Het verkeerskundig
laboratorium
voor studenten

ITS EDU LAB

Application of Macroscopic Fundamental Diagrams to Dynamic Traffic Management

Xiaoyu Qian

August 2009

Rijkswaterstaat

TU Delft

Ministerie van Verkeer en Waterstaat

Rijkswaterstaat

Application of Macroscopic Fundamental Diagrams to Dynamic Traffic Management

Xiaoyu Qian

17 August, 2009

Final report

MSc Thesis Transport, Infrastructure and Logistics
Delft University of Technology

Colophon

Published by: ITS Edulab, Delft
ITS Edulab is a cooperation between the Rijkswaterstaat center for Transport and Navigation and the Delft University of Technology

Information: Henk Taale
Email: Henk.Taale@rws.nl

Author: Xiaoyu Qian
Delft University of Technology
Master Transport, Infrastructure and Logistics

Graduation committee:
Prof. Dr. Ir. Serge P. Hoogendoorn
Committee chairman
Delft University of Technology
Faculty of Civil Engineering and Geosciences
Dr. Ir. John H. Baggen
Delft University of Technology
Faculty of Technology, Policy and Management
Dr. Ir. Winnie Daamen
Delft University of Technology
Faculty of Civil Engineering and Geosciences
Dr. Ir. Sascha Hoogendoorn-Lanser
Rijkswaterstaat, Centre for Transport and Navigation
Dr. Ir. Henk Taale
Rijkswaterstaat, Centre for Transport and Navigation

Date: 17 August, 2009

Status: Final report

Summary

This thesis project is a part of Dutch project PraktijkProef Amsterdam (PPA), in which the coordinated network traffic management in the regional area is analyzed. One of control levels in the project PPA is sub-networks, where the concept of the macroscopic fundamental diagram (MFD) is applied. Unlike a conventional link fundamental diagram, an MFD relates the output and number of vehicles in a large network, and enables road operators make a real-time control more efficiently.

This graduation project makes a first attempt to use MFD in the Netherlands. The study area of the project PPA is the metropolitan area of Amsterdam. Because the empirical data are not available, especially on the urban roads, the simulation model is used to generate the traffic variables for deriving the MFDs.

In this case, the macroscopic model RBV is firstly used. Compared to the theoretical fundamental diagram as well as the MFDs obtained based on empirical data in previous studies, the MFD derived by using the RBV model shows two special patterns. One is that the flow is always lower when congestion is dissolving than that during the onset of congestion. The other characteristic is that flows keep rising with the increasing of density and the congestion branch in a conventional fundamental diagram is missing. The two patterns are observed in all MFDs for different demand levels and sub-networks. After analyzing the principles of the RBV model, the reasons for two strange characteristics are revealed. The drop of flow between the onset and the resolving of congestion results from the fact that the locations for measuring flow and density are not corresponding in the RBV model. In terms of the missing congestion part, it is due to the assumption of the RBV model that the flow of a link is constant, which is the saturation flow, even during the congestion period. Since the critical density is not visible in the MFDs derived by RBV, they cannot be used for traffic control. Hence, the RBV model is not suited for deriving MFD.

Then the microscopic model VISSIM is applied. The congestion branch is observed in the MFDs derived from VISSIM. However, the drop of flow between the onset and the resolving of congestion still exists. The further analysis reveals that the OD matrix used in this project leads to a dramatic decrease of flow when congestion is resolving. The inflow becomes very low when the density is still high on the link. Due to the same problem in RBV with respect to measurement locations, the drop is also observed in the MFDs based on the data from VISSIM. However, this defect does not affect reading the important patterns on MFD such as the critical density and the maximum flow. So the VISSIM is proven a feasible model to derive MFD.

Afterwards, two DTM measures, ramp metering and extra lane, are implemented in the VISSIM model. The MFDs in the different networks are derived for each scenario. When ramp metering is applied, the MFD of the whole network almost remains same. But the large decrease of the maximum density is seen in the MFD of the motorways. By contrast, the maximum density on the urban roads increases, implying a worse traffic situation in the urban network after using ramp metering systems. In terms of extra lanes, they are implemented on the different road sections with two speed limits. The simulation results show that only when the A10 west is expanded, the MFDs of the study area experience significant changes. The maximum density decreases greatly and the congestion part disappears from the MFDs. The scenario with a lower speed limit seems a bit better due to a slight smaller maximum density.

In addition, this project also investigates the possibility of using the MFD as an evaluation method. A multi-criteria analysis is made to compare the MFD and the conventional method, in which the traffic situation is revealed by travel time and travel speed. By assessing the MFD and the conventional method against the criteria of accuracy, visualization, feasibility and costs, the MFD performs worse than the conventional method, from the viewpoints of two stakeholders in this case, Rijkswaterstaat and the city of Amsterdam. However, using the MFD to evaluate the effects of DTM measures is still possible on the motorways because the traffic data are easily collected. The

combination of the MFD and the conventional method will also improve the reliability of the evaluation results.

Key words: Macroscopic fundamental diagram, Dynamic traffic management measures, simulation models, Multi-criteria analysis

Preface

After seven months' working, I have made this report as the final product of my thesis project, and I am approaching the end of my master study in Delft.

First of all, I would like to thank my parents for your love. You made it possible for me to study abroad and always encouraged me throughout my master program. I am also grateful to Anli for your support and encouragement, which helped me to pass the hard time during the thesis project.

I would like to extend my thanks to my daily supervisors, Winnie Daaman and John Baggen, for giving me patient guidance. You helped me to learn the way to do a scientific research and your comments enabled me to improve this thesis greatly. I would also like to thank other committee members, Prof. Serge Hoogendoorn, Sascha Hoogendoorn and Henk Taale. You gave me an opportunity to do a research in ITS Edulab, where I could be involved in a Dutch project. Your suggestions helped me to finish the thesis project more smoothly.

I am also indebted to my colleagues in Edulab and Rijkswaterstaat. It is a great experience to work with you and to share ideas. Finally I am grateful to all my friends and classmates in the Netherlands, with whom I spent much wonderful time in last two years.

