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Adaptive ramp metering

Development of an adaptive capacity-demand ramp metering method

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Samenvatting

Filevorming op autosnelwegen is een dagelijks voorkomend probleem, met grote gevolgen voor de samenleving. De files kunnen worden verminderd door de capaciteit uit te breiden of de verkeersvraag te verminderen. Oplossingen op de lange termijn zijn kostbaar en laten vaak lang op zich wachten. Een oplossing op de korte termijn is Dynamisch Verkeers-Management. Dit is een verzameling maatregelen die erop gericht zijn om de benutting van autosnelwegen te vergroten. Een van deze maatregelen is toerit dosering. Hierbij wordt de hoeveelheid voertuigen die een autosnelweg op gaan, gereguleerd door een verkeerslicht op de toerit, een zogeheten toerit doseer installatie (TDI). Het aantal voertuigen die worden doorgelaten, wordt bepaald door het toerit doseer algoritme. In Nederland zijn TDIs uitgerust met het RWS algoritme, wat een intensiteit-capaciteit doseer algoritme is. Dit type algoritme berekent de toegestane hoeveelheid voertuigen door de intensiteit op de autosnelweg van de snelweg capaciteit af te trekken. Hiervoor wordt in het besturingsprogramma in de TDI een vooraf ingestelde, constante capaciteitswaarde aangenomen. Echter, de werkelijke capaciteit is niet een constante, maar varieert over de tijd als gevolg van veranderingen in bijvoorbeeld het weer. Aangezien de capaciteit aantal doorgelaten voertuigen bepaalt, is de werking van een TDI zo goed als de kwaliteit van de aanname over de capaciteit.

Dit onderzoekt heeft als doel het verbeteren van de werking van TDIs, door het toevoegen van een schatter van de actuele snelweg capaciteit aan het besturingsprogramma van de TDI. Dit wordt een adaptieve regeling genoemd.

Verschillende capaciteitsschatters zijn bekeken. Uiteindelijk zijn vier methodes geselecteerd voor het verdere onderzoek. Hiervoor zijn deze gecombineerd met het RWS algoritme, en getest in simulaties. Daarnaast zijn ook andere toerit doseer algoritmes bekeken. Hiervan zijn er twee ook getest in simulaties. The RWS algoritme is ook getest, en zal dienen als referentie.

De resultaten van de simulaties laten zien dat de werking van de TDI kan worden verbeterd door een combinatie van een actuele capaciteitsschatter met het RWS algoritme, of door het toepassen van een geheel nieuw algoritme. Echter, de resultaten van de simulaties laten ook zien dat slecht één capaciteitsschatter geschikt is voor implementatie in het besturingsprogramma van een TDI, waarbij er nog wel een aantal aanpassingen gedaan moeten worden aan zowel het besturingsprogramma als aan de TDI zelf. Voor toekomstig onderzoek wordt het aanbevolen om de schatter die niet geschikt waren voor implementatie verder te ontwikkelen en te testen. Het wordt aanbevolen om de schatter die wel geschikt is voor implementatie te testen met actuele verkeersmetingen, en uiteindelijk te testen in een TDI.

Abstract

Motorway congestion is a daily occurring problem, with a large impact on society. Relieving congestion requires increasing the motorway capacity or reducing the traffic demand. Where long-term solutions are costly and take time to realize, a short-term solution is offered in the form of Dynamic Traffic Management. This is a range of measures that are aimed at increasing the efficiency of motorway usage, by positively changing the behaviour of drivers. One of these measures is ramp metering, whereby the flow of vehicles entering the motorway is regulated by means of a traffic light. The number of vehicles allowed to enter the motorway, or the metering rate, is determined by the ramp-metering algorithm. In the Netherlands all ramp meters are equipped with the RWS ramp-metering algorithm, which is a demand-capacity algorithm. This type of metering algorithm calculates the metering rate by subtracting the motorway traffic demand from the motorway capacity. For this purpose a value for the capacity is assumed by the control application in the ramp meter. However, the motorway capacity is not constant, but changes over time due to changes in, e.g., the weather, the driver population, or general travel purpose. Since the value for the assumed capacity determines the metering rate, the performance of a ramp meter will be as good as the quality of the assumption of the capacity.

This thesis aims to improve the performance of the demand-capacity algorithm by adding an online capacity estimator to the control application in the ramp meter. This type of control is referred to as *adaptive* control.

Various capacity estimation methods have been reviewed. Finally four methods have been selected and implemented with the ramp meter control application in a simulation. Also other ramp metering algorithms have been reviewed, of which two have been implemented in the simulation as well. The RWS ramp-metering algorithm has been implemented as reference.

From the results of the simulations it is concluded that by adding a capacity estimator to the control application, the performance of the demand-capacity algorithm can be increased. However, only one capacity estimator is found to be suited for implementation, although it will require some modifications of the ramp meter and the control application. The performance of the ramp meter was also increased by the implementation of other ramp-metering algorithms. For future research, it is recommended that the capacity estimators that were unsuited for implementation are further tested and developed. The capacity estimator that was suited for implementation should be considered for testing with real-life traffic observations, and eventually field-testing.

Preface

This report is the final product of my Master-thesis.

This study is executed on behalf of Rijkswaterstaat (RWS), the implementation organisation of the Dutch Ministry of Transport, Public Works and Water Management. Amongst others, the task of RWS is to provide for the smooth and safe flow of traffic on the Dutch motorway system.

In the efforts by RWS towards short-term congestion relief, the focus is on maximizing utilization of existing motorways. This study tries to contribute to that. I would like to thank RWS for the opportunity to tackle such an interesting and relevant problem, and for the assistance in doing so.

I would also like to thank my committee members for their guidance, advice, criticism and support. And off course my fellow "Edulabbers" for the great time, and the change to exchange ideas.

Finally, I would like to thank my family who have always remained supporting and motivating, my friends for their support and help, and Marijn, who means more then the world to me.

Contents

Figures

Tables

1. Introduction

The first traffic jam in The Netherlands was on the 29th May 1955. Since then the number of vehicles and the distance travelled have grown explosively. In 2005 over 75 percent of the distance travelled was done by car, in total almost 150 thousand million kilometres. And it is expected that the total travel distance will increase even more up to 2020 [1].

With the growth of the distance travelled, the total time that was spent in congestion grows alongside. A total of 44 million hours were spent in traffic jams on motorways in the Netherlands in 2006, resulting in an estimated 700 million euros in direct economic damages [2].

Figure 1.1: Traffic jam on the A13 motorway near Delft

Traffic jams are caused by the traffic demand exceeding the motorway capacity, because of either an increase in the demand, or a decrease in the capacity. Congestion is deemed recurrent when the demand exceeds the capacity regularly, e.g., during the peak hour. Non-recurrent congestion can be caused by both a temporary and non-regular increase of the demand or decrease of the capacity, for example as a result of a concert (demand) or by bad weather conditions (capacity).

Increasing the motorway capacity or reducing the traffic demand can reduce congestion. However, increasing capacity by expanding the infrastructure is costly and time consuming, and will eventually lead to an increased traffic demand. On the other hand, plans to reduce the

traffic demand by raising the cost of travel are continuously delayed and faced with public and political resistance.
In the mean time, the Dutch Ministry of Transport, Public Works and Water Management tries to relieve congestion in the short term as much as possible. The implementation organisation of the Ministry, Rijkswaterstaat (RWS), focuses on maximizing the utilization of the existing motorways.

1.1 Dynamic Traffic Management

Recent years have seen many measures being developed that help increase the utilization. These options are aimed at increasing the efficiency of motorway usage, by positively changing the behaviour of drivers. They usually consist of roadside systems that inform drivers or implement certain traffic measures, based on current traffic observations. This collection of measures is called Dynamic Traffic Management (DTM). Examples of DTM are variable speed limits, opening of the hard shoulder during peak hours or Dynamic Route Information Panels advising drivers which route to take.

Ramp metering
Another DTM measure is ramp metering, whereby a traffic light at the end of an on-ramp can regulate the flow of vehicles entering the motorway. Figure 1.2 shows a ramp meter near the city of Delft. The main control variable is the cycle time. A cycle time is the time in which a traffic light passes through the green, amber and red phase. The duration of the green and amber phases in ramp meters are normally fixed or vehicle actuated. This means that a reduction in the cycle time leads to a shorter red phase, allowing more vehicles to pass.

Figure 1.2: Ramp meter at the A13 Delft North on-ramp

Ramp metering has two direct effects [3]. The first is the reduction of the flow entering the motorway, and aims to prevent, or at least postpone, the motorway capacity downstream of the on-ramp being exceeded. The second is the spreading of dense groups of vehicles, or platoons, on the on-ramp. These platoons are usually formed by traffic lights at the intersection upstream of the on-ramp. Platoons merging onto the motorway can seriously disrupt the traffic flow on the motorway, causing a temporary reduction of the motorway capacity. This might even lead to a traffic jam at a relatively low traffic flow. Both direct effects result in a reduction in congestion.

An indirect effect of ramp metering is a changed route choice [3]. The increased waiting time on the on-ramp and reduced congestion on the motorway can persuade drivers to choose a different on-ramp, or to not enter the motorway at all. This effect might be either positive or negative as it may also cause a route choice that causes other problems with e.g. traffic safety and rat running. The effects of ramp metering dependen on the circumstances at the on-ramp, but application of ramp metering has an overall positive effect on the flow of traffic on the motorway [4].

When the metering rate (number of vehicles allowed to pass) is lower than the demand on the on-ramp, vehicles will have to wait before they can enter the motorway, and a queue will form. To prevent this queue blocking intersections upstream of the on-ramp, a queue override can be installed. When a queue of a certain length is detected, it forces the ramp metering installation to use a shorter cycle time, and thus allowing more vehicles onto the motorway.

This study will focus on the first direct effect of ramp metering: the reduction of the on-ramp flow.

Ramp metering in the Netherlands

In 1989 ramp metering was introduced in the Netherlands. These were reactive ramp metering systems that used real-time traffic observations for determination of the control cycle time. Reactive ramp metering systems consist of detectors, a controller and traffic lights (see Figure 1.3). In Dutch ramp metering systems the controller software consists of two parts, the metering algorithm and the Standard Ramp Metering Application (SRMA). The SRMA controls traffic lights based on the cycle time and on detection of vehicles on the on-ramp.

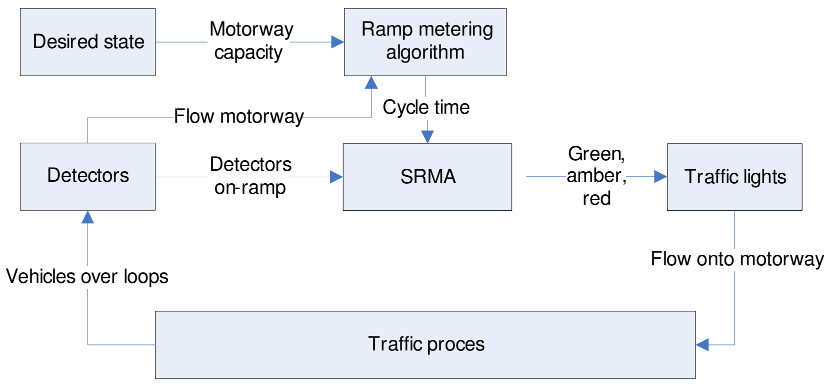


Figure 1.3: Schematic representation of a Dutch ramp metering system

The metering algorithm, based on traffic observations from the motorway, calculates the cycle time. What traffic observations are needed depends on the metering algorithm. What observations are available can however be limited by the detectors. For this study it is assumed that observations are only available from induction loops in the road surface. Induction loops can detect metal objects above it. Using that information at least the following traffic variables can be determined: flow, speed, loop occupation, headways (time between passing of consecutive vehicles) and vehicle length.

Several metering algorithms have been developed for the cycle time calculation. In The Netherlands, all ramp metering systems use the RWS metering algorithm. This algorithm is a so-called capacity-demand algorithm. In Section 3.2.1 the algorithm will be described in more detail. For now it is sufficient to explain that the cycle time is based on the observed flow, also called the demand, and the motorway capacity, hence the name demand-capacity. Currently a pre-specified value is used for the motorway capacity. However, the next section will show that this is not always correct.

1.2 Motorway capacity

Motorway capacity can be described as the volume of traffic that a (section of) motorway can carry. A more comprehensive definition of capacity is given by the American Highway Capacity Manual (HCM 2000). There capacity is defined as:

"the maximum hourly rate at which persons or vehicles reasonably can be expected to traverse a point or a uniform section of a lane or roadway during a given time period under prevailing roadway, traffic and control conditions" [5].

Capacity variation

The Highway Capacity Manual also mentions that any change in the prevailing conditions changes the capacity of the point or road section under consideration. Many studies have been done on the variation of driver behaviour and its effect on motorway capacity. Two studies will be discussed briefly.

Brilon *et al.* [6] studied data over 3 years from 15 sites in Germany, and mapped the changes in the speed that were not caused by changes in the traffic flow. Two types of dependencies were found. First there is the dependency on changing environmental conditions, such as darkness and rain or snow. Secondly, it was found that there was an influence from varying driver and traffic composition, with a seasonal, weakly and daily variation.
Imbrahim *et al.* [7] studied the influence of adverse weather conditions on the "Queen Elizabeth Way" motorway in Canada. Where Brilon *et al.* [6] only distinguished between wet and dry conditions, [7] divided the weather conditions into several classes. They found that the reduction in light precipitation caused only a minimal effect, while heavy rainfall and especially heavy snow had a more noticeable effect. Although both studies had similar results, the capacity reduction factors that were found for certain circumstances might not directly be applicable to the Dutch situation. Dutch drivers might not respond to changing conditions in the same manner as German or Canadian drivers, and the vehicle composition might also be different. They do however indicate that there is an effect from changing conditions on the motorway capacity.

1.3 Problem formulation

An incorrect value for the capacity in demand-capacity metering control algorithms leads to unnecessary delays on both the motorway and the on-ramp. If the actual capacity is higher, then the motorway will not be fully utilized and vehicles will be delayed on the on-ramp needlessly. If the actual capacity is lower then too much traffic will be allowed onto the motorway, adding to the occurrence of congestion.

So for an ideal ramp meter control it is necessary to know the actual capacity of the motorway. It is logical that the effectiveness of a demand-capacity ramp meter controller can be improved by adding an online capacity estimation method, as shown in Figure 1.4. This type of control is referred to as *adaptive* control. A more detailed description of adaptive control is given in Section 2.2.

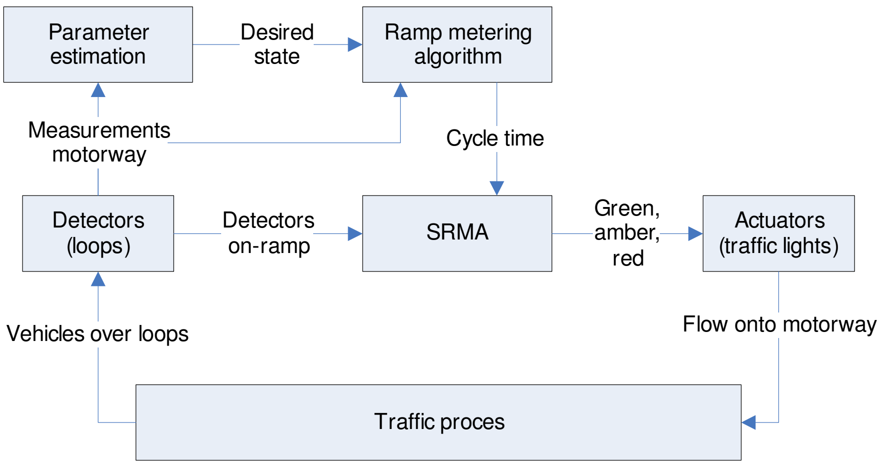


Figure 1.4: Schematic representation of an adaptive metering system

This gives rise to the following research questions:

- What capacity estimation methods exist, and can they be used online in combination with the RWS metering algorithm and the SRMA?
- Does online capacity estimation improve the performance of a metered on-ramp using the RWS metering algorithm?
- Do any metering methods exist that are capable of estimating and using the actual capacity, or that in general are more capable of adapting to changing conditions than the RWS metering algorithm?

Thesis objective
The problem formulation leads to the objective of this thesis:

"Find and investigate metering methods that are able to increase the performance of a metered on-ramp using the Dutch Standard Ramp Metering Application, by estimating online the motorway capacity using current traffic observations."

1.4 General approach

In this section the general approach of this study will be described. The approach aims to reach the thesis objective by answering the research questions. The approach consists of two parts: a literature review and an experiment.

Literature review
The first two questions are answered by a literature review. The literature review is split into two parts. The first part focuses on existing ramp metering controllers. The second part focuses on capacity estimation methods. Based on the results of this review, new adaptive metering methods will be proposed. These methods consist of a ramp meter controller and a capacity estimation method.

Experiment
The third research question will be answered by experiment. The selected methods will be implemented in a simulation environment, for various scenarios. Afterwards, their performance will be compared. The simulation environment consists of three components: traffic simulation, ramp meter control, and capacity estimation. An overview of the relations between the components is presented in Figure 1.5.

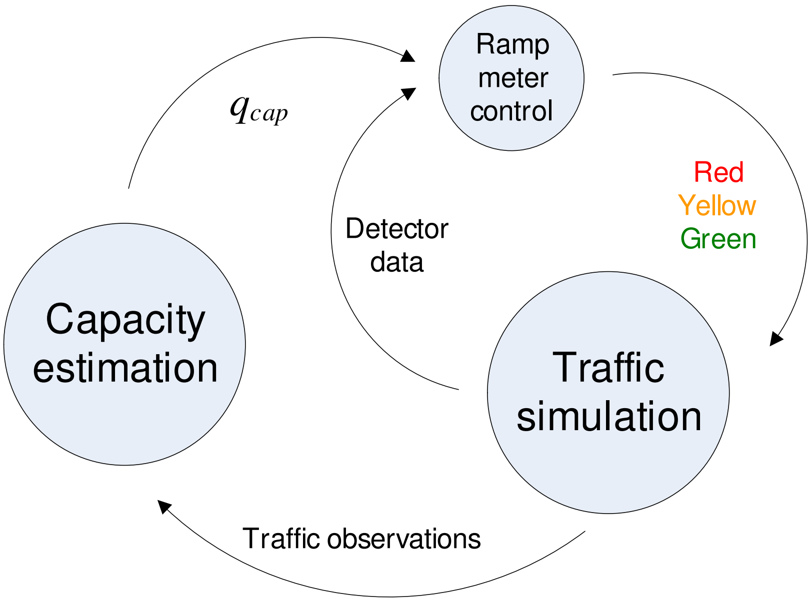


Figure 1.5: Simulation environment

The traffic simulations are done using the micro-simulation model Vissim, the ramp meter will be controlled by the SRMA, and the calculations for the capacity estimations will be done in Matlab. Simulations will be done for the proposed metering methods, under four different capacity reduction scenarios, and ten different random seeds, as shown in Figure 1.6.

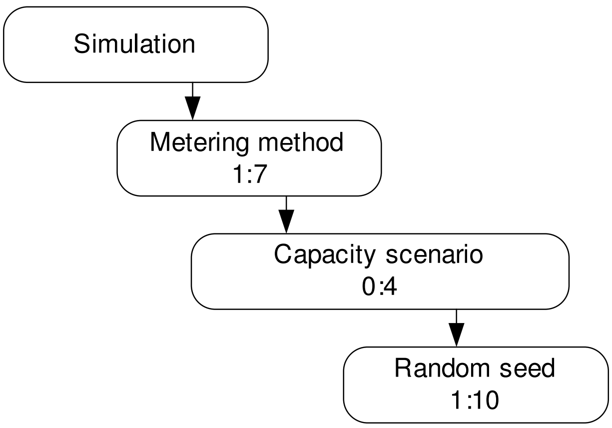


Figure 1.6: Simulation setup

Performance indicators
The performance of the various metering methods will be measured using performance indicators. The main performance indicator is the **total change of the vehicle delay**. Secondary performance indicator can be divided into three groups:

- Congestion occurrence
- On-ramp queue detection

A more detailed description of the performance indicators can be found in Sections 6.4. A detailed description of the calculation methods is given in Section 8.1.

1.5 Thesis outline

After the section a short review will be given into control systems, and adaptive control systems. In Section 3 we will examine existing metering methods, and in Section 4 available capacity estimation methods will be reviewed. In Section 5 the three previous sections will be put together. In Section 5 adaptive metering methods will be proposed, which will be formed by combining a metering algorithm with a capacity estimator. Section 6 describes how the metering methods proposed in Section 5 will be tested. To this end a simulation environment will be constructed and calibrated in Section 7. The simulation environment will be modelled after an existing on-ramp, which is also selected in Section 7. With the simulation environment complete, the proposed methods will be tested. The results of the experiments will be presented and discussed in Section 8. Based on that discussion a conclusion and recommendations will be made in Section 9.

Some names and abbreviations are used for both metering algorithms and capacity estimators, such as RWS. To avoid confusion metering algorithms will always be referred to as algorithms, while capacity estimator methods will always be referred to as methods.

2. Systems and control

Before an adaptive metering method is developed, a small explanation of control systems is required. In this Section 2.1 the general functioning of control systems will be explained. In Section 2.2 adaptive control systems will be discussed.

2.1 Control systems

Control systems are used to alter the functioning of a plant, in order to meet the required plant performance [8]. A plant can be any process characterized by one or more inputs u and outputs y, see Figure 2.1.

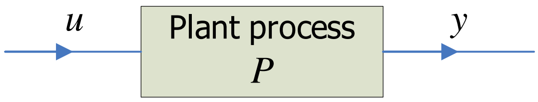


Figure 2.1: Plant process P

A control system modifies the inputs u such that the outputs y satisfy the set performance requirements. The control system can be open-loop feed-forward or closed-loop feedback systems [9]. An open-loop feed-forward controller uses the observed inputs u to modify the plant input u^*; see Figure 2.2. In a closed-loop feedback control system and the controller uses the observed output y to modify the plant input u^*; see Figure 2.3.

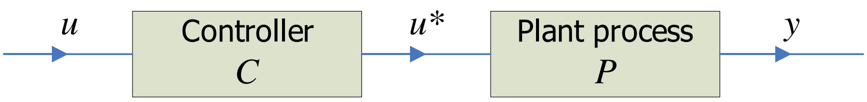


Figure 2.2: Open loop feed-forward control

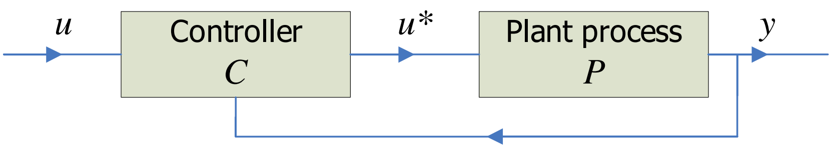


Figure 2.3: Closed loop feedback control

In the context of this thesis, the plant process represents the on-ramp, merge area at the bottom of an on-ramp and the up and downstream motorway sections. The control system represents the ramp meter. The output y represents the traffic state, from which the performance is measured.

2.2 Adaptive control systems

A special type of control system is the *adaptive* control system. An adaptive control system may be defined as:

"A control system in which in addition to the basic control structure, explicit measures are taken to automatically compensate for slowly changing or uncertain system parameters, in order to maintain an optimal performance of the system" [10].

The simplest forms of adaptive control is gain scheduling [8]. Gain scheduling involves adjusting the controller according to a schedule based on knowledge about the influence of the variables on the system's parameters.

Combining a control law with an online parameter estimator can form a more sophisticated adaptive control system; see
Figure 2.4. This type of adaptive control will be used in this study, by combining the ramp meter (controller) with a capacity estimation method (online parameter estimator).

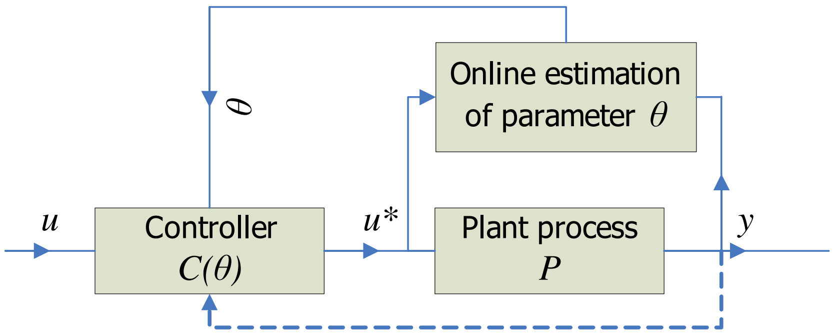


Figure 2.4: Adaptive control

3. Ramp metering control

In the Section 1.3 the thesis objective and the research question have been determined. The second research question is:

"Do any metering methods exist that are capable of estimating and using the actual capacity, or that in general are more capable of adapting to changing conditions than the RWS metering algorithm?"

In this section an answer to this question will be given. In Section 3.1 a distinction is made between three types of ramp metering. Based on the review of various existing ramp meter controllers in Section 3.2, conclusions are made in Section 3.3 regarding the research question.

3.1 Local, coordinated and integrated ramp meter control

Three main types of ramp meter control can be distinguished; local, coordinated and integrated. They all aim to prevent that the flow exceeds the capacity of the downstream bottleneck. Local ramp metering control uses only the first ramp meter upstream of the bottleneck, influencing only the ramp flow at that on-ramp. Coordinated ramp metering combines the use of several ramp meters to control the ramp flow on several on-ramps. Integrated ramp meter control combines one or more ramp meters with other DTM measures, such as Dynamic Route Information Panels. This way not only the on-ramp flow, but also the motorway flow, is manipulated.

This study will focus on local ramp meter control.

3.2 Local ramp metering algorithms

Numerous tests using different metering algorithms have shown that implementation of ramp metering has a positive effect on the throughput of motorway traffic on busy motorways [11,12,13]. However, many ramp metering algorithms have never made it past the theory, and have never been implemented. In this section several metering algorithms will be reviewed, to investigate if they can improve on the performance of the RWS metering algorithm. The following metering algorithms will be reviewed:

- RWS algorithm
- ALINEA algorithm
- V-ALINEA algorithm
- AD-ALINEA algorithm
- ANCONA algorithm
- Model Predictive Control

These metering algorithms calculate a desired metering rate q_{cont} in vehicles per hour. The SRMA however needs a cycle time t_{cycle} in seconds. t_{cycle} is calculated using:

$$t_{cycle}(k) = \frac{n_{lanes} * 3600}{q_{cont}(k)}$$

where n_{lanes} equals the number of lanes on the on-ramp. The calculated cycle time can be overruled under certain conditions [14]. A minimum cycle time is set if the queue on the on-ramp grows beyond a certain length (queue detection). A maximum cycle time is set for congestion on the motorway.

3.2.1. RWS algorithm

The RWS algorithm is currently the only algorithm implemented in Dutch ramp metering systems, and has been in use since 1989. It is a capacity-demand feed-forward control algorithm, a type that is also commonly used in North America.

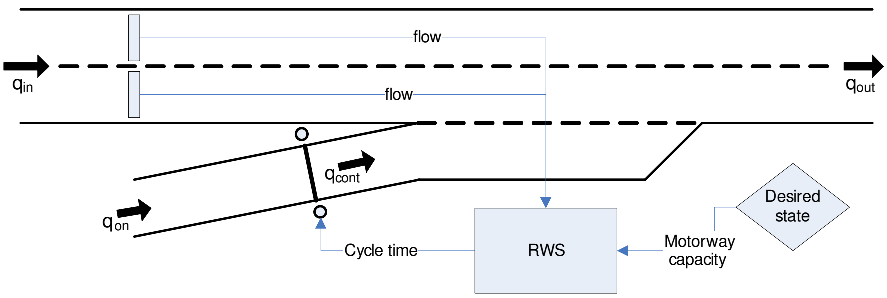


Figure 3.1: Schematic representation RWS algorithm

The demand-capacity algorithm aims to prevent or postpone the formation of congestion. Once congestion on the motorway has formed and the speed drops below the congestion threshold, the performance of the ramp meter will be mostly determined by the motorway congestion detection and the on-ramp queue detection. When congestion on the motorway is detected the flow on the on-ramp is restricted, by implementing the maximum cycle time. When a (too long) queue is detected on the on-ramp the flow on the on-ramp is increased, by setting the cycle time to zero. In practice this leads to a cycle time of approximately 4.5 seconds. The cycle time set by the on-ramp queue detector overrules the cycle time set by the motorway congestion detection.

Cycle time calculation

The RWS algorithm measures the motorway flow upstream of the on-ramp during an interval of one minute. The measurements are smoothed to prevent large, sudden changes in the calculated cycle times. The metering rate q_{cont} is calculated using:

$$q_{cont}(k) = q_{in}(k) - c_{cap}$$

Test results

The effect of ramp metering using the RWS algorithm has been evaluated on several locations after the introduction of ramp metering in The Netherlands [12]. It was concluded that the application of ramp metering results in increased speeds and throughputs on the motorway, reduced total delays, reduced rat running and increased ease of merging into the motorway. These effects were observed in both wet and dry conditions.

During the evaluations on the A10 at Amsterdam and the A12 at Zoetermeer, also the ALINEA algorithm was also implemented and evaluated. Although results varied between the two evaluations [15], overall it was concluded that the RWS algorithm when compared to the ALINEA algorithm is easier to use for traffic operators, shows calmer traffic behaviour, but has a reduced throughput.

Discussion

Demand-capacity algorithms are limited by the fact that after formation of congestion the performance of the ramp meter will be mostly determined by the motorway queue detector and the on-ramp queue detector. This means that the best way to increase the network efficiency is to postpone the start of congestion.

Also variations of the actual motorway capacity, which are addressed in Section 0, hamper the effectiveness of the demand-capacity RWS algorithm. If the actual capacity is higher then vehicles are held back unnecessarily. If the actual capacity is lower then the formation of congestion cannot be prevented.

Based on the above, it seems possible to improve the functioning of the RWS algorithm before and during congestion by using online capacity estimation. The RWS metering algorithm will be used as the reference against which to measure the performance of existing and newly proposed metering methods.

3.2.2. ALINEA algorithm

The ALINEA algorithm was developed by Markos Papageorgiou *et al.* [16] and is an occupancy-based feedback control strategy. The occupancy o is the portion of time that a vehicle is detected at a certain location. The advantage of using the occupancy for the ALINEA metering algorithm is that it has a unique value for both high and low speeds, see Figure 3.2. Each flow observation can be linked to either a high speed, indicating free flowing traffic, or a low speed indicating congested traffic. Separate speed measurements are needed to determine the traffic state. When the flow is near to the capacity this becomes increasingly difficult. It can happen that a ramp meter based on flow and speed observations, can still assume a free flowing traffic state while congestion has already started to form. This confusion cannot occur in an occupancy-based ramp-metering algorithm.

