while a value for the A9 remained inconclusive. This reduction is demonstrated for the A9 in figure 3.5. These estimated values are backed up by reports following the implementation of mobility management (Grotenhuis, 2008).

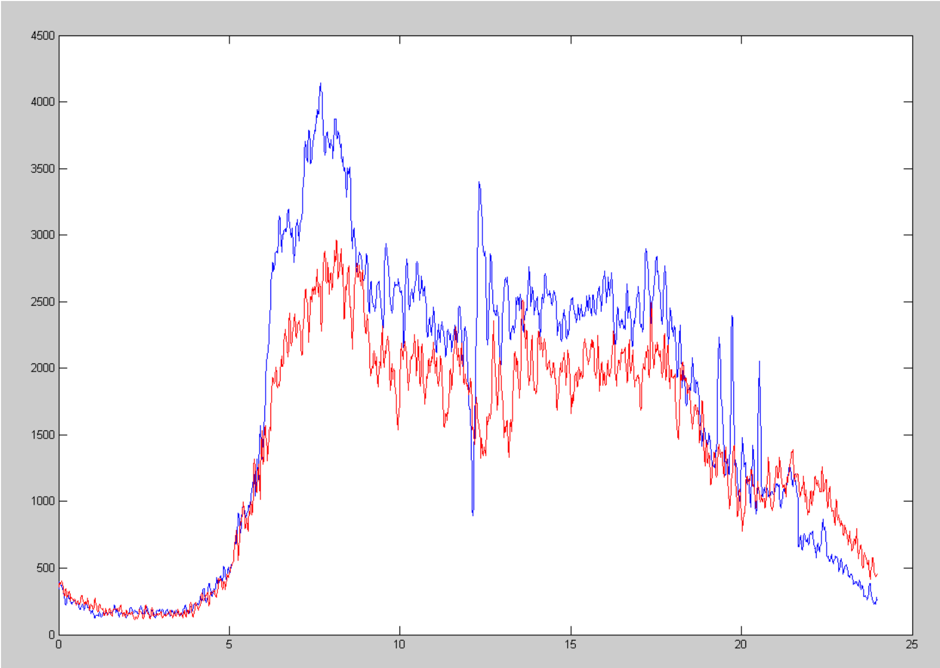


Figure 3.5: Traffic flow during roadworks (red) and for the reference (blue) situations on the A9.

[14] For an extensive overview of the measures on the A9 see: http://www.a9bereikbaar.nl/node/24

3.4 Evaluation method

Validation of the developed model is performed using data from an independent roadworks location. This location was previously chosen as the A12 between The Hague and Gouda. The manner in which the model is evaluated is set out in this paragraph along with the performance factors that will be used for the evaluation.

The step-by-step process for the evaluation of the model is as follows:

- Gather measured travel times from the motorway corridor.
- Give the necessary input for the model and run the model.
- Extract travel time predictions from the model for varying days/times.
- Compare the travel time predictions with the measured travel times (both are actual travel times).

The travel times, both measured and predicted, are compared using two categories:

- Absolute difference (MAE)

$$\frac{1}{N}\sum_{N}(|\,tt_{N.m} - tt_{N.p}\,|) \tag{3.1}$$

- Relative difference (MARE, MRE)

$$\frac{1}{N}\sum_{N}\left(\frac{|\,tt_{N.m} - tt_{N.p}\,|}{tt_{N.p}}\right) \tag{3.2}$$

The results of the comparisons offer an insight into the accuracy of the model and may indicate structural errors in the model. The main performance requirement for the model is derived from the original project proposal as constructed by Rijkswaterstaat and is based on the deviation of the relative error:

Performance requirement:
At least 95% of travel time predictions must show a relative error no greater than 20%.

3.5 Conclusions

In this chapter a selection was made for the main modelling approach to be applied in the developed model. This approach is graphically presented in the form of the general algorithm for the model. Arguments are given for which model method should be at the heart of the developed model and from this a choice is made for a certain method.

Selected modelling method

The model method chosen is that of a *first order traffic flow model* as laid out in the *LWR-method* making use of a numerical *Godunov scheme* to solve the model. This modelling method is at the heart of a macroscopic modelling approach, which will make use of traffic demand and road capacity profiles to determine congestion and travel times.

The various data sources required to develop the model are given along with the locations of roadworks from which real traffic data can be collected. The final evaluation criteria are also given together with the performance requirement for the model.

Main data sources

The main data sources of traffic data are from the MoniCa system. When applicable, the use of camera data will also be made. Four roadwork locations are chosen; three to assist with the calibration of the model and one to evaluate the developed model. The influence of mobility management is further cited as an important factor in traffic flow, which must be considered.

Evaluation method

The evaluation of the model will take place using the mean absolute error and the mean absolute relative error as indicators for model accuracy.

4. Model Development: Flow & Capacity estimation

As seen in the previous chapters the capacity of a motorway is significantly influenced during roadworks. There are a number of main factors that may influence the capacity during roadworks, such as the number of lanes available for example. There are however also a large number of other factors that play a role. For many of these other factors the precise influence may not be known. Much research has been performed on the subject of capacity estimation in workzones.

In this chapter an overview of the performed research along with the resulting factors and values derived from the research are presented (4.2). Before these factors are presented, an overview of existing methods (4.1) is given. The selected roadwork factors and their relation to the travel time are given thereafter (4.3 – 4.5).

4.1 Traffic flow demand profile

Modelling expected traffic flows can be primarily performed on the basis of historical data. The raw data however must first be processed to acquire a traffic demand profile in time and space for each of the motorway corridors considered. Average traffic flows for motorways, produced by Rijkswaterstaat, show the traffic flow spread out over the course of a day. Often this data is combined with confidence intervals of the 15^{th} and the 85^{th} percentile. This data should be preferred above locally collected data from a few measurement days, as the data is collected from many representative days and is filtered for incorrect data.

Such data is however not always available for the correct section of road, is not recorded under the right circumstances or for the correct time of year. To ensure independency from any restrictions, the model should also harbour the capability to calculate the traffic flows from the reference traffic data. There are a number of methods available to process the data, some are more accurate though are also often more complicated than others.

The considered parametric methods are: *ARIMA, Kalman Filtering* and *Data Smoothing & Data Fusion*. A neural network is considered as a non-parametric method.

4.1.1. Selected Method

A comparison is made between the main characteristics of the considered methods for processing the raw traffic data, as presented in the literature research (paragraph 2.3.2). An overview of this comparison is given in table 4.1.

Table 4.1:

Demand Profile methods

	AR(I)MA	Kalman Filtering	Data smoothing /Data Fusion	Neural Networks
Based on:	Autoregressive moving average	Gaussian hypothesis	Regression	
Potential accuracy	+	+	+	++
Required data	+/0	+	+	-
Ease of implementation	+	0	++	-
Computational complexity	+	+	+	-
Legend: **+** = *good*, **0** = *average*, **-** = *poor*				

From these methods the filter, as constructed by Hoogendoorn & van Lint, is selected in the model as the main method for processing the raw traffic demand data. As the data remains noisy after filtering it is then processed using a moving average technique into a smoother flow profile (see figure 4.1). The choice falls on these as the filter offers a relatively simple and reliable method to deal with corrupted data and also eliminates unrealistic outliers while maintaining the recorded traffic flow patterns. Further smoothing eliminates the stochasticity leaving the general demand pattern allowing for use in the model. Main advantages of these methods are their relative simplicity in comparison to the quality of results they produce. The Kalman filter and ARIMA method also offer possibilities, however as stated often in literature, the presumed Gaussian distribution used in Kalman cannot be guaranteed to accurately represent traffic distribution (i.e. Kalnay, 2008). The difficulty in processing outliers gives a preference to the Data Fusion

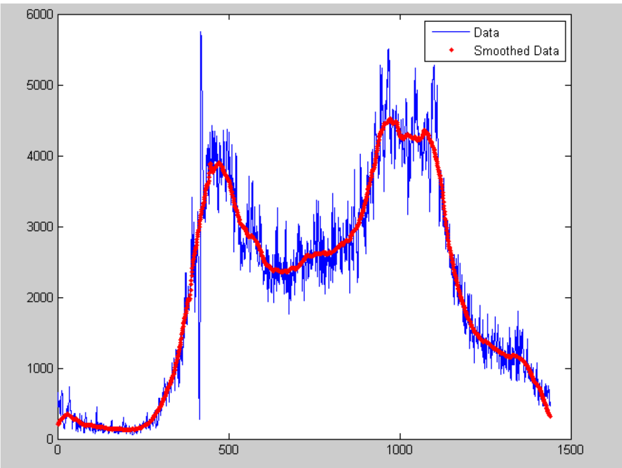


Figure 4.1: Example of smoothing using a moving average technique.

filter over the ARIMA method. In turn the necessity to have large amounts of training data as well as an added complexity forms the main arguments against using neural networks despite a higher potential accuracy.

To gain the relevant traffic flow profiles, the selected methods are fed with processed traffic data from induction loops as recorded in MoniCa. Per motorway corridor two profiles are created: namely for *Thursdays and, with and without roadworks*. These profiles therefore give a good indication of the critical weekday traffic conditions without having to process excessive amounts of traffic flow data.

4.1.2. Demand profile calculation in the model

The traffic demand profile, including confidence bandwidths, is calculated in the model through a number of consecutive steps. The steps are as follows:

1. The traffic observations from an individual day are processed using the **Hoogendoorn & van Lint Filter** to eliminate extreme outliers and missing data. This is performed for all the traffic data from all relevant days and results in space time matrices with 200-metre by 1-minute cell sizes.
2. The observations are averaged and further smoothed using the **Moving Average Filter** for a location[15] with representative traffic flow (i.e. near the start of the motorway corridor where no ramps are present). This results in the average traffic flow.
3. From the filtered data, the observations at the 15th and 85th percentile of the traffic flow are derived and the corresponding traffic flow profiles are constructed to allow the **confidence bandwidths** to be constructed.
4. The influence of the **mobility management** factor (MM%) is then applied. This is performed by applying a reduction in traffic flow over the demand profile. A MM% of 5% would result in the multiplication of the demand profile with 0.95 for example. There is also the option to only apply the MM% to the peak periods or the entire day.

The result of this part of the model is an average traffic flow demand profile with corresponding confidence bandwidths denoting the 15th and 85th percentile of recorded traffic observations. The average demand profile, as well as the bandwidths, are later processed through the main model section to achieve the expected (average) travel time and travel times profiles for both the upper and lower bandwidths.

[15] The location is manually assigned by the user

4.2 Capacity profile

In the literature research a number of methods were presented for use in determining capacities in reference situations without roadworks and for reduced capacities around workzones. The considered methods for use in this research are:

Table 4.2: Capacity determination methods

Theoretical methods	Empirical methods	Reduced Capacity
1. Basic Capacity Estimation 2. Headway Distribution 3. Fundamental Diagram	1. Queue Discharge 2. Product-Limit Method 3. Neural Networks	1. Capacity reduction factor 2. Speed reduction factor 3. Basic Regression 4. Neural Network

The choice for the capacity estimation method is made in favour of the *capacity reduction method*. Although not the most 'state-of-the-art' method, it is a method that with the right tuning will be able to yield good results. A ranking table for this decision is given in table 4.3. Another main advantage is that after the factors are calibrated, the equation should continue to yield good results for other locations other than those for which it was calibrated on. The same cannot as easily be said for methods making use of regression (which neural networks also fall under). Although their potential accuracy may be higher when used for the location on which they are trained, the generic accuracy for other locations is presumed to drop to a similar level as the reduction factor methods. The amount of data required to train a neural network or other regressive method is deemed to be too extensive in comparison to the potential gain in accuracy. It should furthermore be noted that road capacity is a volatile quantity and any improvements in capacity determination may only appear when taking averages, but could still show large errors per individual case.

Table 4.3: Evaluation of Reduced Capacity estimation methods

	Presumed Accuracy		**Necessary data**
	Specific location	*Generically*	
Capacity reduction factor	+	+	+
Speed reduction factor	+	+	+
Regression	++	+ / 0	0
Neural Network	++	+	-

+ = good / 0 = average / - = poor

4.3 Roadwork capacity factors

The roadwork capacity influencing factors potentially suitable for use in the model are split into three categories: *roadwork configurations*, *physical infrastructure* alterations and other *non-infrastructure factors*. The relevant factors are discussed within these categories and recommended factor values are given. The discussed factors in this paragraph are:

Table 4.4: Considered roadwork capacity influencing factors

Roadwork configurations	**Physical Infrastructure**	**Non-infrastructure factors**
Lane closure	Lane width reduction	Traffic composition
Use of hard shoulder	Speed restrictions	HGV factor
Use of Opposite carriageway	Ramps	Extent of work activity
	Lateral clearance	(Other factors)

4.3.1. Set roadwork configurations

When roadworks are planned and workzone planning is implemented, there are set types of configurations that can be applied. In the Netherlands many of these standard configurations are listed, categorized and conditions are set for their use in the CROW Directives for Work on Highways[16]. Such set configurations are for example lane closures, hard shoulder closures, narrowing and re-aligning of lanes or the use of the opposite carriageway. There are particular types of set configurations that have been researched for capacity change, as it is often these types of configurations that are used in practice during roadworks. An overview of the factors used for capacity estimations are given here:

Lane Closure

As lane closure is one of the largest contributors to roadwork capacity reduction, much research and literature has been produced on the subject. It is generally accepted that there are two ways that road capacity is reduced when lanes are closed. The first is the physical absence of one or more lanes, meaning that traffic has fewer lanes available and therefore there is a lower total road capacity. The second is that the remaining open lanes also experience a small drop in capacity due to the fact that traffic must converge to a fewer number of lanes leading to increased interaction between vehicles.

The extent to which a lane closure contributes to the capacity reduction depends on the nominal value that is given to that lane. Estimations for

[16] In Dutch: CROW Richtlijnen 96a: Maatregelen op autosnelwegen

the capacity of a single lane vary greatly between 1300 veh/hr up to more than 2300 veh/hr as base value. In the Highway Design Directives for Dutch Highways an average design capacity of a lane is approximately 2300 veh/hr. The operational capacity values obviously depend on the traffic conditions and on the location of the road (i.e. influence of the physical infrastructure) and more importantly for which free flow speed. Researchers are agreed that the base value is dependent on the location and general traffic conditions of a road, a practical base value for a lane under normal traffic conditions with roadworks is generally chosen between **1600 veh/hr** (HCM, 2000, Zheng et. al, 2006, Heaslip et. al, 2008) and **1850 veh/hr** [17] (Ober-Sundermeier & Zackor, 2001 and Kim, Lovell & Paracha, 2000) for work zones where the free flow speed generally is lower (approximately 70-90km/hr). It is preferred that this value be dependant on the generic traffic flow conditions for a specific road, obviously under the condition that these are able to be measured (Benekohal, Kaja-Mohideen & Chitturi, (2003).

The effect of lane closure on the remaining lanes is judged by a capacity reduction factor in Ober-Sundermeier & Zackor (2001) and Heaslip et al. (2008) of **0.95** and **0.946** respectively. The first value is taken independent of the total number of lanes, while the second value is derived in situations where three lanes are reduced to two or one, or two lanes are reduced to one. In the second paper mentioned here, it is stated that the presence of these factors may not always necessarily depend on the type and extent of works. In Kim et al. (2000) the reduction on capacity is taken by a subtracted value per closed lane of **-168.1 veh/hr**. Various lane closure configurations are used to obtain this value. Real data collected for this study tends to back up both its own factor as well as the previous factors. Benekohal et al., (2003) do not use set values to determine the reduction in capacity due to lane closures, but rather apply speed reduction factors. The reduced operational speed is fed into an empirically constructed table and a value for the capacity per lane given.

The HCM offers theoretical capacities for situations with lane reductions from three to two lanes and two to one lane. These are empirically based estimates, which recommend values of **1860 veh/hr/lane** and **1550 veh/hr/lane** respectively.

[17] These values presume traffic speeds 80 kph and 95 kph (Benekohal et al., 2003)

Use of Hard shoulder
Roadworks on the main carriageway may lead to traffic being confined, in part, to the use of the hard shoulder. As the hard shoulder is not officially a lane and therefore is not ideally set-up for use by through traffic and that the use of the hard shoulder eliminates the possibility of an emergency lane, capacity is deemed to be influenced.

It is not easy to estimate what the effect is of the use of the hard shoulder during roadworks. This depends a lot on the quality of the surface and the layout of the works. While Benekohal et al., (2003) claims the use of the hard shoulder influences speed because of the absence of lateral road surface, it does not give capacity restrictions. Many other papers also do not take the use of the hard shoulder into consideration as a serious capacity restrictive factor. This makes it all the more interesting that Kim et al. (2000) offers a reduction factor of **0.9** for the use of the hard shoulder. It must be stated that this factor is only applied for short-term roadworks and is not considered for long-term works.

Use of Opposite Carriageway (i.e. 5-0, 4-0, 3-1 configurations etc.)
Often when a whole or a large part of a carriageway is closed for roadworks, it becomes necessary to make use of the capacity offered by the opposite carriageway. In this way both traffic flows can remain intact even if it is at a reduced capacity. In the CROW Directives for Roadworks (CROW, 2005) many layouts of such configurations are given.

When the horizontal alignment of a road is altered from its normal path, as is the case with a crossover, the capacity is reduced due to the need to manoeuvre along a bend in the road (Kim et al., 2000). Although it is known in this situation that the capacity will be reduced, it is unclear what this reduction will be. Kim et al. (2000) as do many other publications mention this factor, but do not or cannot determine a relation with the capacity. At most a reduction in speed can be presumed. For long-term roadworks Ober-Sundermeier & Zackor (2001) derived a factor ranging between **0.90 and 0.95** for the crossing over to the opposite carriageway.

4.3.2. Physical infrastructure alterations
Besides the configuration of roadworks where a large part of the capacity reduction can be measured, other more subtle factors can also play a role. These 'other' factors will often also lead to a considerable reduction in the operational capacity of a road and have been researched by multiple institutes. Adjustments to the physical road

infrastructure influencing the capacity come from the dimensions of the lanes. Also the speed that one is permitted to drive at on the lanes and access to these lanes from on- and off-ramps can influence the capacity. The width of a lane, as well as the lateral clearance to either side of a lane lead to road users taking more care and with that reducing their speed. And as we have already seen in the previous chapter, the reduction of speed has a direct influence on the capacity of a road.

Lane width reduction

It is presumed that the width of a lane can be directly linked to the speed at which road users are prepared to drive. The main reasons are that of safety or at the very least the perception of safety. When traffic lanes narrow, road users have a smaller margin for error in their lateral movement and therefore naturally reduce their speed (Fitzpatrick et al., 2000). This is also often taken into consideration in roadwork planning directives. The Dutch roadwork directives (CROW) state that speed limits must be lowered when lanes are used below a certain width (i.e. 70 kph when lane width is < 3.25m).

In research by Fitzpatrick et al. (2000) a linear function was derived for the relation between the width of a lane and the speed at which road users drive. This relation was founded on measurements of lanes ranging from 3.0m to 4.25m. The relation that was found was that the average speed of road users would reduce by approximately **4 kph for each 0.25m**. In Benekohal et al. (2003) a non-linear relation was derived from measurements, which found that for a lane width above 3.6m there is no significant reduction in the average speed. With every 0.3m that a lane is decreased, a set speed reduction is measured (**3 kph for 3.3m, 10.5 kph for 3m** etc.). The reduction in speed shows an exponential increase for every reduction in lane width. Intuitively this would make sense as the impeding danger from a narrow lane will not be as large when the lane is still relatively wide (say 3.25) in comparison to a relatively narrow lane (< 3m).
Other research has placed a set factor on the capacity reduction in relation to the capacity of a lane depending on the width. In Ober-Sundermeier & Zackor (2001) a factor ranging from **0.9 to 0.95** is used for the reduction in lane width, but it is not stated explicitly what the relation is between the factor and the lane width.

Speed restrictions

However one determines the capacity of a road, it is always going to have a direct theoretical connection to speed. As was seen in chapter 2 the speed of traffic is a fundamental quantity. If the capacity is derived using the fundamental diagram or through equations, the capacity of a road will be influenced by the speed. This generally means that as the speed decreases, so the capacity will also as fewer vehicles will be able to transverse a set distance in the same length of time.

As previously mentioned, road authorities will often lower the speed limits for the sake of safety. In the Netherlands most roadwork sites will have a reduced speed limit of **90kph or lower** (SWOV, 2008). The fact that speed limits are lowered will automatically lead to a reduction in capacity in many cases.

In Heaslip et al. (2008) the speed on each lane is given a direct weight in relation to the capacity of the road. Multiple subtractive factor values are given for different lane closure configurations in the paper. Since the speed is not directly related to the capacity and used in relation with other factors, it is not easy to deduct specific values for the influence of each factor.