Xiaoyu Qian
Delft
16 August 2009

Table of contents

List of Figures

List of Tables

Notation

MFD variables:

l_i	:	length of road lane segment i
q_i	:	flow on road lane segment i
k_i	:	density on road lane segment i
q^w	:	weighted average flow
k^w	:	weighted average density

MARPLE variables:

$\hat{c}_k^{rod}$	:	perceived travel costs of traffic departing during time period *k* form from origin *o* to destination *d* using route r
c_k^{rod}	:	travel costs of traffic departing during time period *k* form from origin *o* to destination *d* using route *r*
ε_k^{rod}	:	random component of the travel costs of traffic departing during time period *k* form from origin *o* to destination *d* using route *r*
CF_k^{rod}	:	commonality (overlap) factor for route *r* of OD pair *od* and time period *k*
P_k^{rod}	:	probability to choose route *r* of OD pair *od* during time period *k*
$\Re^{od}$	:	set of feasible routes between origin *o* and destination *d*
v_{at}	:	outflowfor link *a* at time step *t*
Δ_s	:	length of time step *t*
τ_{at}	:	travel time on link *a* at time step *t*
Q''_{at}	:	capacity at the end of link *a* at time period *t*
Ψ_{at}	:	available space on link *a* at time period *t*
$\chi_{a,t}$	:	number of vehicles on link *a* at time period *t*
u'_{at}	:	restricted inflow for link *a* at time period *t*
v'_{at}	:	corrected outflow for link *a* at time period *t*

VISSIM variables:

$T_i^{n,k}$: measured travel time on edge i at time period k in iteration n

$TO_i^{n,k}$: expected travel time on edge i at time period k in iteration n

$p(R_j)$: probability to choose route j

U_j : utility of route j

C_j : costs of route j

1. Introduction

Traffic congestion is witnessed in many large cities and various measures have been studied and applied to improve the traffic situation. Compared with building new infrastructure, effective utilization of existing roads is more attractive because of lower costs and less damage to the environment. To identify the effects of traffic measures, many forecasting models have been developed. However, modelling city traffic effectively and efficiently has always been a challenge to traffic engineers, especially when trying to predict motorway traffic and urban traffic simultaneously. These two kinds of roads often have different priorities, and sometimes they are even maintained by different road operators (Taale, 2006). Existing models usually have drawbacks when modelling urban traffic. In most models, outputs of congested systems are hyper-sensitive to the inputs (Daganzo, 2007). In addition, large amounts of inputs such as time-dependent origin-destination (OD) matrices and link characteristics are required.

In order to model large scale networks more efficiently and realistically, a new concept called macroscopic fundamental diagram (MFD) has been proposed (Daganzo, 2005). Traditionally, a fundamental diagram reveals the traffic condition on a short road section, relating traffic variables such as flow, density and speed. (Hoogendoorn, 2008). Geroliminis and Daganzo (2007) expanded the concept of the fundamental diagram and modelled the traffic situation on a network level. They put forward that entire city neighbourhoods exhibit similar macroscopic fundamental diagrams, relating the rate at which trips reach their destinations (the trip completion rate) to the number of vehicles in the network (the accumulation). By using MFDs, The road operators can take appropriate measures mainly based on the current traffic situation. The forecasting models can be replaced by simple MFDs, ensuring the effectiveness and efficiency of traffic measures.

1.1 Project PraktijkProef Amsterdam

Since the MFD appears quite effective in real time traffic control, the Rijkswaterstaat for Transport and Navigation plans to make a first attempt to use MFDs in the Netherlands. This thesis project is also a part of the project PraktijkProef Amsterdam (PPA), aiming to prove the added value of the coordinated traffic measures. The PPA project covers both motorways and the urban network in Amsterdam region. The coordinated network traffic management in the regional area is analyzed. All coordinated measures are divided into four levels, which are isolated measures, coordination strings, sub-networks and networks respectively (Hoogendoorn & Hoogendoorn-Lanser, 2009).

Figure 1.1 illustrates the structure of four levels of the concepts in PPA. Isolated measures determine the control signals according to the current state of the system. The typical examples include local ramp metering installation and speed signal control. In these cases, the local traffic variables are measured for generating the control plan. Presently, attempts have been made to study the effects when several measures work in coordination, corresponding to the concept of coordination strings. For instance, one local ramp metering installation may work co-ordinately with others as well as the nearby intersection controllers, to derive a more smooth traffic situation on a long road section (Yuan, 2008). The concept of sub-networks is the third level, in which the traffic controls are made based on the viewpoint of a large size area. The MFD is expected to be a useful tool to describe the traffic situation of a network so that it is worthwhile to investigate the characteristics of MFD. This thesis project is trying to make contributions on this topic. If the focus is the general performance of the whole network, the concept of traffic control will be transferred to the top level, network, in which the three lower concept levels are also included to improve the traffic situation of the large network.

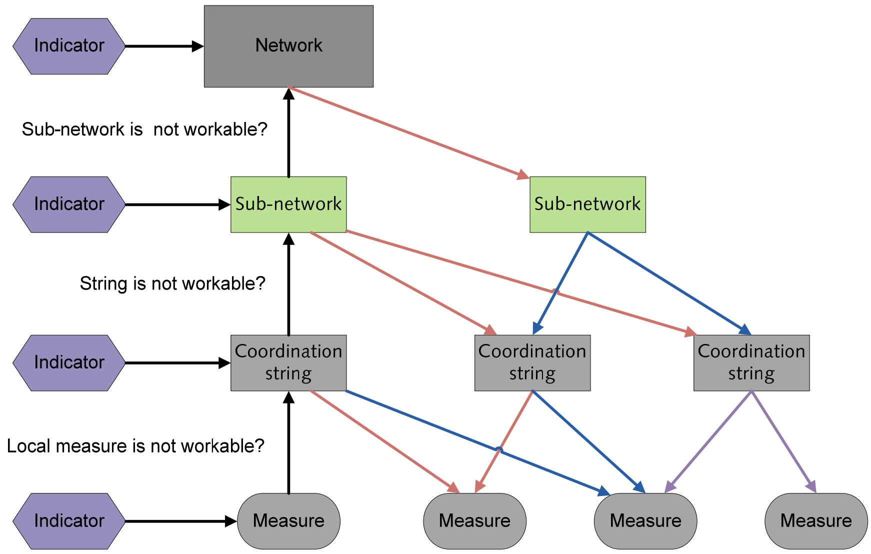


Figure 1.1: Four levels of control concept in PPA

1.2 Problem definition and main objectives

The study of Geroliminis and Daganzo (2007) has proven that an MFD with low scatter can be found for the network with homogeneous traffic conditions, where congestion is (roughly) evenly distributed. However, no researches have been made to analyze the effects of the dynamic traffic management (DTM) measures on the MFD, relating output to accumulations. How the shape of an MFD changes with the implementation of DTM measures is therefore still unknown. In addition, the MFD is also an interesting issue for the Dutch project PPA. However, no MFD has been made for the study area of the project, which is the Amsterdam region.

Therefore, the objectives of the thesis project include deriving the MFDs in Amsterdam region, studying the effects of DTM measures on the shape of the MFDs and analyzing the potential of the MFD as an evaluation method for DTM measures assessment. The main research questions in this project are as follows:

- What do the MFDs look like in Amsterdam region?
- What are the effects of DTM measures on the MFD?
    - How do specific DTM measures affect the MFD?
    - Is it possible to use the MFD to evaluate the effects of DTM measures?

The study region of this project is the city of Amsterdam and its peripheral area (see Figure 1.2). It is mainly composed of the A10 beltway and the inside urban network. Several other motorways such as A1, A2 and A4 are taken into account, as well as the nearby urban roads.