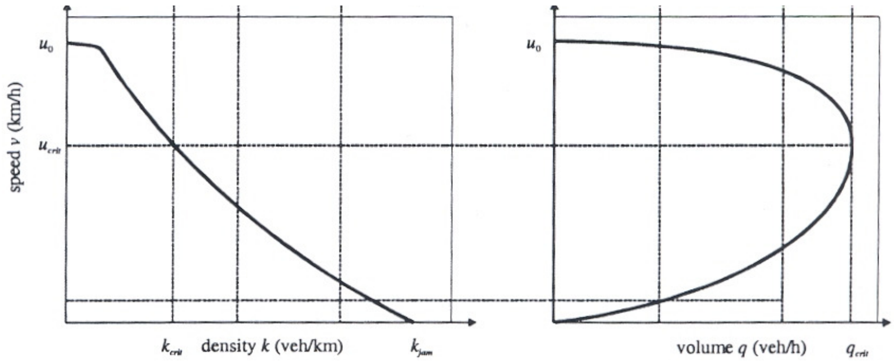


Figure 3.2: density-speed diagram versus flow-speed diagram

Another advantage of using occupancy instead of flow measurements is that the critical occupancy, whereby congestion starts occurring, tends to be less influenced by changes in the traffic and weather conditions than the capacity. This is supported by results of field tests [16].

Cycle time calculation

The ALINEA algorithm adapts the on-ramp flow $q_{cont}(k)$ based on the set critical occupancy $o_{cr}(k)$ and the observed occupancy $o_{out}(k)$, which is measured downstream of the on-ramp. The step size with which the on-ramp flow is raised or lowered depends on the difference between $o_{cr}(k)$ and $o_{out}(k\text{-}1)$, and on the regulator parameter K_r.

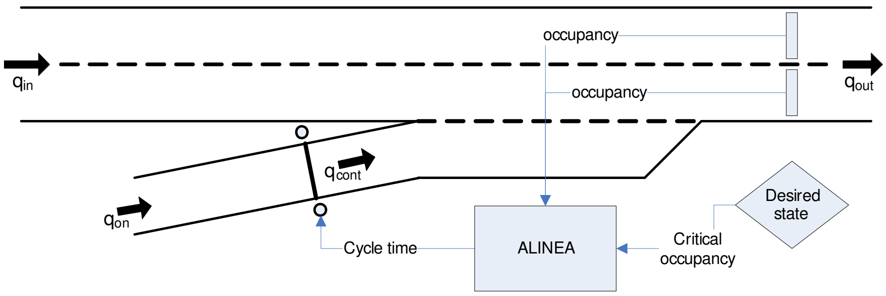


Figure 3.3: Schematic representation ALINEA algorithm

The metering rate q_{cont} is calculated using:

$$q_{cont}(k) = q_{cont}(k-1) + K_r \cdot [o_{cr} - o_{out}(k-1)]$$

As mentioned in the previous section, the ramp metering can be overruled for practical reasons. In the case that the cycle time is set in this way, the calculated value for $q_{cont}(k)$ should not be used for $q_{cont}(k\text{-}1)$ during the next interval. Instead the flow corresponding to the set cycle time should be used. This error can also be prevented by using the observed ramp flow instead of the calculated value for $q_{cont}(k)$.

Test results

The ALINEA algorithm has been tested and implemented at various sites around the world [17], and has grown to become the 'standard' to which other (new) algorithms are compared. Overall it was found that the ALINEA algorithm is simpler, easily transferable, cheaper to implement, more effective and more flexible than the algorithms it was compared to. It was concluded that "ALINEA is a simple, flexible, robust, and efficient local ramp-metering, which can be applied virtually without any theoretical pre-investigation and without calibration to a broad range of motorway ramps where congestion exists".

Discussion
From the literature, it is clear that the ALINEA algorithm is a simple, elegant but effective metering algorithm. Over the years it has become the international standard to which the performance of new algorithms is compared. To better put the value of any new developments in this study in context, it is virtually a necessity to also include the ALINEA algorithm.

3.2.3. V-ALINEA algorithm

The V-ALINEA algorithm, or EDA (simple metering algorithm), is a version of the ALINEA algorithm designed at RWS by Frans Middelham *et al.* [18]. The difference from the ALINEA algorithm is the use of speed measurements instead of occupancy for the metering rate calculation. Also, the V-ALINEA algorithm is not a closed loop feedback controller. The advantage of using the speed instead of the flow is the same as with the occupancy, the observation is unique for both congested and free flowing traffic.

Cycle time calculation
The metering rate $q_{con}(k)_t$ is calculated in roughly the same manner as in the ALINEA algorithm except that the critical speed v_{cr} and the speed measured at the start of the merge area $v_{merge}(k)$ are used instead of the occupancies $o_{out}(k)$ and $o_{cr}(k)$. The regulator parameter K_r influences the step size with which the metering rate is increased or decreased after each interval. Naturally, the value of K_r is different from that of the regulator parameter used in the standard ALINEA algorithm, as described in Section 3.2.2.

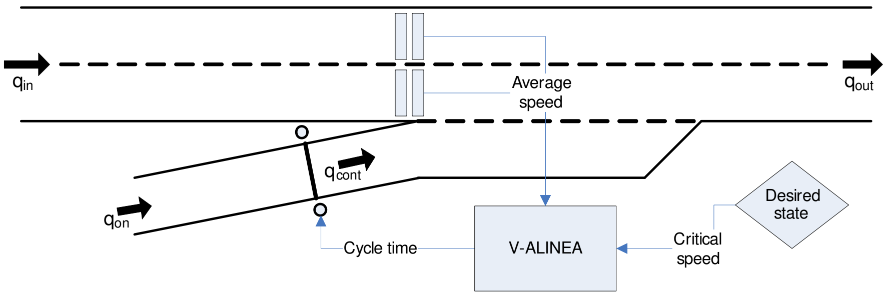


Figure 3.4: Schematic representation V-ALINEA algorithm

The metering rate $q_{cont}(k)$ is calculated using:

$$q_{cont}(k) = q_{cont}(k-1) - K_r \cdot [v_{cr} - v_{merge}(k-1)]$$

As mentioned in the previous section, the ramp metering can be overruled for practical reasons. In the case that the cycle time is set in this way, the calculated value for $q_{cont}(k)$ should not be used for $q_{cont}(k-1)$ during the next interval. Instead the flow corresponding to the set cycle time should be used. This error can also be prevented by using the observed ramp flow instead of the calculated value for $q_{cont}(k)$.

Test results
The V-ALINEA algorithm has been compared to the RWS algorithm using simulations in the simulation program FLEXSYT. There were no large differences in the performance of the two. At present there is a field test planned using the V-ALINEA algorithm on an on-ramp of the A1 near Barneveld. No results of this test are known yet [18].

Discussion
The results are from the tests with the V-ALINEA algorithm are still unknown. As preliminary tests showed, it performs not much differently from RWS. Whether there is an improvement compared to the ALINEA algorithm is also unclear. A main disadvantage of using the average speed is the behaviour of speed in the free flow part of the fundamental diagram. Speed stays relatively constant up to a high traffic volume, only to drop quickly when congestion starts to form. Because of this it is expected that the V-ALINEA algorithm will not perform better than the RWS algorithm. Therefore the V-ALINEA algorithm will not be will not be given further consideration for this study.

3.2.4. AD-ALINEA algorithm
Although occupancy has shown less sensitivity to external circumstances than motorway capacity, it is still difficult to estimate and maintain a correct value for the critical occupancy o_{cr} . To fix this problem Kosmatopoulos *et al.* [19] have developed the AD-ALINEA metering algorithm, an adaptive version of the original ALINEA algorithm. The ALINEA metering algorithm itself remains unchanged. As can be seen in Figure 3.5, only an estimation module has been added to update $o_{cr}(k)$.

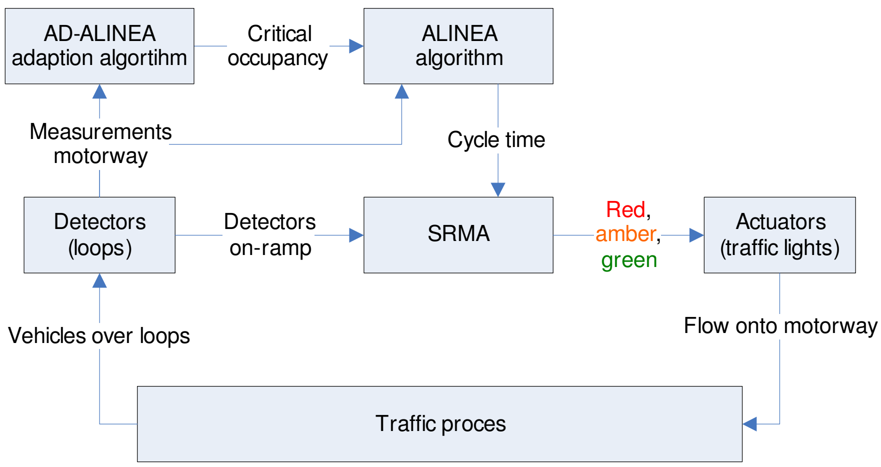


Figure 3.5: Schematic representation AD-ALINEA algorithm

Whether the critical occupancy $o_{cr}(k)$ is updated depends on, among other things, the estimation of derivative $D = \frac{\delta q_{out}}{\delta o_{out}}$, which is based on current traffic observations.

For the estimation of the derivative D two methods have been developed and tested on historic data. One is a simple derivation estimation method that uses measurements of the previous and the current interval according to:

$$\delta q_{out} = q_{out}(k) - q_{out}(k-1)$$

and

$$\delta o_{out} = o_{out}(k) - o_{out}(k-1)$$

The other is an estimation method based on a Kalman filter. A more detailed description of the AD-ALINEA algorithm and the Kalman filter estimation is given in Appendix A.

The critical occupancy $o_{cr}(k)$ is increased by $\Delta = 1\%$, when the estimation of the derivative D is larger than boundary Dplus. When the estimation of the derivative D is below boundary Dmin, $o_{cr}(k)$ will be lowered by $\Delta = 1\%$.

$$ocr(k) = \begin{cases} o_{cr}(k-1)+1 & \text{if } D > \mathrm{Dplus} \\ o_{cr}(k-1) & \text{if } \mathrm{Dplus} < D < \mathrm{Dmin} \\ o_{cr}(k-1)-1 & \text{if } D < \mathrm{Dmin} \end{cases}$$

The thresholds Dplus and Dmin have been chosen such that the estimated $o_{cr}(k)$ always remains in the top of the occupancy-flow diagram; see Figure 3.6.

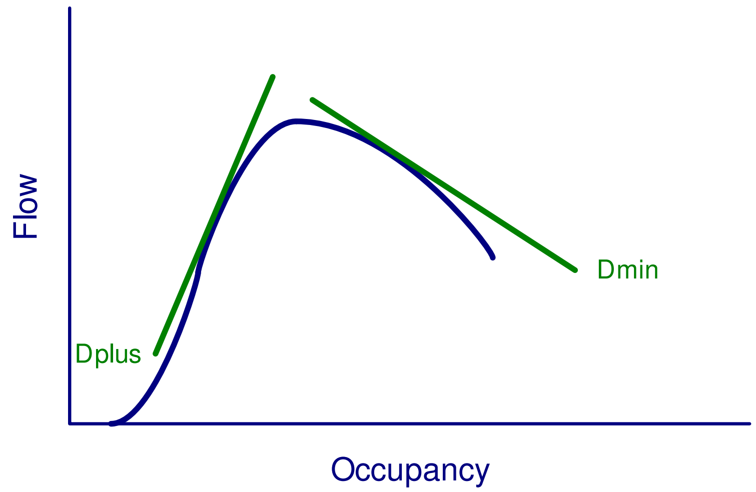


Figure 3.6: Dplus and Dmin in an occupancy-flow diagram

Test results
The first version of AD-ALINEA has been evaluated in a simulation environment using synthetic data [20]. An improved algorithm has been applied to historic data from the M6 motorway in the UK [19]. During these tests the performance of both estimation methods has been evaluated. Both tests found that the Kalman-filter based AD-

ADLINEA proved to be smoother and more robust in its adaptive behaviour and less sensitive to different parameter values compared to the AD-ALINEA using the simple derivative estimation. Unfortunately there were no comparisons made to other metering algorithms.

Discussion
The AD-ALINEA algorithm is a functional adaptive ramp metering system and seems to be an improvement of the ALINEA algorithm. However, the metering method has not yet been implemented or compared to other ramp metering algorithms and therefore no information about its actual performance is available.

Another interesting feature of the AD-ALINEA algorithm is that during the Kalman filter estimation, there also is an estimation made of the motorway capacity. In this study the use of the AD-ALINEA occupancy estimator as a capacity estimation method will be investigated, even though it is not designed for this purpose explicitly. Also a method will be designed based on the AD-ALINEA estimation, but designed more specifically for the estimation of the capacity. A more detailed description of the new estimation algorithm can be found in Section 5.2.

Overall this adaptive algorithm seems to fit well within the objective of this thesis, and it might even be used to improve the functionality of the RWS metering algorithm when used for capacity estimation. Implementing the AL-ALINEA algorithm is even more interesting, since no comparison has ever been made to other metering algorithms.

3.2.5. ANCONA algorithm
This strategy is based on the traffic theory as developed by Boris Kerner, which states that three phases exist in traffic: free flow, synchronized flow and the wide moving jam. Breakdown at a bottleneck such as an on-ramp is associated with a transition from a free-flow to a synchronized flow state. It is on this transition that the control strategy ANCONA is based. After congestion started on the motorway, synchronized flow should be maintained around the on-ramp by switching between a high and a low metering rate [21].

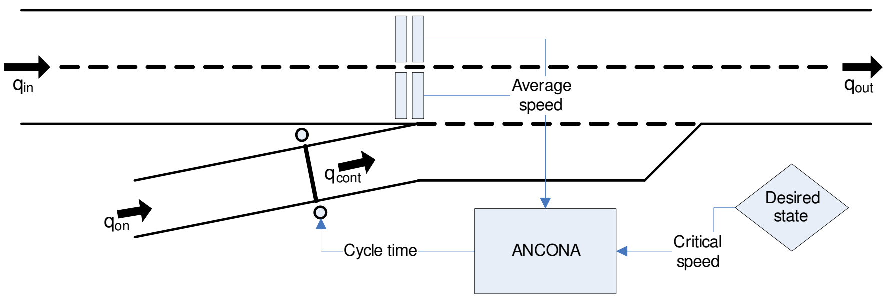


Figure 3.7: Schematic representation ANCONA algorithm

Metering algorithm
The speed v_{avrg} is measured at the nose of the on-ramp and averaged over 5 minutes. Once the speed drops below a certain threshold $v_{congestion}$ the metering rate q_{cont} is set to q_{cont1} (low flow). When as a result the speed on the motorway rises above the threshold $v_{congestion}$

again the metering rate q_{cont} is set to q_{cont2} (high flow). This repeats until some stop-criterion is met. Kerner gives only general expressions for the realization of ANCONA:

$$q_{cont}(k) = \begin{cases} q_{cont1} & if \quad v_{avrg}(k) \le v_{congestion} \\ q_{cont2} & if \quad v_{avrg}(k) > v_{congestion} \end{cases} \quad \text{where } q_{cont1} < q_{cont2}$$

Test results
The performance of the ANCONA algorithm has been determined by comparing results of simulations using both the ALINEA and ANCONA metering algorithms [21]. Based on the results it was concluded that ANCONA leads to a higher throughput on the motorway and on the on-ramp, and to decreased waiting times at the ramp meter. He also states that the ANCONA algorithm prevents any upstream propagation of congestion. As a response to these conclusions and other conclusions concerning the performance of the ALINEA algorithm made in the study, Papageorgiou et al [22] have written 'an answer to flawed criticism' questioning most of the research and conclusions in [21].

Discussion
The behaviour of the ANCONA algorithm as Kerner simulated in his article is also called a "bang-bang" control, meaning that the control signal mainly switches between the extremes. In the evaluation study near Zoetermeer the Fuzzy Control showed similar behaviour [15]. In this evaluation it was concluded that such a control was not desirable. Perhaps the 'bang bang' properties could be reduced by using time-dependent functions instead of constants for the calculation of the metering rate, as suggested in [23].

Based on the behaviour of the controller and the (disputed) test results, the ANCONA algorithm is not expected to perform better than the standard RWS algorithm. The ANCONA algorithm will not be further considered in this study.

3.2.6. Model Predictive Control
Model Predictive Control (MPC) is an on-line control approach that predicts and optimizes the future state of the controlled system using a model and a given input. The optimal control strategy is determined each time step k by optimizing a control signal given a cost function, subject to constraints on the input and output. The cost function rewards desired effects and penalizes unwanted ones. Various effects can be incorporated into the cost function, such as the total delay, number of signals control changes, and the average speed.

To reduce the size and complexity of the computations two computational horizons can be set. The prediction horizon N_p is the maximum number of intervals for which MPC will predict the future state. The control horizon N_c $(N_c < N_p)$ is the number of intervals for which the control strategy is allowed to change. For the intervals beyond the control horizon the control strategy is assumed to remain constant, see Figure 1.1.

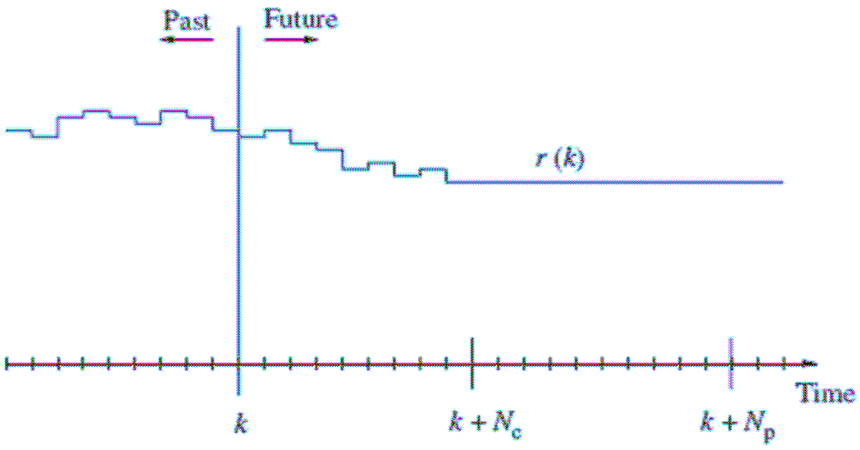


Figure 3.8: Prediction and control horizon

MPC uses a receding horizon framework in which a new optimal control strategy is calculated and implemented each interval.

Metering algorithm
MPC can also be used in a ramp metering system [24]. As mentioned, the future traffic behaviour is simulated using a traffic model. In the case of ramp metering that model should represent the traffic process around an on-ramp. For the prediction of the optimal controls signal $q_{cont}(k)$ the model is run repeatedly using the input variables and a control strategy is proposed. The cost function is calculated for each iteration. Afterwards the control signal with the best outcome for the cost function calculation is implemented. After implementation of the metering rate, the state of the system is updated and the prediction improved using measurements from the on-ramp and the motorway.

Test results
Bellemans *et al.* [24] modelled the E17 Ghent–Antwerp motorway in Belgium and compared the ALINEA based ramp metering control to the MPC based ramp metering control using simulations. The objective function incorporated the total time spent on the motorway sections, the total time spent in the queue at the ramp meter and a term that penalizes fluctuations in the control signal in order to smooth changes of the control signal. The traffic model used by the controller to make a prediction of the traffic behaviour is the METANET model. The METANET model is a deterministic second-order model that is discrete in both space and time [25].

Both controllers were found to have a positive effect, but MPC more so than ALINEA. With the ALINEA algorithm the metering rates were observed to oscillate, due to the queue detection override. This resulted in oscillations in the traffic density and the average speed in the section fed by the on-ramp. The MPC based ramp metering controllers produced very smooth control signals. As a result no large oscillations occurred in the traffic density or in the average speed in the section fed by the on-ramps.

MPC has a higher complexity compared to the ALINEA algorithm. This is caused by the optimization problem that needs to be solved every interval. Choosing the prediction and the control horizons, means making a compromise between the performance and the computational complexity of MPC based ramp metering.

Discussion
Another effect of setting the prediction and the control horizon, which is not mentioned, is the increasing uncertainty of the future state of the traffic system. This effect was not visible in the results in [24], because the deterministic METANET model was used for both the modelled traffic flow and the predictions in the MPC controller. Also in [24], the regulator parameter K_r is set to a very low value (K_r = 0.001). This is different from the value for K_r found by Papageorgiou to "yield excellent result at many different sites" (K_r = 70) [17]. Setting such a low value has a strong negative influence on the performance of the ALINEA algorithm.

Apart from the remarks above, MPC seems to be a promising method for future traffic control, including adaptive ramp meter control. However, MPC doesn't seem to be suited for use within an individual SRMA, where only limited traffic observations and computational capacity are available. Also the method is considered to be too complex to be incorporated within the scope of this thesis. MPC will not be subject to further consideration in this study.

3.3 Conclusions

In the previous section several ramp-metering algorithms have been reviewed. From this review two existing metering methods have been found that are expected to perform better than the RWS metering algorithm under changing circumstances, while still being suited for implementation in the SRMA. These are the ALINEA and AD-ALINEA metering methods. Therefore they will be compared to the RWS algorithm. The other algorithms are not expected to perform better than either the RWS or ALINEA algorithm (see Table 3.1).

Table 3.1: Metering algorithm selection

Metering algorithm	Selected ?	Argument
RWS	Yes	The RWS algorithm is currently the standard metering algorithm used by RWS, and will function as reference.
ALINEA	Yes	The ALINEA algorithm has developed into an international standard. Also the performance relative to RWS algorithm unclear. It is interesting to compare RWS to ALINEA.
V-ALINEA	No	Speed does not change until capacity is almost reached. It is therefore a bad indicator for ramp metering. It is not expected to perform better than ALINEA.
AD-ALINEA	Yes	A working adaptive metering algorithm.
ANCONA	No	Expected not to perform better than RWS or ALINEA.
MPC	No	Not selected due to limitations on available measurements and computational capacity in SRMA, and complexity of implementation.

4. Online capacity estimation

As described in Section 2.2, an adaptive control system consists of a controller and parameter estimation. In this case the unknown parameter is the capacity. Various methods have been developed to estimate capacity from traffic observations. In this section an answer will be given to the first research question:

"What capacity estimation methods exist, and can they be used online in combination with the RWS metering algorithm and the SRMA?"

For this, various capacity estimation methods and their performance are reviewed in Section 4.1. Based on the review, a selection of the estimation methods is made in Section 4.2, which will be combined with the RWS metering algorithm in Section 5.1.

The capacity estimation methods are selected on the following criteria:

- Accuracy of a capacity estimation
- Computational complexity
- Congestion observations required
- Size of required data set

These criteria will be explained in more detail in Section 4.2.

4.1 Capacity estimation methods

Many methods have been developed for estimating the capacity of road sections. In this section capacity estimation methods will be presented that appear to be suited for use in combination with the RWS metering algorithm. A pre-selection of estimation methods has been made based on literature [26,34]. The methods that will be discussed are:

- Empirical distribution method
- Product limit method
- Distribution free estimation approach
- Simple estimation method
- Fundamental diagram method
- DACCORD Online estimation method
- FOSIM method.

PDF/CDF

Since motorway capacity is not a constant, but a stochastic value that varies over time, it is impossible to determine one single capacity for the motorway section under consideration for all circumstances. Instead most capacity estimation methods produce a probability distribution function (pdf) and/or cumulative density function (cdf). The pdf or cdf give a complete description of the probability distribution of the motorway capacity and show how likely it is that a traffic breakdown will occur at a certain flow.

4.1.1. Empirical distribution method

The Empirical Distribution Method (EDM) is generally seen as the most straightforward method. EDM uses observed flows at or just below stream of a bottleneck to determine a capacity distribution of the bottleneck.

Capacity estimation method

The flow q is measured at the bottle neck. Speed is measured at or just upstream of the bottleneck to check the traffic state, and downstream of the bottleneck to check for a downstream blockage. The averaging interval for the measured data is usually between 5 and 15 minutes [26]. Based on the traffic state in the bottleneck, the flows q are divided into free flow and congestion observations. Any observations where a blockage is detected downstream of the bottleneck are ignored.

From N flows observed during congestion a cumulative distribution function (cdf) of the capacity can be constructed using:

$$F(q) = \frac{N(q_i < q)}{N}$$

where $N(q_i < q)$ is the number of congested flow observations q_i that are smaller than the flow q. Obviously observations during congestion are needed. The observation period should be at least one congestion period, but for a more reliable estimation several days should be used. From the capacity distribution function a single capacity value can be determined based on a choice for a certain breakdown probability.

Test results

The EDM is straightforward and produces an unbiased capacity distribution function. All non-congested observations are ignored, even if they have a higher flow than the highest congested flow observation. The resulting capacity distribution therefore only holds for a (post-) congested traffic state [26].

Discussion

The method is not accurate since it estimates the “wrong” capacity. The objective of the RWS algorithm is to postpone the occurrence of congestion by metering towards the free flow capacity. However, the EDM estimates the cdf of the (post-) congested capacity. The EDM is not complex as it requires only limited computation. It does however require congestion observations. For a proper estimation a relatively large dataset is required. The Empirical Distribution Method will not be considered for the rest of this study.

4.1.2. Product Limit Method

Kaplan and Meier [27] first introduced the Product Limit Method (PLM) in the 1950’s for use in life cycle data analysis. It is used to describe the statistical properties of the duration of human life, or to analyze durability of technical components. Van Toorenburg [28] proposed the use of the method for capacity estimation in 1986.

There are two versions of the PLM, Botma/Van Toorenburg [28] and Brilon [29]. The Botma version uses all observed flows, free flow and congested, while Brilon uses only the first observed flow after the start of congestion. This way there is only one congestion measurement per breakdown. It was found that the Brilon version estimates the free flow capacity, while the Botma and Van Toorenburg version estimates a distribution between the free flow and congested capacity [30]. Since the Dutch RWS algorithm uses the free flow capacity, as described in Section 3.2.1, only the Brilon version will be reviewed in this study.

Capacity estimation method

The flow q is measured at or just upstream of the bottleneck. Speed is also measured at or just upstream of the bottleneck to check the traffic state, and downstream of the bottleneck to check for a downstream blockage. Brilon found 5 minutes to be a good averaging interval.
Any observations where a blockage is detected downstream of the bottleneck are ignored. Based on the speed measured upstream of the bottleneck, the flows q are divided into free flow and congestion observations. The congested flow observations are discarded. The last flow observation before a breakdown is labelled {B}, whereby a breakdown occurs when the average speed drops below a speed threshold such as v_{cong} = 70 km/h.
The following capacity estimation can be parametric or non-parametric. The parametric PLM assumes that the probability distribution is distributed according to a certain standard probability distribution, e.g. Normal or Weibull, and tries to fit the distribution to the measurements as close as possible. The non-parametric PLM does not make this assumption to make an estimation of the capacity distribution. As a result it needs more measurements to make a good estimation. Another disadvantage of the non-parametric method is that when the highest measured flow is not followed by a breakdown, no complete capacity distribution can be estimated. Based on his research, Brilon recommends using the parameterised version with a Weibull distribution.
Observations during the congestion and free flow state are both needed. The observation period should at least contain one period with congestion, but for a higher reliability a longer period is recommended [29]. From the capacity distribution function a single capacity value can be determined after choosing a desired breakdown probability.

Test results

Brilon tested the method by estimating the capacity on various 3-lane motorways in Germany, using the Weibull distribution. He found that one shape parameter vary around a value of 13 for all sites, which seems to be typical for 3-lane motorways. The second scale parameter varied over a wide range from site to site. This may be due to different geometric and control conditions, different driver and vehicle populations, and diverse prevailing travel purposes [31].
A study into capacity values for Dutch motorways also incorporated a comparison between different estimation techniques [31,30]. This study found that the parameterized PLM by Brilon is the most accurate of the compared capacity estimation methods.

Discussion
The parameterized Brilon version of the PLM was found to be the most accurate and reliable method available for the estimation of the free flow capacity. The complexity of the un-parameterized method is limited, as it requires little calculations. The parameterized method needs to also to estimate the parameters of the used standard probability distribution, making it more complex. Both versions of the PLM require congestion observations. They also both require a large dataset, although the parameterized version requires a smaller set than the un-parameterized version. The Product Limit Method will not be further considered as a online estimator for this study.

4.1.3. Distribution free estimation approach

The distribution free estimation approach (DFEA) uses headway data to estimate the motorway capacity. Time headways represents the time between two vehicles. Gross time headways include the vehicle, while nett time headways only count the time between vehicles. Gross time headways will henceforth be referred to as headways and nett time headway as gaps.

Capacity estimation method
In order to estimate motorway capacity using a headway method, traffic is split up into followers and free drivers, each with its own free driver headway distribution $h(t)$ or follower headway distribution $g(t)$, according to:

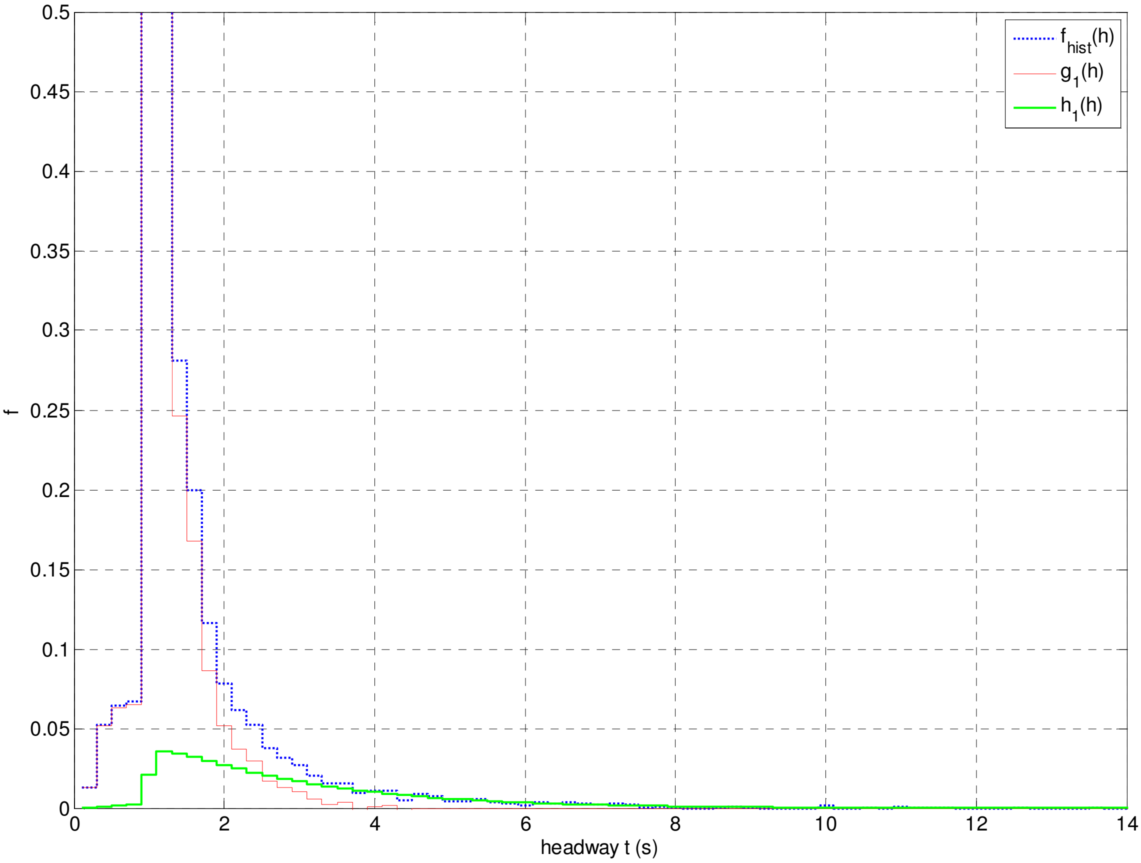
$$f(t)= \phi \cdot g(t)+(1-\phi)\cdot h(t)$$

where $f(t)$ is the observed headway distribution. It is assumed that when the motorway capacity is reached all vehicles are following or the fraction of followers ϕ is 1. Using that assumption, the capacity can be calculated from the follower headway probability distribution function [32].
A distinct feature of the free driver headways is that they are, in theory, exponentially distributed. When all observed headways are plotted on a logarithmic scale, there is a distinct point from where the observations start to deviate from a straight line. This is the point known as the separation parameter T. The deviation implies that not all vehicles with headways shorter than T are free drivers anymore. Using T and the exponential distribution, the free driving distribution $h(t)$ can be estimated iteratively. A more detailed description of the estimation process can be found in Appendix B. After the free driver headway distribution $h(t)$ is determined, the follower headway distribution $g(t)$ can be calculated by:

$$g(t)= f(t) - h(t)$$

This can also be seen in Figure 4.1. A single value for the capacity can be found by calculating the inverse of the mean of the following headway distribution $g(t)$.