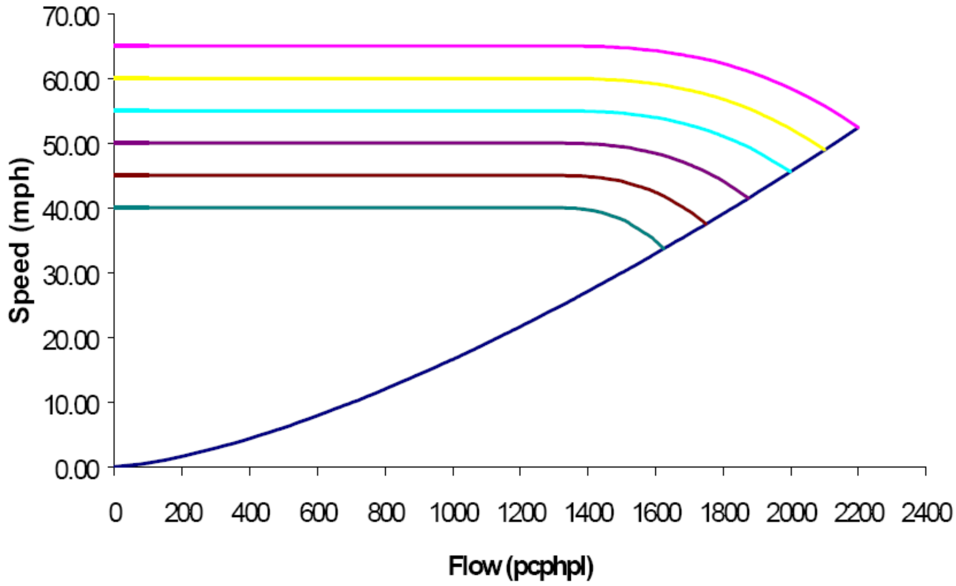
The theoretical relation between the capacity and speed on a road is given by:

$$q_{cap} = k_{cap} \cdot v_{cap} \tag{4.1}$$

Where:	q_{cap}	=	Road capacity
	k_{cap}	=	Capacity density
	v_{cap}	=	Speed at capacity

This is not a stable equation however, as the critical density and speed at which congestion occurs are variable. Relationships between speed and traffic flow are given in the (HCM, 2000) for various speeds and densities. In an extensive report by Benekohal et al. (2003) these relations are further developed for workzones. The relation is given in graphical form, which is shown for the Benekohal et al. (2003) relationship in figure 4.2. From this figure, the relation can be seen between the speed and the capacity flow (to the right hand side of the figure).

Figure 4.2: Speed-Flow curves for workzones (Benekohal et al., 2003)



According to the HCM (2000) a relation exists between the speed and flow capacity ranging from a reduction of **50 to 150 vehicles** for a speed reduction of **10 km/hr**. This is taken for densities ranges from 11 pcu/km/ln to 28 pcu/km/ln. In Benekohal et al. (2003) a non lineair density is given for workzones, which is in the range 20-25 pcu/km/ln for the critical intensities. At these values a reduction in capacity is calculated of approximately **150 vehicles** for a **10 km/hr** speed reduction.

Ramps

While roadworks are carried out, it is often a requirement that one or more on- and off ramps remain open despite the ramps possibly being blocked by the workzone. The influence of additional traffic joining already busy traffic flows affects the capacity of the carriageway (HCM, 2000).

The HCM (2000) states that if there is an onramp within 150m of the beginning of roadworks that an additional reduction factor should be applied for the capacity. This factor is a certain value that has to be subtracted from the base capacity.

According to Heaslip et al. (2008) this value can be as high as half of a lane capacity depending on the inflowing traffic intensity. In this publication the influence of the onramp is also taken as a factor subtracted from the unaffected lane capacity. The factor that is subtracted is the volume of traffic that is expected on the onramp. The effect of an onramp can be rather great and should not be ignored as can be seen from these values.

Indirectly related to the influence of an onramp is an additional factor mentioned in Kim et al. (2000) and which is a further subtractive factor depending on which lanes are closed. Depending on which lane(s) is closed, the additional factor **–37** is taken into account. This factor considers the case whether, for example, the middle lane is closed and the distance therefore to the onramp is greater.

Lateral clearance

Similar to the effect described for the lane widths, the lateral clearance available to either side of a carriageway can affect the speed at which road users (feel they) can drive safely. This is again due to the fact that the margin for error is reduced if a driver would leave their lane. In this case an accident increases and therefore speed is reduced as a precaution. This reduction in speed in turn results in a reduction in the operational capacity for the lane and carriageway.

Both Heaslip et al. (2008) and Kim et al. (2000) propose to take the effect of the lateral clearance into account by subtracting a factor from the unaffected road capacity. In Heaslip et al. (2008) the value proposed is derived statistically and is **92.7 for every 0.3m** of lateral clearance available. Benekohal et al. (2003) once again makes use of a capacity speed reduction method to take the effect of the lateral clearance into account. A lateral clearance of 0.6m or more is deemed to be the base value, with a lateral clearance of **0.3m and 0m** for a reduction in the speed at capacity of **1.5 kph and 3 kph**. This reduced speed is used to determine the corresponding capacity for the carriageway.

4.3.3. Non-infrastructure factors

Traffic composition

As driving is a task that is dependant on human behaviour and interaction, it is not surprising that the composition of the driver population has an influence on traffic conditions. It is easy to presume that if a road user is more familiar with a certain road that they will be more able to transverse it at a higher speed and confidence than someone who less familiar with that road. In a research publication by Heaslip et al. (2007) extensive research was performed on the influence of the driver population on the capacity of roads with roadworks. They found that the familiarity of a road user as well as the road user's ability to adjust to change, aggressiveness and accommodation of others played a significant part in the traffic flow and therefore the road capacity (figure 4.3).

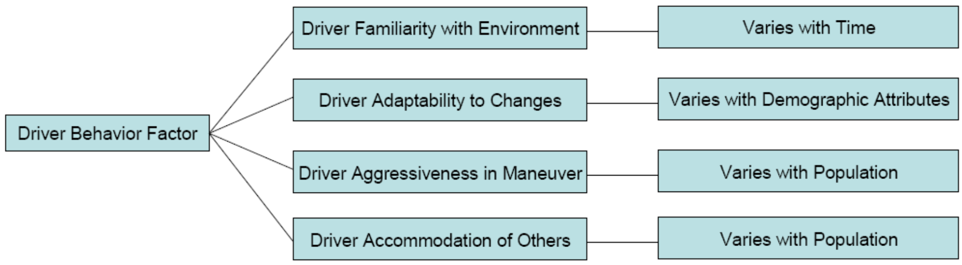


Figure 4.3: Decomposition of driver behaviour on capacity

Heaslip et al. (2007) based their research on two test locations and extensive literature research and found conclusive relationships between familiarity and behaviour, and the road capacity. They integrated this into two factors that can be used in relation to the HCM equation for capacity estimation at work zones[18]. The factors they found are shown in table 4.5.

Table 4.5: Driver familiarity and behaviour adjustment factors (Heaslip ea, 2007)

Familiarity	Adaptability	Familiarity Factor
High	High	1.25
High	Medium	1.1
High	Low	1.0
Medium	High	1.0
Medium	Medium	.9
Medium	Low	.8
Low	High	.95
Low	Medium	.9
Low	Low	.8

Aggressiveness	Accommodation	Behavior Factor
High	High	1.0
High	Medium	.9
High	Low	.8
Medium	High	1.1
Medium	Medium	1.0
Medium	Low	.9
Low	High	.9
Low	Medium	.85
Low	Low	.8

[18] $C_{adj} = (1600 + I - R) \cdot f_{HV} \cdot N$ (HCM)

The use of the table is subject to expertise in determining the height of each category. It is however presumed, and to a large extent proven, that commuters have a high familiarity, adaptability and accommodation, meaning that these factors would be fair to use for rush hour traffic. Recreational traffic on the other hand is presumed to be classed as lower in all four of the categories.

Other research (Heaslip et al., 2008 and Ober-Sundermeier & Zackor, 2001) backs up the large influence of driver population on capacity reduction and has shown that the effect of a rush hour road user population is significantly different to that of non rush hour road users and recreational or vacation traffic. In Heaslip et al. (2007) a factor of **0.93** for non rush hour traffic and **0.84** for weekend traffic is proposed in comparison to rush hour traffic. Ober-Sundermeier & Zackor (2001) makes use of two different categories: the location out of a metropolis and vacation traffic, and proposes values of **0.95 and 0.9** in comparison to the base capacity. The authors of the latter study do recognise the difficulty in determining values for vacation traffic. The proposed approach therefore by Heaslip et al. (2007 & 2008) would seem easier to implement in a model and for that reason might be preferred.

HGV factor

The composition of road users should not only be considered for capacity estimation, but also should contain the composition of the vehicle types. It is accepted that the influence of Heavy Goods Vehicles (HGV) can play a major part in the determination of road capacity. HGV's are usually represented in road traffic by a so called *Passenger Car Equivalent* (PCE), which is a value that represents the nominal value given to a HGV-vehicle if it were to be viewed as a set number of passenger cars.

For roadworks, the HCM (2000) makes use of an equation that uses this PCE value and also takes into consideration the proportion of HGV's in the traffic flow and the effect of gradients. Gradients in the road have a significantly larger effect on HGV's than on passenger cars and therefore are given a greater weight. The capacity adjustment factor is given by the following equation:

$$f_{HV} = \frac{1}{(1 - P_{HV}) + P_{HV} \cdot PCE} \qquad (4.2)$$

Where:	f_{HV}	=	Capacity reduction factor for HGV
	P_{HV}	=	Proportion HGV
	PCE	=	Passenger Car Equivalent

In the papers on capacity estimation of workzones, both Ober-Sundermeier & Zackor (2001) and Heaslip et al. (2008) make use of the equation from the HCM. The coherences in the equation are well considered and show good comparisons to empirical findings Ober-Sundermeier & Zackor (2001). Research by Kim et al. (2000) showed that for their case studys a relationship between the percentage of HGV and the capacity existed of a reduction in capacity of **9.5 veh/%$_{HGV}$**. Quick calculations show that this presumption gives similar results to the HCM equation for common values of the capacity, HGV proportion and PCE. The influence of a gradient however is not taken into consideration in the latter equation.

Extent of work activity

The use of large machinery and/or a large amount of activity in the workzone has been proven to affect the speed at which road users drive. The more activity that is ongoing, the more road users will be aware of movement and in turn will be distracted to a certain extent. The influence of (heavy) work activity has been empirically proven in a number of studies and is taken into consideration in the HCM capacity estimation equation as a subjective term.

In the methodology adopted by Heaslip et al. (2008) the influence of work activity (the presence of workers and machinery) is taken into account by means of a ‘rubbernecking’ factor. This rubbernecking presumes that in the vicinity of work activities, road users are less likely to want to drive close to the activities (although in most cases physical contact is not possible). This leads to a virtual narrowing of the lane according to the perception of the road user and therefore a reduction in speed. This reduction in speed is catered for in Karim & Adeli (2003) by a rather complicated empirically derived equation using a natural logarithm:

$$SR_S = 2.676 \cdot \ln(WI_r) + 11.918 \qquad (4.3)$$

$$WI_r = \frac{w+e}{p} \qquad (4.4)$$

Where:	SR_S	=	Speed reduction due to work intensity
	WI_r	=	Work intensity ratio
	w	=	Number of workers in a group in work activity area
	e	=	Number of large construction equipment

The factor used by Heaslip et al. (2008) in their proposed methodology is a reduction factor for the base capacity of **0.94** where work activity is present.

Other factors

A number of other factors, which may have an influence on the capacity of a roadwork zone on a motorway, are also mentioned in literature. However for the use in the Netherlands and in the proposed model in this research they are not deemed to be relevant and are therefore merely mentioned here.

Weather conditions are widely proven to have an affect on the capacity of a road (various publications). The main factors that play a role is the partial impairment of a driver's vision and that the road surface can become less favourable for vehicles when performing manoeuvres. In this research extreme weather conditions are not considered for the basic reason that the proposed model is designed as a predictive model for up to a few days to weeks in advance. Although the developed model is also envisaged to be used for shorter pre-trip predictions, the accuracy with which the weather conditions can be predicted on a day-to-day basis, let alone on an hourly basis, is insufficient.

The *Illumination of works site* and *Gradient* at the works site are also among the factors that are commonly mentioned in literature to have an influence on the capacity of a road. The illumination of the road at night or dusk can help road users to avoid a reduction in vision. As almost all highways in the Netherlands are equipped with adequate street lighting, but the factor is not relevant for the Netherlands. Similarly the gradient of roads primarily used for the effect of HGV in traffic is almost non-existent for almost all motorways in the Netherlands. There are a few exceptions, but these are so few that the addition of a gradient factor is deemed not to be necessary.

4.4 Selected Roadwork factors

The capacity influencing factors presented in the previous paragraph give a good impression of the influence that roadworks can have on the capacity of a road. From these factors, those deemed most relevant to this research have been selected (see table 4.6). Not all of the factors presented in the previous chapter have been used as not all have sufficient relevance to the development of the model, which is envisaged in this research or can be accurately determined.

Table 4.6: Selected capacity reduction factors

Lane Closure	Speed reductions*	HGV
Use of Opposite Carriageway	Ramps*	Traffic Composition
Lane width reduction	Lateral Clearance	Work Activity Rate

*Considered outside of the capacity equation

Of the previously presented factors, the *use of the hard shoulder* will not be used in the model. The reason for not applying a hard shoulder factor is firstly that the influence from the presence of a hard shoulder is generally most relevant for short-term roadworks, while the effect is limited for long-term works Ober-Sundermeier & Zackor (2001). Secondly a survey of various roadworks in the Netherlands shows that most long-term roadworks do not make use of the availability of a hard shoulder, which makes deriving a significant value for this factor nearly impossible. In all of the works locations selected for this research, none have a complete hard shoulder available for traffic.

For a few of the factors, it was decided to make use of a set default value for the factor value. This basically means that a set value will be used regardless of the specific situation. The reasoning behind this is the limited information available for the *lateral clearance* and *work activity rate*. For the *work activity rate* it is also not possible to say when work activity is heavy and when it is not as there is limited to no information on this. The variation in time of work activity can also be large. This means that the real life data from the roadwork locations will not be used and instead a value exclusively from literature. For this reason a set value is taken, which may be altered manually on expert judgment.

The influence following the *reduction of speed* along the workzone is incorporated into the main model by means of including the reduced speed limit into the calculations. Furthermore the change in traffic flow due to on- and off ramps is included in the demand profile for the specific locations where significant traffic flows are present.

4.5 Relation roadwork factors to travel time

A number of relationships between roadwork characteristics and capacity reduction have been analysed from literature as shown previously. For implementation a choice is made for the influence each factor is to be given in relation to the available capacity. These factors are then implemented in a ruling function for the capacity during roadworks.

The function type proposed here will be of the type using both constant and variable parameters, which influence the capacity with a certain factor or value. This method of calculating the capacity is the most common method and has proven, depending on the factor values chosen, to yield good results. The factor values initially proposed before calibration with the use of real data are given and explained here where necessary and are based on the literature research as presented earlier in this report.

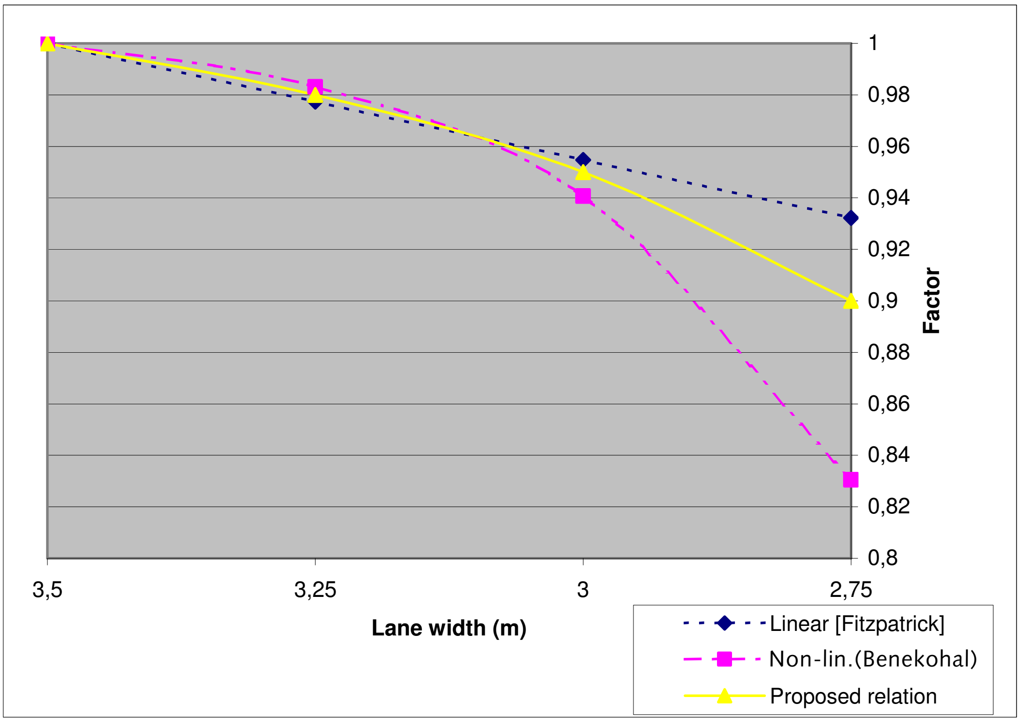
4.5.1. Factor values

Lane closure values given in literature generally show that the closure of a lane where two or three lanes are originally available, gives a reduction of 5% per closed lane in most cases. When presuming a lane capacity of 2300 veh/hr/ln (NOA-RWS, 2007), this results in a reduction of 115 vehicles, which is also not too far off other research, which makes use of a set reduction in the number of vehicles. Therefore the lane closure factor will be given by: f_{LC} **= 0.95**^{LC} with LC being the number of closed lanes for a two or three lane carriageway. When a carriageway has more lanes, LC will be multiplied by 2/(Number of lanes) as the influence of a lane closure is not as high when there are more lanes available.

Use of opposite carriageway is a factor that is sensitive to the precise characteristics of the roadworks and road alignment. For this reason a factor value can vary between 0.9 and 0.95. The number of lanes of the opposite carriageway that are used influences the capacity, as the number of vehicles needing to switch carriageways and are influenced varies. Three values are given for the use of the opposite carriageway. When all two or three of the lanes crossover (a 4-0 or 6-0 system), a factor of f_{OC} **= 0.9** is used. For two out of the three lanes crossover f_{OC} **= 0.93** is used (a 5-1 system), and for one out of two, or one out of three lanes crossover f_{OC} = **0.95** is used (a 3-1 or 4-2 system) as an average capacity reduction factor for all lanes.

Lane width reduction influences the speed at which road users travel, which also has an influence on the capacity. Lane widths are non-linear in relation to the through speed, meaning that narrower lanes will have an even greater influence on traffic flow than an identical reduction of wider lanes. This is taken into account in the proposed factor values: f_{LW} = **0.98** for a 3.25 meter lane, f_{LW} = **0.95** for a 3 meter lane and f_{LW} = **0.9** for a 2.75 meter lane. It is not deemed necessary to make the relation continuous as in almost all cases in Dutch highway management, multiples of 0.25 meters are used (CROW directives 96a). Figure 4.4 shows the relations between the values found in literature and the presumed relation here. From the graph it is clear that the presumed relation is in line with that found elsewhere.

Figure 4.4: Lane width reduction factors



A low value for the **Lateral clearance** is shown to have an influence on the capacity. However because the information collected often does not take precise lateral clearances into account and because recommended values vary, a set value is selected which can be deselected if a larger lateral clearance is available. When the clearance to the edge of the carriageway is lower than 0.3 meters measured from the road markings, a reduction value of V_{Lat} = **-100** is used. For higher clearances this factor is deselected. In most major roadworks in the Netherlands the lateral clearance is lower or equal to 0.3 meters.

Traffic composition affects the manner in which road users drive and therefore also the capacity. Values for capacity reduction vary from 0.84 to a positive value of 1.25 with different road users. In this research an initial value of f_{TC} **= 1.0** will be maintained for peak hour traffic, with f_{TC} **= 0.95** for non-peak traffic and rural motorways, and f_{TC} **= 0.9** for weekends and holiday traffic. The latter groups tend to be less informed of traffic and road conditions and therefore require more physical space reducing the road capacity (which is represented in the factors).

Heavy Goods Vehicles (HGV) are well known to reduce road capacity. In the HCM (2000) a widely accepted relation is given for the reduction of capacity due to the HGV composition of traffic:

$$f_{HGV} = \frac{1}{(1 - P_{HV}) + P_{HV} \cdot PCE} \qquad (4.5)$$

This relation will also be used for the HGV factor in this research. Apart from the standard factor for HGV's, additional reduction factors are used for grades in the road. The extent of (large) gradients on Dutch motorways however is almost non-existent and therefore no grade factor will be considered.