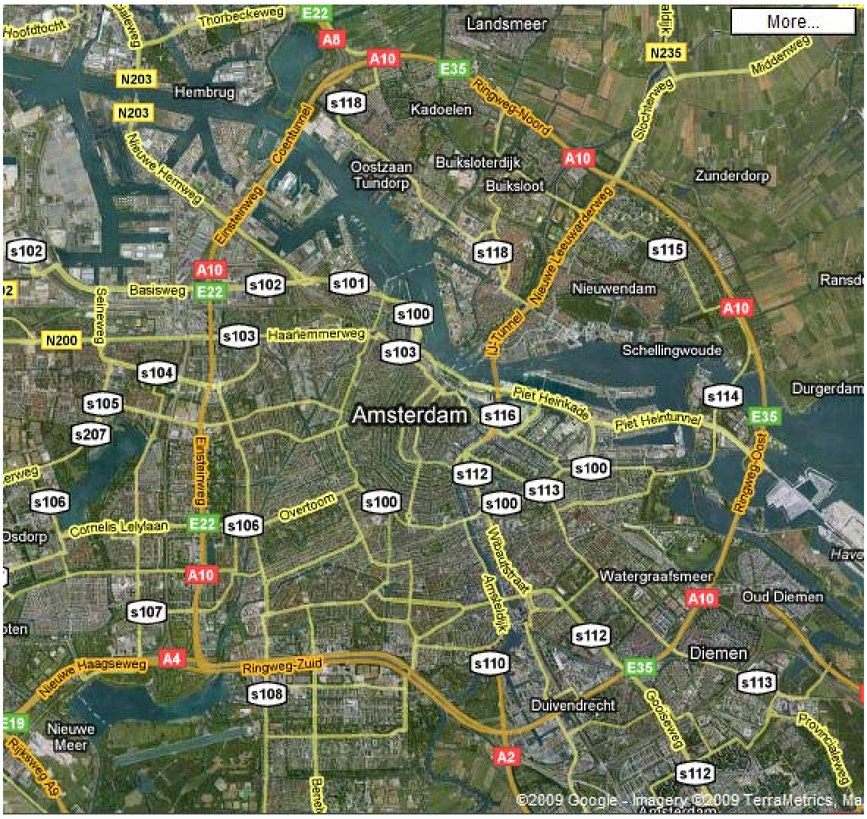


Figure 1.2: Study area of the project

1.3 Research approach

To derive the MFD of a network, traffic-related data like flow and density on almost all links have to be collected in the study area. In general, there are two ways to obtain such data, either by collecting empirical data or by using a simulation model. In order to analyze the situation in the Amsterdam network, collecting the empirical traffic data in that area is firstly considered. However, they are not sufficient to support the research. Although traffic data on motorways are collected by the detectors distributed along almost all motorways, only about 15 detectors are installed in the urban network of Amsterdam. The number of data collection points is too limited to aggregate the link variables for deriving MFD. Therefore, a simulation model is required to generate the traffic characteristics on the links.

The study area has been (partly) modelled in two simulation tools. One is the RBV model, which is the abbreviation of Regionale BenuttingsVerkenner (English: regional traffic management explorer). As a macroscopic simulation model, the RBV model is built as a plug-in of the OmniTRANS transport planning software (Taale, 2006). It covers the whole study area and both urban networks and motorways are involved. On the other hand, VISSIM is a microscopic simulation model. Only the A10 west motorway and the nearby urban roads are included in this model. Both the RBV model and the VISSIM model are able to implement the dynamic traffic measures. They have been used to investigate certain DTM measures in the study area (Taale, 2006; Yuan, 2008). Due to different strategies of traffic modelling in two models, both of them are analyzed. Investigation on the feasibility of deriving MFDs is meaningful to know the potential of two models and to propose possible improvements.

The results of the simulation are used to produce the MFDs for the study area under various conditions. The variables of an MFD like outflows and accumulations will be obtained by aggregating link variables, flow and density, from the simulation models. In this project, the DTM measures applied in the Netherlands will be reviewed. According to the real situation in the Amsterdam network, several measures implemented or to be implemented in this area will be chosen for analysis. In order to learn the influence of the DTM measures on both motorways and urban roads, the whole study area will be divided into several sub-networks based on the road types.

In addition, a multi-criteria analysis will be made to assess the potential of the MFD as an evaluation method. The conventional evaluation method will be compared with the MFD from the viewpoint of different stakeholders, in this case which are Rijkswaterstaat and the city of Amsterdam.

1.4 Outline of the thesis

In this section, the outline of the following chapters in the report is given. The structure of the thesis report is illustrated in Figure 1.3.

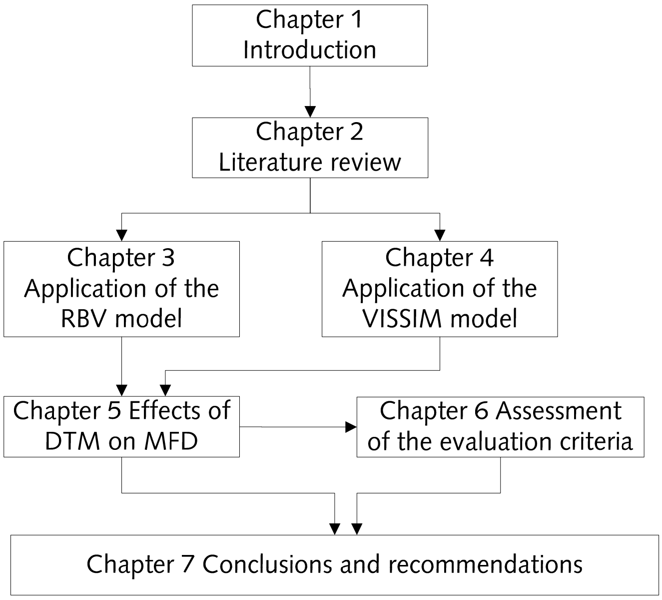


Figure 1.3: The structure of the thesis

Chapter 2 summarizes other researches on the MFD. Based on the literature review, a rough rule for deriving the MFD is generated and the possible factors affecting the shape of the MFD are indicated.

Chapter 3 describes the application of the RBV model. A case study is made of the whole Amsterdam metropolitan area and the feasibility of the RBV model for deriving the MFDs is discussed.

In Chapter 4, VISSIM model is used to obtain the MFDs for Amsterdam A10 west network, followed by the feasibility analysis on using VISSIM to obtain the MFDs.

In Chapter 5, two DTM measures, ramp metering and extra lanes, are applied and MFDs are derived in different conditions. The effects of DTM measures on the MFD in the study area are presented.

Based on the MFDs obtained in Chapter 5, Chapter 6 discusses the potential of the MFD for evaluating the DTM measures. A multi-criteria analysis is made to compare the MFD with the conventional method.