Figure 4.1: Headways distributions



Test results

The method has been applied to data from the 'Doenkade' near Rotterdam [32]. The estimation is based on a histogram with a binsize of 0.2 s, and a data set of less than 2000 vehicles. The distribution free estimation approach seems to function well. The iterative function converged within four steps.
A review of other investigations shows that the distribution free estimation approach seems to overestimate the capacity compared to observed road data and values found in early studies [26]. The overestimation might be the result of the assumption that the headway distribution of the following driver doesn't change when the traffic state approaches congested circumstances.

Discussion

The accuracy of the DFEA is limited because of the known overestimation. The estimation process has a limited complexity, as the iterative element is limited and tends to converge quickly. The method does not require any congestion observation. The required data size is limited, and, with a minimum flow of 3000 to 4000 vehicles per hour, can be collected within 45 minutes.
Even though the method overestimates the capacity, the ability to estimate the capacity before reaching congestion makes it an interesting method to combine with the RWS metering algorithm.

Therefore in the following sections the Distribution Free Estimation Approach will be implemented with the RWS algorithm in the Dutch SRMA.

4.1.4. Simple estimation method

The Simple estimation method was proposed by Martens in 1985 and uses vehicle headways to estimate the motorway capacity [33]. The method is based on the distinction between free drivers and followers. The Simple estimation method assumes that all vehicle headways below the separation parameter T are followers; headways above that threshold are free drivers.

Capacity estimation method

All observed headways t longer than the separation threshold T are discarded. The capacity q_{cap} can be calculated from the remaining headways using:

$$q_{cap} = \left[\frac{\sum_i t_i}{n} \right]^{-1} \quad \text{for all } t_i < T$$

where n is the number of observations $t_i \leq T$.

Based on his investigation of the capacity of the Drechttunnel near Dordrecht, Martens found that the capacity estimation using a separation parameter T = 4 seconds corresponded well to the capacities calculated at that site using other capacity estimation methods.

Test results

In a review of estimation methods the simple method was compared to three other headway estimation methods [34]. It was found that the simple method proved to be more effective on motorways than Buckley's model, and needed fewer detectors than other capacity estimators based on headways.
A similar study was not so positive about the Simple method [35]. There it was concluded that the Simple estimation depended too much on the assumption of the separation parameter T. Also the method does not seem to respond to changing external conditions that are known to have an effect on the capacity. And finally it was found that the method produces great variances between sequential intervals. It was concluded that the Simple method was not fit to be used as an online capacity estimator.

Discussion

The capacity estimation is very dependent on the chosen value of the separation threshold. The method is therefore considered not to be accurate. The method is not complex (hence the name Simple method). The Simple method does not require congestion observation for the capacity estimation. Since the method use the same data as the DFEA method discussed in Section 4.1.3, here it is also assumed that the required data can be collected within half an hour.

The Simple estimation method is considered to be less accurate than the DFEA, without having any substantial advantages over it. Therefore the Simple estimation method will not be subject to further consideration for the purposes of this study.

4.1.5. Fundamental diagram method

It can be assumed that if an average driver is driving at a certain speed, he will on average keep a certain headway to the vehicle in front of his [36]. This implies that a generic relationship exists between the flow q, speed v and density k. Observations of q, v and k for different sites and conditions support this statement. The relationships between flow, speed and density are described in three fundamental diagrams: flow-density $q = q(k)$, speed-density $u = u(k)$ and speed-flow $v = v(q)$. These diagrams all essentially contain the same information, presented in a different manner. The fundamental diagram estimation method uses only the flow-density diagram.

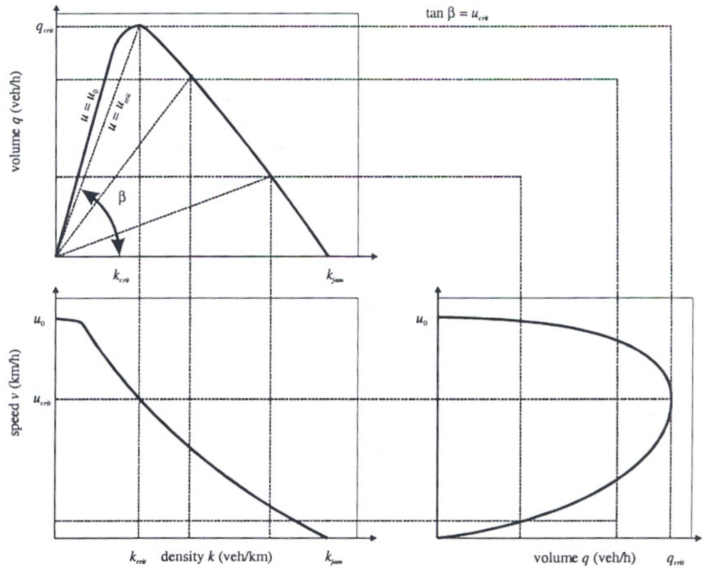


Figure 4.2: Three interrelated forms of the fundamental diagram

The estimation method is based on fitting the model of the fundamental diagram to the observed speeds and densities. There are however many different models of the fundamental diagram available. So before the capacity estimation method can be used, a model should be chosen. Once a model has been chosen and fitted to the data, the free flow capacity can be found by estimating or assuming the maximal density for the free flow traffic state.

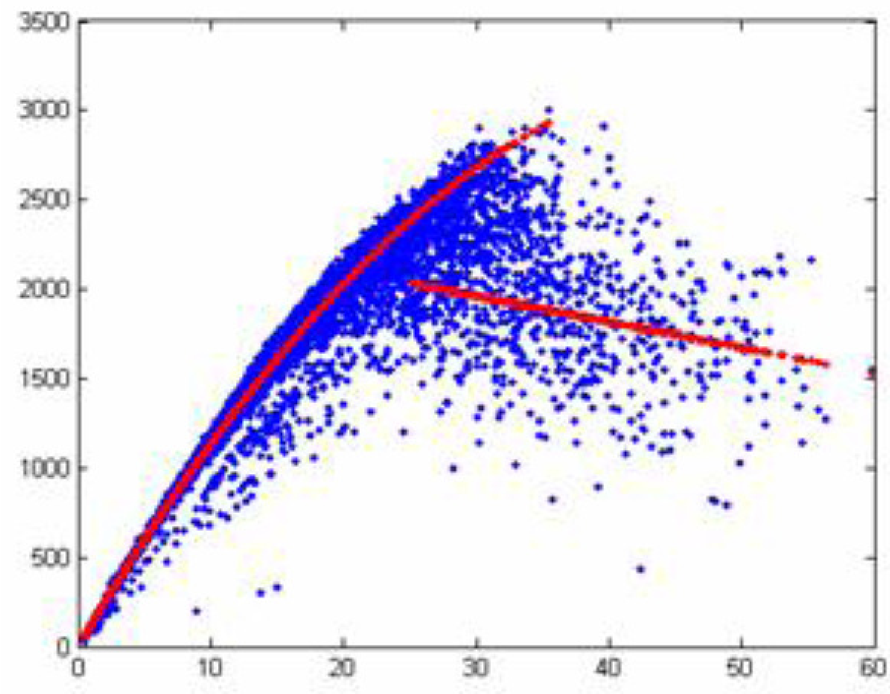


Figure 4.3: Fitting a fundament diagram to flow-density data

Capacity estimation method

Flows q and densities k should be measured inside the bottleneck, using a averaging interval of usually 5 to 15 minutes [30]. Since density k is difficult to measure directly, it can also be derived from the mean distance headway, the occupancy or the relation $q = k \cdot v$ where v is the instantaneous mean speed. More information about the instantaneous mean speed can be found in [36].
Before the capacity estimation method can be used, an appropriate model should be chosen. Since only the free flow capacity is relevant to the RWS metering algorithm, Wu's diagram model can be selected. Wu's model is discontinuous, making a distinction between the free flow and congested state. This makes it possible to use only the free flow part of the model. The free flow part of Wu's model has 4 free parameters that have to be estimated. A least squares method is usually used to determine these parameters. One or more parameter values can be assumed to decrease the computational complexity. Once the estimation has been made, the capacity can be calculated by entering the measured, calculated or assumed critical density into the estimated model.
Even though the fundamental diagram method is static, the capacity could also be estimated dynamically. This would require repeated fitting of the diagram to regularly updated traffic data [26].

Test results

The fundamental diagram method has been applied in a study into the capacity of discontinuities in Dutch motorways [31]. There it was concluded that the capacities estimated using the fundamental diagram method are plausible. This depends however on the fit of the chosen diagram to the available data.

The study warns that observations made during the transition from a congested to free flow state and vice-versa contain data of both traffic states, and should be discarded. They also warn that the single value motorway capacity is purely theoretical, and represents the maximum flow achievable, instead of the capacity distribution as in most other capacity estimation methods. Finally [31] recommends the use of the Brilon PLM for capacity estimation instead.

Discussion
The chosen model for the fundamental diagram has a large influence on the results of the capacity estimation. This makes the estimation less accurate. In theory, no congestion observations are needed. The estimation of the model parameters using a least squares method is relatively complex. The required dataset is large. Assuming parameter values does allow for a smaller dataset and reduces computational complexity, but also reduces the accuracy of the estimation.
The Fundamental Diagram method is considered to be more complex and less dynamic than the DACCORD Online estimator discussed in Section 0, which is also based on fitting a model of the fundamental diagram. Therefore the Fundamental Diagram method will not be subject to further consideration for this study.

4.1.6. DACCORD Online estimator

The DACCORD Online procedure for estimating the current capacity has been designed by TNO, and developed further as a part of the European DACCORD project [37]. It is based on an incident detection algorithm from the McMaster University in Canada [35].

Capacity estimation method
The DACCORD Online estimator uses free flow occupancy, flow and speed, observed over an averaging interval of 1 minute. The flow and speed observations are divided based on vehicle length. Three classes are used: passenger cars (up to 5.10 meters), light lorries (from 5.10 up to 12.50 meters) and heavy lorries (longer than 12.50 meters).
These traffic observations are compared to expected values. The expected values are based on a model of the fundamental flow-occupancy diagram, constructed from a linear and a second order part. The difference between the observations and expected values is used to improve the estimation of the fundamental diagram.
The capacity can be found by entering a calculated maximum occupancy into the flow-occupancy fundamental diagram. A more detailed description of the DACCORD Online estimator can be found in Appendix C.

Test results
Van Goeverden *et al*. [38] used a similar capacity estimator to determine the effect of road lighting. However they assumed a constant critical density. On the capacity estimation they concluded: "The case study demonstrates that the method performs well in practice as long as there are enough frequently observed high free flow rates and densities. If the density frequently exceeds 40 pce/km (on two lane carriageways) the method results in plausible consistent and reliable outcomes."

Discussion
The accuracy of the DACCORD Online estimation method is unknown. The complexity of the method is low. The fact that the required data is not available as standard in the SRMA might increase complexity. The method is dynamic, and requires a limited dataset. No congestion observations are needed for the capacity estimation. This capacity estimation method fits well within the thesis objective. Therefore in the following sections the DACCORD Online estimator will be implemented with the RWS algorithm in the Dutch SRMA.

4.1.7. FOSIM method

The FOSIM method was developed for use in the micro-simulation program of the same name [30]. Even though the FOSIM method is normally used in the micro-simulation program FOSIM, the principle can also be applied to observed data.

Capacity estimation method
Speeds are observed upstream of the bottleneck for different averaging periods (e.g., 1, 5 and 15 minutes). The flow is observed downstream of the bottleneck. When the speed drops below a congestion threshold (e.g., 70 km/h), the highest flow observed so far downstream is added to the dataset, and the observation is stopped. By combining the results from observation periods, a cumulative distribution function can be constructed.

Test results
In studies the FOSIM method seems to underestimate the free capacity [28]. This is caused by a large influence of low capacity values, and is dependent on the natural spread of the free capacity. It is concluded that it is better to use the parameterized Brilon version of the PLM method.

Discussion
Due to the possible underestimation of the capacity, the FOSIM method is considered to be relatively inaccurate. The complexity of the FOSIM is low. The method requires congestion observations and a large dataset. The FOSIM method will not be further considered in this study.

4.2 Conclusions

In the previous section various capacity estimators have been reviewed. In this section the capacity estimators are selected that are to be used for the adaptive metering methods proposed in Section 5.1.

4.2.1. Selection criteria

The capacity estimation methods are selected on the following criteria.

Accuracy
The accuracy of a capacity estimation method is an important aspect. A more accurate method is preferred over a less accurate method.

Computational simplicity

Dutch ramp metering systems have only limited computational capacity. A less complex estimation method is favoured over more complex methods.

Congestion needed
A ramp metering needs to know the motorway capacity before it is reached. An estimation method that is able to make an estimation before occurrence of congestion is preferred over a method that requires congestion observations.

Data set size
Online estimation of capacity is a dynamic process and requires repeated estimation. A method that already is dynamic or can be made dynamic easily is preferred over more static methods. A good measurement is the size of the data set. A large data set is less easily used dynamically.

4.2.2. Results

In Table 4.1 the criteria are applied to the reviewed estimation methods. In the table the performance of the estimators is displayed as follows: very negative (--), negative (-), neutral (0), positive (+) and very positive (++).

Table 4.1: Capacity estimation method selection

Capacity estimator	Accuracy	Computational simplicity	Congestion needed	Size required data set	Selected?
Empirical estimation approach	--	+	--	-	No
Parameterized PLM Brilon	++	--	--	--	No
Distribution Free Estimation Approach (DFEA)	-	+	++	+	Yes
Simple estimation	--	++	++	+	No
Fitting fundamental diagram	0	--	+	-	No
DACCORD Online estimator	0	+	++	++	Yes
FOSIM estimation method	-	+	--	--	No
AD-ALINEA	0	+	+	++	Yes
AD-RWS	0	0	+	++	Yes

There are several capacity estimation methods that are considered to be suitable for implementation with the RWS algorithm in the SRMA. These are the DACCORD Online estimator, the Distribution Free Estimation approach and the AD-ALINEA adaptation algorithm. Although the last was not designed as a capacity estimator, it might prove to function well. The estimation is expected to improve even more if the existing occupancy-based AD-ALINEA estimator is converted to a flow-based estimator. This flow-based estimator will from now on be referred to as the AD-RWS estimator.

The other estimators shall be discarded. They are either not suited for implementation with the RWS metering algorithm in the Dutch SRMA, or are expected to perform worse than the estimators mentioned above.

5. Proposed adaptive metering methods

The previous sections have concluded that improvement of the Dutch metering systems is expected to be possible, either by forming an adaptive metering method from a capacity estimation method and the RWS metering algorithm, or by using a different ramp metering algorithm altogether. In this section four new adaptive metering methods will be proposed. These methods will be implemented in the simulation environment described in Section 6.2. Also three existing metering algorithms were selected, in Section 3.3. These are two non-adaptive ramp metering methods:

- the RWS metering algorithm,
- the ALINEA metering algorithm,

and one adaptive ramp metering method:

- the AD-ALINEA metering algorithm.

These methods will also be implemented in the simulation environment described in Section 6.2.

5.1 Adaptive metering methods

Four new adaptive metering methods are formed by combining the RWS metering algorithm with a capacity estimator, as is shown in Figure 5.1. The following four estimators were selected in Section 4.2:

1. the DFEA estimator
2. the DACCORD Online estimator
3. the AD-ALINEA estimator
4. the AD-RWS estimator

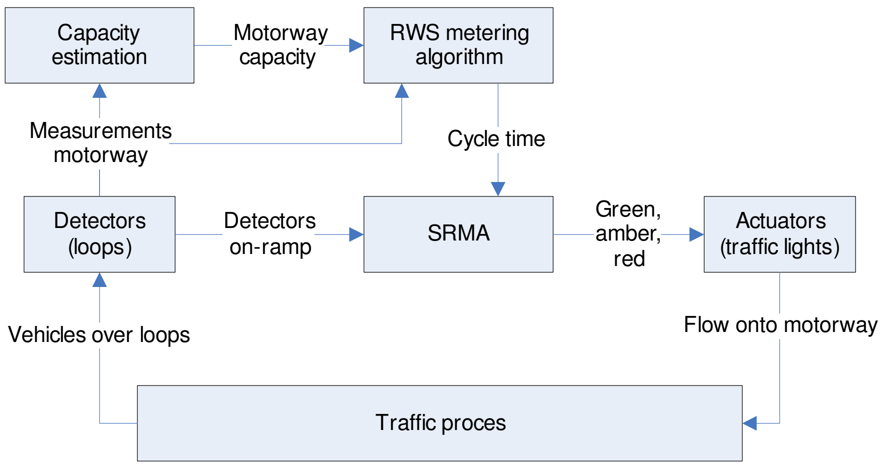


Figure 5.1: Schematic representation of adaptive RWS ramp meter

5.2 AD-RWS estimator

As mentioned in Section 3.2.4, the AD-ALINEA estimator can also be used as a capacity estimator for the RWS algorithm. There are however differences between the metering goals of the ALINEA and the RWS algorithm. The AD-ALINEA estimator is designed specifically for the ALINEA algorithm. This might negatively influence the performance of the RWS algorithm when it is combined with the AD-ALINEA estimator. Instead a new version of the estimator was developed as part of this study, specifically designed for the metering goal of the RWS algorithm.

Estimation boundaries
The AD-ALINEA estimator aims to estimate the critical occupancy o_{cr} in the top of the fundamental diagram. The AD-ALINEA algorithm does so because the ALINEA metering algorithm can respond to disturbances and stabilizes traffic at the critical occupancy.
The AD-RWS estimator aims to estimate the motorway capacity flow q_{cap} just below the top of the fundamental diagram (see Figure 5.2). This is done because the RWS metering algorithm doesn't detect a breakdown (unstable behaviour) until the speed observed by the motorway detectors drops below the congestion threshold. Therefore a safety margin is required.

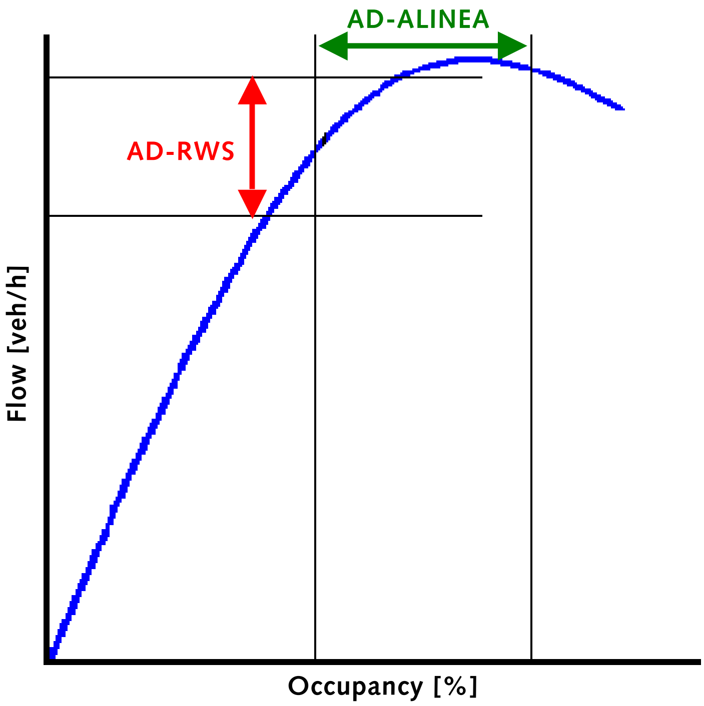


Figure 5.2: Estimation thresholds AD-RWS and AD-ALINEA estimator

AD-ALINEA modifications
The AD-RWS capacity estimator is a modified version of the AD-ALINEA occupancy estimator. In this section the main changes are discussed. The code of the AD-RWS estimator is available on the CD belonging to this report.

The model of the fundamental diagram used in the AD-ALINEA estimator is rewritten, and the derivative D then changes into

$$D = \frac{\delta o_{out}}{\delta q_{out}}$$

The estimated capacity q_{cap} is controlled by the update thresholds $Dmin'$ and $Dplus'$, according to:

$$q_{cap}(k) = \begin{cases} q_{cap}(k-1) + 100 & \text{if } D' < Dplus' \\ q_{cap}(k-1) & \text{if } Dmin' < D' < Dplus' \\ q_{cap}(k-1) - 100 & \text{if } D' > Dmin \end{cases}$$

where $Dplus'$ = 0.01 and $Dmin'$ = 0.02.

The values for $Dplus'$ and $Dmin'$ are determined by analysis of flow-occupancy diagrams, taken from the simulations discussed in Section [X]. D' is estimated using a Kalman filter, similar to the one used in the AD-ALINEA estimator

6. Experimental setup

In Section 1.3 the thesis objective and research questions were formulated. In the previous sections the first two research questions were answered. The third and final research question is:

"Does online capacity estimation improve the performance of a metered on-ramp using the RWS metering algorithm?"

This question will be answered by experiment. In this section the general setup of the experiments is described. First the test method selection is described. Next the setup of the test is presented. Finally the performance indicators are discussed.

6.1 Test method selection

To make an assessment of the effect of a metering method, all other circumstances should remain constant.

Simulations
The metering methods will be tested in simulations. In a simulation environment all variables can be controlled exactly. This makes it easy to assess the effect of a certain metering method in a simulation. The effect measured in a simulation is seldom the same as that measured in reality. However it is indicative of the effect in real life - even more so if the measured effect is compared to the effect measured in a reference simulation.

Other options that have been considered are real life experiments and application of the methods to historic data.

Real life experiments
In real life experiments, measuring the effect of the method ceteris paribus is virtually impossible. Also, real life experiments would prove far too costly and be beyond the scope of this studyfor this study.

Applying the methods to historic traffic data
When the methods are applied to historic data, the influence of the method on the traffic is not measurable. Also, historical observations do not contain all the types of data needed for the cycle time calculation and capacity estimation process.

6.2 Simulation environment

The simulation environment consists of three components: a traffic simulation model, a ramp meter controller and a computational engine containing the capacity estimators. The components will be discussed in the following sections. To function as a whole, data will need to be exchanged between the components. The general data exchange relations are displayed in Figure 6.1.

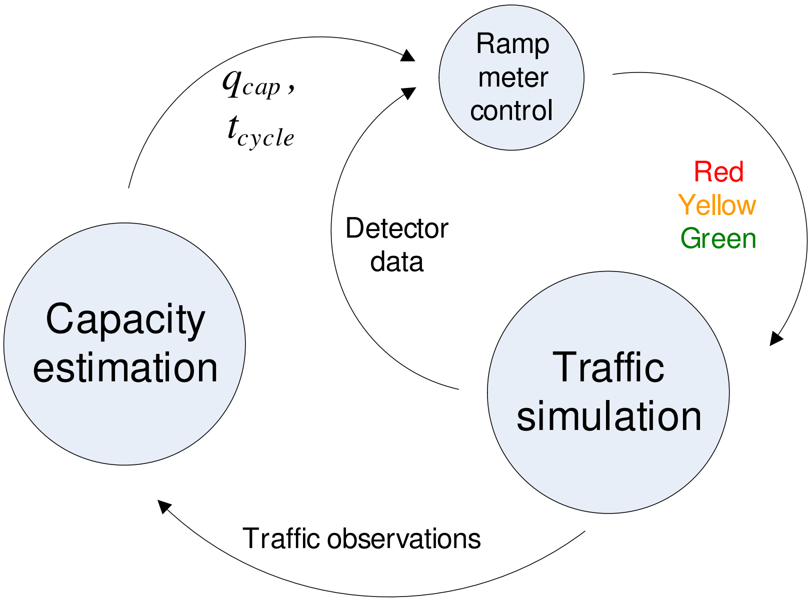


Figure 6.1: Simulation environment setup

6.2.1. Traffic simulation

Overall traffic simulation models can be divided into macro-, meso- and micro-simulation models. The capacity estimation methods require individual vehicles observations. This is only possible using micro-simulation models. The model should also be stochastic to incorporate the stochastic nature of traffic flow and motorway capacity.

Micro-simulation model selection

Available stochastic micro-simulation models are: FLEXSYT-II-, FOSIM, Paramics and Vissim.

Vissim is to be chosen and used, for the following reasons. A (partial) interface between Vissim and the SRMA exists. The vehicle behaviour in Vissim, and therefore the capacity, is based on a vehicle following model. Vissim allows other applications such as Matlab to communicate with it, via a so-called COM interface. Software licences are available. The author has prior experience of modelling in the Vissim application.

FLEXSYT-II- is the in-house micro-simulation model of RWS. It is however not suitable for this study because the vehicle behaviour is based on a given capacity, where in reality the capacity is dependent on the vehicle behaviour. FOSIM is not suited since it does not support external control of traffic lights. Paramics does support external controllers, but there does not yet exist an interface between Paramics and the Standard Ramp Metering Application of RWS (SRMA).

Network size and layout

To test the effect of the metering methods the network contains an on-ramp, the merge area and an up- and a downstream section of motorway. The downstream motorway section is long enough to dissipate the influence of the merge area.

6.2.2. Ramp meter controller

The SRMA is used for the control of the ramp meter. The SRMA has the following functions:

Data collection and smoothing

Each on-ramp lane has seven detectors, each motorway lane two. The on-ramp loops only detect the presence of a vehicle; the motorway loops also detect the speed. The motorway measurements are smoothed. Smoothing prevents that a short drop in the flow or speed directly affects ramp meter operation.

Start and stop of metering

There are two activation thresholds: a low speed or a high flow on the motorway. Metering is deactivated when the speed rises or the flow drops again. The ramp meter is also deactivated in case of a very low flow on the on-ramp. Rapid on- and off-switching may occur when the speed or the flow fluctuate close to the threshold values, causing confusion amongst drivers. A minimum (de)activation period is set to prevent this.

Cycle time calculation

The RWS metering algorithm is included in the SRMA. As discussed in Section 3.2.1, the cycle time is calculated based on the capacity q_{cap} and the flow q_{in}, observed on the motorway upstream of the on-ramp.

Phase control

Once activated, the SRMA controls the traffic lights based on the calculated cycle time and the detector loops around the stop line (see Figure 6.2).

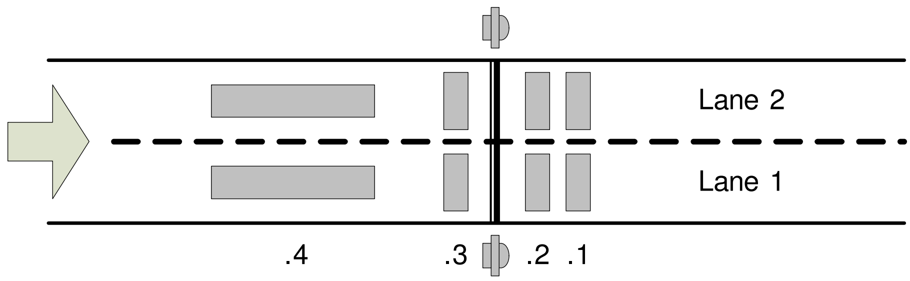


Figure 6.2: Detectors on the on-ramp

As long as no vehicle is detected, the light will stay red. Once a vehicle is detected on the detector .3 the green phase is started. When it reaches detector .2 the light turns amber. When the vehicle reaches detector .1 the traffic light will turn red. The red phase will continue for the remainder of the cycle time. The minimum cycle time in practice is about 4.5 seconds, due to the limitations of the reaction time of drivers and the acceleration of vehicles.

On-ramp queue detection

To prevent blockage of the upstream intersection and urban road network, a queue detection device is used. When this detects a queue spilling back towards the end of the on-ramp, a minimum cycle time is set. This set cycle time overrides the calculated cycle time.

Motorway congestion detection
When the speed on the motorway drops below the first congestion threshold (v = 30 km/h) a maximum cycle time is set which strongly reduces the flow from the on-ramp. This set cycle time overrides the calculated cycle time, but in turn it can be overridden by the cycle time set by the on-ramp queue detection. When the speed on the motorway drops even more (below v = 20 km/h), it is likely that the congestion is caused by an external cause, e.g., a blockage downstream. The cycle time is then set to a minimum cycle time, to allow vehicles to pass when they are able to.

6.2.3. Capacity estimation

The capacity estimators will be implemented in the computational application Matlab. This application has extensive options for executing scripts and function, and for data import and export.

6.3 Capacity scenarios

To test the performance of the combined metering methods under various capacity conditions, five capacity scenarios are to be tested. In Vissim, the capacity can be manipulated by changing the parameters of the used car following model. The Vissim manual identifies the desired time headway CC1 as the parameter with the biggest influence on the capacity.

For the first four capacity scenarios, the parameter CC1 will be kept constant during the scenario.The desired time headway varies for each scenario; as shown in Table 6.1.

Table 6.1: Capacity scenario's

Capacity Scenario	CC1
0	0.9
1	0.95
2	1.0
3	1.2

The fifth scenario represents changing conditions during the simulation, such as a short, but heavy shower or a small incident at the side of the road. During this scenario the desired time headway is temporarily increased, resulting in a lower capacity; see Table 6.2.

Table 6.2: Value of CC1 during capacity scenario 4

Simulation minute	CC1
0 – 75	0.95
75 – 165	1.2
165 – 240	0.95

Number of simulations
Vehicle behaviour in car following models is influenced by various random properties, such as the desired speed, the vehicle model or the moment of vehicle generation. The results of a single simulation only

hold for those specific properties. Considering the average result of multiple simulation runs reduces random effects of a single simulation. Therefore ten simulations will be run, simulating two working weeks. For each of these simulations a small variation in the random properties is introduced by changing the so-called random seed. The results of a metering method for a capacity scenario are expressed as the mean and the standard deviation of the individual simulation results.

6.4 Performance indicators

Performance indicators are defined, so that the different metering methods can be compared. The calculation method for the performance indicators is described in Section 8.1.