The effect of **Work activity** on the capacity reduction during roadworks is hard to determine and cannot be easily expressed in a (generic) mathematical relation. This is especially the case because the input is subjective and variable. For this reason the extent of work activity will be left to expert judgement. The available values range from f_{WA} **= 0.94** for heavy work activity to f_{WA} **= 1.0** for very light work activity with a default value of 0.98. These values correspond to values found in literature.

4.5.2. Reduced Capacity Function

The resulting function for the reduced capacity of a motorway during roadworks is gained from the combination of the factors for capacity reduction:

$$C_{RW} = (Cap - V_{Lat}) \cdot f_{LC} \cdot f_{OC} \cdot f_{LW} \cdot f_{TC} \cdot f_{HGV} \cdot f_{WA} \qquad (4.6)$$

The values that each parameter can take are shown in table 4.7.

Table 4.7: Reduced capacity function parameters

Factor		Chosen Relation (default value)
Lane Closure	f_{LC}	0.95 per closed lane
Use of opposite carriageway*	f_{OC}	0.9 for 2&3-lanes switchover 0.93 for 2/3-lane switchover 0.95 for 1/2-lane & 1/3 switchover
Lane width reduction	f_{LW}	0.9 for 2.75m 0.95 for 3m 0.98 for 3.25m
Lateral clearance	V_{Lat}	100veh for <0.3m 50veh for 0.3m
Traffic composition	f_{TC}	1.0 peak hours 0.95 non-peak/rural 0.9 weekend/vacation
HGV	f_{HGV}	$f_{HGV} = \frac{1}{(1-P_{HV}) + P_{HV} \cdot PCE}$
Extent of work activity*	f_{WA}	0.94 – 1.0, default = 0.98

* Values revised after calibration (paragraph 5.5)

4.6 Conclusions

The considered methods for the calculation of a traffic demand profile have been compared to determine the best choice for the use in this research. It should also be mentioned that the use of an internally determined demand profile is only necessary when no externally calibrated demand profile is available.

In this chapter we have furthermore observed that there are a large number of possible factors that can influence the capacity of a lane during roadworks. For most of these factors the relation to the road capacity is proven. Nine factors were selected for this research.

The existence of complete methodologies was also demonstrated and the main methods have been described in further detail. It is apparent that a number of approaches are possible and that each approach has its specific focus.

Conclusions

For use in this research, an externally calibrated demand profile is preferred, but when not available a demand profile is determined using Data fusion and averaging. For the capacity profile, a capacity reduction factor method is chosen and a mathematical relation is constructed.

5. Model Development: Model Setup

In this chapter the approach applied at the heart of the developed model is discussed. This begins with an overview of the way the reference and roadwork capacities are calculated (5.1). A detailed explanation is given of the specifics of the model and the way it makes use of the input profiles to determine congestion and eventually the travel times (5.2). The final model algorithm is shown in paragraph 5.3 and the results of the model calibration are presented at the end of the chapter (5.4 & 5.5).

The principles of traffic flow theory were explained in chapter 2, in which we saw how the basic quantities in traffic flow affect each other. The importance of capacity in relation to the traffic flow demand in this process is also evident. The basic equation stating that when capacity is exceeded by the traffic demand that congestion will occur lies at the heart of the developed model. The basic model will be further expanded in this chapter.

5.1 Traffic demand & Road capacity profiles

5.1.1. Traffic flow demand Profile

The manner in which the traffic demand profile was presented in the previous chapter. The preferred source is a verified profile per day of the week produced by Rijkswaterstaat. In absence of this however, the profile is determined through data fusion and averaging techniques as previously described.

5.1.2. Reference Road Capacity

The choice was made to use the Product Limit Method (PLM) to determine the reference capacity of motorway sections. This method makes use of a distribution of recorded traffic; both congested and uncongested, spread out using a probability distribution function:

$$L(q_i) = \prod_{i=1}^{n} \frac{m(q_i) - 1}{m(q_i)} \qquad (5.1)$$

where $L(q)$ = $Prob(q_{cap} > q)$
$m(q)$ = Number of observations of intensity q_i
q_i = Observed intensities

In the model the PLM-part is fed with average traffic flows and traffic speeds recorded in a 15-minute period, conform the definition of capacity. These values are sorted in ascending order of the recorded traffic flows and the occurrence of congestion for each interval is determined. Congestion is deemed to have occurred when the average speed during the interval is below 70 kph and the flow is higher than 2000 veh/hr/ln. The choice of these values eliminates data being considered as congestion due to errors in the data. The congested traffic flows are considered with a probability, which is also dependent on uncongested traffic flows. The reason behind this is that a higher flow is recorded that in certain cases may also lead to congestion. Using this distribution, the median value is determined as the decisive capacity value for that section of road.

The capacity values determined from the PLM are averaged over a set segment distance of one kilometre, to avoid an erratic capacity profile. Thereafter a comparison is made with a base capacity value. When the base capacity value is higher than the calculated capacity, the base capacity is taken as the capacity for the corresponding section of motorway. The reason for the use of a base capacity is that the PLM is not capable of determining a capacity value if congestion does not occur on a certain section of motorway. Therefore the method will return a zero-value. The combination of the PLM capacity and the base capacity, where applicable, forms the reference capacity profile used in the model.

5.1.3. Road Capacity Profile

The capacity estimation part of the model is taken from the proposed capacity reduction function derived previously for the capacity of a motorway during roadworks:

$$C_{RW} = (Cap - V_{Lat}) \cdot f_{LC} \cdot f_{OC} \cdot f_{LW} \cdot f_{TC} \cdot f_{HGV} \cdot f_{WA} \qquad (5.2)$$

The function is fed with the relevant information by the road authorities, resulting in a capacity estimation with which the traffic demand can be compared. The function values are calibrated using measured data and will be further calibrated as part of the whole model.

The necessary inputs for the capacity modelling are:

1. Number of lanes in use and closed
2. Configuration of roadworks (such as a lane shift system)
3. Lane widths
4. Lateral clearance
5. Traffic composition

6. Proportion of HGV in traffic
7. Extent of the work activity

The factors for speed reduction and the influence of ramps are considered in other parts of the model.

5.2 Congestion modelling

The manner in which congestion is modelled has great influence on the outcome of the overall traffic flow and more importantly the travel time. The basic theory states that when the traffic flow exceeds the capacity, traffic flow will break down and congestion will occur. However in reality there are (large) stochastic fluctuations in the traffic flow and the practical capacity of the road can also vary. The manner in which congestion is induced therefore is also an entity, which must be considered. Both the onset and the dynamics of congestion itself are considered for the manner of congestion modelling as a whole.

5.2.1. Congestion onset

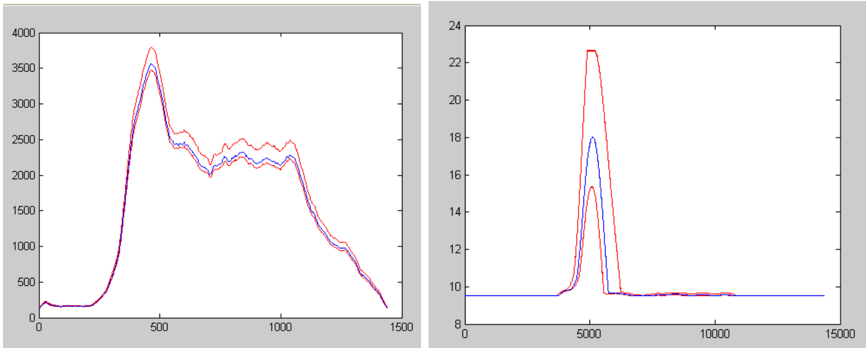
The stochasticity of traffic means that certain traffic intensities close to the practical road capacity may cause congestion on a certain day, while on another days congestion may not occur at that specific location. Certain traffic intensities may only occur for a short time or the composition of traffic may be such that a slightly higher traffic intensity is required to induce congestion. On the other hand congestion may be induced by an extreme circumstance, such as a sudden braking manoeuvre by an individual driver. This has the capability to induce congestion before traffic flow becomes critical.

To take the stochastic character of traffic into account, the developed model makes use of bandwidths for the calculated flow profile used in the model. These bandwidths represent the 15^{th} and 85^{th} percentile of the traffic demand used in the model. The resulting travel times from these demand flows will lie higher and lower than the average predicted travel time and will give an indication of the confidence level of the prediction either side of the predicted travel time. The user can make use of this bandwidth in travel time to give a larger certainty within which boundaries the realised travel time is likely to fall. Figure 5.1 gives an example of the traffic demand profile and the corresponding bandwidths. Also shown is the corresponding travel times for the bandwidths.

Figure 5.1: Example of bandwidths for:

A: Demand Profile (flow x time)

B: Travel times (travel time x time)

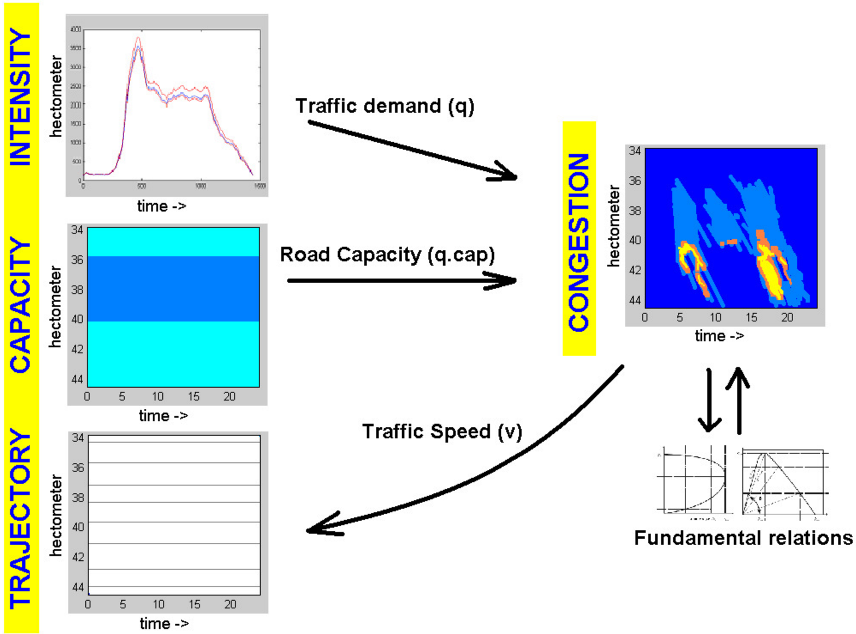


5.2.2. Congestion model

Once congestion sets in, the manner in which it is modelled becomes relevant. The method used in the developed model makes use of the LWR (Lighthill-Whitman-Richards) method solved using the Godunov scheme, which considers first order traffic flow theory on the basis of the conservation equation (this was described in paragraph 2.2 & 3.2). The traffic characteristics (density and flow) for the predetermined sections of the motorway corresponding to the locations of the induction loops (approximately 200m) are calculated iteratively for each time step. When the density of a section reaches the critical density, congestion is triggered. This process is induced through comparison with the relevant fundamental diagram. From this relation the corresponding traffic flows are calculated, which are utilised in the following time step. The method allows for forward traffic flow, while also allowing backwards-propagating congestion. The time steps are chosen such that the *celerity condition* is met, that is that traffic cannot transcend more than one space section in a single time step.

Traffic speeds are derived from the flow definition. This results in a mean speed over the section, which allows for the calculation of the travel time per section at a specific time and therefore a travel time over the entire motorway corridor. It is the actual travel times that are calculated, by considering the time needed to transverse a section and following the trajectory in space and time. Figure 5.2 shows the modelling process graphically.

Figure 5.2: Model Flow-diagram of Travel time modelling including congestion calculation

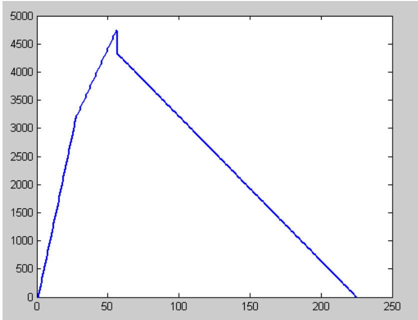


When traffic demand in a section again returns to a value below capacity, the queue disperses from the front of the section. This means that shockwave theory is accounted for, and thus the place and time of congestion is more accurately determined. This therefore also leads to more reliable travel times.

5.2.3. Fundamental Diagram

The fundamental diagram used in the model is a three-regime diagram with resemblance to that of the Daganzo fundamental diagram with linear relations for the flow-density. The three sections of the diagram (see figure 5.3) represent traffic in free-flow, saturated flow and congested flow. This approach is chosen as it gives a good representation of real traffic flows, while not being overly complicated which forms an advantage for the stability of the model. The diagram is constructed in the model such that in the free-flow region maximum speeds can be achieved, while vehicles in the saturated region are restricted in their speed. Congested traffic adheres to much slower traffic conditions (indicated by the gradient from 0) as may be expected.

Figure 5.3: Flow-density Fundamental diagram used in the model



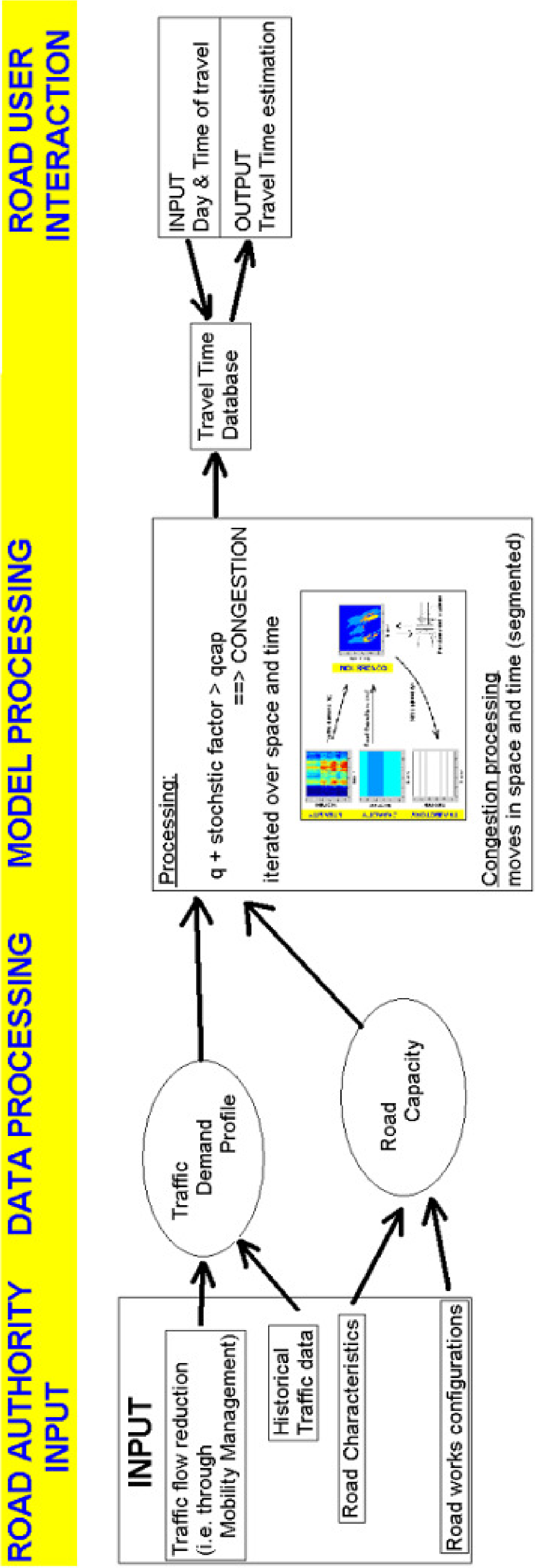
The critical density is chosen as a set value of 28 vehicles per kilometre per lane, while the jam density is set at a value corresponding to nearly four times this value at 120 vehicles per kilometre per lane (Guan & He, 2008 & Helbing & Treiber, 2002). Both these values correspond to fair estimates of the quantities and are fairly generic. A further capacity drop can be viewed in the diagram which is given a value of 6% of the capacity flow. This value is based on external research (Chung, Rudjanakanoknad & Cassidy, 2005). Proof of the stability of this fundamental diagram in the model is given in appendix B.

5.3 Model Algorithm

Combining the various elements of the model, a complete algorithm is constructed. This is shown graphically in figure 5.4 on the following page.

The model is given **input by the road authorities** in the form of *historical traffic data* and *predicted alterations* in traffic flow for the traffic flow demand. As for the road capacity, *road characteristics* and *roadworks configurations* are entered as input. These are processed as described in paragraph 5.1 and 5.2 respectively and act as the input for the simulation part of the model. In this **simulation part**, the data is processed for the traffic flow in space and time including the influence of congestion. Travel times can be produced per time of day and day of the week as the output of the simulations. For implementation, these would be stored in a *database*, which is accessed when a road user makes a request for information. The output given to the **road user** would be an *estimation of the travel time* over the stretch of relevant motorway and/or as travel advice depending on the way the information is eventually processed for public use.

Figure 5.4: Graphical representation of the model algorithm



5.4 Model Calibration

The model as whole is calibrated using recorded data to ensure that the results produced are reliable and correspond to values that may be expected providing the given input. As the real output of the used data is known, the output produced by the model can be compared to this. Adjustments are made in the model when the comparison with the real data shows a significant deviation from the produced output of the model.

The calibration is performed on three sub levels. The three sub levels represent the main components of the model: *Flow Profiling*, *Capacity determination* and the *Flow modelling*. Table 5.1 shows the main input and output variables used in the calibration.

Table 5.1: Variables used for calibration

Model area	Set input value	Input variable	Output value
Flow Profiling	*- Demand Flow Profile*		*- Demand Flow Profile* **(Paragraph 5.6.1)**
Capacity: Reference		*- Segment distance* *- Base Capacity* *- Capacity estimation*	*- Capacity Profile* **(Paragraph 5.7.1)**
Capacity: Roadworks		*- Roadwork factors* *- Mobility Management*	*- Workzone Capacity* **(Paragraph 5.7.2)**
Modelling	*- Fundamental Diagram (incl. Capacity Drop)* *- Critical & Jam Density*		*- Travel times*

5.4.1. Flow Profiling

The developed method makes use of a data fusion and smoothing filter and moving average technique to process the reference traffic flows from induction loops into a single flow profile. Prior to the analysis, the raw data is processed through the data fusion and smoothing filter to eradicate outliers and missing values in the collected data. This leads to a less erratic and completer representation of the traffic flow data over space and time for each of the measurements. This data is combined to a single flow profile using a moving average technique prior to which includes the averaging of the data for the road sections commencing the future workzone. The outcome of the moving average is a single flow profile set out against the time of day.

The traffic data from the three reference locations used in the development of the method were processed in the aforementioned manner. In figure 5.5 a comparison is shown between the original unprocessed traffic data from the significant motorway locations and the resulting flow profile produced.

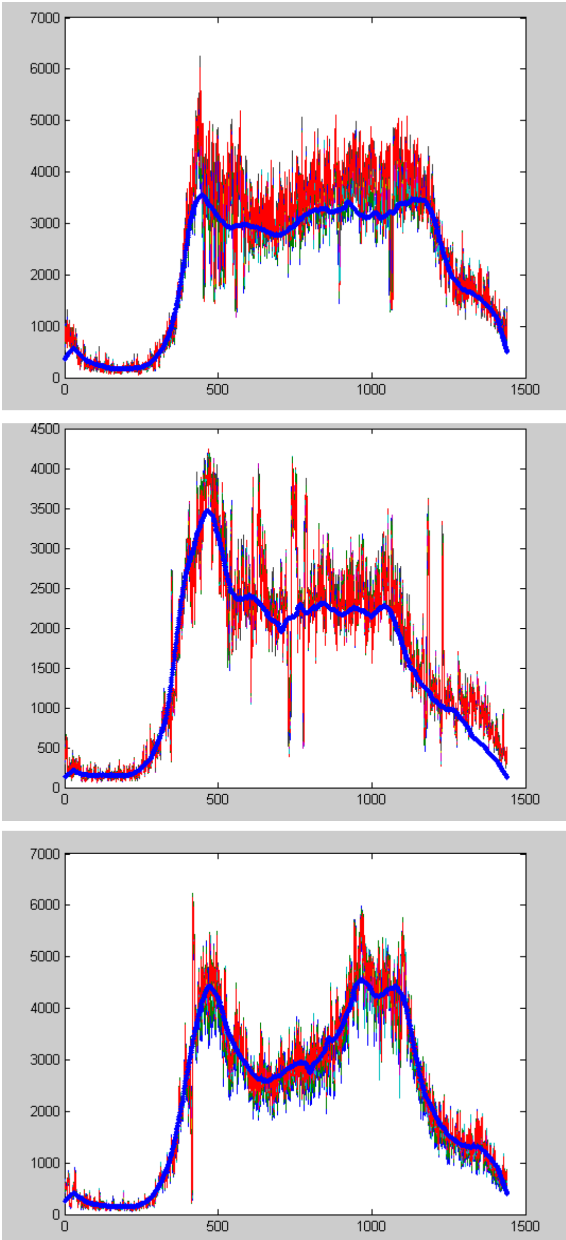


Figure 5.5: Raw flow data (multicoloured) and smoothed demand profile (blue)

A: from A2 calibration data

B: from A9 calibration data

C: from A16 calibration data

The graphs show that the smoothed demand profile follows the raw traffic data nicely. The smoothed demand profile also gives a good representation of the average flow without the erratic stochastic character of the raw data and is therefore ideal for use in the developed model. The stochastic character of the traffic flow is considered in the model through the application of the confidence bandwidths, as described previously.