Chapter 7 summarizes the conclusions and recommendations for further research and improvement are pointed out.

2. Literature survey on macroscopic fundamental diagrams

In this chapter, other studies on MFD are reviewed. First of all, an introduction to MFD is given, presenting some basic characteristics of an MFD. After describing the method for aggregating the local data to the network level, several factors influencing the shape of MFD will be discussed. Finally, the conclusions of the literature review are addressed. The results in this chapter will be used in following chapters for deriving the MFDs and discussing the shapes of the MFDs derived from the simulation models.

2.1 Introduction to MFD

Macroscopic fundamental diagrams have been proven to exist in small networks, revealing the relation between the outflow and accumulation in a network (Geroliminis & Daganzo, 2007). The accumulation is the number of vehicles in the network, and the outflow reflects the rate at which trips reach their destinations. A typical MFD is illustrated in Figure 2.1.

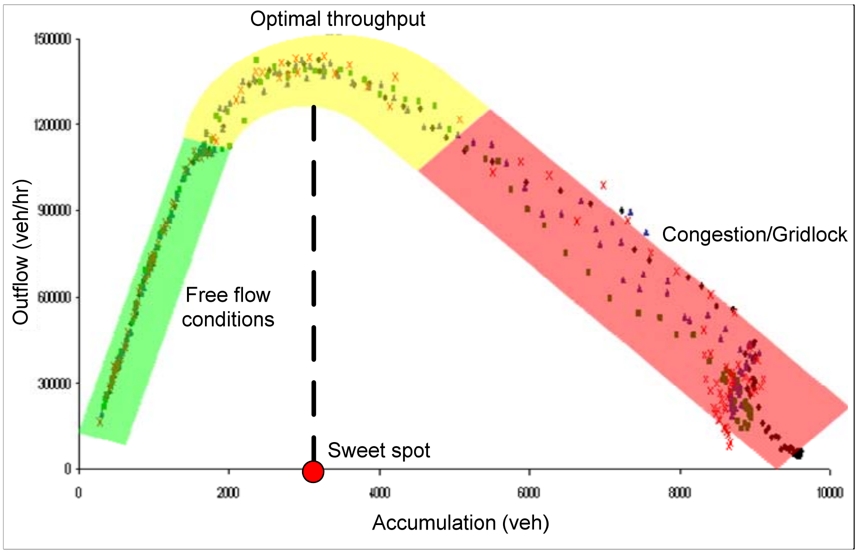


Figure 2.1: MFD of outflow relative to accumulation for a city

(Geroliminis & Daganzo, 2007)

Similar to a conventional link fundamental diagram relating the local flow and density, three states are demonstrated on an MFD. When only a few vehicles use the network, the network is in the free flow condition and the outflow is low, as the green part shown in Figure 2.1. With the increase of the number of vehicles, the outflow rises up to the maximum, indicated by the yellow region. Like the critical density in a link fundamental diagram, the value of the corresponding accumulation when maximum outflow is reached, is also an important parameter, called "sweet spot". As the number of vehicles further increases, travellers will experience delay. If vehicles continue to enter the network, it will result in a congestion state where vehicles block each other and the outflow declines, indicated by the red part in Figure 2.1.

2.2 Deriving MFD from the local traffic data

The MFD relates the outflow and the accumulation in a network. However, outflow is not an observable quantity and it cannot be measured in reality by detectors or other devices. Therefore, another traffic variable, travel production, is proposed. The travel production is the total distance travelled by all vehicles in the network. Data from both reality and simulation have proven that the travel production is proportional to outflow. The ratio of the travel production and the outflow equals the average trip length for all vehicles in the network. (Geroliminis & Daganzo, 2007). Hence, the travel production is applied as a proxy for unobservable data, outflow.

In order to derive the MFD of a network, the link traffic variables such as flow, density and speed are needed. The number of measured links should be as many as possible to derive an MFD which can reflect the network traffic situation correctly. The data on the network level are easily generated by averaging the link data. The weighted average values suggested by Geroliminis and Daganzo (2008) are used to obtain the network data.

$$q^w = \sum_i q_i l_i / \sum_i l_i \tag{2.1}$$

$$k^w = \sum_i k_i l_i / \sum_i l_i \tag{2.2}$$

where i and l_i denote a road lane segment between intersections and its length respectively; and q_i and k_i denote the flow and density in the segment. The weighted average flow q^w and the weighted average density k^w can be regarded as the travel production and the number of vehicles per unit road length respectively. If the link traffic data are measured at a high frequency, usually for every 3 or 5 minutes, for a long time, the traffic variables with great changes can be recorded. By relating the weighted average flow and the weighted average density of all measured links in the network, the MFD of the network are derived.

The timing slice is a significant factor when aggregating traffic data from the link level to the network level. It obviously influences the results, especially for links with signal control. During the red time, vehicles have to queue in front of the stop line, resulting in high densities and zero flow on that section. By contrast, when traffic lights turn to green, the queue dissolves at saturation rate until vehicles can pass the intersection without delay. In that case, the flow and speed will be higher while the densities will be much lower than those in the red phase. The aggregation period should be at least longer than cycle time in order to eliminate the influence of traffic lights. In reality, 120 seconds is commonly used as the maximum cycle time (Van Zuylen & Muller, 2008). So 3 minutes or 5 minutes are usually set as the length the time slice.

Moreover, in order to derive a complete MFD, in which free flow conditions, optimal throughput and gridlock regimes are all involved, the traffic data under both peak and off-peak hour should be collected. Sufficient data under various traffic conditions are necessary to ensure all states in the MFD can be demonstrated, especially if the MFD is used for traffic control.

2.3 Factors in determining MFD

The researches of Gerolimins and Daganzo have proven the existence of a macroscopic fundamental diagram. In the study in Yokohama, data were aggregated for two different days: a weekday and a weekend. The results show even though the OD matrix changes significantly across time periods, the outflow of the network varies only with the accumulation of vehicles in the network in a consistent way (Geroliminis & Daganzo, 2008). It implies that the MFD is not sensitive to OD demand. This is an advantage when using the MFD for traffic control.

However, the study of Buisson and Ladier (2009) showed that the shape of the MFD changes due to several other factors. They selected the network of metropolitan Toulouse, the size of which is similar as that of the Amsterdam network. The MFDs under different conditions were derived. From their research, it can be concluded that three factors, which are distance between detectors and traffic signals, type of roads and onset and resolving of congestion respectively, do affect the shape of an MFD.

- Distance between detectors and traffic signals

In the case in Yokohama, loop detectors are all positioned about 100 meter upstream of major intersections. So the effects of location where the data are collected on the shape of MFD are not indicated. However, it should be intuitive that the shorter the distance between detector and traffic signal, the higher the probability that a queue is observed. The traffic data from detectors with different distance to intersection vary largely. In the case of Toulouse, all detectors are sorted by the distance to downstream traffic signal. An MFD is obtained for each of three categories. The results show that although the maximum outflow is constant under different conditions, the sweet spot value becomes larger when data from detectors closer to the signals are chosen. These detectors are more likely to record high densities caused by the red phases of the downstream traffic lights.