6.4.1. Main performance indicator

The network efficiency can be defined as the ability of a network to get vehicles through and out of the network as quickly as possible. When the network must process more than one vehicle entering it, the travel time of some vehicles will be longer than when the network is empty because of interference between vehicles. The sum of their delays, or the total vehicle delay (in Dutch "*voertuigverliesuren*"), is the main indicator of the network efficiency. The performance of a metering method can be measured relative to the performance of the standard RWS metering method, by calculating the **total change of the vehicle delay**. This reduction can be specified for the two vehicle origins (on-ramp or upstream motorway section).

6.4.2. Secondary performance indicators

RWS also uses other performance indicators specific for the review of ramp metering. Their effect also contributes to (a reduction of) the total vehicle delay. The secondary performance indicators are:

Start time and total duration of motorway congestion
The start of congestion is defined as the first interval in which the speed drops below the congestion threshold of 65 km/h. This is defined as the number of intervals in which the speed just upstream of the on-ramp is below the congestion threshold. A reduction of congestion leads in general to a shorter travel time and thus less vehicle delay.

Start time and total duration of queue detection
The SRMA contains an on-ramp queue detection, which can override the calculated cycle time. When the queue detection is active, then the metering rate is fixed. Overall a reduction in the activity of the queue detection leads to lower total vehicle delay.

Number and average duration of queue detection periods
When the queue detection is active, it allows more vehicles to enter the motorway, which in turn might cause congestion. Once the queue detection is deactivated the number of vehicles allowed to enter is reduced and the congestion can dissolve again. Frequent activating and deactivating of the queue detection can result in shockwaves moving upstream on the motorway.

The metering rate during queue detection is not influenced by the metering method. Instead it is a measure of how high the on-ramp flow is during queue detection activation. Since the queue outflow (set minimum cycle time) is fixed, a queue will dissipate faster with a low inflow than with a high inflow. A long average duration of the queue detection period therefore indicates that queue detection was activated during high on-ramp inflow. A shorter average duration indicates the opposite.

6.5 Summary

In this section the experimental setup is summarized.

6.5.1. Test setup

The simulation environment consists of three components:

- traffic simulation,
- ramp meter control,
- capacity estimation.

The traffic simulations are done using the micro-simulation model Vissim, the ramp meter will be controlled by the SRMA, and the calculations for the capacity estimations will be done in Matlab. Data will be exchanged between the components according to Figure 6.1. The network consists of an on-ramp, merge area, and up and downstream motorway sections.

6.5.2. Capacity scenarios

The seven proposed metering methods will be tested using five capacity reduction scenarios. Four scenarios have constant capacity conditions during the simulations. One scenario has changing capacity conditions.

Vehicle behaviour in car following models is influenced by various random properties, such as the desired speed, the vehicle model or the moment of vehicle generation. The results of a single simulation only hold for those specific properties. Ten simulations with different random seeds will be run to reduce the influence of random properties on the results. See also Figure 6.3.

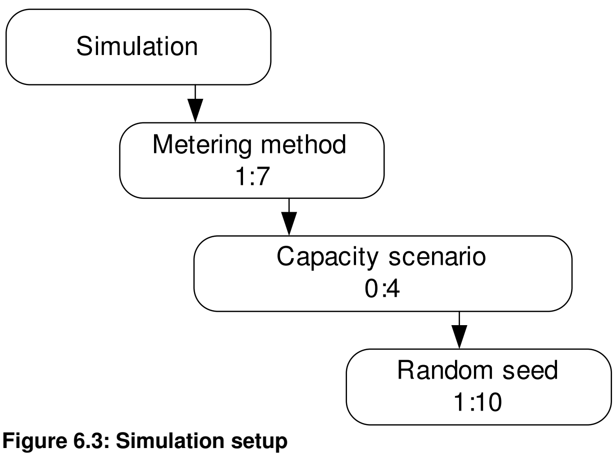


Figure 6.3: Simulation setup

6.5.3. Performance indicators

The primary performance indicator is the **change of the total vehicle delay**, relative to the delay with the use of the RWS metering method. The delay will be specified towards the origin of the vehicles. The secondary performance indicator can be divided into two categories:

Motorway congestion
Performance indicators for the congestion are start time and mean duration of congestion.

On-ramp queue detection
Performance indicators for queue detection are start time, total duration, number of starts and average duration queue detection.

7. Simulation environment

In this section the simulation environment is constructed and calibrated. First the combination of the separate components is discussed. Next the construction and setup of the separate component is presented.

The completed simulation environment is used to test the metering methods as discussed in Section 5.1. The results of the simulations will be presented in Section 8.

7.1 Software architecture

A model of an on-ramp has been constructed in a simulation environment. The main components of this environment are the traffic simulation application Vissim, the SRMA and the computational engine Matlab; see Section 6.2.

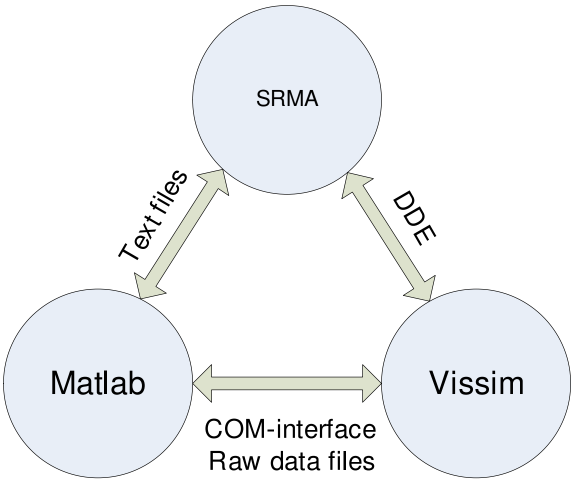


Figure 7.1: Simulation components and connections

7.2 Data transfer interfaces

The three model components have been connected and can exchange data, according to Figure 7.1.

Vissim - SRMA
Vissim and the Standard Ramp Metering Application (SRMA) are connected using the Promit-E application developed by the distributor of Vissim in the Netherlands, Vialis B.V. in Haarlem. The data transfer uses DDE (Dynamic Data Transfer); a standard feature on PC's running the Windows operating system. This feature enables two or more processes to read and write data from and to a shared location in the computer's RAM memory. The speed of DDE allows real-time passing of detector data to the SRMA, and signal changes to Vissim.

Vissim - Matlab

Vissim and Matlab have been connected using an existing communication interface in both applications, the so-called COM-interface. This allows the COM-client Matlab to ask for and receive information from the COM-server Vissim. The client application can also change or set certain properties of the server application.

The COM-interface is slow compared to DDE. This means that using the COM-interface for transferring detector data to Matlab strongly increases simulation time. However, passing averaged observations from Data Collection Points allows faster simulations. Data Collection Points are objects in Vissim which are placed on a link, and capture the properties of each vehicle that passes over it. These properties are averaged over a specified period, and than released towards a text file, database or the COM-interface.

For most capacity estimators these aggregated observations are sufficient. However, there are two estimators that need more detailed vehicle information than can be collected using the COM-interface. This information was acquired from raw data output files (*.mer), which contain the properties of each vehicle passing a Data Collection Point.

Matlab - SRMA
Matlab passes data into the standard ramp metering application using small text files, each containing only the value of one variable. The metering application reads the text files each simulation step and updates its internal variable according to the value in the text file. To read the text files small modifications have been made to the SRMA code. These however do not effect SRMA operations. Even though it is not necessary to read the text files this often, the increase in simulation speed was not worth extra programming effort needed to reduce the update frequency. A full description of changes made to the SRMA can be found on the CD belonging to this report.

7.3 Vissim model

In this section the construction of the Vissim model will be discussed. The model constructed based on an exiting metered on-ramp.

First an existing metered on-ramp will be selected, and the layout and some traffic characteristics of the selected on-ramp are reviewed. Next the layout of the selected location will be used for the construction of the simulation model. Finally the model parameters and settings will be determined based on the traffic characteristics of the selected on-ramp, and improved by a qualitative calibration.

7.3.1. Study area selection
In this section a location will be selected. At first the selection criteria will be mentioned, and the information sources. Next a location will be selected.

Criteria

The location will need to fulfil a number or criteria. The criteria are aimed at selecting an on-ramp with little to none external influences. The criteria that were applied are:

- No separate bus lane
- Two lanes on the on-ramp
- One vehicle per green phase
- The merge area is not a part of a weaving section
- No major bottleneck within 3 kilometres up or downstream
- Occurrence of congestion caused by the on-ramp
- Availability of motorway and ramp meter measurements

Priority vehicles at ramp meters with a separate bus lane can cause extra delay. Ramp meters with a separate bus lane are discarded. Single lane ramp meters have a reduced maximum on-ramp capacity compared to double lane ramp meters. They also have less room available for queuing. Because of this the queue detection will be activated sooner and more often. Single lane ramp meters are discarded. Ramp meters where instead of one, two vehicles per green phase are allowed to pass are discarded. Weaving sections lead to complex lane change behaviour and have a reduced capacity [39]. Locations with a weaving section directly upstream of the on-ramp are discarded. The presence of a bottleneck, such as a motorway intersection or a downstream lane drop, can influence the flow motorway. Locations with a motorway bottleneck within 3 kilometre are discarded. Occurrence of congestion caused by the on-ramp shows that vehicles on the motorway are experiencing delay. Ramp meters where no congestion occurs are discarded. Finally the availability of the ramp meter and motorway data is considered.

Information sources

The criteria determined in the previous section were applied to a database containing all metered on-ramps in The Netherlands. Information concerning the criteria was gathered from several sources.

- RWS ramp meter data base
- Aerial photography available through the internet
- Detector data
- Other sources

The data base contains relevant information about the number of lanes, whether there is a bus lane, how many vehicles are allowed to pass, and location to check for neighbouring ramp meters.

Aerial photography is used to identify all on-ramps that are part of a weaving section, and to check whether any bottlenecks exist within 3 km. It was also used to estimate the length of the on-ramp.

Detector data from the locations was gathered and plotted to speed contour diagrams to verify the occurrence of congestion, and also the availability of the detector data. Detector data was gathered for both morning and evening peak hours, for the previous consecutive Tuesday, Wednesday and Thurday (the 4th, 5th, and 6th of September 2007).

To determine if no other objects or events had a (semi) permanent influence on the data gathered several source were checked, such as information on the RWS intranet, Internet sites and media.

Outcome
The criteria are applied to the RWS ramp meter database, using the information gathered. The results are presented in Table 7.1.

Table 7.1: Study area selection

On-ramp	Bus lane	Ramp lanes	Vehicles per green	Weaving section	Motorway Bottleneck	Congestion at on-ramp	Data availability
Uithof to the A28 towards	Yes						
S101 to the A10-West towards	Yes						
Everdingen to the A2 towards	Yes						
Muiderslot to the A1 towards	Yes						
Maarn to the A28 towards Utrecht	Yes						
Maarn to the A12 towards Utrecht	Yes						
Zoetermeer to the A12 towards	Yes						
S102 to the A10-West towards	Yes						
Leusden-Zuid to the A28 towards	Yes						
Zoetermeer to the A12 towards	Yes						
Hagestein to the A27 towards	No	1					
Breukelen to the A2 towards	No	1					
S104 to the A10-West towards	No	1					
S105 to the A10-West towards	No	1					
Kolkweg to the A8 riching	No	1					
Barendrecht to the A29 towards	No	1					
Vianen to the A2 towards Utrecht	No	1					
Crooswijk to the A20 towards	No	1					
Kleinpolderplein to the A20	No	1					
Muiden to the A1 towards	No	1					
Muiderberg to the A6 towards	No	1					
Soesterberg to the A28 towards	No	1					
Delft-Noord to the A13 towards	No	1					
Bunnik to the A12 towards	No	1					
Almeerderzand to the A6 towards	No	1					
Zevenaar to the A12 towards	No	1					
Utrecht-Noord to the A27 towards	No	1					
Houten to the A27 towards	No	2	2				
Maarssen to the A2 towards	No	2	2				
Maarssen to the A2 towards	No	2	2				
Delft-Zuid to the A13 towards	No	2	1	Yes			
Digna Johannaweg to the A15	No	2	1	Yes			
Delft-Noord to the A13 towards	No	2	1	Yes			
Delft-Centrum to the A13 towards	No	2	1	Yes			
Breukelen to the A2 towards	No	2	1	Yes			

On-ramp	Bus lane	Ramp lanes	Vehicles per green	Weaving section	Motorway Bottleneck	Congestion at on-ramp	Data availability
Papendorp/Nieuwegein to the	No	2	1	Yes			
Papendorp/Nieuwegein to the	No	2	1	Yes			
Boxtel to the A2 towards	No	2	1	Yes			
Schiedam-Noord to the A20	No	2	1	No	Yes		
Schieplein to the A20 towards	No	2	1	No	Yes		
Culemborg to the A2 towards	No	2	1	No	No	No	
Best to the A2 towards 's-	No	2	1	No	No	No	
Barneveld to the A1 towards	No	2	1	No	No	No	
Vinkeveen to the A2 towards	No	2	1	No	No	Yes	No
Velperbroek to the A12 towards	No	2	1	No	No	Yes	Yes

Conclusion

After applying the criteria to the database using the information from the sources one on-ramp remained; The A12 Velperbroek on-ramp towards Utrecht, located on the left carriageway at kilometre 133.2.

7.3.2. Description of study area location

The A12 is the oldest motorway of The Netherlands, and has a length of 137 kilometres from The Hague to Zevenaar. The A12 is one of the busiest motorways in the Netherlands and also one of the most important east-west connections. In this section road and traffic characteristics of the selected location are described, which are used in the simulation model in the coming sections.

Road characteristics

Figure 7.2: Location of Velperbroek on-ramp

The Velperbroek on-ramp is located on the A12 at kilometre 133.2, on the left carriageway (westbound, towards Utrecht) situated on the east side of the city of Arnhem, see Figure 7.3. The motorway section directly upstream of the merge area has two lanes and a length of approximately 1.5 kilometres. The next upstream section is a weaving area for the Velperbroek off-ramp and the Westervoort on-ramp. The merge area has three lanes and a length of 260 meters. The motorway section directly downstream of the merge area has two lanes and length of approximately 4 kilometres. The next downstream section is the A12-A50 motorway intersection. The on-ramp has a total length of a little over 600 meters. The length from the start of the on-ramp to the stop line is approximately 250 meters; as shown in Figure 7.3. The on-ramp is fed by a regulated round-a-bout with 5 directions. Three of those are motorways, one arterial road, and one urban.

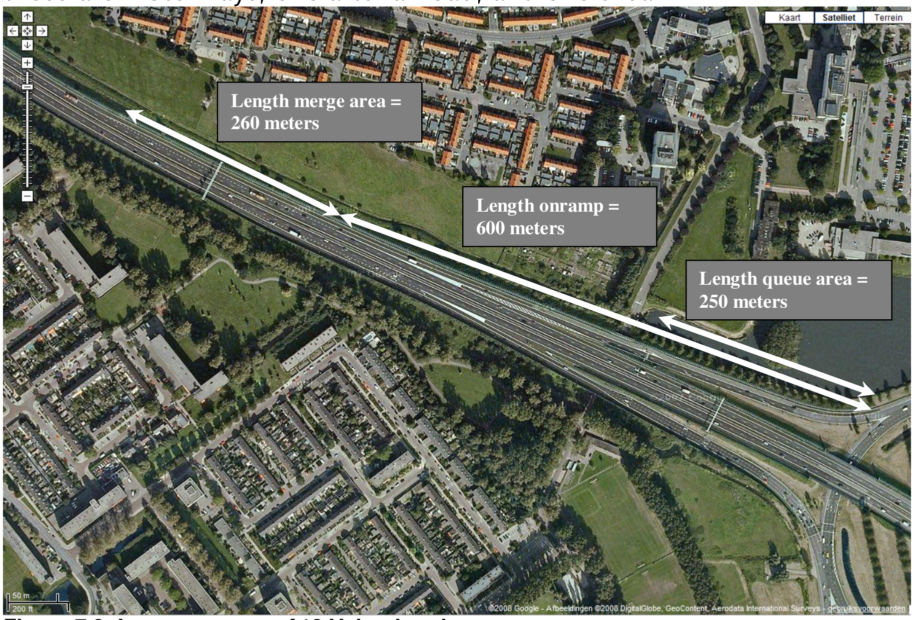


Figure 7.3: Layout on-ramp A12 Velperbroek

Traffic characteristics

On most days working days there is congestion during the morning peak hour. The peak lasts from approximately 6:00h till 9:00h. No congestion was observed coming from downstream blockades. The evening peak hour is normally without congestion. Flow measurements from the on-ramp and the motorway upstream of the merge area were gathered for the period of a year and plotted in time-flow diagrams (Figure 7.4 and Figure 7.5). After a peak at the start of the peak period the flow on the motorway drops slightly. This might be due to the increased flow on the on-ramp. It might also be due to congestion forming at the upstream Velperbroek off-ramp, partially blocking the motorway.

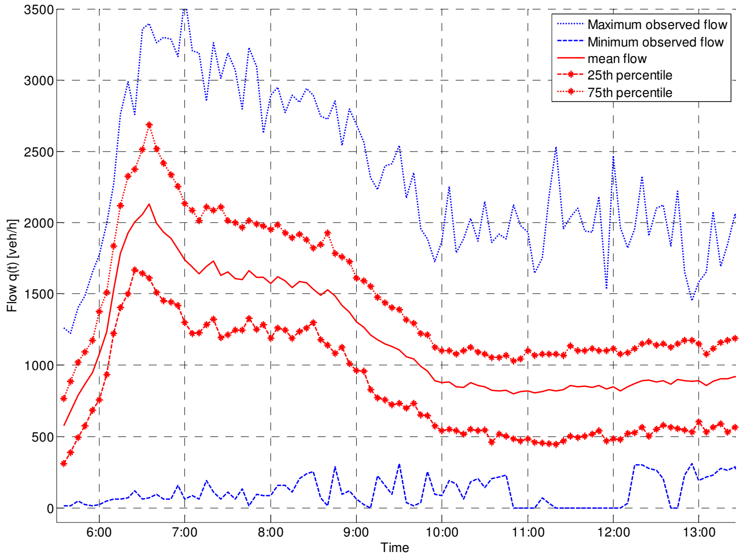


Figure 7.4: Traffic flows approaching from the motorway

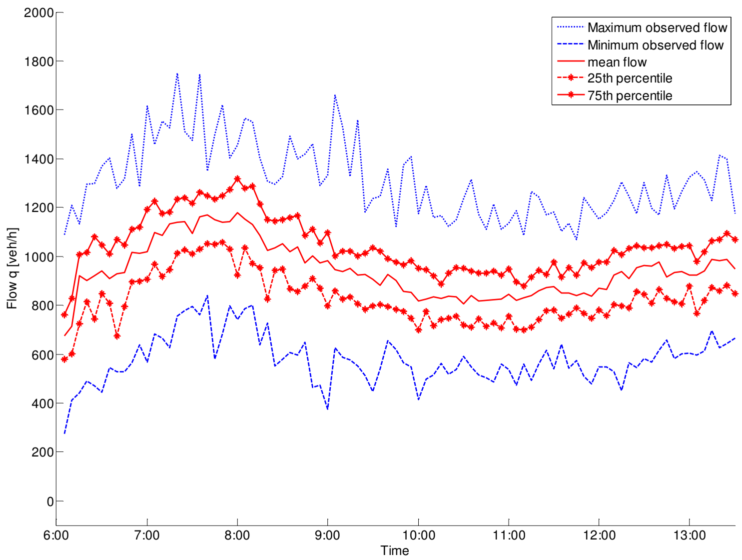


Figure 7.5: Traffic flow entering the on-ramp

7.3.3. Vissim model layout

The Vissim model consists of the on-ramp, the merge section and an upstream and downstream section of motorway of the Velperbroek on-ramp; see Figure 7.6. A detailed description of the Vissim model can be found on the CD belonging to this report.

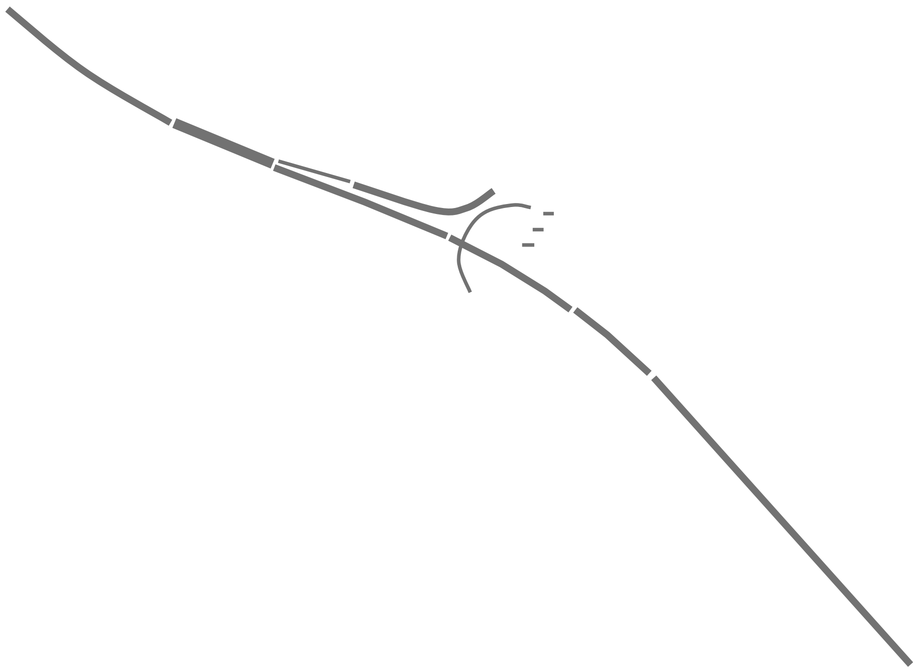


Figure 7.6: Link layout Vissim model

Detectors
The SRMA requires 7 detectors per lane on the on-ramp, 3 dummy detectors, and a detector on each motorway lane up- and downstream of the merge area. The extra controller application also required a detector on each motorway lane up- and downstream of the merge area, and one dummy detector. Since both motorway and on-ramp have two lanes, a total of 22 detectors have been used.

Data collection points
Data collection points where placed approximately 250 to 500 metres apart. A data collection interval of 60 (simulation) seconds was set.

Vehicle inputs
Vehicles can enter the network from so called vehicle inputs. Three vehicle inputs were placed; one at the upstream end of the motorway, one at the beginning of the on-ramp, and one at a link containing a dummy detector.

Desired speed decisions
Several desired speed decisions (DSD's) where placed on the on-ramp and the merge area. DSD's have the same function as a real speed limit sign. When a vehicle passes a DSD, a new desired speed is assigned to it from the according speed distribution.

Signal heads
The model contains two traffic lights, or signal heads, controlled by the SRMA.

7.3.4. Vissim model settings and calibration
In this section the settings of the Vissim model described in Section 7.3.3 will be discussed.

Simulation period

The simulation period is chosen from 5:30 till 9:30. Historic data from the study area shows that during this period congestion occurs regularly. This period amounts to 14400 seconds, or 240 1-minute intervals. The simulation period was later expanded with ten minutes, during which the network could become empty.

Vehicle inputs
Where and how many vehicles enter the network is defined in the vehicle inputs. The simulation period is divided into eight 30-minute intervals. The initial vehicle inputs were roughly based on the maximum flows reached in Figure 7.4 and Figure 7.5. During the calibration process the motorway vehicle input values were increased, as the Vissim model showed to have a higher capacity than the original case location. The final vehicle inputs are defined as showed in Table 7.2. No vehicles enter the network during the last 10 minutes of the simulation. The vehicle inputs are stochastic.

Table 7.2: Vehicle input flows

Interval	5:30-6:00	6:00-6:30	6:30-7:00	7:00-7:30	7:30-8:00	8:00-8:30	8:30-9:00	9:00-9:30
Motorway	1000	1200	1350	1450	1400	1350	1300	1200
On-ramp	3500	3600	3700	3600	3500	3400	3300	3000

Heavy Goods Vehicles (HGV)
The portion of Heavy Goods Vehicles (HGV) has a strong negative influence on merging ability, especially on the on-ramp. They are often unable to find a gap to merge into and are caught at the end of the merge area. Because of their length, vehicles following the HGV have less space for their lane change. This quickly leads to a blocked on-ramp, while the motorway is free flowing. To counter this, the portion of HGV is reduced to 1% for the on-ramp and 2.5% for the motorway. The reduced portion of HGV matches the behaviour that lorries try to avoid using the motorway during the peak hours.
Also the waiting time before a vehicle is removed of the network has been reduced to 30 s. This matches the behaviour that in reality a vehicle will not stand still at the end of the merge area, but will proceed unto the hard shoulder and merge into the traffic beyond the bottleneck. This reduction mainly targets HGV since only they are normally caught at the end of the merge area.
The default HGV vehicle model distribution consists of only one type of rigid non-articulated lorry. However, in The Netherlands both rigid and articulated lorries are common. The HGV vehicle model distribution is expanded with two types of articulated lorries, see Figure 7.7. The three HGV models have an equal portion within the HGV vehicle class.

Figure 7.7: Additional HGV models

Desired speeds
In Vissim, all vehicles receive a desired speed when they enter the network or pass a Desired Speed Decision (DSD). The desired speed for each vehicle is based on a random number and the selected default speed distribution for their vehicle type (car or HGV). All vehicles types entering the network at the on-ramp receive a desired speed according to the default speed distribution '50'. Cars entering the network at upstream end of the motorway receive a desired speed according to the default speed distribution '100', HGV according to the default speed distribution '85'. On the on-ramp several DSD's are passed. At the start of the on-ramp the cars pass either DSD 31 or 32, where speed distribution '90' is set for cars and speed distribution '70' for HGV. At start of the merge area all vehicles (originating from the on-ramp and the motorway) pass DSD 11, 12 or 13 speed distribution '100' is set for cars and speed distribution '85' for HGV.

Lane change behaviour
A large problem in the Vissim application is the unrealistic lane change and merging behaviour. Vehicles that need to merge accept only quite large gaps, and vehicles on the motorway do not create gaps for lane changing vehicles. Reduced merging leads to high speeds on the motorway and long queues on the on-ramp. This behaviour is opposite of the behaviour as observed on Dutch motorways. In reality drivers that need to merge into the motorway will temporarily accept smaller gaps and increase them once they have merged (gap acceptance), and drivers on the motorway will create gaps to allow vehicles to merge (cooperative braking).
Lane changes behaviour can be changed in Vissim in the vehicle behaviour menu, under the tab 'lane change'. A parameter that has a large influence on lane change is the gap acceptance. Smaller gap acceptance is achieved by lowering the *safety distance reduction factor*. This factor controls how much smaller a gap can be during a lane change compared to normal following behaviour. A factor of 0.02 (reduction of 98 %!) was found to give a reasonable result. This reduction only holds during lane change. Once the lane change has been completed, a vehicle will try to restore the normal follow distance.
The results of the qualitative lane change calibration are shown in
Table 7.3, listing all modified parameters with their final value.

Table 7.3: Lane change parameters

Parameter description	Own vehicle	Trailing vehicle
Maximum decelaration	-6.0 m/s^2	6.5 m/s^2
Increase of deceleration with -1 m/s^2 per distance to the end of the merge area	200 m	150 m
Accepted deceleration	-2.5 m/s^2	-2.5 m/s^2
Waiting time before removal	30 s	
Minimum distance between vehicles	1.5 m	
To slower lane if collision time is above	15 s	
Maximum deceleration for cooperative breaking	m/s^2	

Speed adaptation
In the course of this study it was discovered that a third factor influences the merge behaviour, especially around the transition from free flow to congestion. When congestion starts forming, the speed on the main motorway drops drastically. At this moment vehicles from the on-ramp still entered the merge area with a high speed, driving until the end of the on-ramp, stop, and failing to merge into the main flow from there. Without any merging taking place, the speed on the motorway increases again, preventing any further merging. Eventually the on-ramp was completely blocked, while the traffic on the motorway was flowing freely again. This problem appeared to be caused by the speed difference between the main motorway and the on-ramp. In reality, a driver can observe the traffic conditions on the motorway before entering the merge area. The driver can than adjust its speed to that on the motorway, and so more smoothly merge into the main flow. In the simulation a vehicle has no knowledge about the traffic state on the main motorway, until the vehicles enters a link that is part of the motorway. To counter this effect an extra desired speed decision (DSD 21) was placed just after the stop line. The desired speed distribution is adapted to the current traffic state using Matlab. Table 7.4 shows what default Vissim speed distribution is set for a certain measured speed. The boundaries for the measured speed are roughly equal to the maximum spread of the matching speed distribution. This completely resolved the observed merging problems.

Table 7.4: Speed distribution selection

Measured speed <	Measured speed >=	Speed distribution set
55	1	50
65	55	60
75	65	70
85	75	80
-	85	90

7.4 SRMA modifications

The SRMA implementation manual [X] specifies what changes have to be made to the SRMA for a certain specific on-ramp configuration. In this case there are two lanes on the motorway, two lanes on the on-ramp, and no separate bus lane. Also only one vehicle is allowed to pass per green phase per lane.

The existing DDE interface allows only the passing of occupancy information to the SRMA, not of speed information. The speed is required for running the control program. It is however possible pass speeds to traffic light controllers using the programming language CCOL. An existing CCOL controller was stripped and is used to retrieve the speeds. The Vialis interface allows communication between multiple controllers by the use of a virtual connector cable. This connector cable can only transmit ‘on’ and ‘off’. To pass the speed to the SRMA they are converted into a binary value in the CCOL controller, and back again to a decimal value in the SRMA. The files of the CCOL controller can be found on the CD belonging to this report.

The programming language in the SRMA is based on the C++ programming language. It is fairly easy to open the text-files created by Matlab, and to read the data into the appropriate SRMA parameter. Three parameters were updated this way; the motorway capacity, the flow threshold to activate metering, and the flow threshold to deactivate metering. During simulations using the ALINEA metering algorithm the cycle time was calculated outside of the SRMA and also updated using the text-files.
Some minor changes in the code of the SRMA enabled logging of various parameters. The files of the SRMA can be found on the CD belonging to this report.

7.4.1. SRMA calibration

Default parameter settings are used for all parameters in the SRMA. However, the parameters calculated in Matlab are updated accordingly once the SRMA is initiated.

7.5 Matlab coding

As mentioned in Section 7.1, Matlab functions as COM-client and Vissim as COM-server. The simulations are initiated and controlled from Matlab. A series of scripts has been written to accomplish these tasks. The Matlab code can be found on the CD belonging to this report. As part of this project a short manual has been written for the Matlab to Vissim COM-interface. This manual can be found in Appendix D.

RWS metering method
The RWS metering algorithm is already programmed in the SRMA. Because of this no additional scripting in Matlab is done.

ALINEA metering method
The cycle time for the ALINEA method is calculated in Matlab. This cycle time overrules the cycle time calculation in the SRMA.

AD-ALINEA metering method
Analogous to the ALINEA metering method, the cycle time for the AD-ALINEA method is calculated in Matlab. This cycle time overrules the cycle time calculation in the SRMA.