5.5 Travel time & capacity calibration

The calibration of the capacity profile and the model as a whole are combined, as the capacity profile is the main variable for the calculation of the travel time. The calibration of this part of the model is split into two parts: the *Reference Capacity* and the *Roadworks Capacity*. Additional results of the calibration are shown in appendix D.

5.5.1. Reference capacity calibration

The main variables considered during the calibration for the reference capacity are the *segment distance* (that is the distance over which a set capacity is applied), the *base capacity* applied when no capacity estimation is possible (i.e. because no congestion occurred in the input data) and the manner in which the *Product Limit Method (PLM)* is applied. The output values used for the calibration are the recorded travel times, which are derived from MoniCa data and from camera's along the motorway stretch (when applicable) for the data without roadworks.

Applying various values for the **segment distances** for the three calibration cases allowed a choice to be made of an appropriate distance over which the capacity is averaged. It was apparent that a low value had the potential to give a rather 'jumpy' representation of the capacity, while a high value would lead to a loss of data for specific location related capacities. From testing various values, it became apparent the ideal distance lies between one and two kilometers. The decision is made therefore to choose a value for this variable of **one kilometer,** as this lies in the 'stable' region and results in the least loss of data.

Obviously the choice of **base capacity**, which is applied when a capacity cannot be determined, has a significant effect on the travel times. Various values were tested ranging from 1800 veh/hr/ln up to 2200 veh/hr/ln. For all the case studies a value was found in this range to fit the produced travel times derived from the MoniCa and camera data. Further tweaking resulted in a value of **2000 veh/hr/ln** proving to yield closer values to the reference data than a lower base capacity overall. For individual cases a slightly higher or lower value proved however to be more accurate. It must therefore be mentioned that this capacity will not always accurately represent the real operational capacity when the capacity cannot be measured. The process of calibration carried out here, shows that on a whole, the value is close enough to a good overall estimate that good results are yielded.

During the calibration it became clear that adjustment of the variables used in the **PLM** was not required from its original set-up. The method (see paragraph 5.1 for details) is set-up so that a capacity estimation is given when at least two observations, during a 15-minute interval per location, are observed above the 50% probability point and at least two below. From fewer congested observations it becomes difficult to give an accurate capacity estimation, if at all.

Table 5.2: Reference Capacity variables

Variable	Calibrated value
Segment distance	1000 metres
Base Capacity	2000 veh/hr/ln
PLM variables	15-mins / min. 2+2 observations

5.5.2. Roadwork capacity calibration

For the **roadworks capacity** calibration the reference capacity, as calibrated previously, is used with the main calibration variable being the application of the *roadwork factors*. Furthermore the influence of *mobility management* is considered, as the recorded values for this are not decisive. The output values for the calibration are then the travel times recorded, again using MoniCa and camera data, during which roadworks were in progress.

The **roadwork capacity reduction** values from the reduction factor table (table 5.3) consist mainly of values determined externally from scientific research. Of these values, a number are deemed to be reliable, while others may have more room for variation. The values which are deemed to give a good representation of the capacity reduction and are not adjusted during calibration are: *lane closure*, *traffic composition* and *HGV* factors. This leaves the factors for the *use of opposite carriageway*, *lane width* and *work activity* as adjustable variables. The values assigned to each of the roadworks are given in the table below along with the results of the calibration. Furthermore the factor considered for **mobility management** is given. These values do not deflect to much from the externally determined values of 9% for both the A2 and the A9.

Table 5.3: Capacity reduction factor values for calibration cases

Roadwork factor	A2	A9	A16
Lane closure	1	0.95	1
*Opposite carriageway**	0.9	0.95	0.95
*Lane width**	0.98	0.95	0.95
Traffic composition	1	1	1
HGV	0.93	0.95	0.91
*Work activity**	0.95	0.98	0.98
Lateral Clearance	-0	-100 veh/hr/ln	-100 veh/hr/ln
Necessary adjustments in reduced capacity	**1.02x**	**0.9x / 0.94x**	**0.98x**
Used Mobility Management factor	**9%**	**8% / 7%**	**8%**

** Adjustable factors for calibration*

Resulting from the calibration, an adjustment in the total roadwork capacity is required of a factor 1.02, 0.94 and 0.98 for the corresponding motorway cases A2, A9 and A16. As the amount of roadwork cases considered for the calibration is limited it is not possible to accurately determine where tweaking is required in the factors. For this reason common sense is also applied where applicable. Taking the necessary adjustments and the roadwork characteristics into account, it would seem that an adjustment of the factor for the use of the opposite carriageway is in order. The severity of capacity reduction seems not to be as dependable on the type of carriageway switchover rather as the necessity to make use of the opposite carriageway. A change is therefore proposed as indicated in table 5.4. Furthermore the rather subjective influence of the work activity rate is lowered to a lower default value, from 0.98 to 0.96. Making these changes brings the desired capacity reduction for the case studies and can be argumentally justified.

Table 5.4: Changes to the values for the capacity reduction factors

Factor		Previous Relation (default value)	New Relation (default value)
Use of opposite carriageway	f_{OC}	0.9 for 2&3-lanes switchover 0.93 for 2/3-lane switchover 0.95 for 1/2-lane & 1/3 switchover	**0.91** for 2&3-lanes switchover **0.92** for 2/3-lane switchover **0.93** for 1/2-lane & 1/3 switchover
Extent of work activity	f_{WA}	0.94 – 1.0, default = 0.98	0.94 – 1.0, default = **0.96**

Altered values are indicated in **Bold**.

5.6 Conclusions

In this chapter the methods applied to determine the capacities used by the model and the specifics of the main modelling section have been explained. This includes the congestion model and chosen fundamental diagram at the heart of the developed model resulting in the final model algorithm. The developed model is calibrated using data from the previously determined roadwork locations. This led to some small adjustments in the applied capacity reduction factors and let a base capacity be set for the model. The values collected for the direct influence of mobility management and the indirect effects leading to a reduced traffic demand were also confirmed.

Reference Capacity

The reference capacity is determined using the *Product Limit Method (PLM)* over 15-minute intervals and per distance of one kilometre.

Traffic Flow modelling

Traffic flow and congestion is modelled using the *LWR-model* with *Godunov scheme* over sections of 200 metres and the corresponding time step of a tenth of a minute in line with the *celerity condition*. The applied fundamental diagram has a linear free-flow, saturated flow and congested flow regime and makes use of a 6% capacity drop for congestion with set critical density values per lane.

6. Model Evaluation: Case study A12

In this chapter the evaluation results of the developed model on the case study A12 are given. Firstly the set-up of the case study is explained (6.1), followed by the produced results in the case without roadworks and then the case with roadworks (6.2 & 6.3). This is followed by a sensitivity analysis of the results (6.4), which indicates to which extent changes in capacity and/or flow affect travel times.

6.1 Case study set-up

The case study used to evaluate the accuracy and workings of the model is taken from roadworks performed on the A12 during 2008. The choice for this location is given in paragraph 3.3.2 and the specific characteristics of the roadworks are shown in appendix A.

These roadworks were performed in the months of August and September 2008, during which the use of mobility management was utilised to reduce the negative effects of the reduced capacity of the motorway over the period of the works. It is not easy to make an estimate of the realised effect of these measures. A conservative value of a 3% reduction in afternoon traffic (when congestion occurs most regularly on the route) is derived from the available data. However a higher value of up to 5% is possible. Besides the direct reduction of traffic flow from mobility management, it may also be presumed that there will be an (large) indirect reduction in traffic flow. This indirect reduction comes from road users changing their travel patterns to avoid the additional congestion caused by roadworks. Ways that this is done range from the choice of an alternative route, using public transport or travelling outside of the main peak period. It is not possible to accurately determine the reduction in traffic flow due to mobility management and the other indirect factors. For this reason the results are given as a function of the used mobility management factor (MM%), which calculates a percentage reduction in traffic flow in the model. This basically means that different MM% are used and the results are compared. The value for the reduced traffic demand is expected to lie between 5% and 10%, with a lower value in this bandwidth being more likely.

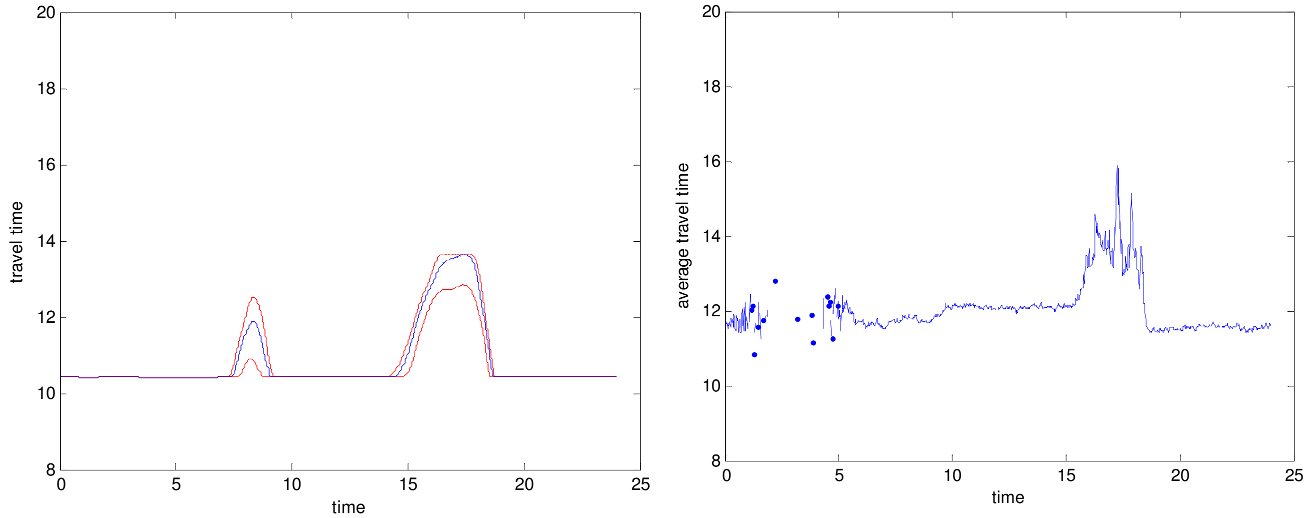
6.2 Results without roadworks

The model is run for the case that roadworks are not carried out in the selected period. The outcomes of these runs give an indication of the correct workings of the model before validation using a reduced roadworks capacity in a workzone. The results are given in figure 6.2. The travel times shown are all actual travel times.

Figure 6.1: Travel times on the A12 without roadworks:

a) produced by the model

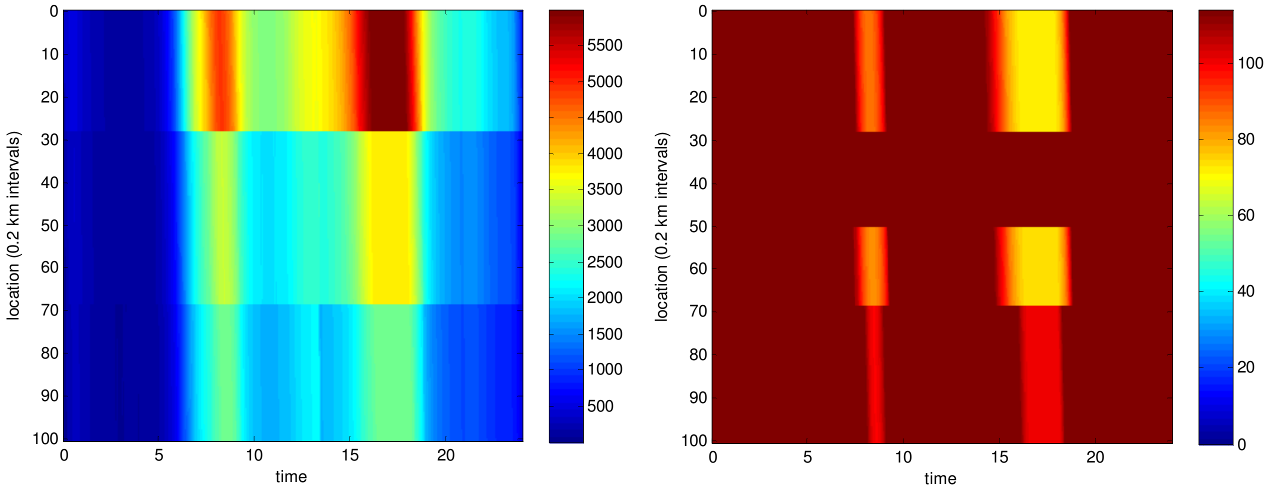
b) empirically recorded average



The results show that a small amount of congestion is recorded for the afternoon peak period in the model, which is also indicated by the real data. However the real data shows this congestion to be more extensive than the model (average travel times 14mins versus 16mins). Furthermore the spread of the travel times is greater in the real data than for the model. This may be explained by the stochastic variance in the used data being greater for the real data than the data travel times in the model. In a larger dataset this difference would be expected to be less. The fact that the non-peak periods show a lower travel time in the model than recorded also plays a roll. This difference (10.5 versus 11.5 minutes) is explained by considering free-flow intensities present on the road, which are also considered by the model, but not in the modelled speeds. This is due to the shape of the fundamental diagram in the free-flow section, which is linear. These differences were expected, but because of their small size were deemed insignificant.

In the modelled travel times shown in figure 6.1a, the confidence bandwidths give an indication of the spread in travel times that may be expected. In the upper bandwidth a ceiling appears to be present for the afternoon peak period. This is the consequence of a prolonged period of critical traffic flow, which results in similar travel times and is shown as a near horizontal line in the travel time graph. Figure 6.2 offers a graphical insight into this behaviour for the upper bandwidth, in showing the intensity and speed plots.

Figure 6.2: Intensity (left) & speed (right) plots for the upper bandwidth without roadworks



The peak in data seen during the morning peak period is similar to the approximate real travel times and does not play any significant role due to its relatively small size.

6.3 Results with roadworks

The results from the model for the travel times with various mobility management factors applied are given numerically in table 6.1 (the graphical results can be viewed in appendix E). The model simulations are initially performed using a base capacity of 2000 veh/hr/ln. The modelled and recorded travel times are actual travel times. The intensity, density, speed and travel time plots for the below results are also given in appendix E.

Table 6.1: Travel times for the A12 with roadworks (Base Capacity = 2000 veh/hr/ln)

Afternoon peak period

MODEL:

MM%	15% bandwidth	Average traffic flow	85% bandwidth
15	15	16	20
12	15	20	25
10	15,5	22,5	27
8	17	25,5	30
7	**18**	**27**	**30**
6	**19,5**	**29**	**30**
5	**20,5**	**30**	**30**

RECORDED DATA:

Recorded travel times	**16**	**20**	**27**
RWS traffic monitor Aug.*	11	13	15
RWS traffic monitor Sept.*	13	23	34

ERRORS (Absolute / Relative):

MM%	15% bandwidth	Average traffic flow	85% bandwidth
10	-0.5 / -3%	2.5% / 13%	0 / 0%
8	1 / 6%	5.5 / 28%	3 / 11%
7	**2 / 13%**	**7 / 35%**	**3 / 11%**
6	**3.5 / 22%**	**9 / 45%**	**3 / 11%**
5	**4.5 / 28%**	**10 / 50%**	**3 / 11%**

Morning Peak Period

Model (MM~5-8%)	13	15	15,5
Recorded travel times	12	14	16
RWS traffic monitor Aug.*	11	12	12
RWS traffic monitor Sept.*	12	12,5	16

Outside Peak Period

Model (MM~5-8%)	12,5
Recorded travel times	12,5
RWS traffic monitor Aug.*	11
RWS traffic monitor Sept.*	12

**considered distance is presumed to be 0,5-1 km shorter.*
***BOLD** indicates the most likely region for MM.*
***Red** indicates values that are limited due to congestion propagating beyond the considered motorway stretch.*

The initial results produced by the model show a significant error (20-50%) in the travel time predictions for the afternoon peak period for the presumed MM factors. For the morning peak period and outside the peak periods the values produced are unspectacular and correspond to what would be expected. Travel times for all the presumed MM-percentages in the afternoon peak period are however overestimated. Only for MM-percentages of 10-12% do the travel times correspond to the values measured, however these values for the reduction in traffic flow are unrealistically high for this study case. This leads to the conclusion that congestion is overestimated and therefore the presumed capacity is too low. The uncertainty corresponding to which base capacity should be chosen is likely to be at the centre of this. For this reason the model is also tested using a base capacity of 2100 veh/hr/ln. The results of this are shown in table 6.2. The plots from these results are also given in appendix E.

Table 6.2: Travel times for the A12 with roadworks (Base Capacity = 2100 veh/hr/ln)

Afternoon peak period

MM%	15% bandwidth	Average traffic flow	85% bandwidth
10	14,5	16	20
8	15	19	23
7	**15**	**20**	**25**
6	**15**	**21**	**26**
5	**15**	**22,5**	**27,5**
Recorded travel times	**16**	**20**	**27**
RWS traffic monitor Aug.*	11	13	15
RWS traffic monitor Sept.*	13	23	34

ERRORS (Absolute / Relative):

MM%	15% bandwidth	Average traffic flow	85% bandwidth
10	-1.5 / -9%	-4 / -20%	-7 / -26%
8	-1 / -6%	-1 / -5%	-4 / -15%
7	**-1 / -6%**	**0 / 0%**	**-2 / -7%**
6	**-1 / -6%**	**1 / 5%**	**-1 / -4%**
5	**-1 / -6%**	**2.5 / 13%**	**0.5 / 2%**

Morning Peak Period

Model (MM~5-8%)	13	14,5	15
Recorded travel times	12	14	16
RWS traffic monitor Aug.*	11	12	12
RWS traffic monitor Sept.*	12	12,5	16

Outside Peak Period
(identical results)

**considered distance is presumed to be 0,5-1 km shorter.*
***BOLD** indicates the most likely region for MM.*

The model, with a base capacity of 2100 veh/hr/ln shows a marked improvement to the previously produced results on the basis of a base capacity of 2000 veh/hr/ln. Moreover the results show an excellent match on the basis of the most probable mobility management (MM) factors (5-7%). For the average traffic flow during the peak periods with MM at 6-7% the relative error is less than 5%. The confidence bands at the 15^{th} and 85^{th} percentile equally show a low error below or in the region of 5%. According to the produced results, a MM factor above 8% is not applicable, which is in line with the expected values. Equally a value below 5%, also in line with expectations, is not applicable.

The results produced by the model for the morning peak period and outside the peak periods again show a marginal error and correspond to the recorded data.

6.4 Sensitivity analysis

To indicate the relative sensitivity of adjustments in the traffic flow / mobility management[19] or the reduced workzone capacity, an analysis is performed using different values for the variables of these quantities for the model. In this way the effect of variations in these quantities is made clear and gives a greater insight into the overall sensitivity.

6.4.1. Traffic Flow / Mobility Management [17]

A result of percentage changes to the level of traffic flow in the traffic flow demand profile used by the model on the travel times is given in figure 6.3. The horizontal axis shows the flow reduction factor (of applied MM-factor) and the vertical axis shows the produced travel times, including the travel time confidence bandwidths, for the corresponding flow reduction.