- Type of roads

The traffic variables on motorways and the urban roads are obviously different. The traffic speed on motorways is much higher than that on urban roads due to different speed limit. Vehicles can usually travel more smoothly on motorways. In the Toulouse network, a motorway ring road has been built around the urban area. The situations on motorways and urban roads are analyzed separately. It is obvious that the maximum outflow in the MFD of the motorways is much higher than that of the urban roads. Moreover, the sweet spot value is low for the motorways due to lower occupancy rate.

- Onset and resolving of the congestion

The number of vehicles will increase during the peak time and decline during the off-peak period. If the traffic demand varies dramatically, the congestion will not be distributed in the network or dissolve evenly, especially in a large network. If an MFD is derived based on the data from rapid transformation period, the homogeneity of traffic situation in the network is not held, leading to the high scatter in the MFD. The network of Toulouse is too large to ensure a homogeneous traffic condition. In the case of Toulouse, the traffic data are collected in two days, on one of which congestion occurs on the motorways due to slow driving of truck drivers. High scatter is shown on MFD, corresponding to the resolving period of congestion. However, when only centremost part is considered, the scatter does not emerge any more. This sub-network is small enough to ensure traffic situation are similar in the whole network even when congestion occurs or dissolves quickly.

2.4 Conclusions

In this chapter, an overview has been made of characteristics of the macroscopic fundamental diagrams. Given sufficient link traffic data, a fundamental diagram can be derived for the network level. The MFD does not change with the demand variation, but it indicates different patterns when traffic data are collected from detectors having various distances from the downstream intersections, on various types of roads, and during the period when the traffic situation changes dramatically.

In this project, the MFDs are derived by using the simulation models so the influence of the distance between detectors and traffic signals can be eliminated. However, the other two factors mentioned in previous section have potential influence on the shape of MFDs. To get an MFD which can be used for traffic control the network partition must be made not only based on geographical patterns but also on types of roads. Besides, the dramatic changes of traffic during the onset and resolving of the MFDs probably cause high scatter on the MFD.

3. Application of the macroscopic model RBV

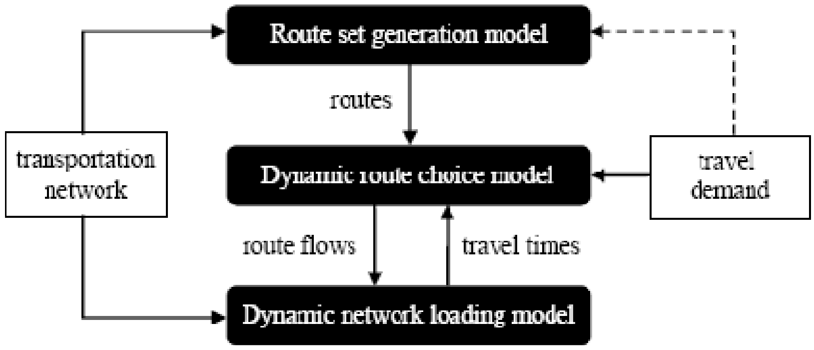
This chapter describes the application of the RBV model to derive MFDs. First of all, the principles of the RBV model are indicated in section 3.1, followed by the introduction of the Amsterdam network modelled in RBV. In section 3.3, the MFDs based on simulation results are demonstrated. Afterwards, in section 3.4, the shapes of MFDs are discussed and the explanations of results in the previous section are presented. Finally the conclusions on the feasibility of using the RBV model to derive MFDs are given.

3.1 The RBV model and the DTA model MARPLE

The RBV model is a part of a traffic management approach, Sustainable Traffic Management (STM) described by Taale (2006). Traditionally, Dutch traffic management only works on a local level. Road operators pay attention to the network they are responsible for, resulting in a lack of combination and coordination between each other. With a step by step approach, STM helps policy makers to translate policy objectives into tangible measures, taking opinions of different stakeholders into account. Focus is shifted from the local level to the regional level and various types of roads are considered. The RBV model is able to simulate the traffic situation on certain road networks with various road types and to evaluate the effects of proposed traffic measures.

The core of the RBV model is called MARPLE (Model for Assignment and Regional Policy Evaluation). As a dynamic traffic assignment (DTA) model, MARPLE makes it possible to simulate the real traffic situation in the RBV model. In addition, the DTM measures can be implemented in MARPLE to analyze their influence on traffic. MARPLE is made up of three components: (i) Route set generation model, (ii) Dynamic route choice model and (iii) Dynamic network loading model (Taale, 2008), as illustrated in Figure 3.1. In this section, these three models are explained in more detail.

Figure 3.1: DTA components of MARPLE (Taale, 2008)



- Route set generation model

Given the transportation network, routes are generated for each Origin-Destination (OD) pair. Firstly, the real shortest route between origin and destination is determined according to integrated route costs. The costs are calculated based on route attributes including free travel time and travel distance. Then, a random disturbance term in the travel time and/or travel distance is introduced for each link. The costs of each route change and another shortest route may be selected. By repeating the calculation, multiple routes are obtained. This step reflects the fact that drivers will choose multiple routes rather than only the shortest one in reality. In MARPLE, the random term will be changed until sufficient routes are found. The number of these routes generated for each OD pair is determined by the user. Usually, 50 is set as the default number, from which routes will be chosen for dynamic route choice model (Taale, 2007).

In order to reduce the simulation run time, the number of routes used by the drivers travelling between a specific OD pair is limited. Those 50 routes generated in the route set generation model are checked whether they are almost same. If two routes share more than 85% common links, they are regarded as the same route and only the shortest route is chosen. It ensures that routes are sufficiently different. Otherwise, the drivers between an OD pair may not have an alternative when several links on a route are heavily congested. For each OD pair, several shortest routes are used as alternative routes. This number can be modified by the user of the RBV model. The default value is four in this project, considering a trade-off between reality and the computing time.

- Dynamic route choice model

In the RBV model, both deterministic and stochastic assignments are available. In reality, drivers do not have perfect knowledge on the route travel costs and they only know a limited number of routes. The usual considered costs include travel time, travel distance and tolls. Drivers predict route travel costs based on their expectations, which may deviate from the real costs. Rational drivers choose a route with the lowest travel costs from all route alternatives they know. Hence, the stochastic dynamic user optimal assignment is applied in the model to reflect the real situation more correctly. The traffic situation reaches equilibrium when any road user travelling between a specific origin and destination and departing during a specific time interval cannot improve his or her perceived route travel costs by unilaterally changing routes during that time interval. The simulation keeps running until the stochastic dynamic user equilibrium (SDUE) is achieved, on which the route choice proportions and travel times are consistent.