RWS – AD-ALINEA metering method
The RWS – AD-ALINEA metering method uses the standard AD-ALINEA estimator. The estimated capacity is used in the SRMA to calculate the cycle time.

Distribution Free Estimation Approach metering method
The DFEA estimator is based on a headway distribution estimation script designed and used in [32]. The estimation method uses vehicle headways. These are not available with the used COM-interface interval. Headway data are collected from the Data Collection raw data file. The estimated capacity is used to calculate the cycle time in the SRMA.

AD-RWS metering method

The AD-RWS estimator is based on the AD-ALINEA critical occupancy estimator, as described in Section 5.2. The estimated capacity is used to calculate the cycle time in the SRMA.

DACCORD Online metering method

The DACCORD Online estimator uses speeds and flows divided into classes based on vehicle length. Speeds divided by vehicle length class are not available through the COM-interface. Instead these data are gathered from the Data Collection raw data file. The estimated capacity is used to calculate the cycle time in the SRMA.

7.5.1. Matlab setup and calibration

Random seed

To simulate different days, each scenario was simulated ten times, each with a small variation. This variation is based on the random seed. Even though the specific order of the random seed does not affect the variance, it was chosen to spread the random seed using the following (arbitrary) formula:

$$randomseed_i = \left|15 \cdot i - 15^{0,2 \cdot i}\right|$$

where i is the simulation number for the specific scenario. The calculated random seeds for the simulation number (1 to 10) are listed in Table 7.5.

Table 7.5: Random seed calculation

i	1	2	3	4	5	6	7	8	9	10
Random seed	13	27	40	51	60	64	61	44	4	75

SRMA parameter calculation

Matlab writes three parameters to the text files; the capacity value for use in the RWS algorithm, the flow threshold for activation of the ramp meter, and the flow threshold for deactivation of the ramp meter. The value of the three parameters is calculated by multiplying the estimated capacity with a reduction factor. For the first parameter the reduction factor is 0.95. Metering toward a value slightly below the actual capacity keeps the traffic flow on the motorway in a more stable region. The reduction factor for the second parameter is 0.85, and for the third parameter 0.80.

Desired Speed Decision on-ramp

A Desired Speed Decision (DSD 21) is placed downstream of the stop line to improve merge behaviour during congestion. The control of this DSD is done in Matlab, based on the speed measured at a Data Collection Point upstream of the merge area, as discussed in Section 7.3.4.

7.5.2. Metering method setup

In this section some general features for the metering methods will be described.

RWS algorithm

In practice, the capacity value for the RWS metering algorithm is set below the known 'normal' motorway capacity for a ramp metering site, such as at 95% of that capacity. This safety factor is used in practice so that the ramp meter still functions under capacity variations.

The (implemented) capacity in the RWS algorithm is set to:

$q_{cap} = 0.95 \cdot 4800 = 4560$ vehicles per hour.

Since the capacity estimators should adapt to capacity variation, this safety factor is not used for capacities estimated by the capacity estimation methods.

ALINEA

The parameter Kr in the ALINEA metering algorithm has been set to Kr=70. This value is based on available literature.

Congestion threshold

Some metering algorithms and capacity estimators use a speed threshold to determine the occurrence of congestion. However, almost all studies mentioned a different value for the threshold (50/60/70/80 km/h). The optimal value has to be found from the data analyse, or the simulations.

Initial capacity

Each simulation the capacity was initialised at q_{cap} = 4800 veh/h, the critical occupancy at o_{cr} = 25%. The methods using the AD-ALINEA, the AD-RWS and the DACCORD Online capacity estimator require a lower initialization of q_{cap} and o_{cr}, as listed in Table 7.6. The DFEA and do not require a initialization of q_{cap} and $o_{cr.}$. The initialization values have been assessed from flow-occupancy diagrams, as seen in Figure 7.8.

Table 7.6: Initialisation value of capacity and/or critical occupancy

Metering method	Initial value
RWS	q_{cap} = 4560 veh/h
ALINEA	q_{cap} = 4800 veh/h; o_{cr} = 25%
AD-ALINEA	q_{cap} = 4400 veh/h; o_{cr} = 18%
AD-ALINEA with RWS algorithm	q_{cap} = 4400 veh/h; o_{cr} = 18%
Distribution Free Estimation Approach	-
AD-RWS	q_{cap} = 4400 veh/h; o_{cr} = 18%
DACCORD Online	q_{cap} = 4400 veh/h

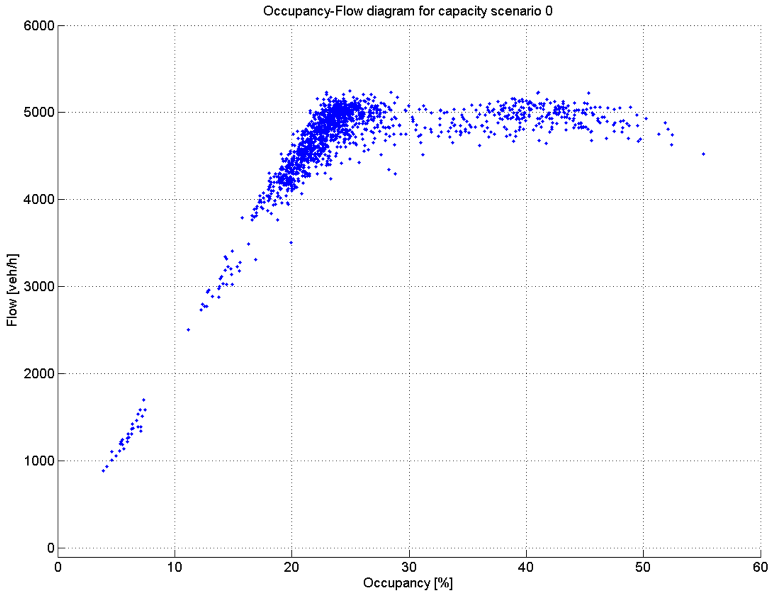


Figure 7.8: Flow-occupancy diagram of simulation results

All initial capacity values are below the maximum flow observed in Figure 7.8. This has a practical reason. By approaching the capacity from below it is prevented that traffic is congested before a capacity is estimated.

Estimation interval
All metering methods us an estimation interval of one minute, expect for AD-RWS. Tests showed that the estimation is smoother with an estimation interval of five minutes. The flow is averaged over 5 intervals, as is the occupancy.

The DFEA metering method has an estimation interval of one minute. However, to make an (plausible) estimate, more data is needed that can be gathered in one minute. Instead data is aggregated for a period of a half an hour, or 30 simulation intervals. From the first interval a variable Data is created which contains the headways collected each minute. After 30 intervals the first estimation is made. After that, estimations are made each minute using headway data collected during the previous 30 intervals. Headways more than 30 intervals old are discarded.

Detector location
Not all metering algorithms and capacity estimators can use the same detectors as the standard RWS algorithm. All ALINEA based metering algorithms and capacity estimators (ALINEA, AD-ALINEA, AD-RWS and RWS+AD-ALINEA) need a detector downstream of the on-ramp, near enough to on-ramp to measure the influence of it. Flow-occupancy plots indicate that the downstream detector measures only queue discharge rates. Instead the detector located at the merge area of the A12 case study is used (detector location km 133.2).

For the DACCORD Online and DFEA estimators the downstream motorway detectors have been used. These detectors observe only queue discharge rates. How this choice affect the estimation is unknown. Using the detector at the merge area as with the ALINEA based methods was difficult. The merge area has three lanes, the motorway section downstream of the merge area only two. This means that the detector at the merge area measures three lanes, while the capacity is estimated for a two-lane bottleneck. It was unknown how this would effect the estimation, and modifying both estimators is expected to take considerable time and effort.

8. Simulation results

In this section the simulations results will be presented. First the calculation methods for the performance indicators will be discussed. Next the behaviour of the estimators will be tested. Then the results will be presented for the various scenarios. Finally the results will be discussed. Based on the results a conclusion will be made in Section 9. Throughout this section the metering methods are abbreviated as follows:

R = RWS algorithm
AL = ALINEA algorithm
AD = ALINEA algorithm with AD-ALINEA estimator
RAD = RWS algorithm with AD-ALINEA estimator
DFEA = RWS algorithm with DFEA estimator
ADR = RWS algorithm with AD-RWS estimator
DAC = RWS algorithm with DACCORD Online estimator

8.1 Performance indicators

The performance indicators are described in more detail in Section 6.4. All metering methods were simulated ten times for each capacity reduction scenario, with a different random seed. The overall result will be expressed as the mean and the standard deviation of the ten separate results. All metering methods are compared for all performance criteria to the standard RWS metering algorithm. Their relative performance is expressed in a proportional gain or loss.

Capacity estimation

The capacities estimated over time during the simulations will be displayed in a time-capacity diagram for each section. The plotted estimates are the mean of the ten capacities estimated in the simulations, during that simulation interval. The overall mean capacity estimation made is the mean value of all capacity estimates made during all ten simulation runs. The same holds for the standard deviation.

The 'actual' motorway capacity is determined by using the non-parameterized Brilon PLM estimation method; see Figure 8.1. As described in Section 4.1.2, the Brilon version of the PLM is the most accurate method for estimating the free flow capacity. The PLM derives a cumulative probability distribution function (CDF). The 'actual' capacity mentioned in the text, and listed in Table 8.1, is the mean value of the cumulative distribution function.

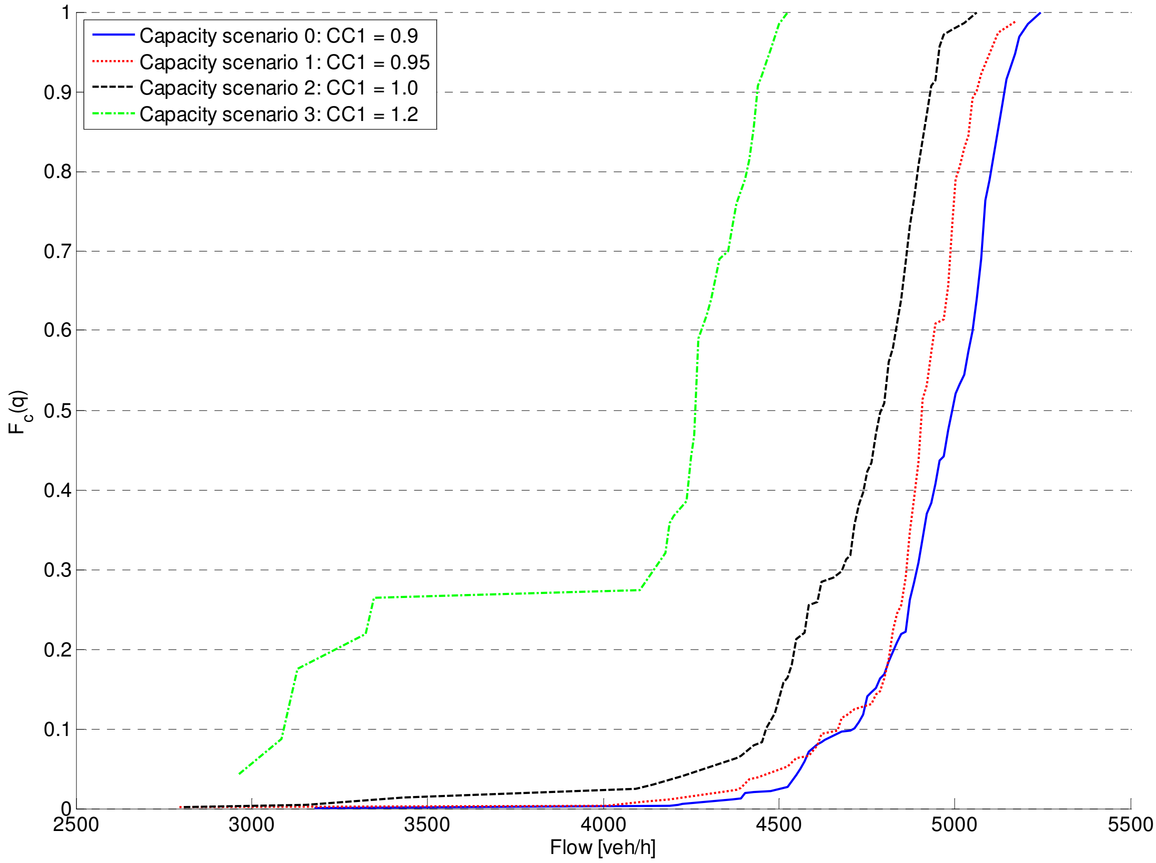


Figure 8.1: CDF of capacity scenarios

The CDF of capacity scenario 4 appears to be influenced by outliers, causing a strange shift in the CDF around Fc(q)= 0.28. Review of the data confirmed this. It is suspected that these outliers are caused by stop and go traffic inside a traffic jam. The outliers have been removed, and the mean capacity has been recalculated.

Table 8.1: Mean capacity calculated using Brilon PLM

Capacity scenario	*0*	*1*	*2*	*3*
Mean capacity [veh/h]	4960	4828	4726	4329
Mean capacity reduction [%]	-	2.67	4.72	12.73

Total vehicle delay

Delays can be determined using cumulative vehicle curves. This is a function that represents the amount of vehicles that has have pass a cross-section since the start of the measurement. For a road section an entering cumulative vehicle function *A(t)* and an exiting cumulative vehicle function *D(t)* can be constructed. If t_{empty} is the time that it takes a vehicle to cross the road section if it is empty, than for a situation with out delay the following is true:

$$t_{empty} = D^{-1}(t) - A^{-1}(t)$$

When delay does occur vehicles will take longer to pass the section of road. In Figure 8.2 the total delay is the area between the translated function $V(t) = A(t - t_{empty})$ and $D(t)$.

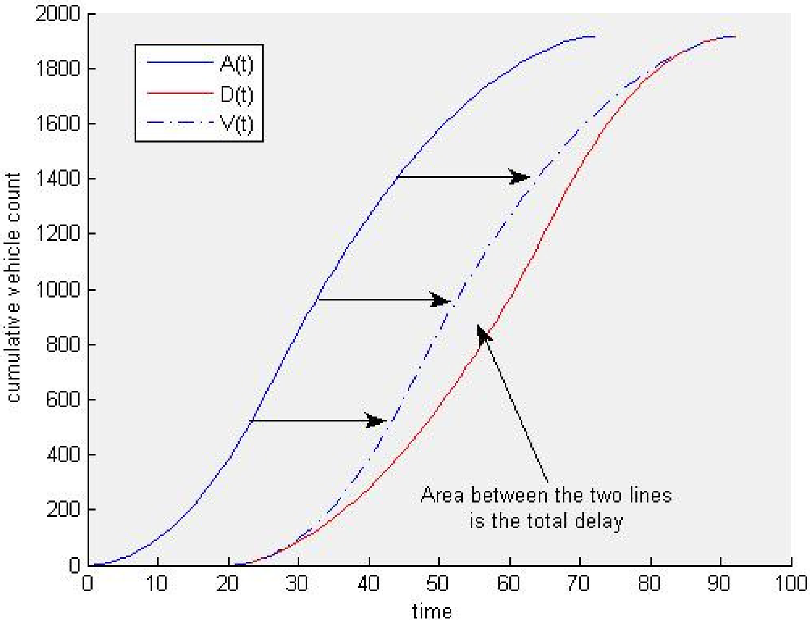


Figure 8.2: Delay calculation using cumulative vehicle curves

However, the simulations did not provide a reliable cumulative vehicle curve for vehicles entering the motorway. The congestion originating from the on-ramp reached the vehicle inputs several times. Vehicles that can not enter the network are 'stacked' outside the network until the can enter. The entering cumulative vehicle function A(t) can not be measured in this stack.
There was however detailed data available of the time that each vehicle left the network. This made it possible to compare the exit time for a vehicle for the various metering methods. In the context of this comparative study a relative performance is just as well as an absolute performance. The change of the individual delay can be calculated by subtracting the time $t_{i,method}$ that vehicle i leaves the network during the metering method $method$, from the time $t_{i,RWS}$ that the vehicle i left the network during the reference metering method RWS. By summing over all vehicles the change of the total delay δW is found, according to:

$$\delta W_{method} = \sum_{i=1}^{N} t_{i,RWS} - t_{i,method}$$

where N is the number of vehicles exiting the network in both simulations.

Congestion
A congested interval is defined as a 5 minute interval in which the average speed measured at the upstream motorway detector is below 70 km/h. This is similar to the definition that is used in the SRMA. Total duration of congestion is equal to the amount of congested interval

multiplied by the interval length. First occurrence of congestion is the first congested interval.

Queue detection
The SRMA produces log-files in which various variables and parameters are recorded, including the parameter *file_tr*. This parameter is used in the SRMA to activate and deactivate the queue detection override. The queue detection override is active during all intervals in which the parameter *file_tr* equals 1. Total duration queue detection equals the amount of intervals during which *file_tr* = 1, multiplied by the interval length. First activation queue detection is the first interval for which *file_tr* equals one. Number of queue detection periods is the number of intervals during which the current *va_doseren* equals one, and during the previous interval *file_tr* equals zero. Average duration of queue detection period duration is equal to the total time queue detection divided by the number of queue detection periods.

8.2 Results initial test runs

In this section results of some initial tests are described. During these tests the estimator were applied to scenarios 0 to 2. Based on the observations the experimental setup is modified.

Capacity estimation behaviour
The mean capacity estimates by various estimation methods are listed in

Table 8.2. The standard deviations are listed in Table 8.3. Figure 8.3 shows the mean capacity estimation during the simulations for capacity scenario 0.

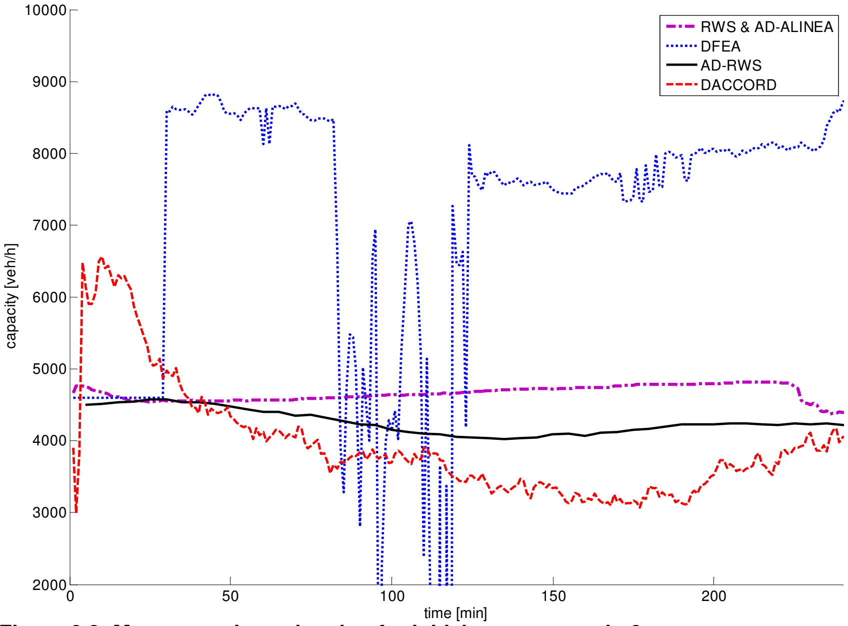


Figure 8.3: Mean capacity estimation for initial tests: scenario 2

Table 8.2: Mean capacity estimated during initial testing

Scenario	CC1	PLM	RAD	DFEA	ADR	DAC
0	0.9	4960	4824	7933	4567	4447
1	0.95	4828	4742	6674	4249	4054
2	1	4726	4657	6995	4266	4018

Table 8.3: Standard deviation of estimation during initial tests

Scenario	RAD	DFEA	ADR	DAC
0	405	11611	356	978
1	206	12380	658	1023
2	199	6774	448	1150

AD/RAD method
The estimations made by AD-ALINEA estimator seem to fit well to the capacity estimated by the PLM. Also the estimation seems to be stable during the simulation runs.

DFEA method
The DFEA method has a 30 minute data collection period before the first estimate is made. The capacity is overestimated even more than was expected based on Section 4.1.3. The DFEA method shows very unstable behaviour during congestion. The unstable behaviour might be prevented by not estimating the capacity during congestion. Unclear is how the underestimation can be resolved.

ADR method
The ADR method underestimates the motorway capacity. This is probably the result of conservative settings of the capacity update thresholds *Dmin'* and *Dplus'*. Improving the capacity estimation would require calibration of the capacity update thresholds.

DAC method
The DAC method is unstable in the initial half hour of the simulations. The method underestimates the capacity during most of the simulation. After minute 225 the behaviour appears to become more stable. The unstable behaviour in the first 10 minutes is likely to be the result of incomplete observations. The DAC method is based on flow, speed and occupancy observations of the previous ten minutes. These are not all available until ten minutes after the start of the simulation. It is unclear how long the effect of this initialisation error lasts. The initial instability could be resolved by holding back the estimation until ten observations are collected.

Conclusions
The application of the methods reveals that the DFEA, ADR and DAC estimation methods underestimate the capacity or are unstable. The RAD method seems to function well. The DAC method is expected to improve with some small modifications. The DFEA and ADR method will require more elaborate testing and development. These method will not be improved, as there is only limited time available. Their results will be discarded.

8.3 Results capacity scenario 0

In this section the results of the capacity reduction scenario 0 will be presented. First the behaviour of the estimators is discussed shortly. Next the results of the various performance indicators are given.

Capacity estimation behaviour
The capacity estimates by the various metering methods are plotted in Figure 8.4 and listed in Table 8.4.

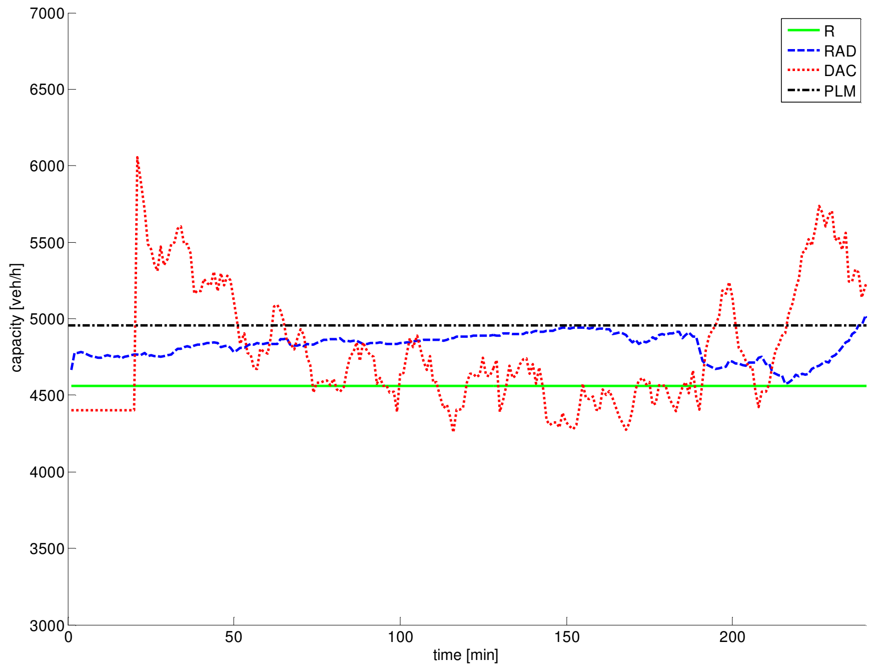


Figure 8.4: Mean capacity estimation: scenario 0

During the first 20 minutes the DAC method does not make an estimation, it only collects data. After 20 minutes, the initial estimation is high, but it is lowered quite rapidly. The estimation is somewhat unstable. Towards the end of the simulation period the estimation goes up again. The RAD method is more stable. Similar to the DAC method, the behaviour towards the end of the simulation becomes more instable. The motorway capacity for capacity scenario 0 is estimated at **4960** is vehicles per hour, using the Brilon PLM. The complete CDF for this scenario is plotted in Figure 8.1. Table 8.4 shows that the mean estimation by the RAD method is close to the actual motorway capacity, and has a limited variance.

Table 8.4: Mean and std-dev of estimations: scenario 0

	R	*RAD*	*DFEA*	*ADR*	*DAC*
Capacity	4560	4859	-	-	4539
std-dev	0	408	-	-	1398

Total delay
In Figure 8.5 a distinction has been made between the delay for vehicles originating from the on-ramp and from the upstream motorway section.

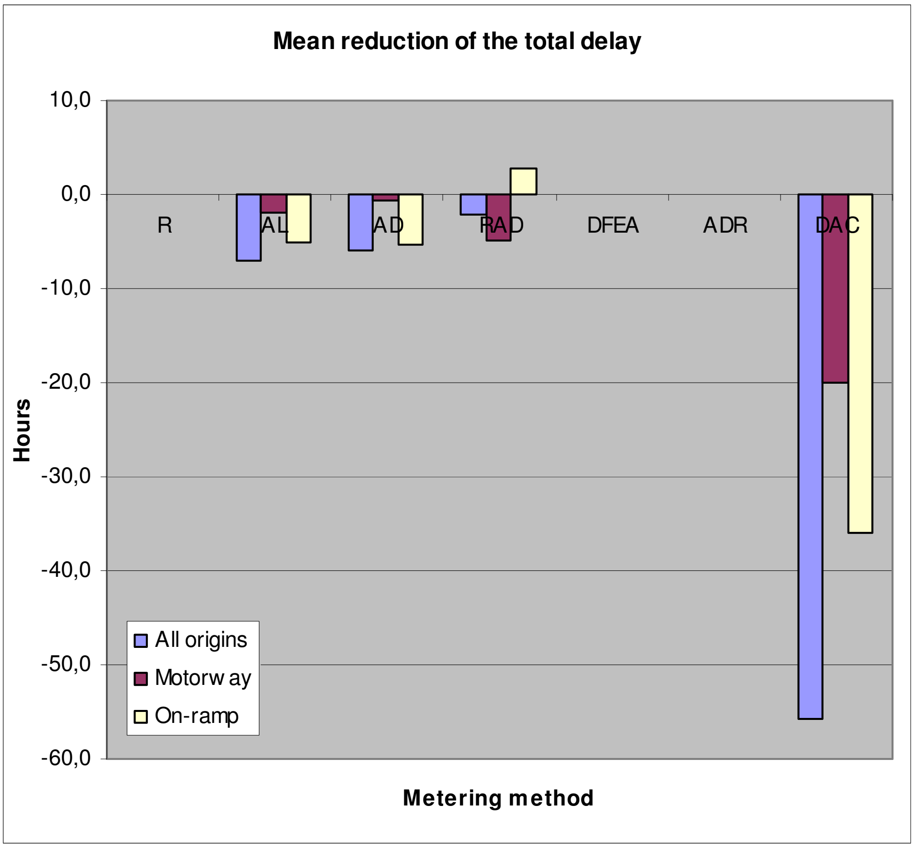


Figure 8.5: Mean reduction total delay: scenario 0

Figure 8.5 shows that no method is able to reduce the total delay. The RAD method is able to reduce the delay from the on-ramp. However this results in a larger increase of the delay on the motorway. The higher capacity estimated by the RAD method results in a higher metering rate.

Table 8.5 shows that the AL, AD and RAD methods have rather large standard deviations, relative to the reduction in the delay. This shows that there also have been positive results in individual simulations.

Table 8.5: Reduction of total delay in hours: scenario 0

	R	*AL*	*AD*	*RAD*	*DFEA*	*ADR*	*DAC*
All	**0.0**	**-6.9**	**-5.9**	**-2.2**	**-**	**-**	**-55.8**
std-dev	0.0	25.8	33.2	20.5	-	-	28.8
Motorway	**0.0**	**-1.8**	**-0.6**	**-4.9**	**-**	**-**	**-19.9**
std-dev	0.0	17.0	21.4	15.6	-	-	24.9
On-ramp	**0.0**	**-5.1**	**-5.3**	**2.7**	**-**	**-**	**-35.9**
std-dev	0.0	11.0	13.7	10.9	-	-	15.8

Congestion
The total duration of congestion is only reduced by the AL method. The AD method is able to postpone the first occurrence of congestion.

Table 8.6: Start and duration of congestion: scenario 0

	Mean duration [min]	Std-dev [min]	Change [%]	**Start time [min]**	Std-dev [min]	Change [%]
R	**45.0**	26.0	-	**86.5**	11.6	-
AL	**44.0**	22.0	-2.2	**82.0**	11.9	-5.2
AD	**47.5**	32.0	5.6	**93.0**	16.9	7.5
RAD	**53.5**	29.2	18.9	**86.0**	11.6	-0.6
DFEA	**-**	-	-	**-**	-	-
ADR	**-**	-	-	**-**	-	-
DAC	**53.5**	26.8	18.9	**84.0**	8.1	-2.9

Queue detection

The RAD method results in the biggest reduction of queue detection, and latest activation. The AL method results in the fewest queue detections. The RAD method results in the shortest queue detection period.

Table 8.7: Start and duration of queue detection: scenario 0

	Mean duration [min]	Std-dev [min]	Change [%]	**Start time [min]**	Std-dev [min]	Change [%]
R	**41.2**	27.7	-	**91.8**	13.7	-
AL	**43.1**	27.1	4.6	**88.0**	14.9	-4.1
AD	**46.4**	28.1	12.7	**93.3**	16.8	1.7
RAD	**35.9**	25.3	-12.9	**96.4**	14.0	5.0
DFEA	**-**	-	-	**-**	-	-
ADR	**-**	-	-	**-**	-	-
DAC	**67.5**	18.3	63.8	**7.4**	1.2	-91.9

Table 8.8: Number and duration of queue detection periods: scenario 0

	Number detection periods	Std-dev [min]	Change [%]	**Duration detection period [min]**	Std-dev [min]	Change [%]
R	**4.3**	2.1	-	**11.3**	13.2	-
AL	**4.2**	2.3	-2.3	**12.1**	11.8	7.2
AD	**4.7**	3.0	8.5	**13.3**	13.3	17.5
RAD	**5.0**	1.7	16.3	**7.2**	4.5	-36.8
DFEA	**-**	-	-	**-**	-	-
ADR	**-**	-	-	**-**	-	-
DAC	**11.8**	2.1	174.4	**5.9**	2.0	-47.7

Overall

The RAD method makes a good estimation of the capacity, but performs not much better then the RWS metering algorithm.

8.4 Results capacity scenario 1

In this section the results of the capacity scenario 1 are presented. First the behaviour of the estimators is discussed shortly. Next the results of the various performance indicators are given.

Capacity estimation behaviour

The capacity estimates by the various metering methods are plotted in Figure 8.6 and listed in Table 8.9.