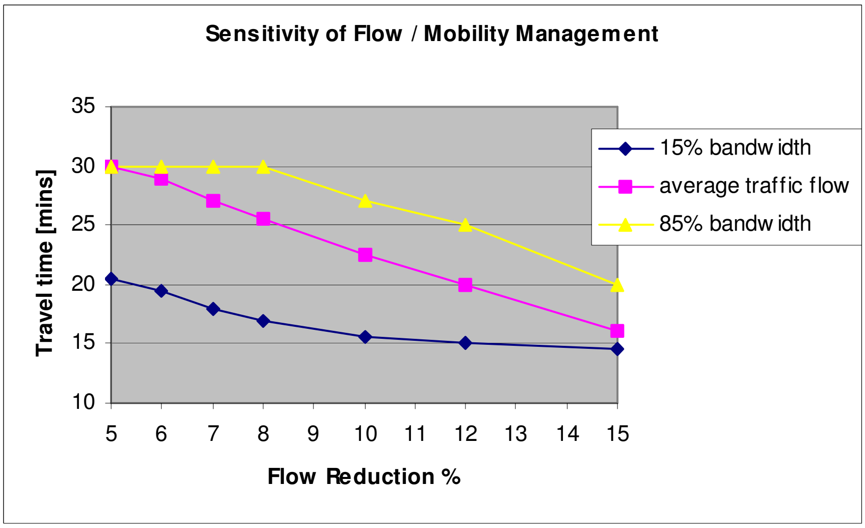


Figure 6.3: Flow demand sensitivity results

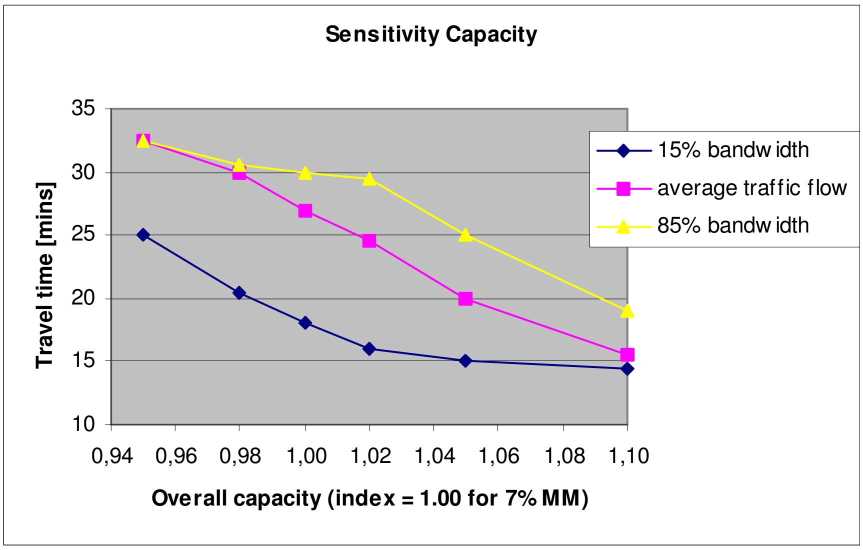
Although it is most likely that the graph shows a negative-exponential relation on a larger scale, for the region considered a linear relation is presumed. Out with the asymptotic behaviour near the base travel time (approximately 12.5 minutes), the relation between the flow reduction and the travel time is approximately 1.4 minutes lower travel time for every 1% reduction in traffic flow. Obviously this value is case bound, however it does gives insight into variations in sensitivity of the traffic flow. It must also be noted that the 85th % bandwidth has a ceiling at 30 minutes due to congestion that propagates out with of the considered motorway corridor.

[19] Mobility management is modelled by a reduction in the traffic demand and therefore corresponds to the same quantity as the flow reduction for the sake of this analysis.

6.4.2. Capacity

As the capacity is equally important and is shown not to be easily determined, the sensitivity of variations for this quantity are also analysed. The results are shown in figure 6.4, where the base capacity in the workzone is 1.00.

Figure 6.4: Capacity sensitivity results



Unsurprisingly the relation is similar to that of the traffic flow. This is due to the relative relationship between the flow and capacity of a road; i.e. an increase in the flow has a similar effect as the same decrease in capacity and v.v. The relation between the travel time and the capacity is therefore also an approximate 1.4 minutes reduction in travel time for an increase of the capacity of 1%. For the higher travel time values, there is again a ceiling as a consequence of extreme congestion propagating beyond the considered motorway corridor. This is seen in the average and 85^{th} percentile graphs for the lower capacities.

6.5 Performance requirements

The main performance requirement set for the model was at least 95% of travel time predictions should show a relative error no greater than 20%. Figure 6.5 shows the comparison between the average model travel times and the recorded travel times during the entire day. The absolute relative error between the travel time sets are shown in the histogram in figure 6.6. Both quantities are *actual travel times*. The recorded travel times are derived from MoniCa data and the modelled travel times from the produced traffic data from the model.

Figure 6.5: Travel time comparison: Model (red) & Recorded (blue)

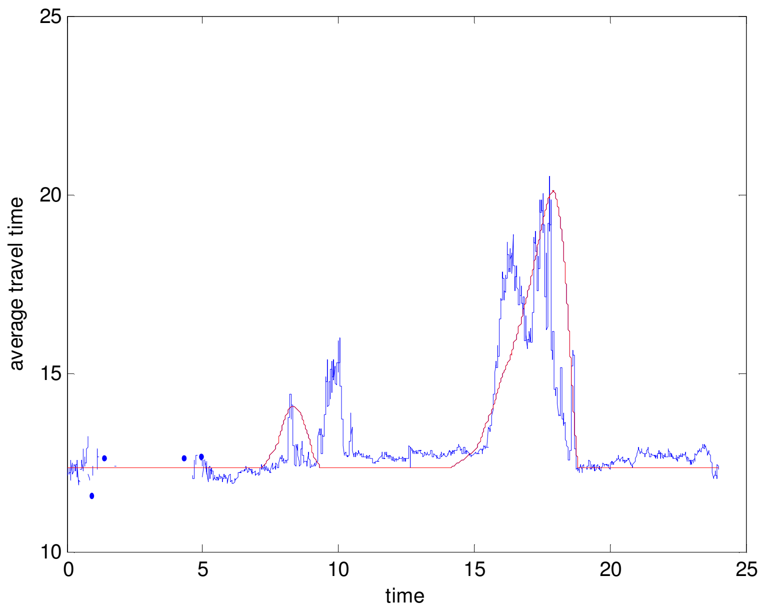
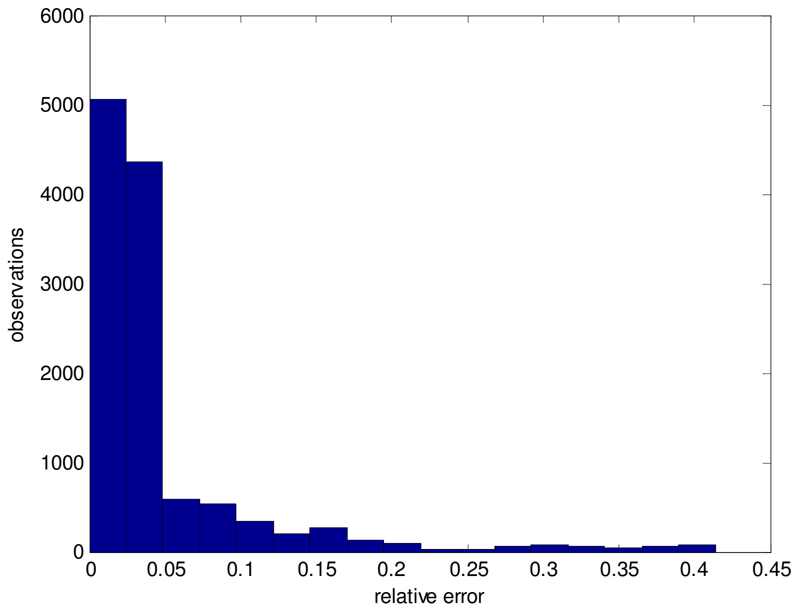


Figure 6.6: Distribution of the absolute relative error produced by the model



The histogram shows the distribution of the absolute relative error for each recorded time step in the day. Due to missing data between 1 am and 4 am, 12030 observations could be made (the entire day exists of 14400 observations). Of these 12030 observations 11550 showed an absolute relative error of less than 20% between the modelled and recorded travel times. This corresponds to 96.0% of the observations and is therefore above the performance requirement of 95% set previously[20].

[20] Including and presuming that the missing hours were also correctly modelled, the performance rate would be 96.7%

6.6 Conclusions

The analysis of the model results has been given in this chapter, including a sensitivity analysis and the performance of the model for the case study A12 Den Haag-Gouda. The afternoon peak period is the decisive period for this stretch of motorway. This is due to commuters returning home at the end of the workday from or near The Hague.

The model shows that under normal circumstances in which no roadworks are carried out, a good likeness in travel times is produced between the model and the recorded data. The limited size of the bandwidth produced is due to the relatively low amount of data days (5) used in the model. A more extensive input would lead to a broader bandwidth, as the variations grow.

Under roadwork conditions, for which a base capacity of 2000 veh/hr/ln is used, the model returns higher travel time values than might be expected for the presumed Mobility Management factor[21] (MM) of a 5-8% reduction in traffic flow demand. Not until an MM value of approximately 12% does the model produce correct travel times. This leads to the conclusion that congestion is overestimated and therefore the capacity is presumed too low. This is backed up by the results of the model using a base capacity of 2100 veh/hr/ln. For the adjusted base capacity the absolute relative error for a MM-factor of 6-7%, is in the region of and below 5%.

The results for the morning peak period and outside peak periods are in all simulations near to that of the recorded travel times with negligible errors.

The sensitivity analysis showed that a reduction in the inflowing traffic demand or an increase in the capacity of 1%, leads to a 1.4 minute reduction in travel time and an increase for the opposite case during the afternoon peak period. Furthermore both show asymptotic behaviour towards the free-flow travel times.

The overall results using a 2100 veh/hr/ln base capacity and an MM-factor of 7% lead to a performance rate of 96% of travel times over the entire day, with an absolute relative error less than 20%. This is in keeping with the *performance requirement* of a rate of at least 95%.

[21] The Mobility Management factor (MM) also includes indirect alterations in traffic flow demand other than directly from mobility management itself.

To summarise the results of the case study:

Conclusions

- The afternoon peak period is decisive for the A12 in the direction: The Hague -> Gouda.
- For simulations without roadworks the model shows good results (<5% error), however the bandwidths are limited.
- For roadworks a base capacity of 2100 veh/hr/ln gives good results with an absolute relative error of less than 5% for a mobility management factor of 6-7% during the afternoon peak period.
- With a base capacity of 2000 veh/hr/ln, congestion seems to be overestimated leading to travel times that are too high.
- The sensitivity analysis shows that for each 1% change in capacity or traffic flow, a 1.4 minute change in travel time occurs.
- For a base capacity of 2100 veh/hr/ln and a mobility management factor of 7%, 96% of travel times show an absolute relative error of less than 20%.

7. Model applications

The developed model is assembled with the goal to predict travel times during roadworks before the roadworks are in place. Assuming that the resulting travel times show a suitable level of accuracy, the information produced has the capability to be used in more than one manner in a number of applications. In this chapter the most suitable applications envisaged as a possibility to make use of the developed model are discussed.

7.1 Main application

When considering the various applications in which the model can be utilised, we will start with the main application at the heart of this research: *informing road users*.

In the original proposal by Rijkswaterstaat Noord-Brabant, the envisaged goal was informing road users of delays that may be experienced due to the future roadworks. The manner in which this would be performed is through the use of a central website, to which road users would be directed. Use of the public roadworks site of Rijkswaterstaat: *vanAnaarBeter.nl*, would be an ideal place for this purpose. The information that visitors of the site would originally be given would be the general delay expectation (similar to the current advice). Visitors then have the option to acquire a personal travel time prediction for the relevant stretch of motorway, by entering the time and day they wish to transverse the specific route. This would result in a prediction of the travel time for the desired day at the desired time. The travel times for each day and time are pre-calculated using the model and stored in a database, which would be accessed when a visitor requires information with a query through the website.

7.2 Alternative applications

7.2.1. Roadwork planning

The fact that the model predicts travel times on the basis of roadwork characteristics opens up the possibility for the use of the model in *roadwork planning* applications. When considering options for roadwork configurations, the model has the possibility to be used to give guidance to which configurations lead to the least delay and disruption for traffic in the future situation.

If this application is to be realised, control and interface additions and adjustments will need to be made to allow the model to be used to produce the desired information with the available input. Without giving a complete design for how this might happen, a few considerations for these adjustments are given here. It might be desired, for example, to have a list of comparable roadwork configurations given by the model with differing travel time predictions from which the road controller can choose and thereafter further specify. Additionally the option to make small adjustments and to immediately see what the impact is could be a good addition.
Obviously the accuracy of the roadwork factors on the travel time prediction would need to be further ratified, as changes to certain qualities need to represent the capacity conditions with a higher relative accurately. It therefore should yet again be mentioned and taken into consideration that the art of capacity determination is not an exact science.

7.2.2. Route planner subpart

The next possible application in which the model could be utilised is much closer to the original goal of informing the public of the likely travel times. The inclusion of the model as a *subpart of a route planner* has the capability to allow the model to be used not just to predict travel times, but also to have an influence in the route choices of road users.

The manner in which this could be achieved is to allow a route planner to take the travel times from the developed model for a specific stretch of motorway where roadworks are to be carried out and use these travel times rather than the time calculated for the same stretch by the route planner itself. In this way, the route planner considers the future roadworks and takes the predicted delays into account when advising a route. The inclusion is made easier through the fact the model will calculate travel times between explicit points on a motorway, such as interchanges or major intersections, allowing for a 'copy-paste' approach for that specific piece of road. Obviously the route planner would only make this adjustment when a specific day is selected in the future on which the roadworks will be carried out. As most route planners nowadays work on specific day selection, this is also easy to implement.

The likelihood of the use of this application is greatest for a route plan given approximately a week or less before the start of roadworks. Most road users will not plan their journeys more than a week, or in a lot of cases, a few days in advance and therefore its use is predicted not be great for predictions made any earlier.

7.3 Conclusions

In this chapter the main applications in which the developed model could be used are given and have been discussed in short. The main uses for the model are those which involve information provision, as considered in this research. This consists of both the original application of the model as a stand-alone application for travel times, as well as the use as a subpart of a route planner. Both these applications are in direct line with the development of the model up to the current point, while the use in a route planner has possibly the greater value as this offers a more complete solution. The use of the model to plan roadworks is also conceivable, though may require further adaptations to the model and interaction with users.

8. Conclusions and Recommendations

The overall findings of the research presented in this report along with the final conclusions and recommendations of the research are given in this chapter. First the findings from this research during the development of the model are given per category (8.1). The conclusions given in paragraph 8.2 give answers to the research questions and give a general summary of the most important results from the findings. Finally the recommendations (8.3) are made to bring the research to a conclusion.

8.1 Main findings

The findings from this research are given here and are presented as answers to the secondary research questions used in the research to underline the main research question.

1. How can travel times be predicted for future scenarios without knowledge of the future traffic conditions?

- Travel time estimates can be made for future scenarios by estimating the expected conditions and modelling these conditions to give a travel time prediction.
- The quantities that must be estimated are the *capacity* and the *traffic flow*.
- Congestion and mean vehicle speeds are calculated using *first order traffic theory* with a *Godunov scheme* to solve the equations numerically. A first order model offers the best option in simplicity and reliability while still producing a good representation of traffic flow.
- The capacity during roadworks can be determined by taking the normal capacity as a reference and applying a reduction factor. The reduction factor is dependent on the roadwork characteristics. Other data intensive methods are less useful as a large amount of data is required to achieve a good level of accuracy.
- The traffic demand during roadworks must be expected to change once roadworks are in place. This is actively sought through the application of mobility management. There is also an indirect reduction in demand from road users taking measures to avoid the roadworks location (during peak periods).

- The influence of mobility management and indirect demand reduction must not be ignored, as in some cases this can reach 10% or higher of traffic flow and therefore have a significant influence on travel times.

2. Which factors influence workzone capacity and what are their relations to travel times?

- A number of workzone capacity factors were found that influence the capacity of a road. However not all factors can be considered as either the influence they have is not accurately known or the necessary information to determine the factor is not available.
- The factors that were available and for which a relation could be determined are: *lane closure, use of opposite carriageway, lane width reduction, lateral clearance, traffic composition, HGV and the extent of work activity*.
- The influence of *speed reduction* and *on & off ramps* are also significant, but were chosen to be included at the congestion modelling stage. In the model they therefore affect the traffic flow, rather than the capacity in the model.
- As the capacity of a section of road is not a constant, it is desirable to determine the local capacity of a road section. For this, congestion must occur during observations. The Product Limit Method (PLM) is suited to this as it calculates capacities for multiple locations (where congestion occurs) and gives the pre-congestion capacity, which is useful for determining the start of congestion.
- When congestion does not occur we are compelled to make use of a presumed capacity, which for normal motorway lanes varies between 2000-2100 veh/hr/ln in most cases.

3. Which modelling methods are applicable in travel time prediction for traffic demand profiling?

- Firstly the conclusion is made that a complete externally verified day specific traffic demand profile is preferred when available.
- When a demand profile is internally created in the model, a simple moving average method of the available traffic data is sufficient to give a good and smoothed representation of average traffic flows.
- Pre-processing of the data prior to smoothing is required to eradicate errors in the data. Although the data should be chosen to minimise errors, it should be taken into consideration that corrected errors may lead to a bias in the overall data. The magnitude is dependent on the severity and number of errors.

4. Are travel time predictions using the developed model reliable and sufficiently accurate?

- Results from the study case A12 showed that the predicted travel times during roadworks can be estimated with an error of less than 5% of the recorded travel times at the decisive peak periods. The predictions over a complete day also show a good accuracy within the predetermined performance requirement.
- The influence of the applied base capacity[22] and reduction factors for mobility management play a significant role and must be correctly selected to avoid structural errors in the predictions.
- Estimating a reduction factor for mobility management and indirect demand reduction in advance proves to be a difficult and an inexact task. Good rough estimates can be made, but it remains to be seen if anything more than an expert estimate can be made.
- The extent of the generic reliability of the developed model from this research is inconclusive. The model is proved to be accurate in the case study, but a larger number of case studies will need to be required to validate the models overall reliability under a wide range of roadworks at differing locations. It must be noted that the same input variables at different locations can lead to very different outcomes. However the author is confident that further case studies will also show good results.

8.2 Final Conclusions

Using the main findings and the sub-conclusions from this research project allows the main research question to be answered in this paragraph. The main research question posed is:

How can a-priori travel times be predicted on motorway corridors for situations during roadworks, prior to the commencement of the roadworks?

The final conclusions of this research state that predicting the travel times for future roadworks in advance is definitely possible as has been shown in this research.

By considering the main traffic flow quantities: *traffic demand* and *capacity* separately, an estimation of the future values can be made

[22] The default capacity used when no local capacity can be determined

which takes the expected changes found under roadworks into account. The use of first order traffic theory with a Godunov scheme is proven sufficient to process the data and produce the predicted traffic flows.

The main factor influencing the traffic demand stems from the expected reduction in traffic flow, predominately due to the efforts of mobility management. The main influence on the capacity comes from the expected reductions from various road characteristics and which base capacity is chosen when a reference capacity cannot be determined.

The majority of the factors known to influence capacity during roadworks are considered in the model. However not all influencing factors can be considered due to a lack of information on the quantities and the relation to the capacity reduction.

The case study showed that the developed model is capable of producing accurate travel times during roadworks without prior knowledge of the realised travel times. The reliability of the model over a wide range of different type of roadworks and locations cannot be confirmed from this research and will require a larger number of further case studies.

The application of the model is most suited to implementation in the roadworks website of Rijkswaterstaat and/or as part of a route planner. For these applications the currently indicated nuisance categories should remain intact as advice with the developed model acting as a further personal travel time extension to this.

8.3 Recommendations

This research does not only result in conclusions from the performed work, but also leads to a number of recommendations concerning the further development and implementation of the model. Recommendations are also made for further research directly related to the subject at hand. These are given first, followed by the recommendations for further model development.

8.3.1. Further research in this field

The outcome of this research leads to recommendations that can be split into three groups for further research. These relate to the capacity estimation and the traffic demand reduction during roadworks, which are given here, and the modelling method given in the next paragraph.

Capacity estimation

- As many sections of a motorway do not show congestion, determining capacity at these locations is nearly impossible. Therefore the development of a reliable capacity estimation technique independent of the occurrence of congestion is recommended.
- For the application of roadwork capacity reduction factors, more extensive research into the relationship between the factors and the capacity is desired. When this leads to the use of regressive methods, such as neural networks, a technique to implement such a method with limited data is required.
- A physical program to collect and register specific quantities during roadworks is recommended to give a more complete and useful dataset when performing roadwork capacity research.

Traffic demand reduction

- The magnitude of traffic reduction due to mobility management currently cannot be accurately predicted. Research is recommended into a methodology leading to a good estimation technique for predicting the influence of these measures.
- Also the effect of indirect reductions in traffic demand due to the commencement of roadworks desires further research to determine a generic relation, if possible, for the expected reduction of traffic.

8.3.2. Model development and implementation

Further development recommendations are made for the developed model with a vision to improving and validating the models performance to a greater extent.

Model

- Further analysis is desired to determine and set a definitive base capacity value in the model. However a generic base capacity may not exist and therefore research into a relation between a motorway characteristics and the base capacity is recommended.
- The implementation of more accurate mobility management and capacity reduction factors follows from the previously recommended research into the preciseness of these quantities. A robust method to implement these quantities is furthermore recommended as a possible improvement.