Drivers choose routes according to the perceived route costs of four routes obtained by the route set generation model. The perceived route costs $\hat{c}_k^{rod}$ for OD pair od, route r and time period k can be represented by

$$\hat{c}_k^{rod} = c_k^{rod} + \varepsilon_k^{rod} \tag{3.1}$$

where c_k^{rod} are the real travel costs and ε_k^{rod} is the random component.

If the random term is assumed to be mutually independent, identically distributed Gumbel variate, the logit model is attained. Given actual travel costs, the probability to choose route *r* for OD pair *od* and time period *k*, can then be described by

$$P_k^{rod} = \frac{e^{-\theta c_k^{rod} - CF_k^{rod}}}{\sum_{s \in \Re^{od}} e^{-\theta c_k^{sod} - CF_k^{sod}}}, \ \forall o,d,r \in \Re^{od}, k \tag{3.2}$$

where $\Re^{od}$ is the set of feasible routes between *o* and *d*. $\theta > 0$ is a parameter that indicates the degree of uncertainty in the travel time knowledge of all travellers. When θ is large enough (>100), it can be seen as that travellers have perfect route knowledge and a deterministic user equilibrium is obtained. Although the routes having many overlapping links have been eliminated, the alternative routes may still have the common links, which reduces the accuracy the logit model. Hence, the C-logit model is applied by including a commonality factor *CF*, reflecting to what extent several routes share common links.

In order to reach SDUE, the flows are calculated iteratively. The method of successive averages (MSA) is used to smooth the value until the convergence criterion of the MSA is met. It should also be noticed that when parameter θ is constant, the results of the simulation remain the same. Hence, a single simulation run is sufficient for the RBV model.

- Dynamic network loading model

The dynamic traffic assignment generates, for each time period, the route flows, which need to be loaded onto the network to obtain the link indicators. Taale has developed a deterministic dynamic network loading (DNL) model because no other DNL model was readily available. To reflect the changes in demand, the total simulation period is partitioned into several time periods with a length between 5 minutes and 30 minutes. To load traffic through the network, each time period is further divided into time steps with 5 to 30 seconds. It is assumed that during each time step, the arrival rate of the vehicles is constant. In this project, 5 minutes and 10 seconds are selected for the lengths of time period and time step respectively to investigate the precise changes in the simulation. The steps of the DNL model can be described in the following algorithm (Taale, 2008).

Algorithm 3.1 Dynamic network loading model

Step 1: Initialize all variables needed.

Step 2: Calculate splitting rates μ_k^n for every node *n* and time period *k*.

Step 3: Propagate traffic through the network using the following steps:

For every time step *t*:

- Determine delay and travel time per link.
- Calculate the outflow per link.
- For every node determine the inflow.
- Calculate the available space for every link.
- For every node *n* determine the outflow with the splitting rates μ_k^n.
- Determine the inflow for every link.
- Determine links with blocking back and adjust the outflow for those links.
- Calculate link indicators.

Step 4: Calculate delay and travel costs c_k^{rod} for every route *r* from origin *o* to destination *d* and time period *k*

In step 1, the traffic variables in the first time period are initialized. Numbers of vehicles on each link and link travel time are calculated according to free flow travel conditions. Afterwards, for each time period, the splitting rates μ_k^n of each node *n* are determined to propagate traffic through the network based on demand distributed to routes generated in the dynamic route choice model. The splitting rates remain the same during one time period and several traffic variables are then calculated in order for each time step.

First, the degree of saturation of a link is determined as a function of the number of vehicles on the link, the capacity of saturation flow and the length of the time step. The outflow v_{at} , which is the number of vehicles willing to leave link *a* in time step *t*, can be calculated by combining link inflow μ_{at}, queue length κ_{at} in the previous time step and the number of vehicles on the link χ_{at}

$$v_{at} = \max(u_{a,t-1}\frac{s_a^p}{s_a}, \frac{\Delta_s}{\tau_{at}}\chi_{at} + \kappa_{a,t-1}) \tag{3.3}$$

Where Δ_s is the length of the time step, τ_{at} the link travel time and s_a the parameter to determine the number of time steps for link *a*. It is obvious that the outflow v_{at} is limited by capacity at the end of the link Q''_{at}.

The inflow of a node *n* is the sum of outflows of the incoming links. These flows are then distributed to the outgoing links according to splitting rates. The splitting rate of a node is determined by route flows which pass this node. However, the possible inflow of a specific outgoing link is also limited by the capacity of this link, which is called available space Ψ_{at} in the DNL model. The available space is a maximum for the link inflow, determined by the total link space minus the number of vehicles on the link. When the available space is smaller than the total node outflow, part of the traffic cannot pass the node and stays on the incoming links. Therefore, a queue appears on the incoming links and the outflows of these links have to be corrected. Then, the outflow of an incoming link, which has a relation with the outgoing links causing the blocking back, is determined by unconstrained outflow and queue length in the previous time step. The difference between unconstrained outflow and corrected outflow is used as queue length for next time step.

Hence, the number of vehicles on the link is corrected using the following formula

$$\chi_{a,t+1} = \chi_{a,t} + u'_{at} - v'_{at} \tag{3.4}$$

where u'_{at} and v'_{at} are the restricted inflow and the corrected outflow of link *a* in time step *t* respectively.

Then the travel time on each link is calculated based on the traffic situation. According to the types of traffic control in the end of the link, the links are divided into four types, namely normal links (no special characteristics), controlled links, roundabout links and priority links. The formulas used to calculate the link travel time are quite different, but in general they are all functions of the degree of saturation and queue length on the link. The higher the saturation degree and the longer the queues are, the longer the travel time will be. By adding the travel times of links forming a route using a trajectory method, the route travel time is generated. They are used as an input for the next time step and all variables will be recalculated. For each time period, the route travel time is obtained by averaging values in all time steps. The route travel times are an input to the dynamic route choice model to determine the route choice in next time period. Therefore, the components of MARPLE are connected and the dynamic traffic assignment is made.