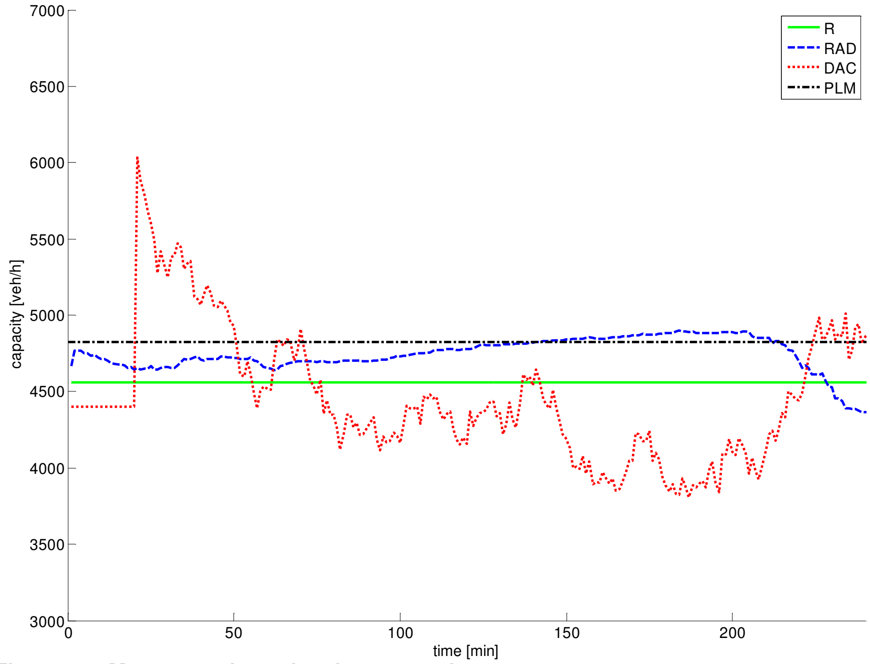


Figure 8.6: Mean capacity estimation: scenario 1

The motorway capacity for capacity scenario 1 is estimated at **4827** vehicles per hour, estimated using the Brilon PLM. The complete CDF for this scenario is plotted in Figure 8.1. During the first 20 minutes the DAC method does not make estimations, it only collects data. After 20 minutes, the initial estimation is high, but it is lowered quite rapidly. The estimation is somewhat unstable. The RAD method seems to be stable, and has a higher estimate then the R method during the whole simulation. Similar to the DAC method, the behaviour towards the end of the simulation becomes more instable, probably due to low traffic flow. Table 8.9 shows that the mean estimation by the RAD method is close to the actual motorway capacity, and has a limited variance.

Table 8.9: Mean and std-dev of estimations: scenario 1

	R	AL	AD	RAD	DFEA	ADR	DAC
Capacity	4560	-	-	4747	-	-	4203
std-dev	0	-	-	187	-	-	1314

Total delay

In Figure 8.7 a distinction has been made between vehicles originating from the on-ramp and from the upstream motorway section.

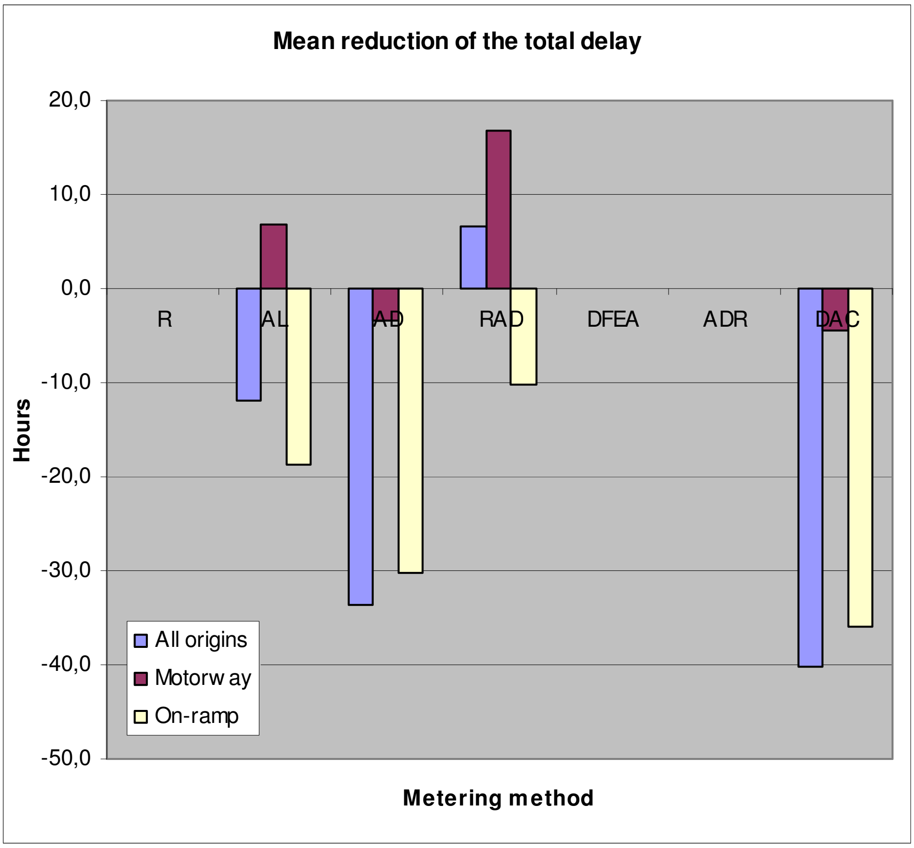


Figure 8.7: Mean reduction of total delay: scenario 1

Figure 8.7 shows that the RAD method is able to reduce the total delay. However, the delay for vehicles coming from the on-ramp is increased. It is suspected that the higher capacity estimate causes the queue detection to be less active, leading to longer delays on the on-ramp.

Table 8.10: Reduction of total delay: scenario 1

	R	*AL*	*AD*	*RAD*	*DFEA*	*ADR*	*DAC*
All	**0.0**	**-11.8**	**-33.6**	**6.7**	**0.0**	**0.0**	**-40.3**
std-dev	0.0	58.4	75.9	66.7	0.0	0.0	64.4
Motorway	**0.0**	**6.9**	**-3.3**	**16.9**	**0.0**	**0.0**	**-4.4**
std-dev	0.0	42.1	53.3	48.2	0.0	0.0	47.8
On-ramp	**0.0**	**-18.7**	**-30.3**	**-10.2**	**0.0**	**0.0**	**-35.9**
std-dev	0.0	20.3	25.4	23.4	0.0	0.0	19.5

Congestion

The AD method leads to a reduction in the congestion duration. The occupancy-based methods are able to postpone occurrence of congestion most.

Table 8.11: Start and duration of congestion: scenario 1

	Mean duration [min]	Std-dev [min]	Change [%]	**Start time [min]**	Std-dev [min]	Change [%]
R	**116.5**	20.5	-	**72.0**	11.3	-
AL	**117.0**	14.9	0.4	**79.0**	9.5	9.7
AD	**115.0**	17.3	-1.3	**79.0**	9.5	9.7
RAD	**117.0**	15.5	0.4	**74.5**	9.0	3.5
DFEA	**-**	-	-	**-**	-	-
ADR	**-**	-	-	**-**	-	-
DAC	**115.0**	18.4	-1.3	**72.0**	9.9	0.0

Queue detection

The RAD method results in the biggest reduction in total queue detection duration. This method is also able to postpone first queue detection. The AL, AD and RAD methods realize an increase in the average duration of queue detection periods. This indicates that on average the queue detection was activated during periods with a high inflow on the on-ramp.

Table 8.12: Start and duration of queue detection: scenario 1

	Mean duration [min]	Std-dev [min]	Change [%]	**Start time [min]**	Std-dev [min]	Change [%]
R	**89.4**	10.7	-	**81.5**	11.8	-
AL	**90.5**	11.8	1.2	**81.6**	13.1	0.1
AD	**101.2**	13.7	13.2	**75.0**	11.7	-8.0
RAD	**76.3**	12.8	-14.7	**84.7**	10.6	3.9
DFEA	**-**	-	-	**-**	-	-
ADR	**-**	-	-	**-**	-	-
DAC	**108.3**	13.4	21.1	**7.4**	1.0	-90.9

Table 8.13: Number and duration of queue detection periods:scenario 1

	Number detection periods	Std-dev [min]	Change [%]	**Duration detection period [min]**	Std-dev [min]	Change [%]
R	**11.0**	1.7	-	**8.3**	1.5	-
AL	**8.9**	2.5	-19.1	**11.0**	3.4	32.8
AD	**11.2**	3.5	1.8	**10.3**	4.4	23.7
RAD	**9.2**	3.7	-16.4	**10.5**	6.3	26.5
DFEA	**-**	-	-	**-**	-	-
ADR	**-**	-	-	**-**	-	-
DAC	**14.4**	2.9	30.9	**8.0**	2.4	-4.1

Overall

The RAD method is able to reduce the total delay. The estimation is stable, and close to the motorway capacity determined by the PLM.

8.5 Results capacity scenario 2

In this section the results of the capacity reduction scenario 1 are presented. First the behaviour of the estimators is discussed shortly. Next the results of the various performance indicators are given.

Capacity estimation behaviour
The capacity estimates by the various metering methods are plotted in Figure 8.8 and listed in Table 8.14.

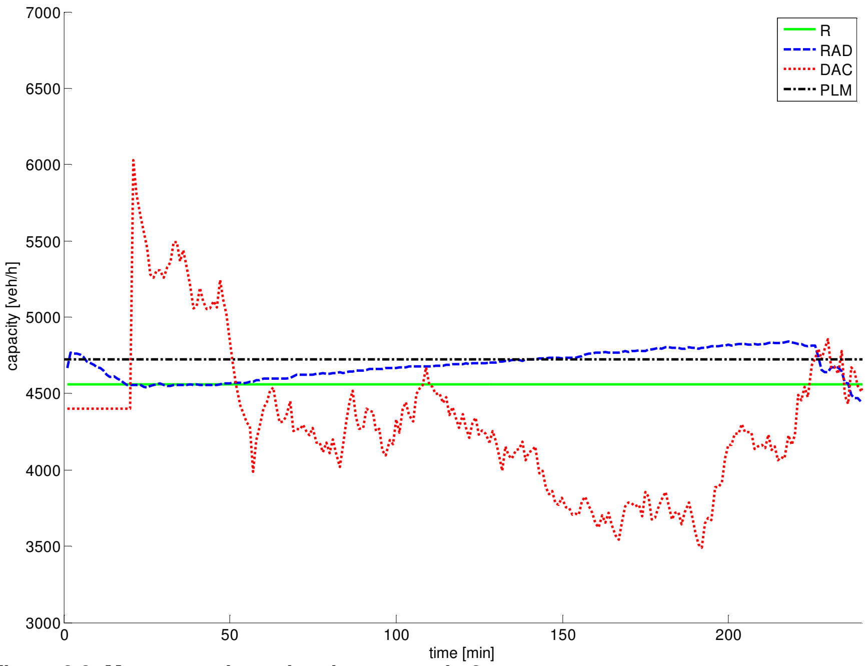


Figure 8.8: Mean capacity estimation: scenario 2

The mean capacity estimated for the capacity of reduction scenario 2 using the non-parameterized Brilon PLM estimation method is **4725** vehicles per hour. Table 8.14 shows that the DAC method on average underestimates the capacity. No estimation is made during the initial 20 simulation minutes. The first estimation is high. Towards the end the capacity seems to be approached. During the simulation the RAD method slowly approaches the mean capacity estimated by the PLM.

Table 8.14: Mean and std-dev of estimations: scenario 2

	R	*AL*	*AD*	*RAD*	*DFEA*	*ADR*	*DAC*
Capacity	4560	-	-	4678	-	-	4095
std-dev	0	-	-	199	-	-	1150

Total delay
A distinction has been made between vehicles originating from the on-ramp and from the upstream motorway section.

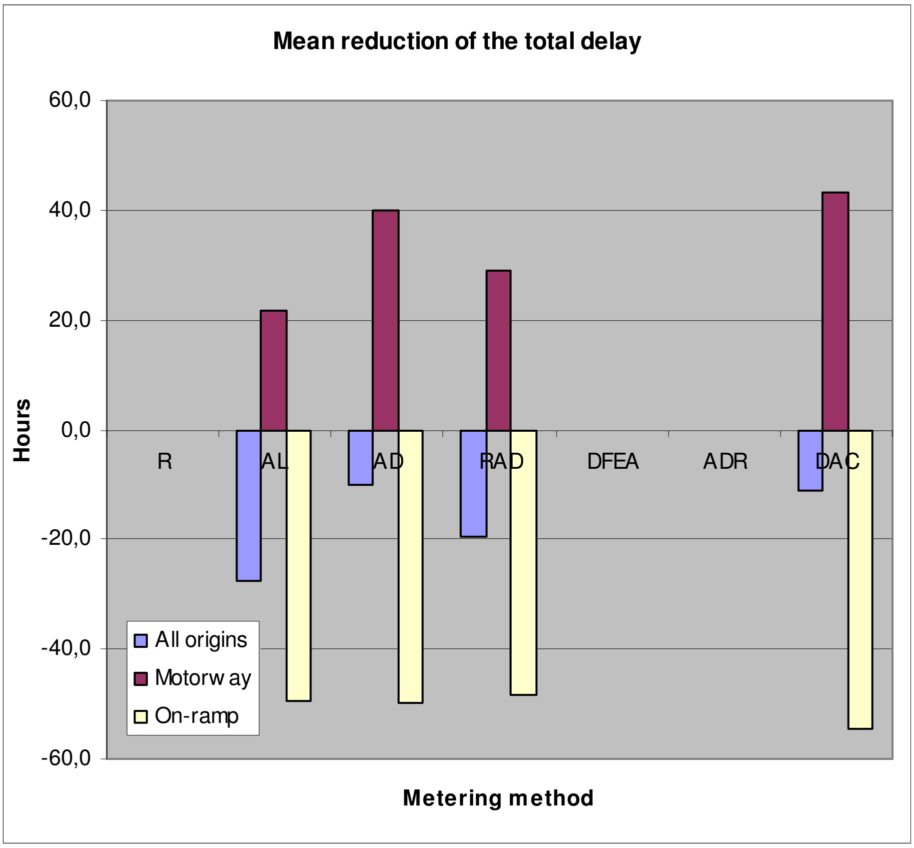


Figure 8.9: Mean reduction of total delay: scenario 2

Figure 8.9 shows that no method is able to achieve a reduction of the total delay. They however all reduce the delay on the motorway. This indicates that they reduce congestion. The increase of the delay on the on-ramp is probably the result of less queue detection. The DAC method seems to perform best, even though it showed unstable estimation behaviour.

The AD method performs better then the RAD method, even though these methods use the same estimator. This confirms the assumption in Section 5.2 that the AD-ALINEA estimator is tuned for use with the ALINEA metering algorithm, and that the AD-ALINEA estimator would perform worse with the RWS algorithm.

Table 8.15: Reduction of total delay: scenario 2

	R	*AL*	*AD*	*RAD*	*DFEA*	*ADR*	*DAC*
All	**0.0**	**-27.6**	**-9.9**	**-19.3**	**-**	**-**	**-11.3**
std-dev	0.0	27.5	35.2	53.7	-	-	29.6
Motorway	**0.0**	**21.7**	**40.0**	**28.9**	**-**	**-**	**43.2**
std-dev	0.0	28.0	31.1	41.9	-	-	26.3
On-ramp	**0.0**	**-49.3**	**-49.9**	**-48.2**	**-**	**-**	**-54.4**
std-dev	0.0	10.8	9.1	16.6	-	-	10.1

Congestion
The AL method is able to reduce total congestion duration. Congestion was not postponed any more then with the reference R method.

Table 8.16: Start and duration of congestion: scenario 2

	Mean duration [min]	Std-dev [min]	Change [%]	**Start time [min]**	Std-dev [min]	Change [%]
R	**146.0**	10.4	-	**63.5**	8.9	-
AL	**144.0**	11.4	-1.4	**62.5**	8.7	-1.6
AD	**148.0**	7.8	1.4	**63.5**	8.9	0.0
RAD	**153.0**	7.1	4.8	**62.0**	.85	-2.4
DFEA	**-**	-	-	**-**	-	-
ADR	**-**	-	-	**-**	-	-
DAC	**145.5**	12.3	-0.3	**58.0**	13.1	-8.7

Queue detection

The RAD method is able to postpone queue detection activation, and has the shortest total queue detection duration. This indicates that queues do not form as quickly as with other methods. All methods have a longer average queue detection period duration. This indicates that the queue detection is only activated during periods with a high on-ramp flow.

Table 8.17: Start and duration of queue detection: scenario 2

	Mean duration [min]	Std-dev [min]	Change [%]	**Start time [min]**	Std-dev [min]	Change [%]
R	**103.2**	8.6	-	**68.8**	6.7	-
AL	**109.9**	11.4	6.5	**67.2**	5.9	-2.3
AD	**110.2**	37.4	6.8	**66.0**	10.3	-4.1
RAD	**93.7**	9.6	-9.2	**70.8**	6.8	2.9
DFEA	**-**	-	-	**-**	-	-
ADR	**-**	-	-	**-**	-	-
DAC	**119.5**	-9.2	15.8	**7.4**	1.0	-89.2

Table 8.18: Number and duration of queue detection periods:scenario 2

	Number detection periods	Std-dev [min]	Change [%]	**Duration detection period [min]**	Std-dev [min]	Change [%]
R	**13.8**	2.7	-	**7.9**	2.2	-
AL	**10.2**	2.5	-26.1	**11.7**	3.9	47.4
AD	**11.4**	4.3	-17.4	**9.7**	4.2	22.8
RAD	**10.6**	3.2	-23.5	**10.4**	4.9	31.1
DFEA	**-**	-	-	**-**	-	-
ADR	**-**	-	-	**-**	-	-
DAC	**14.7**	3.4	6.5	**8.8**	3.1	11.5

Overall

The RAD method makes an estimation close the ‘actual’ motorway capacity. However the AD method, which uses the same estimator, has a better result. The unstable DAC method has the best result.

8.6 Results capacity scenario 3

In this section the results of the capacity reduction scenario 1 are presented. First the behaviour of the estimators is discussed shortly. Next the results of the various performance indicators are given.

Capacity estimation behaviour

The capacity estimates by the various metering methods are plotted in Figure 8.10 and listed in Table 8.14.

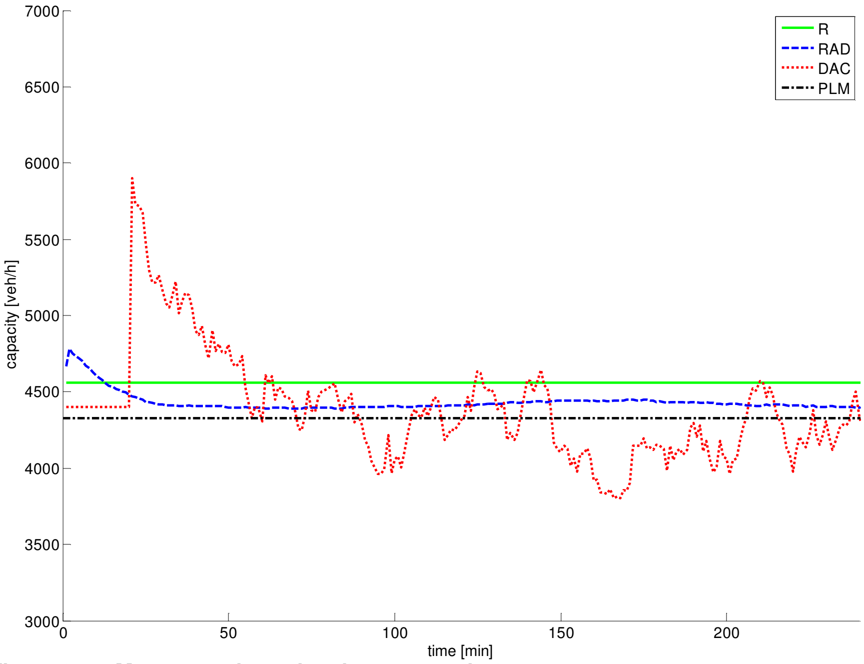


Figure 8.10: Mean capacity estimations: scenario 3

The mean capacity estimated for the capacity of reduction scenario 3 using the non-parameterized Brilon PLM estimation method is **4328** vehicles per hour. Table 8.19 shows that the all estimations, on average, were above the actual capacity. During the simulation, the DAC method on occasion is below it. The initial estimation of the DAC method is high, but for the rest of the simulation the estimation is reasonable.

Table 8.19: Mean and std-dev of estimations: scenario 3

	R	AL	AD	RAD	DFEA	ADR	DAC
Capacity	4560	-	-	4411	-	-	4440
std-dev	0	-	-	173	-	-	797

Total delay

Figure 8.9 shows that the AD method is able to reduce the total delay. All methods reduce the delay on the motorway, while increasing the delay on the on-ramp. Again the performance of the RAD method is lower than the AD method, even if they are using the same estimator. The DAC method also performs somewhat better then the RAD method. Table 8.20 shows that the non adaptive AL method performs comparable to the adaptive methods. This indicates that in the simulation changing the desired headway time CC1 has more effect on the capacity than on the critical occupancy.

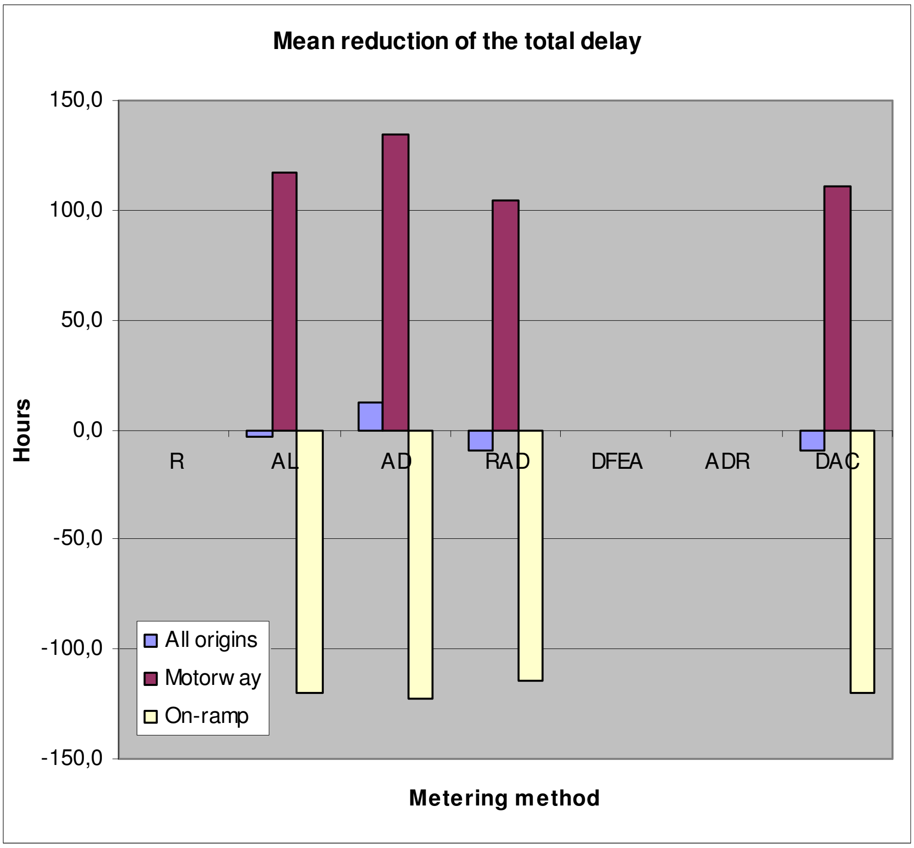


Figure 8.11: Mean reduction of total delay: scenario 3

Table 8.20: Reduction of total delay: scenario 3

	R	*AL*	*AD*	*RAD*	*DFEA*	*ADR*	*DAC*
All	**0.0**	**-3.3**	**11.9**	**-9.5**	**0.0**	**0.0**	**-9.5**
std-dev	0.0	31.7	51.5	22.7	0.0	0.0	49.1
Motorway	**0.0**	**116.9**	**134.2**	**104.8**	**0.0**	**0.0**	**110.5**
std-dev	0.0	20.0	36.3	16.8	0.0	0.0	33.3
On-ramp	**0.0**	**-120.2**	**-122.4**	**-114.4**	**0.0**	**0.0**	**-120.1**
std-dev	0.0	13.9	16.2	8.8	0.0	0.0	16.9

Congestion
The AL method is able to reduce total congestion duration most; next is the RAD method. The occurrence of congestion was postponed only by the AD method. Noticeable is that the start time of almost all the methods is the same.

Table 8.21: Start and duration of congestion: scenario 3

	Mean duration [min]	Std-dev [min]	Change [%]	**Start time [min]**	Std-dev [min]	Change [%]
R	**209.0**	16.2	-	**20.0**	6.0	-
AL	**214.5**	6.5	2.6	**20.0**	6.0	0.0
AD	**204.5**	9.3	-2.2	**26.0**	8.7	30.0

RAD	**211.5**	13.6	1.2	**20.0**	6.0	0.0
DFEA	**-**	-	-	**-**	-	-
ADR	**-**	-	-	**-**	-	-
DAC	**210.5**	9.9	0.7	**20.0**	6.0	0.0

Queue detection
The AL and AD methods result in the longest total queue detection duration. None of the methods can reduce the total queue detection duration. Since all methods estimate a value below the capacity used in the R method, the queue detection is activated sooner and longer.

Table 8.22: Start and duration of queue detection: scenario 3

	Mean duration [min]	Std-dev [min]	Change [%]	**Start time [min]**	Std-dev [min]	Change [%]
R	**100.7**	16.3	-	**62.4**	8.3	-
AL	**131.3**	13.7	30.4	**39.1**	3.0	-37.3
AD	**150.4**	9.2	49.4	**24.3**	7.8	-61.1
RAD	**103.5**	11.8	2.8	**50.3**	8.4	-19.4
DFEA	**-**	-	-	**-**	-	-
ADR	**-**	-	-	**-**	-	-
DAC	**114.7**	11.3	13.9	**51.7**	12.3	-17.1

Table 8.23: Number and duration of queue detection periods:scenario 3

	Number detection periods	Std-dev [min]	Change [%]	**Duration detection period [min]**	Std-dev [min]	Change [%]
R	**11.9**	3.0	-	**9.0**	2.8	-
AL	**14.6**	1.7	22.7	**9.1**	1.3	0.7
AD	**18.6**	2.2	56.3	**8.3**	1.6	-8.6
RAD	**13.5**	4.7	13.4	**8.7**	3.2	-3.5
DFEA	**-**	-	-	**-**	-	-
ADR	**-**	-	-	**-**	-	-
DAC	**13.9**	2.7	16.8	**8.6**	2.1	-4.4

Overall
The AD method performs best. Even though the DAC method shows more unstable behaviour, it performs better then the RAD method.

8.7 Results capacity scenario 4: Capacity variation

In this section the results of the capacity scenario 4 are presented. In this scenario the value of CC1, and therefore the capacity, is varied during the simulation. The changes in CC1 and the resulting capacities are listed in Table 8.24. The values of the mean capacities have been taken from scenario 1 and 3, and plotted in Figure 8.12.

Table 8.24: Changes in CC1 and the capacity during scenario 4

Simulation minute	**CC1 [s]**	**Mean capacity [veh/h]**
0 – 75	0.95	4827
75 – 165	1.2	4328

165 – 240	0.95	4827

In this section the results of the simulations will be discussed. First the behaviour of the capacity estimators is reviewed. Next the performance indicators are listed separately.

Capacity estimation behaviour

The capacity estimates by the various metering methods are plotted in Figure 8.12.

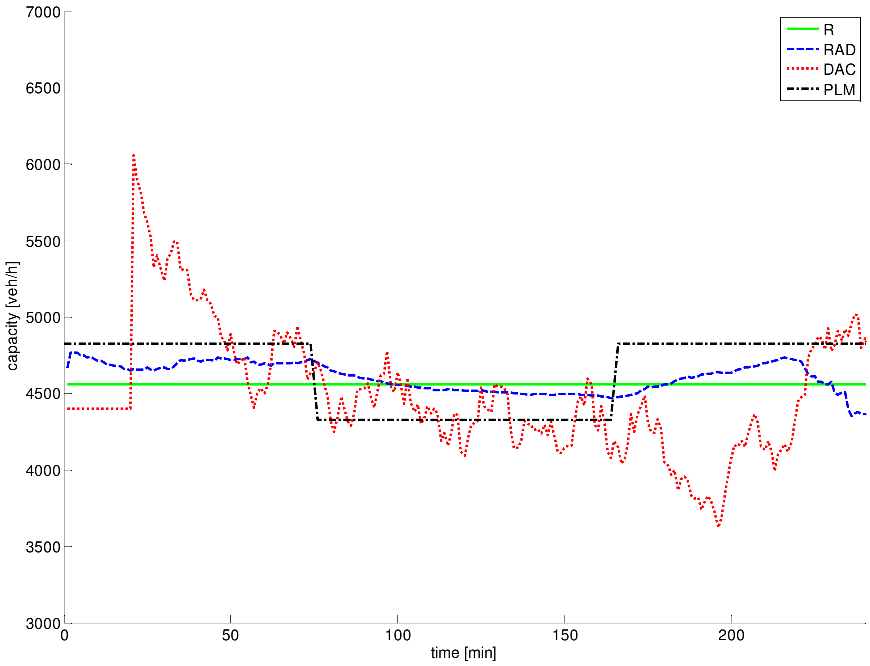


Figure 8.12: Mean capacity estimation: scenario 4

During the first 75 minutes CC1, and therefore the capacity, is equal to capacity scenario 1. From minute 75 to 165 CC1, and again also the capacity, is changed to the value of Capacity Scenario 3. After minute 165 CC1 is returned to the initial setting. The resulting capacity pattern can be seen in Figure 8.12.

The RAD method responds immediately to the capacity change. However the capacity estimation is lowered quite slowly. As the capacity is raised again the capacity estimation goes up again. Towards the end of the simulation period the estimation drops for unknown reasons. It is suspected that it is caused by low flows.

The DAC method behaves unstable. It might respond to the capacity reduction; however the unstable estimation behaviour make it difficult to tell. Toward the end of the simulation period the DAC method seems to become more stable.

Total delay

All methods reduce the delay on the motorway, and increase the delay on the on-ramp; as can be see in Figure 8.13. The AL method is the only one that is able to reduce the total delay. The increase of the delay on the on-ramp is suspected to be caused by a reduction in queue detection activity. The AD method performs better then the RAD method, even though these methods use the same estimator. This confirms the assumption in Section 5.2 that the AD-ALINEA estimator is tuned for use with the ALINEA metering algorithm, and that the combination of the AD-ALINEA estimator with the RWS algorithm would perform worse.