- The implementation of a second order traffic flow theory model in the developed model may lead to overall improvements in performance, presuming that the second order model operates in a robust fashion.
- A further evaluation of the developed model is recommended in a series of further case studies to determine the generic reliability of the model over a wider range of locations and types of roadworks.

Following this research, the presented recommendations are given with the view for further research in this field of expertise on both the developed model and on a wider scale. This will allow for a greater knowledge of the ruling dynamics and allow for a further practical advancement in the manner in which roadwork are carried out and reported on.

List of definitions

Capacity reduction factor	Multiplication factor for the reduction of road capacity.
Capacity reduction value	Absolute value for the reduction of road capacity.
Carriageway	A cordoned section of road consisting of one or more lanes.
Celerity condition	A traffic flow modelling condition which indicates the iteration step sizes to prevent model instability by vehicles skipping sections in time or space.
Delay	The amount of time that one or more vehicles takes more than the time under normal or free-flow conditions.
Driver	(see road user)
Free-flow	The ability for traffic to proceed at the speed limit without significant interference from other vehicles.
Grade/Gradient	A vertical change in road slope, either positive or negative.
Hard Shoulder	Reserved area along major roads meant as an emergency stopping area.
HCM	The Highway Capacity Manual; an extensive list of guidelines, well respected in traffic.
Heavy Goods Vehicle (HGV)	A large transport vehicle (with trailer) capable of holding at least 3.5 tons in weight.
Lane	A section of road capable of a single row of traffic.
Lateral clearance	The lateral distance between the outside lines of a lane and the nearest stationary object.
Meldwerk	Central registration system for roadworks held by Rijkswaterstaat.
Mobility Management (MM)	The process of traffic management used to organise traffic flows and the involved parties, especially applied during abnormal road conditions, such as roadworks.
Motorway	Identical term to ‘highway’ of ‘freeway’ describing major carriageway roads for fast and large quantities of traffic.
Neural Network (NN)	Mathematical model that tries to simulate the structure and functional aspects of various traffic quantities.
Nuisance class	Descriptive ranking for the level of disruption caused by road works on the flow of vehicles.
Operational capacity	Capacity flow realistically achievable in practice for a road; normally given in vehicles per hour (veh/hr).
Passenger Car Equivalent (PCE)	The equivalent number of passenger cars represented by a HGV or other large vehicle.
Peak period / Peak hour	The nominal hours of a day in which the maximum traffic flows are expected; normally there is a morning and afternoon peak period.
Rijkswaterstaat (RWS)	Executive arm of the Ministry of Transport, Public Works & Water Management.
Road	A designated area for motorised vehicle use.
Road user	Anyone controlling a vehicle on a road.

Roadworks	Work performed on a road for which influence is exerted on road users.
Rush hour	(see Peak period)
Theoretical capacity	Capacity flow theoretically achievable for a road; normally given in vehicles per hour (veh/hr).
Traffic management	Any form of interference in traffic flow in order to control traffic flows.
Vehicle	A single transport unit regardless of size or weight.
Work Activity	Any active movement involved with roadworks in a workzone.
Workzone	A section of road on which or besides which roadworks are carried out.
WPK	Central roadwork planning overview, held by Rijkswaterstaat, stating all roadworks to be carried out under the jurisdiction of Rijkswaterstaat.

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Appendix A: Roadwork details

Test case locations

The locations used in this research to calibrate and validate the model are roadwork locations on the A2, A9, A12 and A16 of Dutch motorways in recent years. The characteristics of these motorway locations are given here:

Calibration case: A2

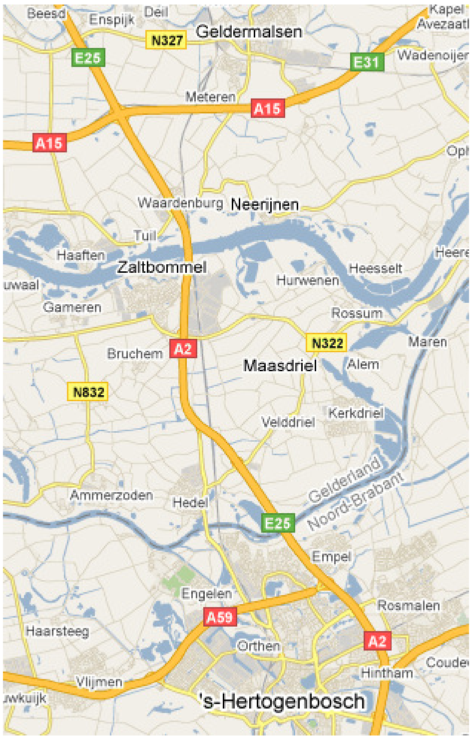
<u>When (*Complete Roadwork dates*):</u> May 2009 (*May 2009 – September 2009*)

<u>Where:</u> Intersection Deil (hct 91) – intersection Empel (hct 112)

<u>Traffic direction:</u> R (southbound)

<u>RWS Road district:</u> Noord-Brabant

Figure A.1 & A.2: Roadwork locations test case A2 and A9



Calibration case: A9

<u>When (*Complete Roadwork dates*):</u> August 2007

<u>Where:</u> Intersection Beverwijk (hct 55.4) – intersection Raasdorp (hct 40)

<u>Traffic direction:</u> L (southbound)

<u>RWS Road district:</u> Noord-Holland

Validation case: A12

When (*Complete Roadwork dates*): August 2008 – September 2008
Where: Intersection Prins Clausplein (hct 6) – intersection Gouwe (hct 27)
Traffic direction: R (westbound)
RWS Road district: Zuid-Holland

Figure A.3: Roadwork location test case A12

Calibration case: A16
When (*Complete Roadwork dates*): February 2007 (*November 2006 – July 2009*)
Where: Drecht-tunnel (hct 34) – intersection Klaverpolderplein (hct 46)
Traffic direction: R (southbound)
RWS Road district: Zuid-Holland

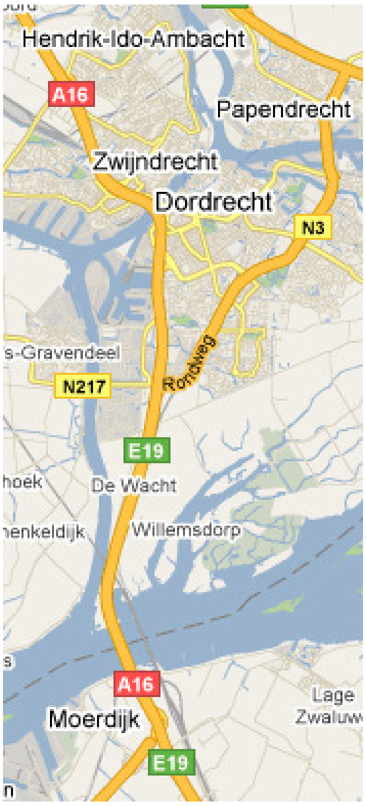


Figure A.4: Roadwork location test case A16

Details of roadworks

Each roadworks location has been chosen as a representative location, for which sufficient information is available about the roadworks and the traffic flows. Each location has differing roadwork characteristics. The characteristics are given here:

Table A.1: Roadwork characteristics for test cases

Location	Type of roadworks	Lane configuration	Roadworks configuration	Use of opposite carriageway
A2	*Construction of new road (lanes/carriageway)*	2x2 (3x3 in parts)	3x0	Yes
A9	*Resurfacing*	2x2	4x0	Yes
A12	*Construction of new road (lanes/carriageway)*	2x2 (3x3 in parts)	4x0	Yes
A16	*Bridge repairs*	3x3	4x2	Yes, in part

Location	Number of lanes available	Hardshoulder available	Lane width reduction	Max. speed limit	HGV %
A2	2/2	No	To 3.25m	90	15%
A9	1/2	No	Yes	70	11%
A12	2/2	No	Yes	90	9%
A16	3/3	No	Yes	90	20%

The data used in this research for the motorways are from all Thursdays between the following dates:

Table A.2: Traffic data dates

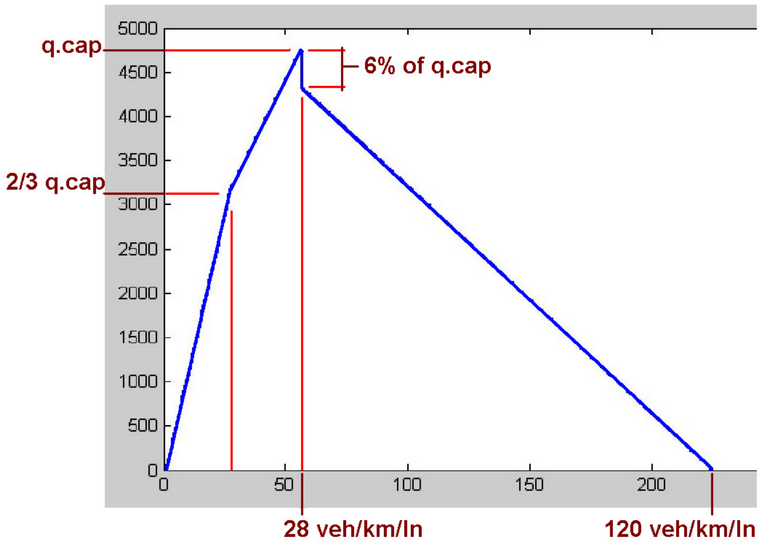
Location	Reference flows	Roadwork flows
A2	22nd May 2008 – 5th June 2008	21st May 2009 – 4th June 2009
A9	10th August 2006 – 26 August 2006	9th August 2007 – 23rd August 2007
A12	9th August 2007 – 13th September 2007	14th August 2008 – 11th September 2008
A16	9th February 2006 – 23rd February 2006	8th February 2007 – 22nd February 2007

Appendix B: Fundamental diagram, proof of robustness

As the fundamental diagram used in the proposed model is dependent on various variables and will change in size for differing capacities, a short proof of robustness against these changes is given here.

To prove: Stability of fundamental diagram for applicable capacity flows and maximum speeds.
Potential instability problem: Speed in the saturated area is higher than the maximum speed. This is result of the free-flow and the congested areas being bounded by set points, while the saturated area is dependant on the boundaries of both these areas.

Figure B.1: Fundamental diagram with set points indicated



Variables: Capacity flow and Maximum Speed.
Constants: Critical density (28 veh/km/ln) and jam density (120 veh/km/ln).
Variable dependant constants: Intensity and density at the switch point between free-flow and saturated flow.

Table B.1: Critical intensities per speed limit

Speed Limit *(km/hr)*	**120**	**100**	**90***	**80**	**70***
Critical intensity *(veh/hr/ln)*	3360	2800	2520	2240	1960

* *Standard maximum speed limits during roadworks*

The table shows that the critical intensity for stability of the fundamental diagram in all cases for normal driving conditions without roadworks is sufficiently high to regard the diagram stable. At 80 km/hr an intensity of 2240 veh/hr is the decisive value, which is sufficient to avoid instability. For the speed limits under roadwork conditions, a value of 1960 veh/hr is critical for a speed limit of 70 km/hr. Although this would cause problems under normal conditions, capacities during roadworks can always be presumed to be lower than 90% of the normal capacity and therefore this value also suffices.

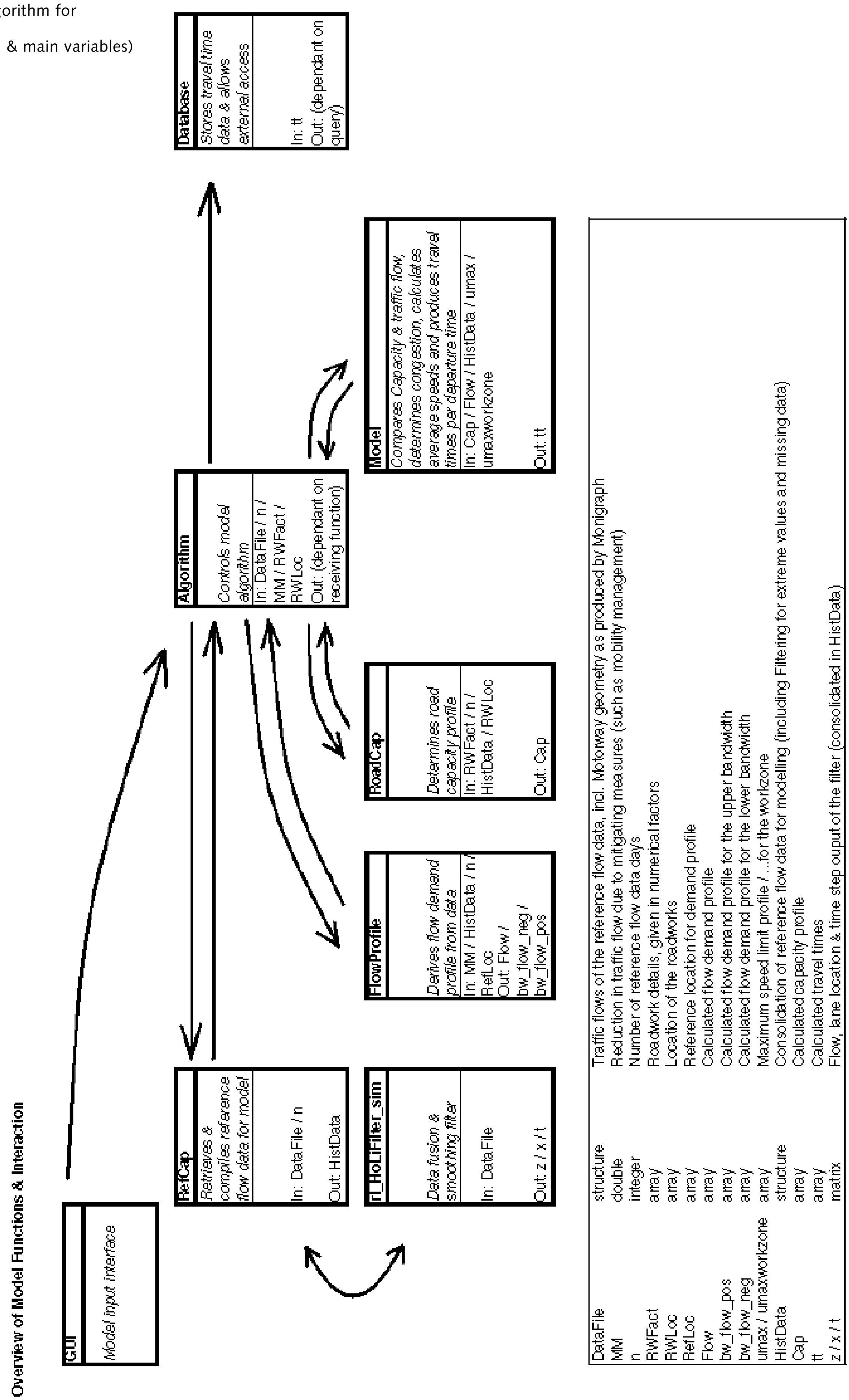
Appendix C: Main model code

The MatLab code for the main section of the model is given here. The code shows the processing of the demand and capacity profiles to calculate the travel times using the Godunov scheme. The process is described in paragraph 3.2. The Modelling scheme for the model in MatLab is given thereafter in figure C.1.

```
function [tt] = Modelv7(Cap,Flow,HistData,RWLoc,umax,umaxWorkzone,lanes);
%%% INITIAL VARIABLES
a = min(HistData.LocLanes.r1); % START POINT IN KMS
b = max(HistData.LocLanes.r1); % END POINT IN KMS
k0 = 1e-03; % initial density
tcell = 6/60; %in mins
kcrit = 28.*lanes;
kjam = 120.*lanes;

%%% DETERMINE CELL SIZES & NUMBER OF CELLS
h=0.2; %S dist step in km
M=ceil((b-a)./h); %S
g=tcell/60; %S time step in hr
N=ceil(24/g); %S ~14400 time steps

%%% MAKE TIMESTEPS 6 sec FROM 1 min %%%%%
time = 0.1;
tstep = 1:(1440*(1/tcell));
for i = 1:size(Flow,2)
for j = 1:(1/tcell)
TFlowStep(:,((1/tcell)*(i-1)+j)) = Flow(:,i);
end
end
Flow = TFlowStep;
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

%%% CONSTRUCT MAX SPEED PROFILE %%%
umaxtot = umax*ones((M+1),1);
umaxtot(RWLoc,1) = umaxWorkzone*ones(size(RWLoc,2),1);
%%% CALCULATE THE OUTCOMES
r = zeros(M+1,N+1);
r(:,1) = k0; % SETS INITIAL DENSITY
```

```
d = zeros(M,N+1);
s = zeros(M,N+1);
q = Qeq(r(:,1),Cap,umaxtot,kcrit(1,1),kjam(1,1)); % SETS INITIAL FLOW

for j=1:N
    cong = r(:,j) >=  kcrit';
    d = [Flow(j) ; (1-cong).*q(:,j) + cong.*Cap'];
    s = [((1-cong).*Cap' + cong.*q(:,j)) ; 1e5];
    qflow = min(d,s);
    qleft = qflow(1:M+1);
    qright = qflow(2:M+2);
    if j<8000 % AM
    qleft(29,:) = qleft(29,:).*0.69; %ON-/OFFRAMPS (CHANGE PER LOCATION!!!)
    qleft(69,:) = qleft(69,:).*0.86; %ON-/OFFRAMPS (CHANGE PER LOCATION!!!)
    else % PM
    qleft(29,:) = qleft(29,:).*0.64; %ON-/OFFRAMPS (CHANGE PER LOCATION!!!)
    qleft(69,:) = qleft(69,:).*0.75; %ON-/OFFRAMPS (CHANGE PER LOCATION!!!)
    end
    r(:,j+1) = r(:,j) + (g/h).*(qleft-qright);
    q(:,j+1) = Qeq(r(:,j+1),Cap,umaxtot,kcrit',kjam');
    v(:,j+1) = q(:,j+1)./r(:,j+1);
end
%%% CALCULATE SPEEDS & TRAVEL TIMES PER SECTION %%%
ttsection = h.*60./v;
ttsection(isinf(ttsection)) = 0; % REPLACES 'INF'-VALUES WITH '0'
for i=1:30 % PREVENTS BOUNDARY ERROR
    extra(:,i)=ttsection(:,size(ttsection,2));
end
ttsection=[ttsection extra];
for i=i:90 % PREVENTS BOUNDARY ERROR
    extra(:,i)=ttsection(:,91);
end
ttsection=[extra ttsection(:,91:size(ttsection,2))];
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
 %%% CALCULATE TOTAL TRAVEL TIMES %%%%%%%%%%
for t=1:N
    t0=t;
    for x=1:M
        ti=floor(t);
        t=ttsection(x,ti)+t;
    end
    tt(t0)=t-t0;
                    end; end
```

Figure C.1: Model Algorithm for MatLab (per function & main variables)



Appendix D: Calibration results

The results of the calibration procedure used for the model are given here. As the calibration led to many graphs and much data being produced for each variation, only the main results are shown.