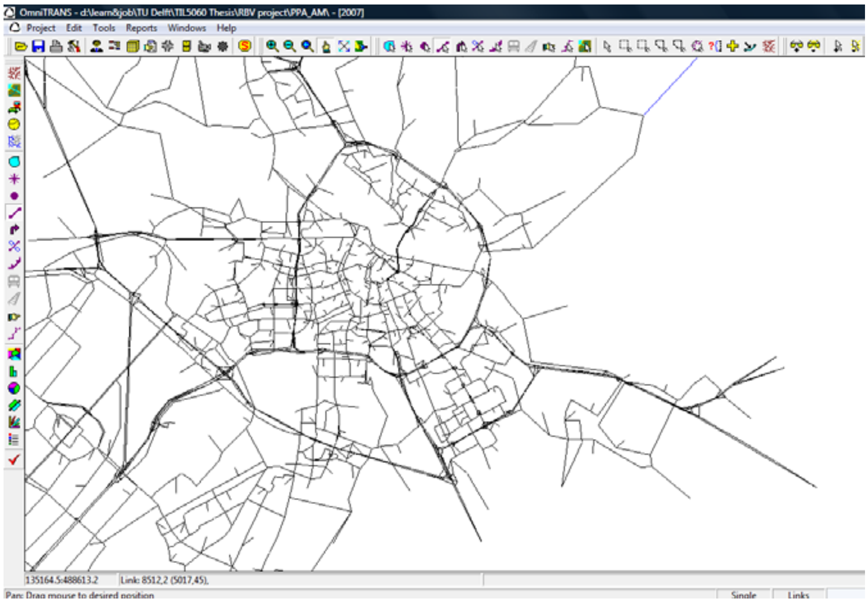
In the output file of the MARPLE model, the values of the traffic variables on each link in each time period are exported, including flow, density and speed. Flow is obtained by counting the number of vehicles entering the link in one time period. Hence it is the inflow of each link, which is only restrained by the available space on the link. The density is defined as the number of vehicles on the link divided by the link length. In each five-minute time period, there are 30 ten-second long time steps. The number of vehicle for each time period can be obtained by averaging all 30 values for the time steps. The density is then generated by using the average value of the number of vehicles divided by the link length. Similarly, speed reflects the traffic situation over the whole link. In each time step, the link travel time is calculated, as a function of the congestion level on the link. Link travel time per time period can easily be represented as the mean value of those for all time steps. Link speed is attained by the link length divided by the average link travel time.

In the project, link flow and density will be aggregated based on formula (2.1) and (2.2). The network variables will be obtained for each time period so that the MFD across a long period, including both peak and off-peak hour will be derived. When empirical data are not available, the RBV model is expected to be a good substitute.

3.2 The Amsterdam network in the RBV model

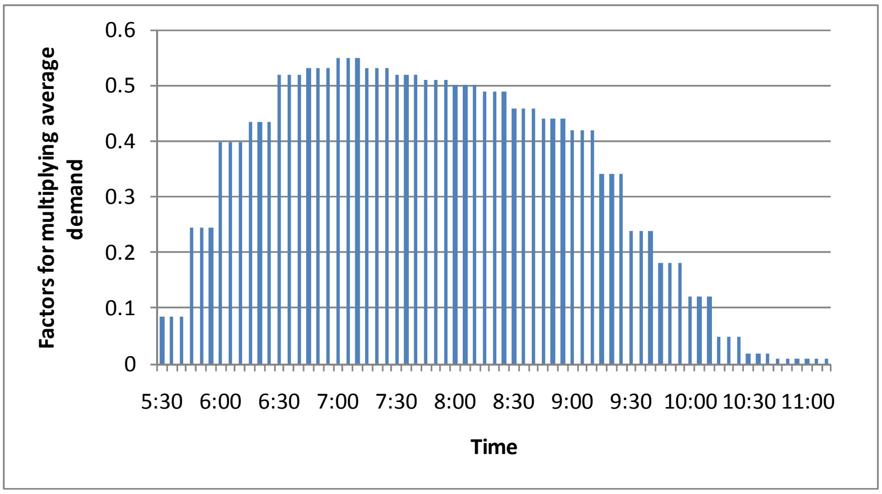
In this section, the basic information about the Amsterdam network modelled in RBV is described. Figure 3.2 illustrates the network of the municipality of Amsterdam in the RBV model. The network covers the whole study area, including motorways and the urban roads in Amsterdam. The model contains 4699 links, the lengths of which vary from 10 meters to more than 8000 meters. Most long links are in the outside of Amsterdam area and near the boundaries of the network. The main part of the study area is made up of short links so that the traffic conditions over the network can be reflected precisely by the sufficient link variables.

Figure 3.2: Amsterdam network in the RBV model



The RBV model is able to simulate the traffic situation in both the morning and the evening period. The morning period starts at 5:30 and ends at 11:00, and the evening period lasts from 14:30 to 20:00. In each simulation period, a static OD matrix of two-hour peak time has been obtained from a strategic model. The matrix can be modified into a dynamic one by multiplying time step function changing every 5 minutes, to cover the whole simulation period of five and half hours. For each 5 minutes, the static OD matrix is multiplied by a factor to derive the dynamic OD matrix. The time step function is shown in Figure 3.3. The vertical axis shows the factors used for multiplying the average demand to derive the dynamic OD matrix in the RBV model.

Figure 3.3: Time step function for deriving dynamic OD matrix



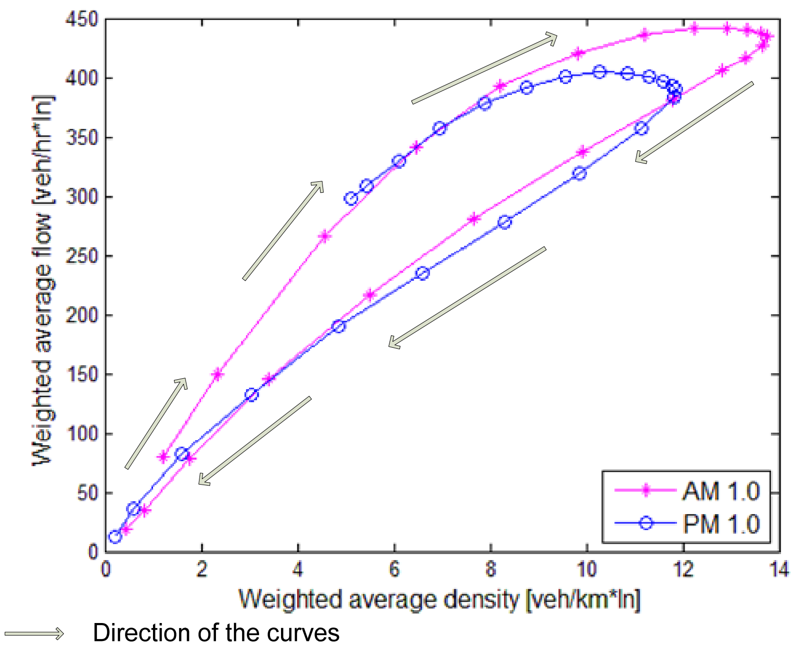
The OD matrix has been calibrated by comparing the simulation results with the empirical traffic data on motorways (Taale, 2008). However, calibration on the urban roads is not feasible due to a lack of real data. Therefore, the model was calibrated to only reflect the traffic situation on motorways closely. After calibration, the OD matrix represents the average traffic demand of one year. So it needs to be scaled to simulate the situation under different demand levels.

3.3 The MFD derived from the RBV model

By using the RBV model, the MFDs can be derived for the study area. In this section, the MFDs at the average demand level is firstly derived, for both the morning peak hour and the evening peak hour. Then the demand is multiplied by different factors to study the change of the MFDs under different demand levels. Afterwards, the whole study area is divided into several sub-networks because the types and sizes of networks are expected to affect the shape of the MFD. The MFDs are obtained for these small areas make up of the same type of links. Therefore, the MFDs under different conditions are derived which give a complete insight on the potential of the RBV model for getting the MFDs.