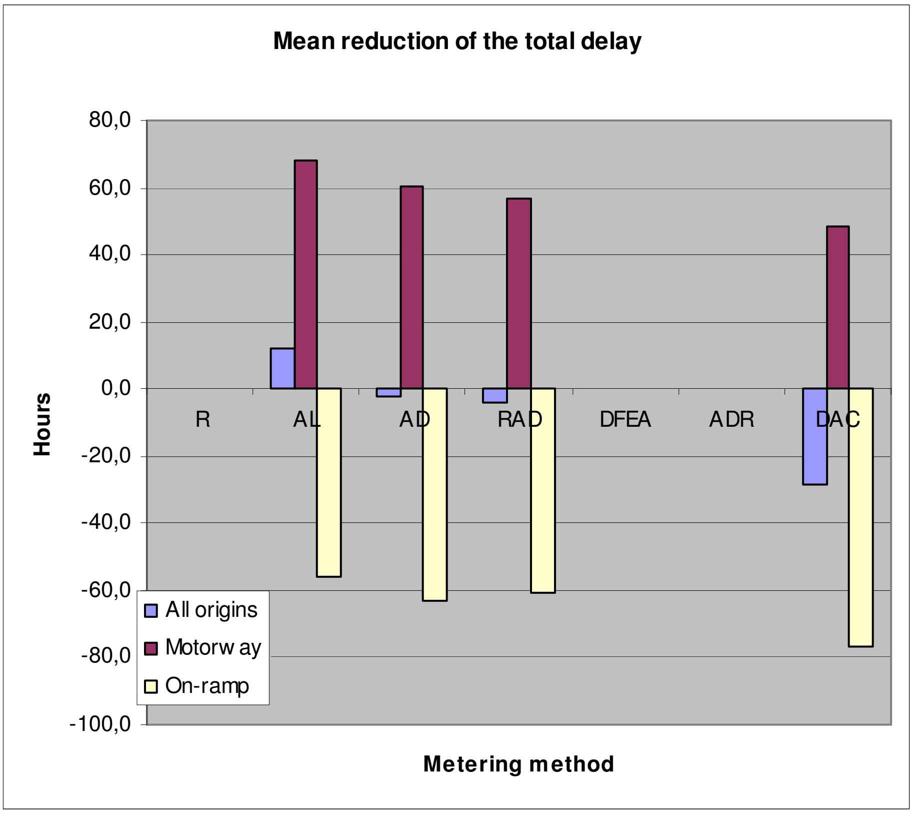


Figure 8.13: Mean reduction of total delay: scenario 4

Table 8.25: Reduction of total delay: scenario 4

	R	*AL*	*AD*	*RAD*	*DFEA*	*ADR*	*DAC*
All	**0.0**	**12.2**	**-2.4**	**-4.3**	**-**	**-**	**-28.3**
std-dev	0.0	43.1	38.1	39.8	-	-	33.6
Motorway	**0.0**	**68.1**	**60.5**	**56.6**	**-**	**-**	**48.2**
std-dev	0.0	35.0	30.6	31.8	-	-	26.0
On-ramp	**0.0**	**-56.0**	**-62.9**	**-60.9**	**-**	**-**	**-76.5**
std-dev	0.0	11.2	10.7	9.5	-	-	10.7

Congestion

The AD method is able to reduce total congestion duration. The first occurrence of congestion was postponed most also by the AD method.

Table 8.26: Start and duration of congestion: scenario 4

	Mean duration [min]	Std-dev [min]	Change [%]	**Start time [min]**	Std-dev [min]	Change [%]
R	**133.0**	9.5	-	**70.5**	8.4	-
AL	**134.0**	8.9	0.8	**73.0**	4.2	3.5

AD	**126.5**	16.3	-4.9	**76.5**	7.3	8.5
RAD	**134.0**	14.6	0.8	**71.0**	7.4	0.7
DFEA	**-**	-	-	**-**	-	-
ADR	**-**	-	-	**-**	-	-
DAC	**136.0**	16.4	2.3	**69.5**	10.0	1.4

Queue detection
Total queue detection activity is shortest with the RAD method, and it also postpones the activation of the queue detection. The AD method has the longest queue detection period. All methods have a longer average queue detection period duration. This indicates that the queue detection is only activated during periods with a high on-ramp flow. The very early start of queue detection using the DAC method indicates that the initial capacity value is too low.

Table 8.27: Start and duration of queue detection: scenario 4

	Mean duration [min]	Std-dev [min]	Change [%]	**Start time [min]**	Std-dev [min]	Change [%]
R	**93.8**	7.9	-	**75.0**	6.3	-
AL	**101.4**	9.4	8.1	**76.0**	10.5	1.3
AD	**113.8**	6.8	21.3	**72.7**	8.5	-3.1
RAD	**92.7**	13.4	-1.2	**79.1**	4.8	5.5
DFEA	**-**	-	-	**-**	-	-
ADR	**-**	-	-	**-**	-	-
DAC	**103.3**	24.6	10.1	**7.4**	1.0	90.1

Table 8.28: Number and duration of queue detection periods:scenario 4

	Number detection periods	Std-dev [min]	Change [%]	**Duration detection period [min]**	Std-dev [min]	Change [%]
R	**10.8**	3.2	-	**9.9**	4.1	-
AL	**9.6**	2.7	-11.1	**11.6**	4.1	18.0
AD	**10.5**	2.1	-2.8	**11.3**	2.4	14.6
RAD	**10.5**	3.5	-2.8	**10.0**	3.9	1.3
DFEA	**-**	-	-	**-**	-	-
ADR	**-**	-	-	**-**	-	-
DAC	**14.7**	3.2	36.1	**7.2**	2.0	-26.8

Overall
All methods perform better then the reference method. The AL method reduces the total delay.

8.8 Discussion

In this section the results displayed in the previous sections will be reviewed and discussed. The outcome of this discussion is used for the formulation of the conclusion in the next section. Throughout this section the metering methods are abbreviated as follows:

R = RWS algorithm
AL = ALINEA algorithm
AD = ALINEA algorithm with AD-ALINEA estimator

RAD = RWS algorithm with AD-ALINEA estimator
DFEA = RWS algorithm with DFEA estimator
ADR = RWS algorithm with AD-RWS estimator
DAC = RWS algorithm with DACCORD Online estimator

Capacity estimation
The RAD method shows very stable estimation behaviour, close to the mean capacity determined by the PLM. Towards the end of the simulations the estimation becomes less stable. During capacity scenario 4, the RAD method reacts immediately to the change in capacity. The change in the estimation during scenario 4 is slow. The DAC method shows less stable behaviour. This might be caused by the downstream bottleneck at the on-ramp. Because of this behaviour it is not clear if the DAC method reacts to the capacity changes. On average it underestimates the motorway capacity.

Total delay
The total delay is reduced in very few occasions. In scenarios 2, 3 and 4 the delay is clearly redistributed from the motorway to the on-ramp by all methods. All methods perform well, although the occupancy-based methods seem have a slightly better performance. For scenarios 0 and 1 the RAD method has the best performance. In scenario 0 the RAD method decreases the delay on the on-ramp, at the cost of an increased delay on the motorway. This indicates that the RAD method estimates a too high capacity. For scenarios 2, 3 and 4 the RAD method performs worse then the AD method, which uses the same estimator. It is suspected that this is also caused by the estimation of a too high capacity. This is where the AD-RWS estimator developed in Section 5.2 could improve the performance, if properly calibrated.
The reduction of the delay on the motorway and the increase of the delay on the on-ramp in scenarios 2, 3 and 4 are roughly of equal size. Since the flow on the motorway is larger then the flow on the on-ramp, this might indicate that the average delay reduction on the motorway is much smaller then the average delay increase on the on-ramp. However, review of the data revealed that the especially the extreme values of the on-ramp delay increase and the motorway delay decrease are not very far apart, as shown in Table 8.29. The mean values have been calculated after removing all the vehicles that had no change in their delay.

Table 8.29: Mean and extreme change of delay

Scenario	Mean delay change motorway [s]	Largest delay decrease motorway [s]	Mean delay change on-ramp [s]	Largest delay increase on-ramp [s]
0	2.9	-482.1	12.0	547.0
1	-1.6	-628.9	25.0	688.8
2	-13.1	-775.9	51.7	744.8
3	-52.6	-1042.1	128.5	985.1
4	-27.4	-971.2	74.2	1010.1

Congestion

The occupancy-based methods show the best performance in reducing and postponing congestion.

Queue detection
The RAD method performs best with respect to queue detection activation. The DAC method shows strange behaviour. The queue detection is initiated very early in the simulation. This is most likely caused by the initial capacity value being too low.

Overall
The RAD method makes the best estimation of the two remaining capacity estimators. It is accurate and stable. Even though the RAD method does not performs best during all scenarios it does perform well overall. The occupancy-based methods also perform well, both the adaptive and non-adaptive methods. The RAD method is considered to have the overall perform best.

9. Conclusions and recommendations

The main goal of this thesis work was to find and investigate metering methods that are able to increase the performance of a metered on-ramp using the Dutch Standard Ramp Metering Application, by estimating online the motorway capacity using current traffic observations. In this section the study will be summarized, conclusions regarding the research goal and questions will be made, and recommendations for further research and development will be given.

9.1 Summary

Much work has been done in the course off this thesis. In this section the a short summary will be given of the study. More details can be found throughout the report.

9.1.1. Proposed metering methods

In the literature review various ramp metering and capacity estimation methods have been discussed. In the end seven methods were proposed for testing, of which one has been developed in the course of this study.

RWS metering algorithm
The current Dutch metering algorithm is not a method as intended in the research goals. It was used as a reference to which the performance of new methods can be measured.

ALINEA metering algorithm
This occupancy-based metering algorithm is partly a method as intended in the research goal. Using this method might increase the output of a metered on-ramp, but it will do so without estimating the capacity. The other function of the method is also as a reference to which the performance of new methods can be measure.

AD-ALINEA adaptive metering algorithm
This method combines the ALINEA metering algorithm with a critical occupancy estimator.

RWS-AD-ALINEA adaptive metering algorithm
This method uses the capacity estimator from the AD-ALINEA method, and combines it with the Dutch RWS metering algorithm.

RWS-DACCORD Online estimator method
This method is formed by combining the RWS metering algorithm with the DACCORD Online estimator.

RWS-DFEA adaptive metering algorithm
The Distribution Free Estimation Approach is a static method that estimates the capacity using vehicle headways. The method has been made dynamic and is combined with the RWS algorithm.

AD-RWS adaptive metering algorithm
This method has been designed as a part of this project. It is based on the capacity estimator from the AD-ALINEA method, and designed to optimize the estimation for the RWS metering algorithm.

The estimation behaviour of all methods has been tested using the simulation model. The DACCORD Online method, the DFEA method and the newly developed AD-RWS method showed unstable behaviour and a over- or underestimation of the capacity. It was decided that the DACCORD Online method could be improved within this project. It was also decided that the DFEA and AD-RWS method would require considerable more time and effort. These methods have therefore not been improved, and were not implemented in the final simulations.

9.1.2. Test setup
The tests are aimed at the main goal of this thesis work. It was chosen that the seven methods would be tested using simulations. To test the performance of the selected metering methods under varying capacities, five capacity scenarios were used. The first four scenarios will each have a different capacity. However the capacity will remain constant during the simulations. In the fifth scenario the capacity will vary during the simulation. The reliability of the test results has been increased by doing ten runs for each method for each capacity reduction scenario. Small variations were introduced into the simulations by varying the random seed. See Figure 9.1.

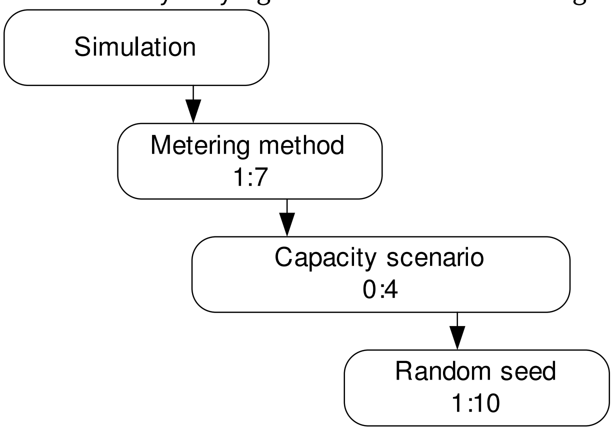


Figure 9.1: Simulation setup

9.1.3. Simulation environment
A simulation environment has been created in which the methods were tested. The environment consists of a traffic simulation model, a ramp meter controller and a calculation engine. Vissim, a micro simulation model, was used for the traffic model. Since main goal of this thesis is to find methods for use in the Standard Ramp Metering Application (SRMA), the SRMA was used as the ramp meter controller. Matlab served as calculation engine, and contained the capacity estimators and simulations controls. Various types of data were exchanged between the three components, as depicted in Figure 9.2.

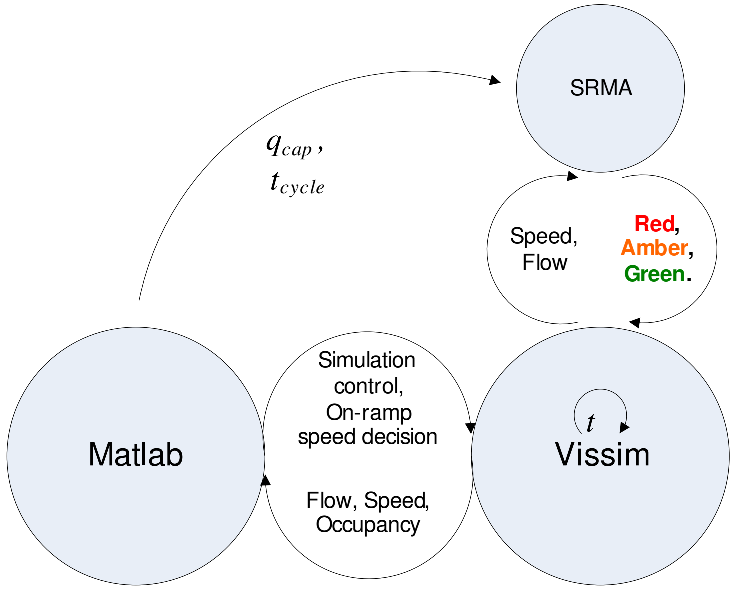


Figure 9.2: Final simulation environment

The model was configured using qualitative calibration to represent the functioning of a metered on-ramp. Specifically the merge behaviour was improved by modifying model parameters, and by dynamically matching the speed of vehicles on the on-ramp to the speed of vehicles on the motorway. Capacity changes was modelled by changing the desired headway time parameter CC1.

9.1.4. Results

The seven methods have been tested under five different capacity reduction scenarios, and their relative performance reviewed according to defined indicators.The main performance indicator is the reduction of the total vehicle delay. Secondary performance indicator can be divided into three groups; Congestion performance, Metering performance and Queue detection performance. The estimation behaviour was also regarded, and compared to the actual capacity for the simulations, which was estimated using the non-parameterized Brilon PLM method, see Section 4.1.2. The estimations are listed in Table 9.1.

Table 9.1: Estimation for capacity scenarios 0 to 3

	Capacity reduction	PLM	RWS	AD-ALINEA	DFEA	AD-RWS	DACCORD Online
Capacity	**0**	**4960**	**4560**	**4859**	**-**	**-**	**4539**
std-dev		194	0	408	-	-	1398
Capacity	**1**	**4827**	**4560**	**4747**	**-**	**-**	**4203**
std-dev		190	0	187	-	-	1314
Capacity	**2**	**4725**	**4560**	**4678**	**-**	**-**	**4095**
std-dev		258	0	199	-	-	1150
Capacity	**3**	**4328**	**4560**	**4411**	**-**	**-**	**4440**

std-dev		100	0	173	-	-	797

During capacity scenario 4 the capacity is changed during the simulation; from the level of scenario 1, to the level of scenario 3, and back again. The results of the main performance indicator are given in Table 9.2.

Table 9.2: Summary of results

	RWS	ALINEA	ALINEA & AD-ALINEA	RWS & AD-ALINEA	RWS & DFEA	RWS & AD-RWS	RWS & DACCORD Online
Scenario 0							
Total delay [h]	0.0	-6.9	-5.9	-2.2	-	-	-55.8
Motorway delay [h]	0.0	-1.8	-0.6	-4.9	-	-	-19.9
On-ramp delay [h]	0.0	-5.1	-5.3	2.7	-	-	-35.9
Scenario 1							
Total delay [h]	0.0	-11.8	-33.6	6.7	-	-	-40.3
Motorway delay [h]	0.0	6.9	-3.3	16.9	-	-	-4.4
On-ramp delay [h]	0.0	-18.7	-30.3	-10.2	-	-	-35.9
Scenario 2							
Total delay [h]	0.0	-27.6	-9.9	-19.3	-	-	-11.3
Motorway delay [h]	0.0	21.7	40.0	28.9	-	-	43.2
On-ramp delay [h]	0.0	-49.3	-49.9	-48.2	-	-	-54.4
Scenario 3							
Total delay [h]	0.0	-3.3	11.9	-9.5	-	-	-9.5
Motorway delay [h]	0.0	116.9	134.2	104.8	-	-	110.5
On-ramp delay [h]	0.0	-120.2	-122.4	-114.4	-	-	-120.1
Scenario 4							
Total delay [h]	0.0	12.2	-2.4	-4.3	-	-	-28.3
Motorway delay [h]	0.0	68.1	60.5	56.6	-	-	48.2
On-ramp delay [h]	0.0	-56.0	-62.9	-60.9	-	-	-76.5

Discussion

Most methods show little improvement for scenario 0, compared to the standard RWS algorithm. The DACCORD Online estimator however performs badly. It also has a bad performance for scenario 1, where the RAD method performs well. For the scenarios 2, 3 and 4 all method are able to redistribute the delay from the motorway to the on-ramp, mostly without large increase of the total delay. The results of the simulations were limited by the unstable and inaccurate estimation behaviour of the DFEA and AD-RWS estimators. This limited the comparison to just two capacity estimation methods. Also the behaviour of the DACCORD Online estimator remains somewhat unstable. Still it was able to perform reasonable well for scenarios 2, 3 and 4. Also during these scenarios the AD-ALINEA method performs a little better then the RWS & AD-ALINEA method. This indicates that the AD-ALINEA is indeed tuned for the ALINEA algorithm, and that the

AD-RWS estimator developed in Section 5.2 could improve the performance, if properly tuned to the RWS algorithm.

9.2 Conclusions

In the beginning of this report three research questions were posed, and from them the objective was formulated, according to:

"Find and investigate metering methods that are able to increase the performance of a metered on-ramp using the Dutch Standard Ramp Metering Application, by estimating online the motorway capacity using current traffic observations."

First the research questions will be answered. Then, from the answers given, an overall conclusion will be drawn.

1. *What capacity estimation methods exist, and can they be used online in combination with the RWS metering algorithm and the SRMA?*

Literature review has returned three capacity estimation methods that might be used as online estimators, the DACCORD Online estimator, the DFEA estimator and the AD-ALINEA estimator. Also the new AD-RWS estimation method was developed during this study. The initial test results showed that the AD-RWS and DFEA estimators are not suited for online implementation at this time. After the simulation some questions remain about the stability of the DACCORD Online estimator. It is not considered to be ready for on-line implementation. The AD-ALINEA estimator is considered to be suited for on-line use; however it will requires some modification to the SRMA.

2. *Does online capacity estimation improve the performance of a metered on-ramp using the RWS metering algorithm?*

The simulation results show that online capacity estimation reduces the delay of vehicles on the motorway. However, the improved capacity estimation leads to less queue detection which leads to an increase of the delay for vehicles on the on-ramp. This shows that a better estimation leads not directly to an improvement for all vehicles. Of the capacity estimation methods tested during this study, the RWS metering method is concluded to have the best overall estimation, and increases the performance of the ramp meter.

3. *Do any metering methods exist that are capable of adapting to changing conditions, better than the RWS metering algorithm?*

Literature review returned two metering methods that might perform better for changing capacities then the RWS metering algorithm; the ALINEA and AD-ALINEA metering algorithms. They both function well, and reduce the motorway delay in most cases. It is concluded that the occupancy-based methods perform better under changing conditions as simulated in this study. However, these methods control the ramp meter based on critical occupancy instead of capacity flow. The effect of changing the desired headway time on the critical occupancy is unknown. This makes a comparison with the reality more difficult.

Overall, it can be concluded from this study that metering methods are available that increase the performance of a ramp meter, and that these methods are suited for use in combination with the Dutch SRMA. The RWS metering algorithm combined with the AD-ALINEA estimator was found to be the method that achieves the best ramp meter performance.

The results also show accurate capacity estimation does not lead to an reduction of the delay for all vehicles around a metered on-ramp. Vehicles on the on-ramp do not profit from the increased ramp meter performance. Also, the methods have been tested in a simulated environment. The observed increased on-ramp performance does not necessarily translate directly into similar effects in reality.

An accurate capacity estimation, if the estimation is higher than the standard capacity in the RWS algorithm, leads to a reduction of the queue detection activity. If the estimation is higher than the standard capacity in the RWS algorithm, congestion is resolved sooner. This is confirmed by the simulation results. It is clear that accurate capacity estimation leads to a better ramp meter performance, since a ramp meter is supposed to increase the delay on the on-ramp. And the results of the new methods have been compared to the RWS metering algorithm, which is currently used in reality, for different random seeds. This ensures that even if the results will not be precisely as they might be in reality, at least they will give a well-founded indication of the effect of implementation in reality.

9.3 Recommendations

In the following section some suggestions are done for further research and development.

Improvement of estimators
In this study several capacity estimators have been reviewed. A number of these have never been implemented online. The performance of these estimators could certainly be improved if they would be properly calibrated. Off-line or real time data can be used to improve the estimation of the capacity. Similar to what was done in this study; the capacity estimated using a method known to be accurate such as the Brilon PLM estimation can be compared to the capacity estimated by the real-time capacity estimators. Also improvements could be made in the calculations and rules in methods; such as for the Distribution Free Estimation Approach, which becomes unstable during congestion. Rules could be added to prevent estimation or even data collection during congested circumstances.
And also the DACCORD Online estimator should be considered, as the estimation behaviour remains somewhat unstable, even after the improvements suggested in Section 8.2. The AD-ALINEA estimator shows a sharp drop in its estimation at the end of the simulation, when the flow into the network is set to zero. This might be resolved by not allowing the estimator to update the capacity for low flows, e.g., lower than 1000 vehicles per hour.

From the simulation results it is clear that the AD-ALINEA estimator works better for the ALINEA algorithm than for the RWS algorithm. This indicates that the performance of the RWS algorithm can be increased even more by the AD-RWS estimator. This estimator however will require further tuning of the update thresholds and the algorithm, to overcome the underestimation.

MPC

Even though the MPC was not implemented in this simulation, it remains a promising method for the future. If MPC could be implemented in the SRMA, using additional traffic observations and computational power, the performance of the on-ramp is expected to increase. It also appears to be suited for coordinated control using the CVMS (Central Traffic Management System).

Flow threshold calculation

In this study the flow thresholds for activation and deactivation of the metering system were calculated using the estimated capacity. The threshold for activation was set at 85% of the estimated capacity, the threshold for deactivation at 80%. These ratios were estimated on literature and experience. Although the results didn't show them to be incorrect, these ratios thresholds should be optimized. By using a simulation model similar to the one used in this study, several ratios can be implemented and their results compared.

Simulation environment

The simulation environment that was used to test the methods consisted of the microscopic traffic simulation VISSIM, the SRMA and Matlab. Apart from the improvements mentioned, there were several other problems that have not been addressed.

One problem was with the car following model. Around an on-ramp the traffic on the right motorway lane is confronted with vehicles merging into the motorway from the on-ramp. These extra vehicles cause a drop in the speed. Vehicles on the left motorway lane however do not have this problem, and continue at their desired speed. For realistic behaviour, a portion the vehicles from the right motorway lane should change into the faster lane. However, if the speed difference between the left and right motorway lane is large enough, than suitable gaps for lane changing will become scarce. This behaviour can be reduced by making the desired speed dependent on the speed of vehicles on adjacent lanes.

Another problem was with the interface between the SRMA and Vissim, which is provided by the Promit-E application developed by Vialis B.V. in Haarlem. This interface has not been designed to work with the SRMA, but with traffic light controllers using the same programming language. In this report it was already mentioned that speed observations were not passed. Another problem was the activation and deactivation of the ramp meter. These problems have been overcome, but in a very provisional manner. So provisional, that the correct functioning of the ramp meter in Vissim is not 100% guaranteed. The interface between the SRMA and Vissim should be programmed into a working application to guarantee the correct functioning of the ramp meter.

Field testing
Finally, after the effect of the improved metering methods has been sufficiently demonstrated in simulations, the method should be field tested, in order to measure if the adaptive metering method also increases the performance in reality.

Implementation requirements
It was concluded that only the AD-ALINEA estimator is suited for implementation at this time. However, some modifications of the ramp meter, and the SRMA are required. The AD-ALINEA estimator uses detectors at the merge area. Even though these detectors are present, they are not yet connect with the SRMA. Once the detector data is available in the SRMA, all that remains is programming the estimator. The same detector data is also used by the AD-RWS estimator and the ALINEA metering algorithm.
The DACCORD Online estimator and the DFEA estimator both used the existing downstream motorway detectors in the simulations. The DACCORD Online estimator needs traffic observations divided into vehicle classes. This data is currently not yet available. The required calculations should be programmed into the SRMA, along with the estimator. The same holds for the DFEA method.

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38 C. van Goeverden, H. Botma, P. Bovy, *Determining impact of road lighting on motorway capacity*, Transportation Research Record 1646, 1998

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Appendix A AD-ALINEA

The AD-ALINEA estimator does not estimate the capacity directly, but approaches it. Each interval k the observed traffic variables occupancy o_{out} and flow q_{out}, are compared to various thresholds. If, according to these thresholds, the critical occupancy o_{cr} is not yet reached, then $o_{cr,est}$ is increased. If o_{cr} is overestimated, $o_{cr,est}$ will be reduced.

The first threshold is the absolute difference between the observed occupancy o_{cr} and estimated critical occupancy $o_{cr,est}$. This should be at least 5%, if not then $o_{cr,est}$ is not updated.

The second threshold compares the derivate $D = \frac{\delta q_{out}}{\delta o_{out}}$ to the thresholds Dmin and Dplus. If D is larger then Dplus = 40, then $o_{cr,est}$ is increased with Δ = 1%; If D is smaller then Dmin = -15, then $o_{cr,est}$ is decreased with Δ = 1%, as follows:

$$ocr(k) = \begin{cases} o_{cr}(k-1)+1 & \text{if } D > D\text{plus} \\ o_{cr}(k-1) & \text{if } D\text{plus} < D < D\text{min} \\ o_{cr}(k-1)-1 & \text{if } D < D\text{min} \end{cases}$$

[13] and [14] suggest two methods to estimate the derivate D from the traffic observations. The first produces the estimation of D(k) by exponentially smoothing the values of time derivatives δ(k) that are based on two consecutive measurements of o_{out} and q_{out}:

$$\delta(k) = \frac{q_{out}(k-1) - q_{out}(k-2)}{o_{out}(k-1) - q_{out}(k-2)}$$
$$D(k) = \alpha \cdot \delta(k) + (1-\alpha) \cdot D(k-1)$$

The second method estimates D(k) using a Kalman-filter. A Kalman filter estimates a process in two steps. The first step projects the current estimate forward in time, to obtain the estimate for the next interval. The second step uses the new measurements to improve the estimation.

A comparison between the two estimation methods was done in [13]. There, it was concluded that the Kalman filter estimation (KFE) performed best. Based on that article only the Kalman filter estimation is used in this study.

A.1 KFE based estimation algorithm

The general problem that the Kalman filter addresses is the estimation of the state x(k) of a discrete-time controlled process that is governed by the general state equation:

$$x(k) = A \cdot x(k-1) + B \cdot u(k-1) + z(k-1)$$

based on measurements y(k) according to the measurement update, or output equation:

$$y(k) = C \cdot x(k) + w(k) .$$

where A, B, C are some system parameters and u(k) is an (optional) non-system-dependent input. z(k) and w(k) represent the random noise on, respectively, the system and the measurements.

The AD-ALINEA algorithm uses a simplification of the fundamental diagram for the estimation of D:

$$q_{out} = D \cdot (o_{out} - o_{cr,est}) + E$$

where E is the flow corresponding to the estimated derivative D. This equation only holds in a small region around the measured values. The KFE estimates recursively the parameters D and E, by assuming the following state equation

$\mathbf{x}(k)=\mathbf{x}(k-1)+z(k)$

where $\mathbf{x}=[D\ E]^T$. The measurement update, or output equation is

$y(k)= \mathbf{c}(k)\mathbf{x}(k)+w(k)$

where in view of the simplified model, $y(k)=q_{out}(k)$ and $\mathbf{c}(k)=[(o_{out} - o_{cr,est})\ 1]$. The resulting Kalman filter used in the AD-ALINEA algorithm reads:

$$\hat{\mathbf{x}}(k) = \hat{\mathbf{x}}(k-1) + \mathbf{H}(k-1)[y(k) - \mathbf{c}(k)\hat{\mathbf{x}}(k-1)]$$

where the filter gain vector **H**(k-1) is calculated from

$$\mathbf{H}(k-1) = \frac{[\mathbf{\Pi}(k-1) + Z] \cdot \mathbf{c}^T(k)}{\mathbf{c}(k) \cdot [\mathbf{\Pi}(k-1) + Z] \cdot \mathbf{c}^T(k) + W}$$

while the error covariance matrix **Π**(k) is update via

$$\mathbf{\Pi}(k) = \left[\mathbf{\Pi}(k-1) + \mathbf{Z}\right] - \mathbf{H}(k-1) \cdot \mathbf{c}(k) \cdot [\mathbf{\Pi}(k-1) + \mathbf{Z}] .$$

A.2 Estimation algorithm

The complete KFE AD-ALINEA algorithm is as follows:

a) Initialization of D(0) = 0, k=1, E(0) = $q_{cap,est}$, $o_{cr,est}(0) = o_{cr,min}$.

b) Enter new measurements $q_{out}(k)$, $o_{out}(k)$.

c) Reduce $o_{cr,est}(k)$ after K intervals with Δ = 1%, unless $o_{cr,est}(k) = o_{cr,min}$.

d) If $|o_{cr,est}(k) – o_{out}(k)| > P$, then $o_{cr,est}(k) = o_{cr,est}(k-1)$; go to step i.

e) Calculate **H**(k-1), **x**(k), **Π**(k), in this order.

f) If D(k) > Dplus, then set s(k) = +1; if D(k) < Dmin, then set s(k) = -1; otherwise set s(k) = 0.

g) Calculate $o_{cr,calc}(k) = o_{cr,est}(k-1) + s(k) \cdot \Delta$, and update $o_{cr,est}(k)$ according to:

$$o_{cr,est}(k) = \begin{cases} o_{cr,calc}(k) & \text{if} \quad o_{cr,calc}(k) \in (o_{cr,\min}, o_{cr,\max}) \\ o_{cr,\min} & \text{if} \quad o_{cr,calc}(k) \leq o_{cr,\min} \\ o_{cr,\max} & \text{if} \quad o_{cr,calc}(k) \geq o_{cr,\max} \end{cases}$$

h) If s(k) ≠ 0, then set E(k) = E(k) + D(k)D and D(k) = 0.

i) Set k = k+1 and go to step b.