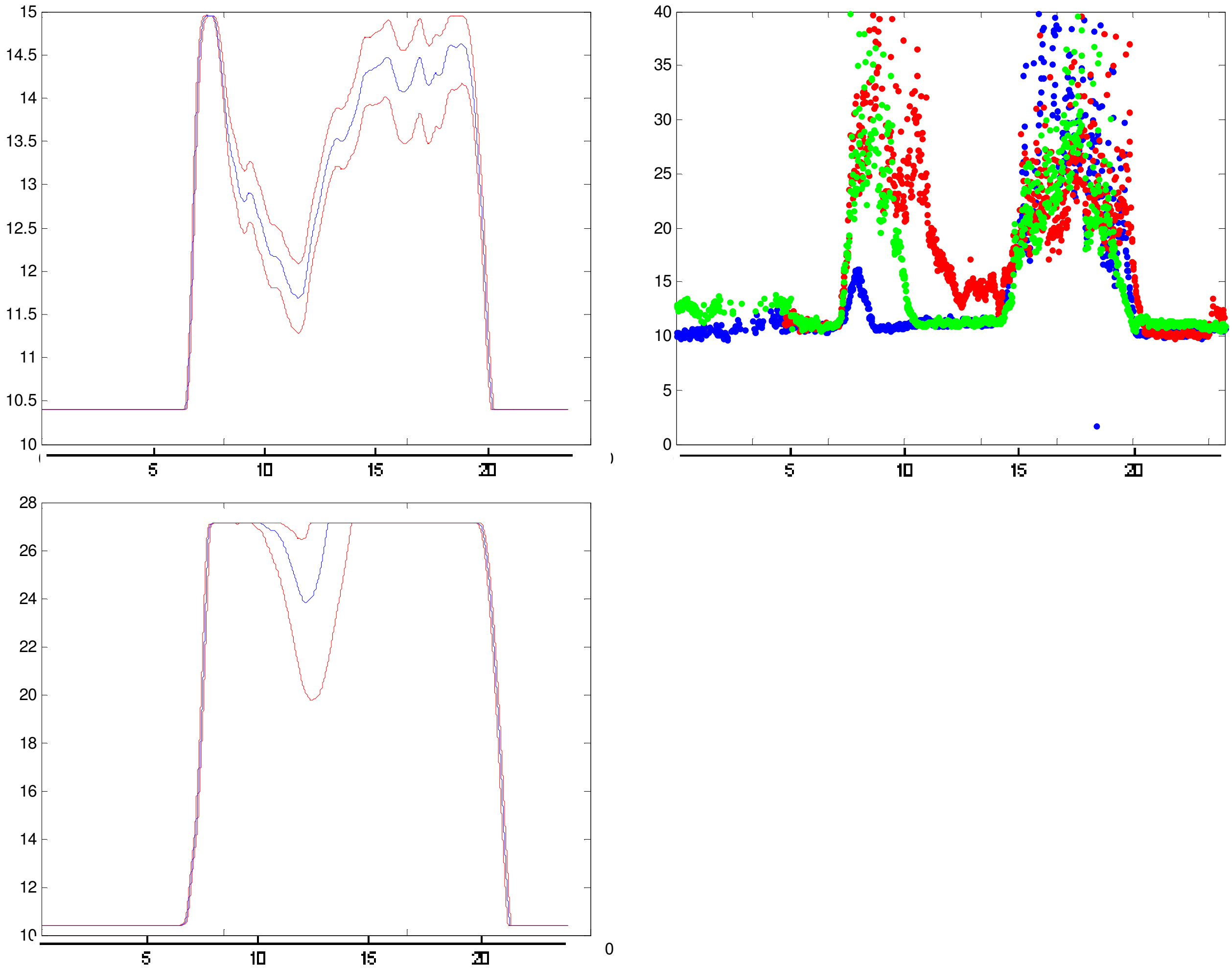
Results case A2

The final results for the calibration case A2 are shown here in figures D.1-D.3. The travel times under normal conditions show an underestimation of the travel times. The travel times during roadworks do closely represent the recorded times. From the MoniCa data it was not possible to produce a travel time profile during roadworks. The travel times are derived from travel time tables held by Rijkswatersaat Noord-Brabant for the corresponding period.

Figure D.1-D.3: A2 Travel times:

Pre-works model; Pre-works recorded;

Roadworks model



Results case A9

The final calibration results show an excellent likeness to the collected data for the A9 case. The travel times during roadworks, shown in figure D.7, shows a large spread. This is due to missing data and therefore not all data points are shown accurately. However the main pattern is recognizable and is backed up by reliable camera data shown in figure D.8.

Figure D.4-D.7: A9 Travel times:

Pre-works model; Pre-works recorded;

Roadworks model; Roadworks recorded

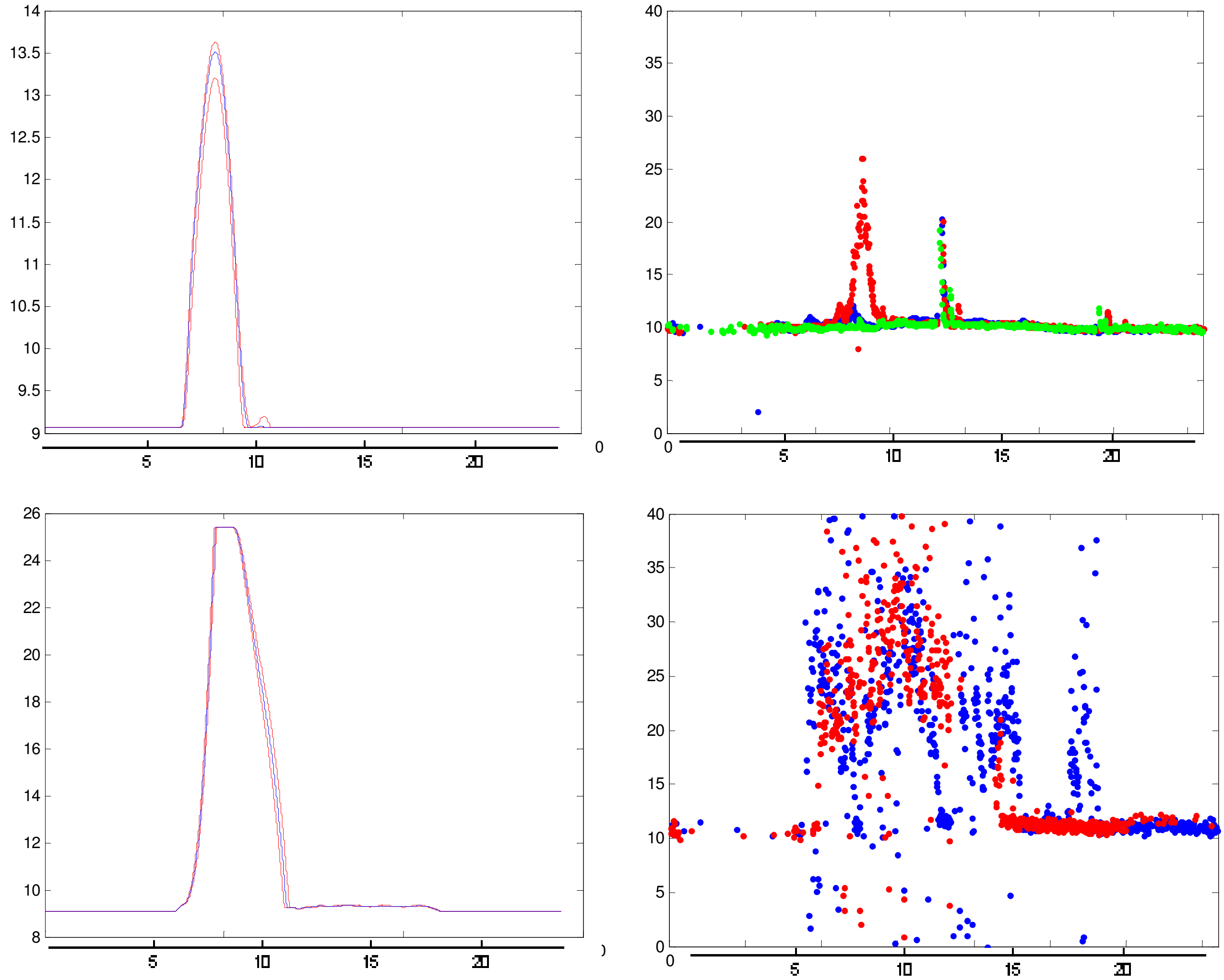
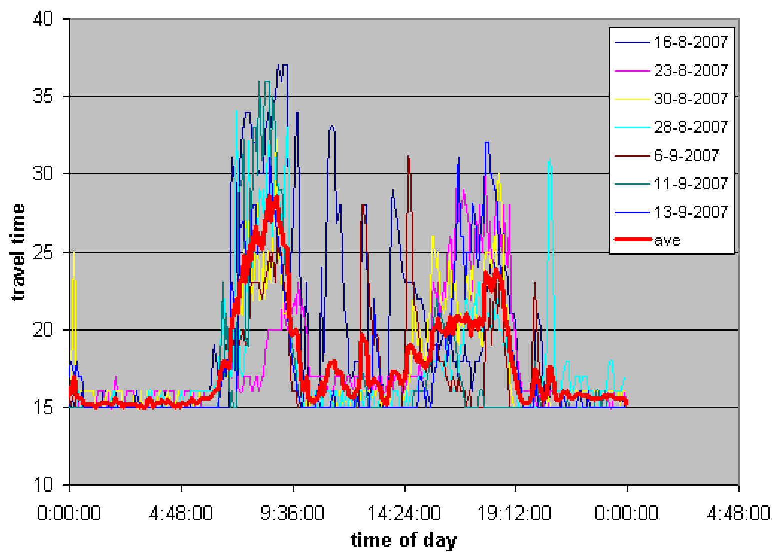


Figure D.8: A9 Travel times:

During roadworks from camera’s



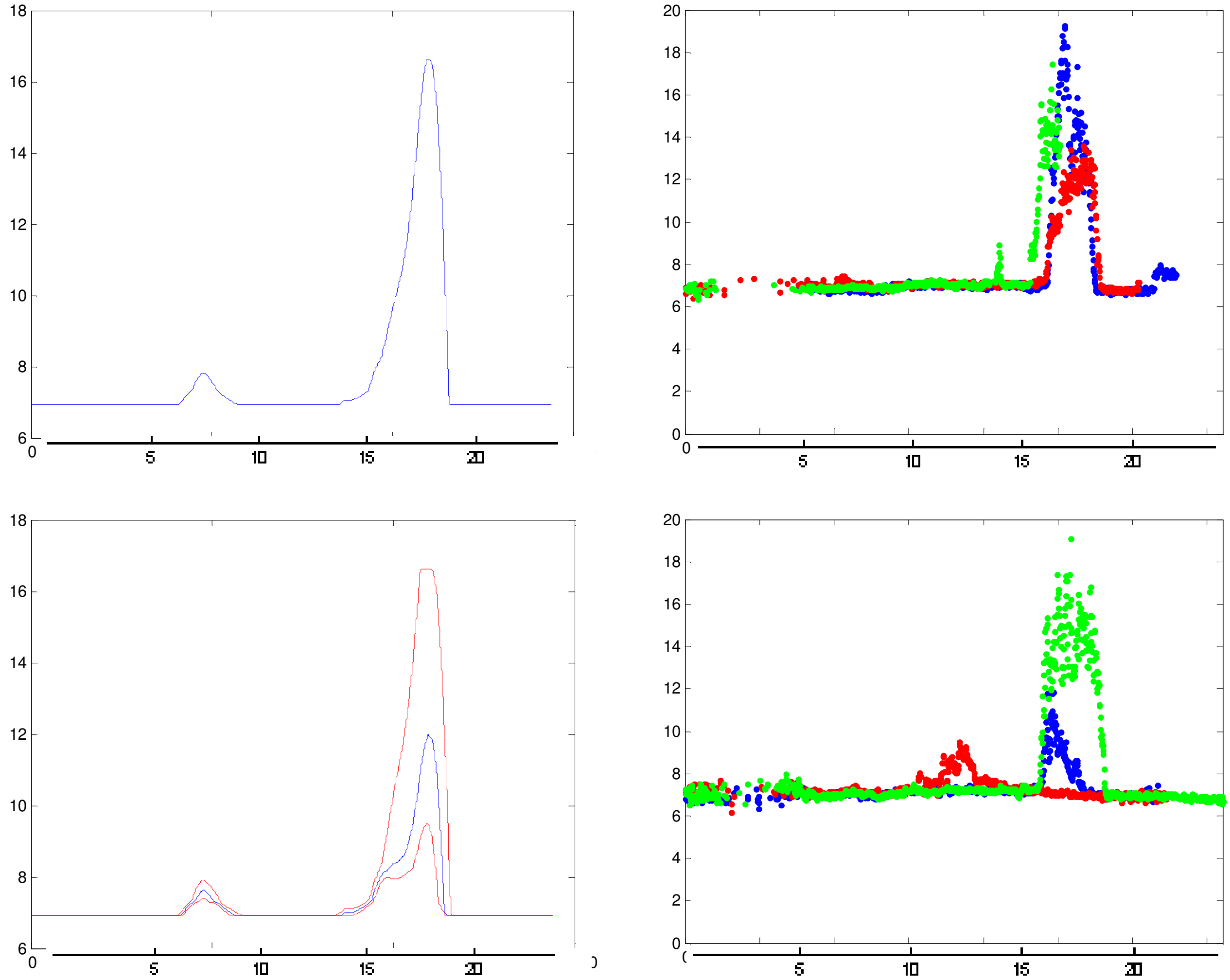
Results case A16

The consequences of the roadworks in the A16 case seem not to have a severe effect on travel times. This is represented in the produced results seen in figures D.9-D.12. This is mainly attributed to effect of (in)direct mobility management.

Figure D.9-D.12: A16 Travel times:

Pre-works model; Pre-works recorded;

Roadworks model; Roadworks recorded



Appendix E: Complete test case results

In this appendix the complete results produced by the model are given for the test case A12, with which the developed model is validated. The results are given for the model results using a 2000 veh/hr/ln base capacity and for a 2100 veh/hr/ln base capacity, as explained in the main report.

Travel times (2000 veh/hr/ln Base Capacity)
The results produced by the model, with a base capacity of 2000 veh/hr/ln, are given graphically in the order shown in table E.1 (from MM=15 to MM=5). The critical values for all MM-factors are shown in the table with the corresponding bandwidths. After an overview of the travel times, an example of the produced intensity, density and speed plots are given for the decisive MM% of 7%. These plots offer a deeper insight into the way the travel times are determined.

Table E.1: Critical travel times with bandwidths for a 2000 veh/hr/ln base capacity

Afternoon peak period

MM%	15% bandwidth	Average traffic flow	85% bandwidth
15	15	16	20
12	15	20	25
10	15,5	22,5	27
8	17	25,5	30
7	**18**	**27**	**30**
6	**19,5**	**29**	**30**
5	**20,5**	**30**	**30**

Morning Peak Period

Model (MM~5-8%)	13	15	15,5

Red *indicates values that are limited due to congestion propagating beyond the considered motorway stretch.*

Figure E.1 - E.6: Travel times with

MM-factor: 15% ; 12%

10% ; 8%

7% ; 6%

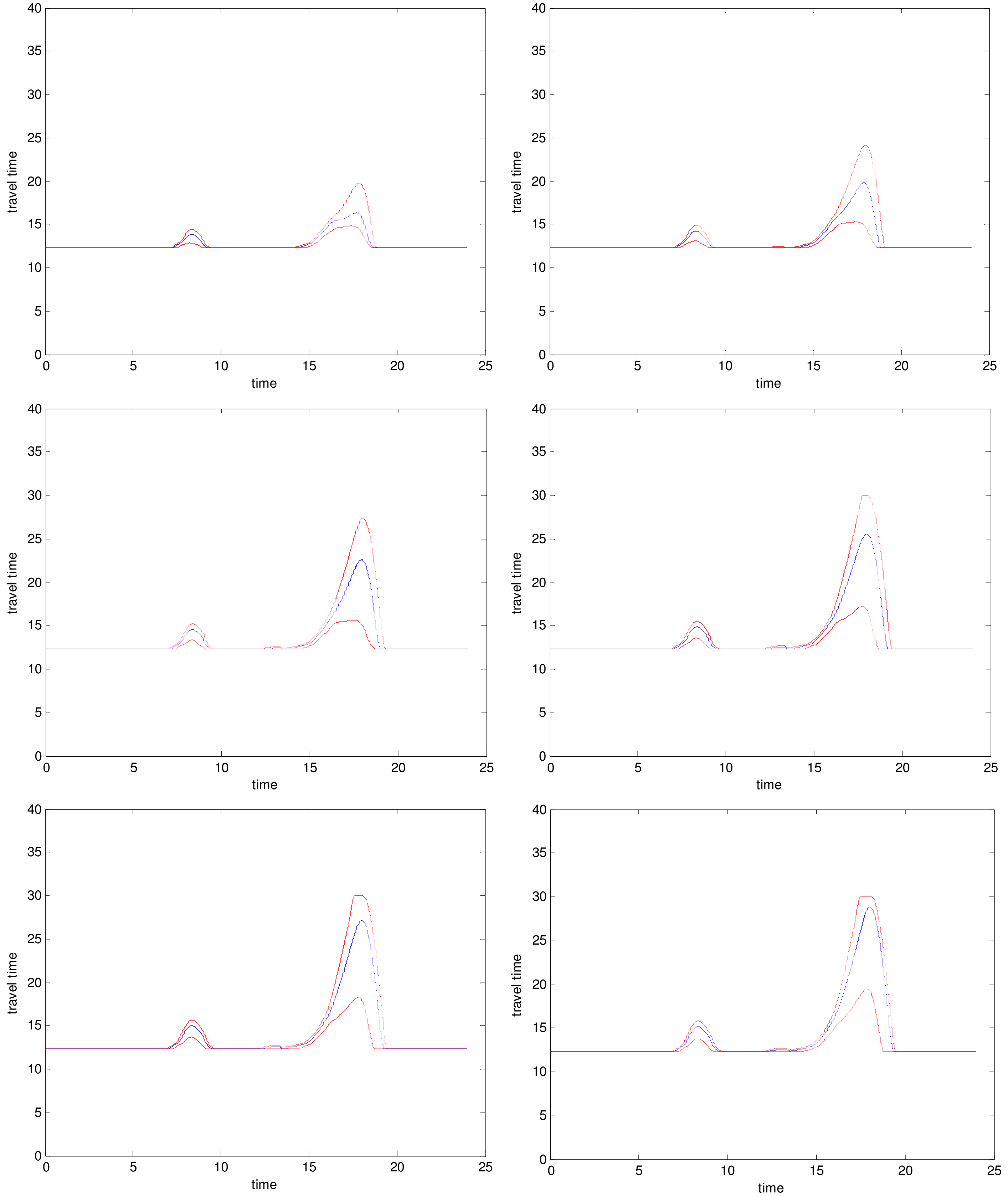


Figure E.7: Travel times with MM-factor 5%

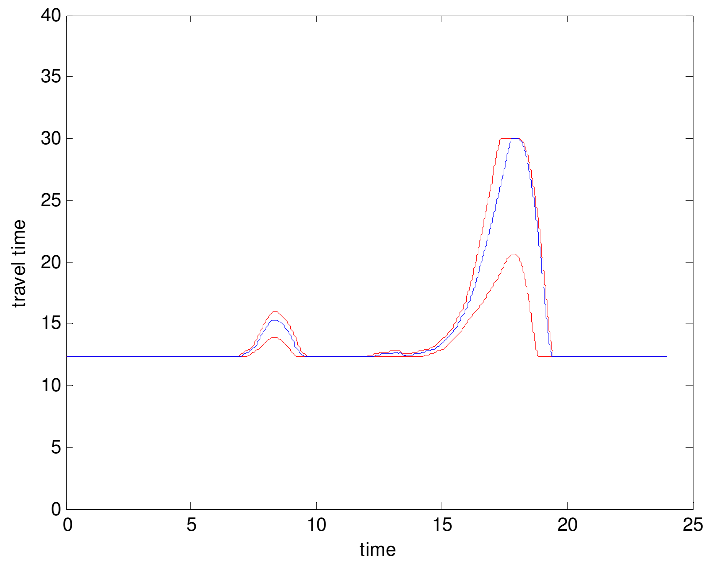
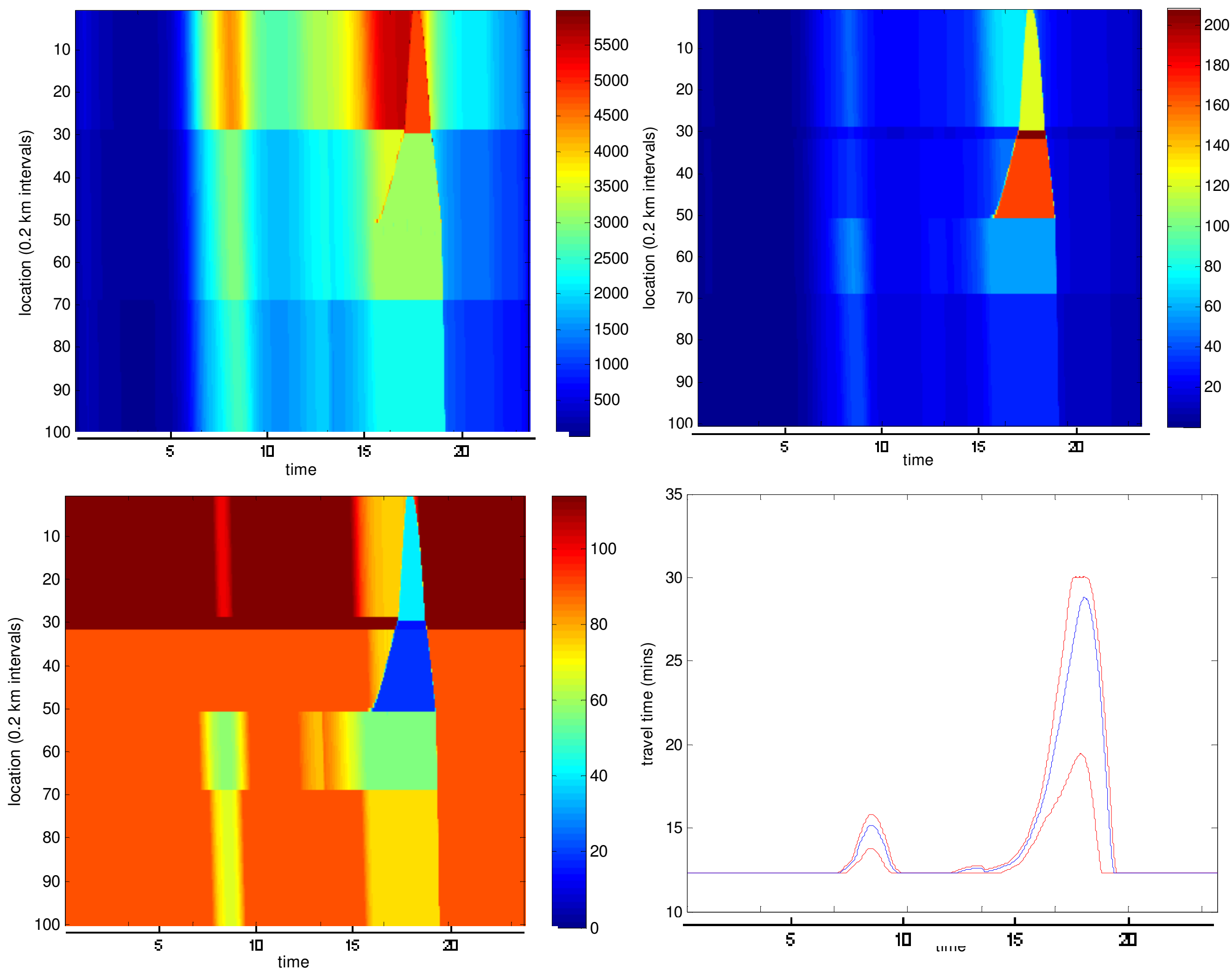


Figure E.8: 2000 veh/hr/ln Base Capacity and 7% MM% Plots:

a: Intensity **b: Density**

c: Speed **c: Travel times**



Travel times (2100 veh/hr/ln Base Capacity)

The results produced by the model, with a base capacity of 2100 eh/hr/ln, are given graphically in the order shown in table E.2 (from MM=10 to MM=5). The critical values for all MM-factors are, yet again, shown in the table with the corresponding bandwidths. After an overview of the travel times, an example of the produced intensity, density and speed plots are given for the decisive MM% of 6%.