Before the estimation the parameters $o_{cr,max}$, $o_{cr,min}$ and $q_{cap,est}$ should be defined. [13] suggests the following values:
$o_{cr,max}$ = 32% (maximum allowable value of the critical occupancy)
$o_{cr,min}$ = 15% (minimum allowable value of the critical occupancy)
$q_{cap,est}$ = 1700 veh/h/lane (initial estimation of the motorway capacity)

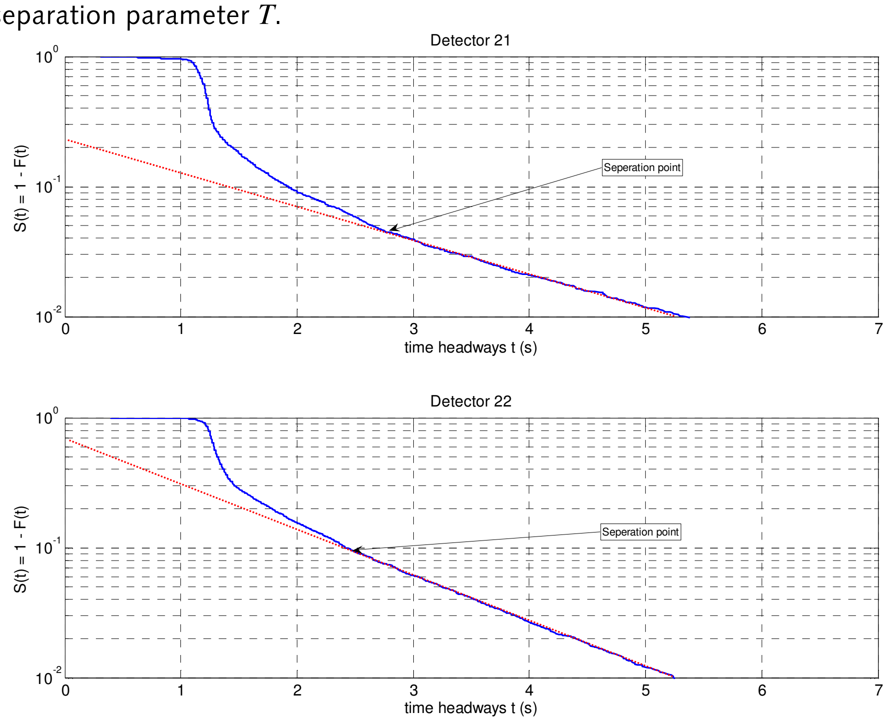
Appendix B DFEA estimation

In order to estimate motorway capacity using a headway method, traffic is split up into followers and free drivers, each with his own free driver headway distribution $h(t)$ or follower headway distribution $g(t)$, according to:

$$f(t)= \phi \cdot g(t)+(1-\phi) \cdot h(t)$$

where $f(t)$ is the observed headway distribution. It is assumed that when the motorway capacity is reached all vehicles are following, or the fraction of followers ϕ is 1. Using that assumption, the capacity can be calculated from the follower headway probability distribution function according to the method specified in [30].

A distinct feature of the free driver headways is that they are exponentially distributed. When all observed headways are plotted on a logarithmic scale, there is a distinct point from where the observations start to deviate from a straight line. This is the point known as the separation parameter T.



[Figure: separation point for headways at detector 21 and 22

The deviation from the straight line implies that not all vehicles with a headways shorter then T are free drivers anymore. Using T and the exponential distribution, the free driving distribution $h(t)$ can be estimated iteratively. The estimation of h(t) is initialized by evaluation of parameters λ (arrival rate for free vehicles) and A (normalization constant) from all headways t_i greater then T.

$$\hat{\lambda} = \left[\frac{1}{m} \sum_i (t_i - T) \right]^{-1}$$ for all headways $t_i > T$

$$\hat{A} = \frac{m}{n} \exp(\hat{\lambda} T)$$

where m is the number of headways larger then T, and n is the total number of headway observations. Using the parameters derived above the following iterative function can be solved:

$$\hat{h}_1^{(i)}(t) = \hat{A}\hat{\lambda}\exp(-\hat{\lambda}t)\left[1 - \frac{1}{\hat{\phi}^{(i-1)}} \int_t^{\infty} [\hat{f}(s) - \hat{h}_1^{(i-1)}(s)]ds\right]$$

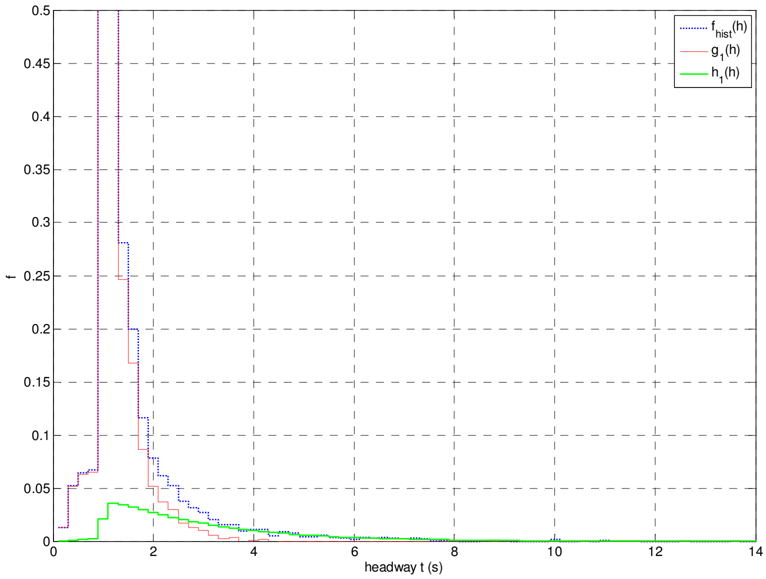
subject to

$$\hat{\phi}^{(i-1)} = \int_0^{\infty} [\hat{f}(s) - \hat{h}_1^{(i-1)}(s)]ds$$

where f(s) is an estimate of the headway distribution based on collected data. An appropriate initial solution is $h_1^{(0)}=A\lambda\exp(-\lambda T)$ and $\phi=0,9$. When the error between subsequent iterations becomes sufficiently small, the iteration stops, usually within 5 iterations. After the free driver headway distribution *h(t)* is determined, the follower headway distribution *g(t)* can be calculated by:

g(t)= f(t) - h(t)

This can also be seen in Figure [. The motorway capacity can be found by calculating the inverse of the mean of the following headway distribution *g(t)*.



Appendix C DACCORD Online estimator

The DACCORD Online estimator is based on fitting a custom model of the fundamental diagram through traffic observations, measured during one minute. This custom model consists of a straight and a curved part. Each interval the observations are compared to the estimation, and the result is used to improve the next estimation. The DACCORD Online capacity estimator can be broken down into parts, according to the Figure below. In the following section these parts will be described separately.

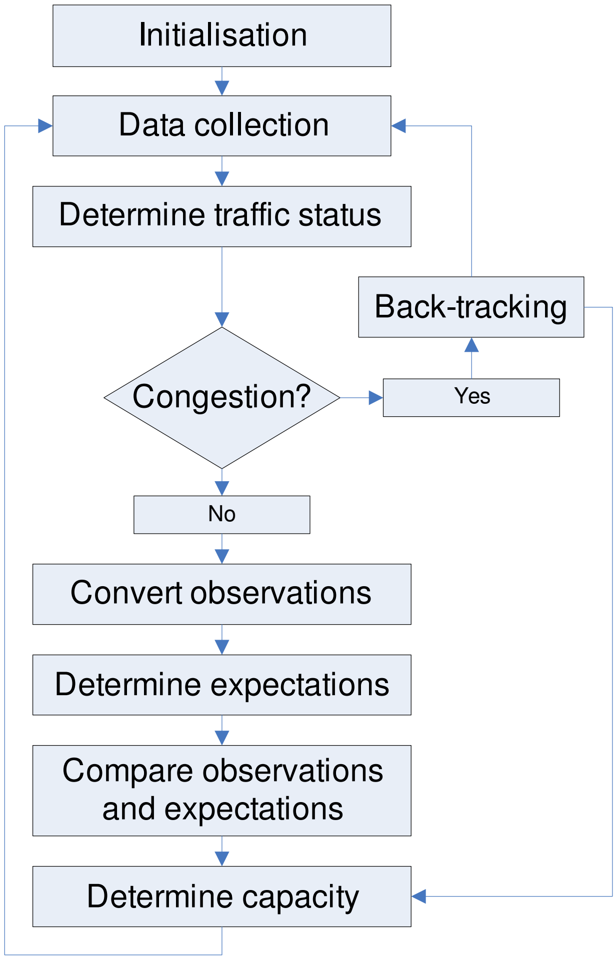


Figure: DACCORD Online estimator

C.1 Determining traffic status

Since the estimator only works under free flow conditions, the first step checks whether the average speed for all vehicle classes is not below a congestion threshold to confirm free flow state. Normally a threshold of 80 km/h is used. If it is below the threshold, the procedure skips to the backtracking module.

Measurements	**Symbol**	**Defined as**
Flow Category 1	A1h	Flow on all lanes during the current interval for vehicles with a length < 5.1 metres.
Flow Category 2	A2h	Flow on all lanes during the current interval for vehicles with a length between 5.1 and 12.5 metres.
Flow Category 3	A3h	Flow on all lanes during the current interval for vehicles with a length larger then 12.5 metres.
Average speed per category in km/hr	V1h (Cat1) V2h (Cat2) V3h (Cat3)	The sum of the speeds of the vehicles in the category divided by the flow in that category.
Observed occupancy	OccIh	The proportion of the time during which a vehicle is detected.
Off-ramp flow (Category 1)	A1a	Flow on the (eventual) exit with a vehicle length of < 5.1 metres.
Off-ramp flow (Category 2)	A2a	Flow on the (eventual) exit with 5.1 m. <= vehicle length < 12.5 metres.
Off-ramp flow (Category 3)	A3a	Flow on the (eventual) exit with 12.5 m. <= vehicle length.

Parameter	**Symbol**	**Defined as**
Number of traffic lanes	AS	Number of traffic lanes on the carriageway under consideration
Effect of exit presence	IAF	If measurements are made more than 750 metres downstream of the start of, or upstream of an exit; IAF = 0. If the observation point is located precisely at the start of the exit; IAF = 1. Else; IAF = (750-y)/750; where y is the distance between the observation point and the start of the exit.

The average speed in km/h is calculated using:

(1)

C.2 Converting input data

The second step converses the data from the different categories into PCE's, so that it can be used in the estimator. This results in values for PAEN (observed standardised measured passenger car equivalent) and OccN (standardized measured occupancy). The influence of an upstream exit is incorporated in the estimator. Even though such influence it not included in the simulation model, it will be included in this description. The following parameters are used:

Parameter	Symbol	Defined as
Average length of Cat1	L1	3.38 metres
Average length of Cat2	L2	7.78 metres
Average length of Cat3	L3	15.41 metres
Conversion factor from Cat2 into PCE	F2	L2/L1 = 2.30
Conversion factor from Cat3 into PCE	F3	L3/L1 = 4.48

The effect of the exit if present is expressed in factor IA2, which is dependent on the observed occupancy:

$$IA2 = \begin{cases} 0 & \text{if OccIh} < 0.04 \\ OccIh - 0.04 & \text{if OccIh is between 0.04 and 0.05} \\ 0.01 & \text{if OccIh} > 0.05 \end{cases} \qquad (2)$$

The flows for each category observed at the measurement point are compensated for the flow leaving the motorway at the exit upstream (if present):

(3)

(4)

(5)

Estimate of point occupancy rate calculation taking traffic on the exit into account:

(6)

For the rest of the estimation speed in metres per second will be used. The average speed, and the speed for each category are converted.

(7)

$$V1 = \frac{V1h}{3.6} \qquad (8)$$

$$V2 = \frac{V2h}{3.6} \qquad (9)$$

$$V3 = \frac{V3h}{3.6} \tag{10}$$

The average flow is converted to Passenger Car Equivalents (PCE):

(11)

The average length based on the actual vehicle length in metres is calculated using:

(12)

The average headway is calculated from the total flow.

(13)

The average gap is calculated by subtracting the average passage time of vehicle from the headway:

$$VTva = VTvv - \frac{GemL_I}{VGem} \tag{14}$$

The occupancy is 'standardized' by basing it on the defined vehicle length for each category is calculated using:

$$OccB = \frac{\left(\frac{(A1 * L1)}{V1} + \frac{(A2 * L2)}{V2} + \frac{(A3 * L3)}{V3}\right)}{60 * AS} \tag{15}$$

The standardized average length based on the defined category vehicle length in metres is calculated using:

$$GemLN = GemLI \cdot \frac{OccB}{OccI} = \frac{(OccB * 60 * VGem * AS)}{(A1 + A2 + A3)} \tag{16}$$

The standardised average headway in seconds equals:

(17)

The standardised flow in PCE equals:

(18)

The standardised occupancy is calculated using:

(19)

C.3 Determining expectations

Step three estimates the expected passenger car equivalent (PEAS) based on the OccN and the scaling factor r. This factor was determined at the end of the previous estimation, or set to 1 during the initialisation. It is the indicator of the road's ability to operate.The following parameters are defined and used in this section:

Parameter	**Symbol**	**Defined as**
Transition point between the straight and curved part of the model	O_K	0.03 (This is an assumption, as the value of O_K was not listed in the literature)
Straight portion parameter for passenger cars	α_{1p}	5.92 (max. speed 120 km/hr) 5.03 (max. speed 100 km/hr
Straight portion parameter for light lorries	α_{1kv}	4.93 (max. speed 120 km/hr) 4.59 (max. speed 100 km/hr)
Straight portion parameter for heavy lorries	α_{1gv}	4.19 (max. speed 120 km/hr) 4.19 (max. speed 100 km/hr)
Curved portion parameter for passenger cars	α_{2p}	7.52 (max. speed 120 km/hr, 2 lanes) 7.12 (max. speed 120 km/hr, 3 lanes) 5.91 (max. speed 100 km/hr, 2 lanes) 5.71 (max. speed 100 km/hr, 3 lanes)
Curved portion parameter for light lorries	α_{2kv}	5.73 (max. speed 120 km/hr, 2 lanes) 5.53 (max. speed 120 km/hr, 3 lanes) 5.11 (max. speed 100 km/hr, 2 lanes) 4.98 (max. speed 100 km/hr, 3 lanes)
Curved portion parameter for heavy lorries	α_{2gv}	4.39 (max. speed 120 km/hr, 2 lanes) 4.39 (max. speed 120 km/hr, 3 lanes) 4.39 (max. speed 100 km/hr, 2 lanes) 4.39 (max. speed 100 km/hr, 3 lanes)

The proportion X2 of flow for category 2 relative to the complete flow equals:

(20)

The proportion X3 of flow for category 3 relative to the complete flow equals:

$$X3 = \frac{(A3 * F3)}{(A1 + (A2 * F2) + (A3 * F3))} \quad (21)$$

As mentioned before, the DACCORD Online estimator uses a custom model of the fundamental diagram. This model consists of a straight and a curved portion. The standardized occupancy where the straight and curved section meet equals:

$$O_k N = O_k + (X2 * O_k) + (X3 * 2 * O_k) \quad (22)$$

Model parameters $\alpha_1 N$, $\alpha_2 N$, βN and γN are calculated using:

$$\alpha_1 N = [(\alpha_{1p} - X2 \cdot (\alpha_{1p} - \alpha_{1kv}) - X3 \cdot (\alpha_{1p} - \alpha_{1gv})] \cdot r \quad (23)$$

$$\alpha_2 N = [(\alpha_{1p} - X2 \cdot (\alpha_{2p} - \alpha_{2kv}) - X3 \cdot (\alpha_{2p} - \alpha_{2gv})] \cdot r \quad (24)$$

$$\beta N = \frac{\alpha_1 N - \alpha_2 N}{2 * O_k N} \quad (25)$$

$$\gamma N = (\alpha_1 N - \alpha_2 N) * O_k N - (\beta N * O_k N^2) \quad (26)$$

The variable BP is used to indicate whether the curved section is applicable (BP = 1) or not (BP = 0).

$$BP = \begin{cases} 0 & \text{if OccN} < O_k N \\ 1 & \text{if OccN} \geq O_k N \end{cases} \quad (27)$$

The flow estimation PEAS in PCE is calculated by entering the standardized occupancy in the model:

$$PAES = (BP \cdot \alpha_1 N \cdot OccN) + (1 - BP) \cdot (\gamma N + (\alpha_2 N \cdot OccN) + (\beta N \cdot OccN^2)) \quad (28)$$

C.4 Comparing observations and expectations.

Step four calculates the new value for the scaling factor r based on the measured and the expected PCE's (PAEN and PAES) and the old value of r. A smoothing factor is included in this estimation to reduce fluctuations. Smoothing factor G consists of two parts; g1 and g2.

$$g1 = \begin{cases} 0.01 & \text{if } \Delta PAEN > 10\% \\ 0.025 & \text{if } \Delta PAEN \leq 10\% \end{cases} \qquad (29)$$

$$g2 = \begin{cases} 0.075 & \text{if } \Delta VGEM > 10\% \\ 0.03 & \text{if } \Delta VGEM \leq 10\% \end{cases} \qquad (30)$$

$$G = g_1 + g_2 \qquad (31)$$

The new value of the scaling factor r is calculated by:

(32)

The estimation can be influenced by high average speeds at low flow observations, resulting in a overestimation of the capacity. To prevent this the scaling factor r is not allowed to have a great value then 1,05. The scaling factor is modified according to:

(33)

C.5 Determining capacity.

The objective of this module is to determine the value of the current capacity. This is expressed in PCE's per lane per minute. The capacity of the motorway is determined using the portion of lorries *AV*. *AV* is based in the flow observations A1I10 for category 1, A2I10 for category 2, and A3I10 for category 3, all collected during the previous 10 intervals:

(34)

The maximum or critical occupancy is calculated using:

(35)

The capacity is determined using:

$$q_{cap,est} = \gamma N + (\alpha_2 N * MBPG) + (\beta N * MBPG^2) \qquad (36)$$

For the calculations indicated here for the various capacities, it is always assumed that vehicles are of standard lengths. To make the conversion into 'real' vehicles, the values for capacity need to be corrected using the factor:

C.6 Backtracking

When congestion is detected during the present interval the backtracking is activated. Distinction is made between the first and later congested interval. If congestion is detected for the first time, then the situation of 4 minutes back is restored, and the capacity recalculated. Observations from later congested intervals are ignored.

Also once congestion has dissolved, the first four intervals the observations are ignored and no estimation is made.

Appendix D Matlab-VISSIM COM-manual

In this section a short manual to the use of the VISSIM COM-interface from Matlab is given. First the COM-interface will be introduced shortly. Next VISSIM will registered and called from Matlab. Then some basic COM-interface commands will be explained. Finally some practical examples are given.

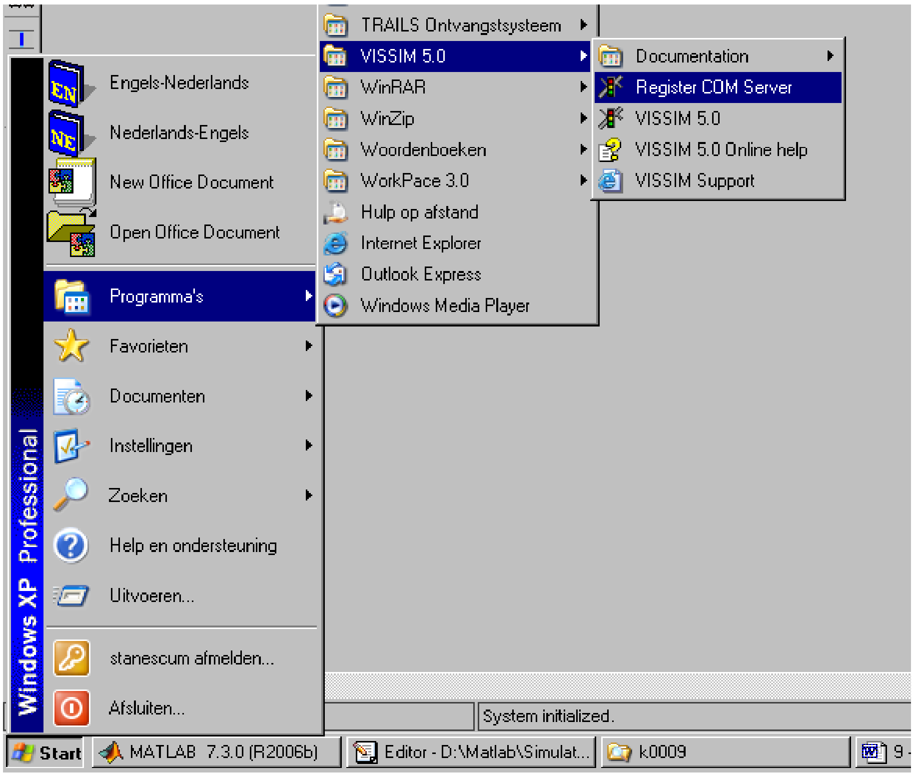
D.1 COM introduction

The Component Object Model (COM) is an interface standard introduced by Microsoft in 1993. It is used to enable inter-process communication and dynamic object creation in any programming language that supports COM.

The essence of COM is a language-neutral way of implementing objects that can be used in environments different from the one they were created in, even across machine boundaries. Although the interface standard has been implemented on several platforms, COM is primarily used with Microsoft Windows.

D.2 Registering and calling VISSIM

Before a COM-interface can be established, the VISSIM application needs to be registered as a COM-server. In the start menu (Start button, usually in the left-bottom corner of your screen), go to the 'Programs' folder, and then to the 'Vissim *X*' folder, in which *X* stands for the version of Vissim you are using. There you should find and click the 'Register COM-server' shortcut.



If this shortcut does not exist, you might not have the correct VISSIM license, or another problem has occurred. In this case, please consult the VISSIM COM-interface manual, included in the installation directory.

Once VISSIM has been registered, it can be called from Matlab using:

>> *h = actxserver('VISSIM.Vissim.500')*

The handle h can now be used to refer to the VISSIM COM-server.

D.3 COM-interface basics

In this section the main COM-interface commands *get*, *set* and *methods* will be discussed. These commands allow the user to access the available properties and commands of the VISSIM COM-interface. For more information on the available properties and methods, please refer to the VISSIM COM-interface manual.

D.3.1 Get

The *get* command queries and returns the properties of an object, in this case the VISSIM COM-server. The properties of the VISSIM COM-server can be queried using:

>> *h.get*

returning:

Net:

[1x1 Interface.VISSIM_COMServer_5.00_Type_Library.INet]
Simulation:
[1x1 Interface.VISSIM_COMServer_5.00_Type_Library.ISimulation]
DynamicAssignment:
[1x1
Interface.VISSIM_COMServer_5.00_Type_Library.IDynamicAssignment
]
Graphics: [
1x1 Interface.VISSIM_COMServer_5.00_Type_Library.IGraphics]
Evaluation:
[1x1 Interface.VISSIM_COMServer_5.00_Type_Library.IEvaluation]
Online:
[1x1 Interface.VISSIM_COMServer_5.00_Type_Library.IOnline]
Animation:
[1x1 Interface.VISSIM_COMServer_5.00_Type_Library.IAnimation]
Presentation:
[1x1 Interface.VISSIM_COMServer_5.00_Type_Library.IPresentation]
NewWorldPoint: 0

The results indicate that the properties of the VISSIM COM-server are mainly interfaces, which again can be called using the *get* command.

>> *h.simulation.get*

returns the following properties of the h.simulation object.

Comment: ''
Period: 15002
StartTime: '05:30:00'
Speed: -7
Resolution: 10
ControllerFrequency: 10
RandomSeed: 13
BreakAt: 61
LeftSideTraffic: ' '
RunIndex: 0

D.3.2 Set

The *set* command allows Matlab to set the value of object properties. In general, Matlab implicitly uses the set command. This will be explained in more detail using some examples in the next section.

D.3.3 Methods

Methods are commands that can be given directly to VISSIM, with or without arguments. The command:

>> *h.methods*

returns the available methods for the VISSIM COM-server:

Methods for class COM.VISSIM_Vissim_500:

AttValue *LoadNet* *ShowMinimized* *get*
save
BringToFront *New* *ShowNormal* *interfaces*
send
DoEvents *SaveLayout* *addproperty* *invoke*
set
Exit *SaveNet* *constructorargs* *load*
GetWindow *SaveNetAs* *delete* *move*
ImportANM *SetWindow* *deleteproperty* *propedit*
LoadLayout *ShowMaximized* *events* *release*

Notice that the VISSIM methods start with an upper case, the general Matlab methods with a lower-case. Usually only the VISSIM methods are used. Also notice that the methods command is case sensitive, this in contrast to the get and set commands. The function of the VISSIM methods, and whether they require arguments can be found in the VISSIM COM-interface manual.

10.1 VISSIM COM-interface examples

In this section some examples will be given, concerning the most commonly used functions. First the use of the *set* command will be illustrated.

D.3.4 Implicit use of set command

In the previous section the *set* command was discussed. There it was stated that Matlab implicitly uses the *set* command. This will be explained using the next example.

Also in the previous section, it was shown how properties of an object can be queried using the get command. In this example the properties of the VISSIM.Simulation object are queried using:

>> *h.simulation.get*

This returns the following properties:

Comment: ''
Period: 15002
StartTime: '05:30:00'
Speed: -7
Resolution: 10
ControllerFrequency: 10
RandomSeed: 13
BreakAt: 61
LeftSideTraffic: ' '
RunIndex: 0

Normally the set command should be used to change the value of these properties. However, in Matlab it is sufficient to appoint a value to them, similar as a value is appointed to a variable. Matlab then implicitly uses the *set* command to change the value of the property, in this case BreakAt.

>> *h.simulation.BreakAt=121;*

D.3.5 Explicit use of set command

In the previous sections the *set* command was discussed. There it was stated that Matlab implicitly uses the *set* command. However, this is not true in all cases.

AttValue

The VISSIM COM-server allows the value of some properties (attributes) to be changed using the method *AttValue*. Normally methods can be executed directly. However, since this method changes a property, Matlab requires that these attributes are changed using the *get* and *set* commands.

You first need to get a handle to the attribute. Getting the handle will also return the present value of the attribute, in this case DATACOLLECTION.

```
>> s=h.Evaluation;
>> t=s.get('AttValue','DATACOLLECTION')
t =
    0
```

The *get* command returns 0, indicating that DataCollection is not enabled. DataCollection can be enabled by setting the attribute to 1, as specified in the VISSIM COM-interface manual.

```
>> t=s.set('AttValue','DATACOLLECTION','1')
t =
   NaN
```

Using the get command again shows that the value of the attribute has changed, and that DataCollection has been enabled.

```
>> t=s.get('AttValue','DATACOLLECTION')
t =
    1
```

What attributes are available through the COM-interface, and what values can be assigned to them, is described in the VISSIM COM-interface manual.

AttValue1

Another method that requires more then one argument is *AttValue1*. This method requires three arguments. The attribute can be changed similar to *AttValue*, as described above. However, an error in the VISSIM application prevents the attributes from changing.

D.3.6 Methods

What methods are available can be found in the VISSIM COM-interface manual, or by using the *methods* command. In this case the methods for the VISSIM.Simulation object are queried using:

>> *h.simulation.methods*

returning the following available methods:

Methods for class
Interface.VISSIM_COMServer_5.00_Type_Library.ISimulation:

AttValue	*RunSingleStep*	*delete*	*invoke*	
LoadSnapshot	*SaveSnapshot*		*deleteproperty*	*release*
RunContinuous	*Stop*	*events*	*set*	
RunMulti	*addproperty*	*get*		

The methods starting with an upper case are VISSIM methods. The method RunSingleStep is a method without arguments, and can be called as follows:

>> *h.simulation.RunSingleStep*

This method commands VISSIM to run a single step. A method with one argument is LoadNet, instructing VISSIM to load the specified inp-file. This method is called using:

>> h.LoadNet ('D:\Vissim\network.inp')

All available methods and their function are described in the VISSIM COM-interface.

D.3.7 Run simulations

In this section two ways to run a simulation are presented.

Simulation without intermediate breaks

To run a simulation without intermediate breaks, set VISSIM to break at the end of your simulation period in seconds, plus one if you are using some form of data collection. Plus one allows VISSIM to write away the collected data of the last full interval. See the VISSIM user manual for more info on data collection and intervals.

```
h.simulation.BreakAt = simulation_period+1;
h.simulation.RunContinuous
h.simulation.Stop
```

Simulation with intermediate breaks

Running a simulation with intermediate breaks allows you to take measurements and update you simulation during the simulation. To do so, set VISSIM to break at each interval in seconds, plus one for the data collection. After each interval data can be retrieved from VISSIM, or properties and attributes can be changed.

```
for interval = 1:240
        h.simulation.BreakAt = interval+1;
```

```
        h.simulation.RunContinuous

        [retrieve data, call methods, or change properties or attributes]

end
h.simulation.Stop
```

D.3.8 Retrieve data

In this section two ways to retrieve data from VISSIM are presented.

DataCollection

Data can be received from DataCollections. Using the COM-interface only allows reading certain predefined data types, aggregated over the interval you specify in VISSIM. These predefined data types are the same as the types available through regular Data collection in VISSIM. See the VISSIM user manual for more information.

Assume the following: a network which has 16 DataCollectionPoints, grouped per pair into 8 DataCollections, numbered 1 to 8. These DataCollections have been configured in VISSIM to collect the flow, speed and occupancy for each interval. To retrieve these data, a handle to each DataCollection should be retrieved using:

```
dc =
h.net.datacollection.GetDataCollectionByNumber(DataCollection);
```

The data from each DataCollection can then be received from VISSIM using the *GetResult* method. Data from all DataCollections can be received using:

```
for DataCollection = 1:8
   dc =
h.net.datacollection.GetDataCollectionByNumber(DataCollection);
   flow{DataCollection}    = dc.GetResult('NVEHICLES','SUM',0);
   speed{DataCollection}   = dc.GetResult('SPEED','MEAN',0);
   occ{DataCollection}     =
dc.GetResult('OCCUPANCYRATE','SUM',0);
end
```

More information about retrieving data through the COM-interface, and about the arguments of the *GetResult* method, can be found in the VISSIM COM-interface manual.

Raw data file

Another way to get more detailed data from the DataCollectionPoints, is to read the raw data file (.mer-file). This does however slow down the speed of your simulation. Before the simulation, the box 'raw data' in the Data collection configuration screen has to be checked.

```
fid=fopen('D:\Vissim\network.mer');
C = textscan(fid, '%n%n%n%n%n%n%n%n%n%n%n',
'headerLines', length_RawData+35);
fclose(fid);
```

The value for *length_headerfiles* can be found by running a short simulation, and then counting the header lines printed in the mer-file. The value for *length_RawData* needs to be initiated before the start of the simulation with the value 0 (zero).

[Csize1 Csize2]=size(C{1});
length_RawData=length_RawData+Csize1-1;
RawDataPreviousInterval=[C{1}(1:Csize1-1,:) C{2}(1:Csize1-1,1) C{3}(1:Csize1-1,1) C{4}(1:Csize1-1,1) C{5}(1:Csize1-1,1) C{6}(1:Csize1-1,1) C{7}(1:Csize1-1,1) C{8}(1:Csize1-1,1) C{9}(1:Csize1-1,1) C{10}(1:Csize1-1,1) C{11}(1:Csize1-1,1) C{12}(1:Csize1-1,1)];

clear C fid ans*

The last observation in the raw data file is not included in the matrix *RawDataPreviousMinute* using *(1:Csize1-1,:)*, since it often is incomplete. By deducting one from *length_RawData* this observation is included in the next interval. *RawDataPreviousMinute* can be used directly, or be included in a cell-array using:

RawDataPerInterval{interval}=RawDataPreviousInterval;

See the VISSIM manual for more information on the raw data file and the data it contains.