Table E.2: Critical travel times with bandwidths for a 2100 veh/hr/ln base capacity

Afternoon peak period			
MM%	**15% bandwidth**	**Average traffic flow**	**85% bandwidth**
10	14,5	16	20
8	15	19	23
7	**15**	**20**	**25**
6	**15**	**21**	**26**
5	**15**	**22,5**	**27,5**
Morning Peak Period			
Model (MM~5-8%)	13	14,5	15

Figure E.9 - E.12: Travel times with MM-factor: 10% ; 8%, 7% ; 6%

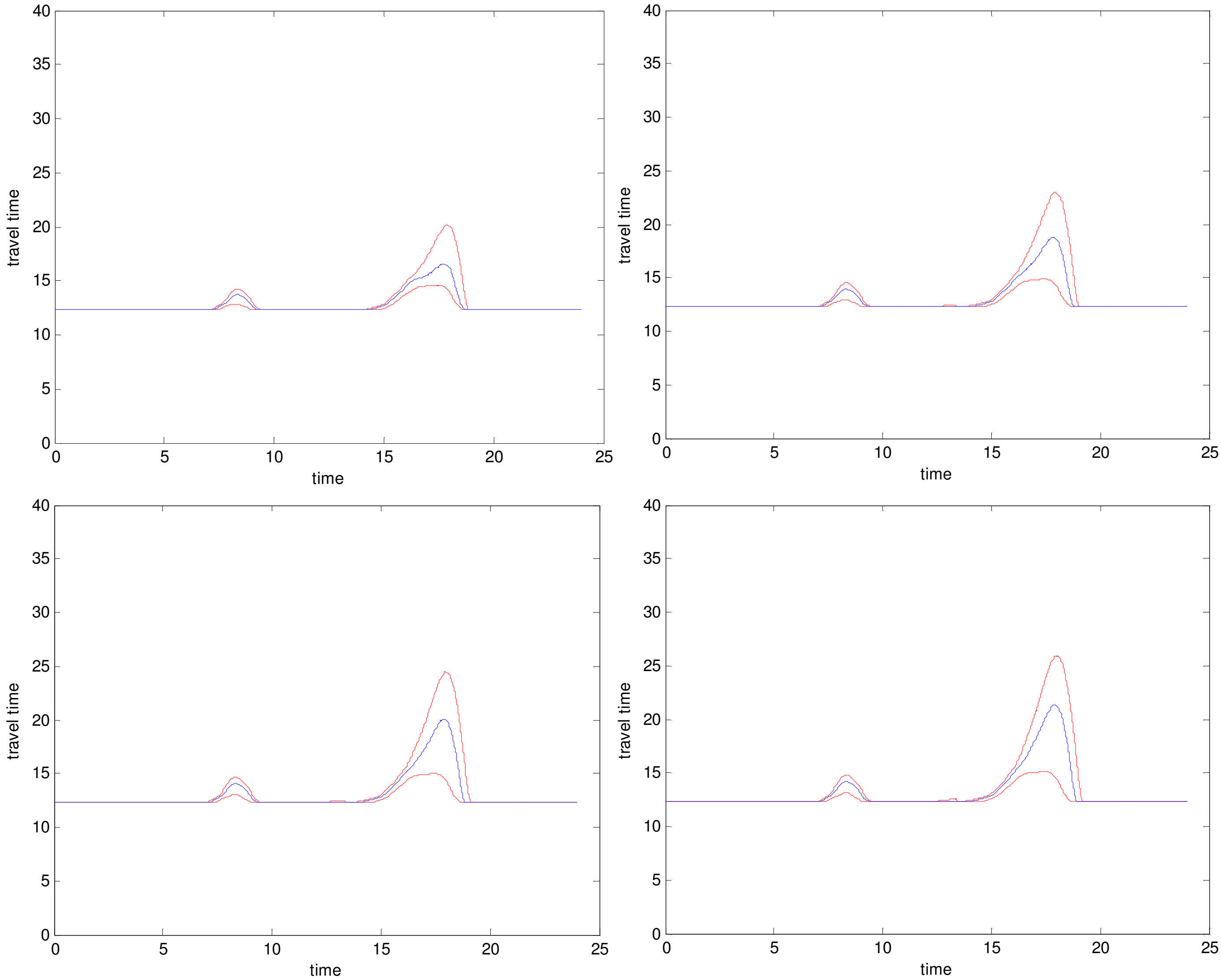


Figure E.13: Travel times with MM-factor 5%

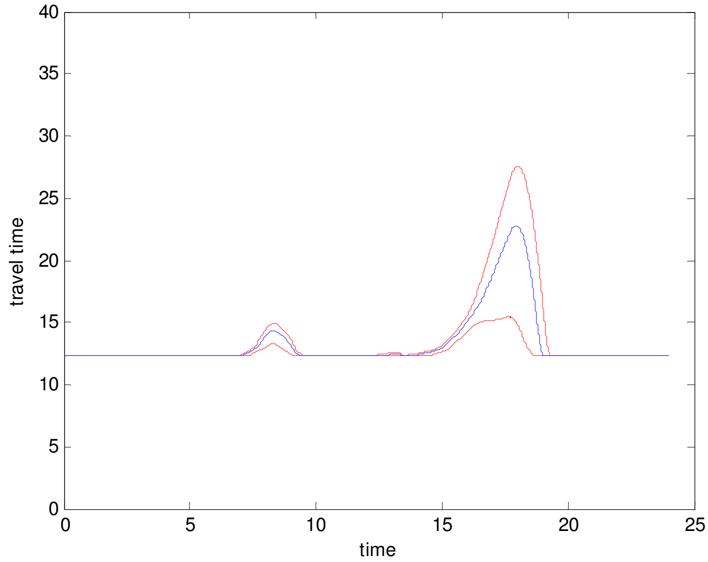
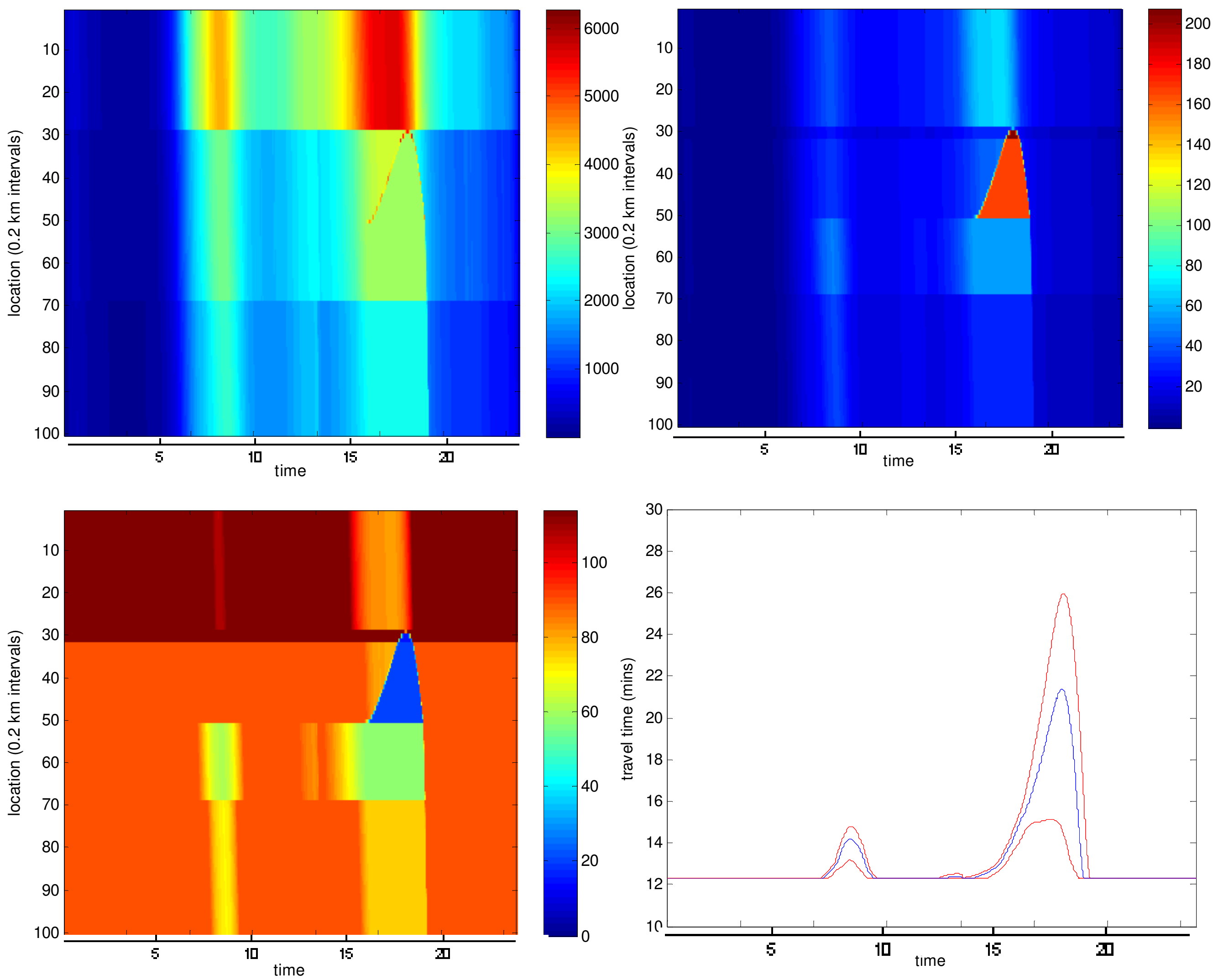


Figure E.14: 2100 veh/hr/ln Base Capacity and 6% MM% Plots:

a: Intensity **b: Density**

c: Speed **c: Travel times**



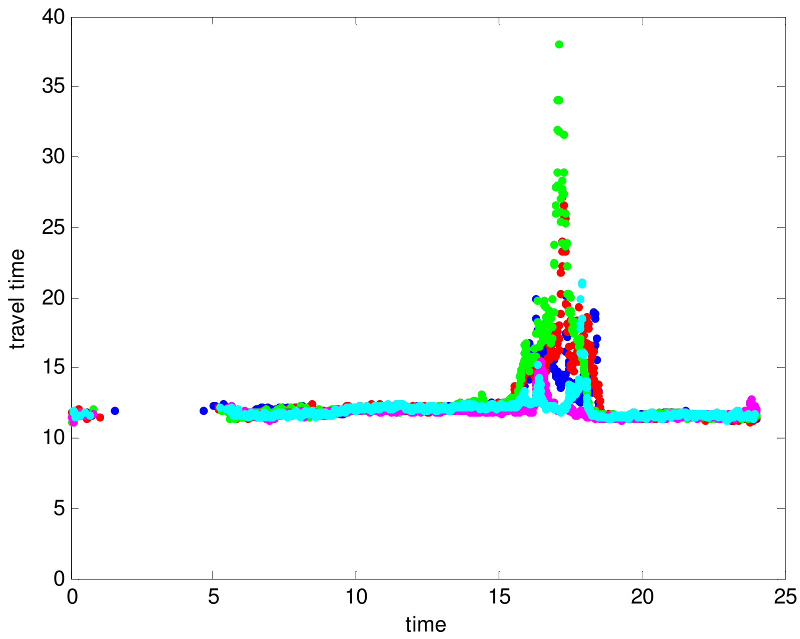
Appendix F: Validation data

In this appendix the recorded data used to validate the test case A12 is displayed. The data is processed from MoniCa loops present on the A12 motorway. First the data, collected from non-roadworks situation, which is used as reference data is shown. Thereafter the roadworks data and the comparison with the model is shown.

Non-roadworks data

The travel times shown here are from data on the A12 during the months **August and September 2007** between intersections 'Prins Clausplein' and 'Knooppunt Gouwe'.

Figure F.1: Travel times for the A12 in Aug. & Sept 2007



Roadworks data

The travel times shown in figure E.2 and E.3 are from data on the A12 during the months **August and September 2008** between intersections 'Prins Clausplein' and 'Knooppunt Gouwe' during roadworks. The second set of data is a complete picture of all data from all days in the concerning months as processed by Rijkswaterstaat.

Figure F.2: Travel times on the A12 in Aug. & Sept. 2008

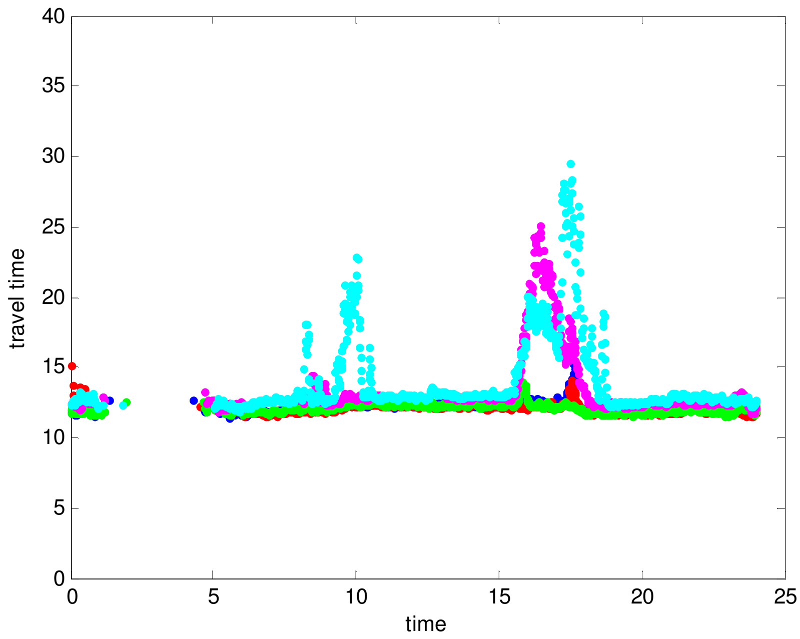
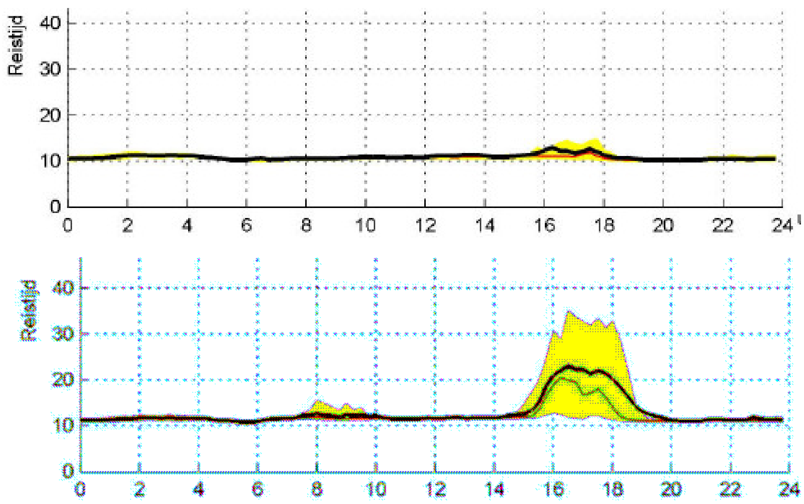


Figure F.3: Travel times on the A12 for all days in Aug. & Sept. 2008 (Rijkswaterstaat, 2008)



Comparison with model

A comparison is made between the modelled travel times and the recorded travel times. The difference and the recorded error is given in figure F.4 and F.5.

Figure F.4: Travel time comparison between the model (blue) and real data (red)

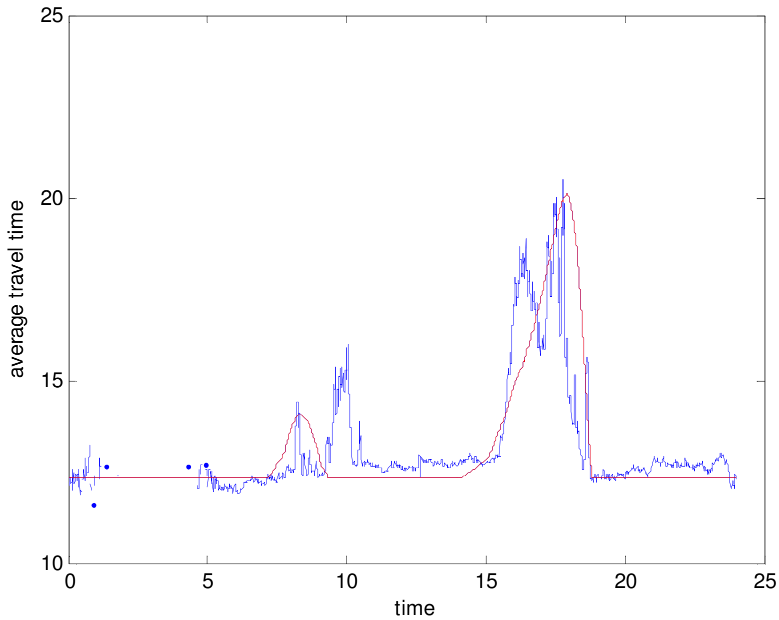
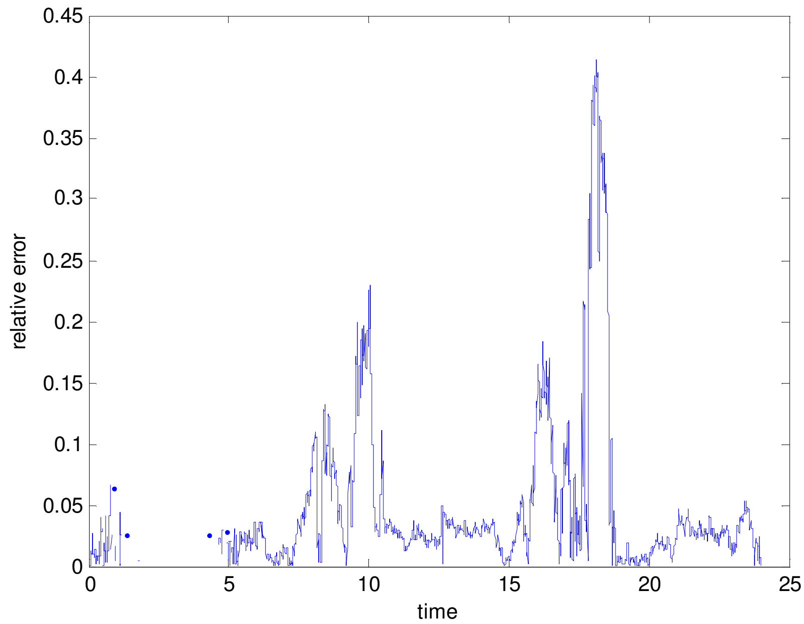


Figure F.5: Absolute relative error in travel times between the model and real data



Using the results given in figure F.5 the histogram, found in paragraph 6.5 (figure 6.5) indicating the number of observations that exceed the 20% threshold, is constructed.