After running the RBV model, the traffic variables including density and flow on all links can be collected. The link data are aggregated to the network level by formula (2.1) and (2.2). The MFDs with average demand in both morning and evening perk derived by the RBV model are illustrated in Figure 3.4. Compared to the MFDs obtained in previous studies, these MFDs show totally different patterns. While traffic is in the free flow state, the curves are similar as those in conventional fundamental diagrams. The maximum average flow in the morning and in the evening are 450 and 400 veh/hr*lane respectively. This is logical because the total demand of two hours static demand for the morning period is higher than that for the evening period (451527 and 363583 vehicles respectively). However, when the traffic dissolves after peak hour, the curves do not go back along the shape they built up. There is a drop of weighted flows between the onset and the resolving of congestion indicated in Figure 3.4. Furthermore, the congestion branch on a conventional fundamental diagram is missing.

Figure 3.4: MFD of the whole network at the average demand level



Then, the default OD matrix in the RBV model is scaled by different factors to investigate how the MFD changes at various demand levels. In general, the shapes of the MFDs are similar in all cases (see Figure 3.5). While traffic load is increasing, the free flow parts of the curves follow almost the same shape. However, when density becomes higher, they diverge with different slopes. The scenario with a higher demand level has larger flow at the same density. In addition, the curves never go down at high densities like a conventional fundamental diagram and the MFDs derived in previous researches. Even when traffic demand is 30 percent higher than the average level, the flow still grows with increasing density. Hence, the sweet-spot at which the flow reaches the maximum cannot be found in these MFDs. Moreover, no matter what the demand level is, the drop between weighted flows of the onset and the resolving of congestion always exists. The higher the demand, the larger the drop in flow is shown. Only when OD demand is lower than 60 percent of the average demand of one year, the drop of flow is not clear any more (see Figure 3.6). In that situation, the traffic in the network is quite low and the queues are recorded on only a few links during the peak hour. It implies that the drop is caused by congestion.

Figure 3.5: MFD of the whole network at different demand levels

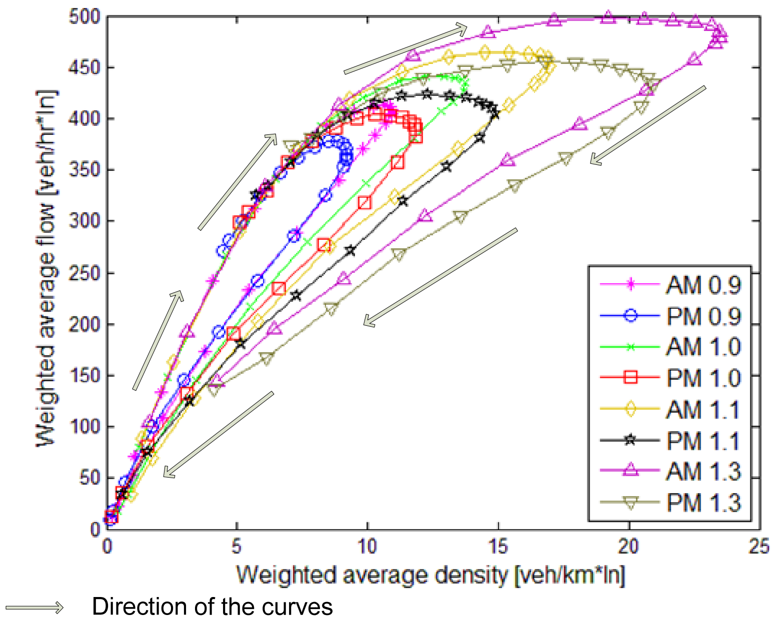
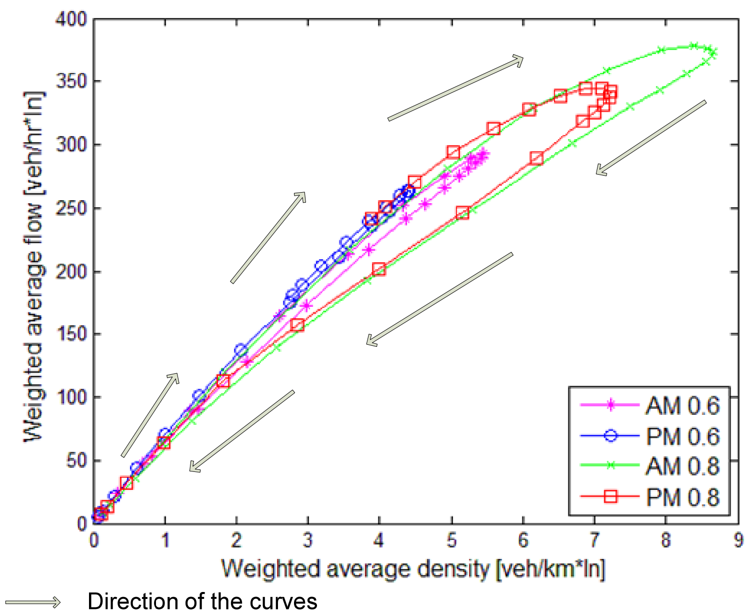
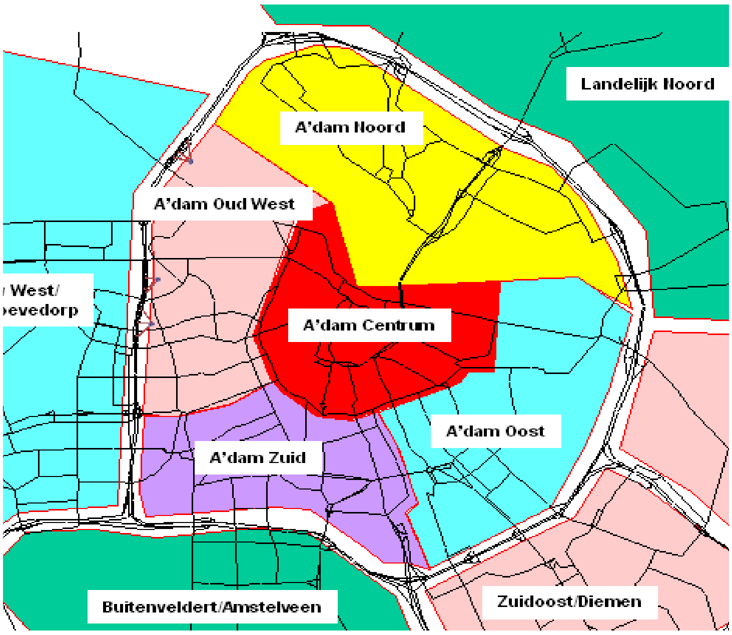


Figure 3.6: MFD of the whole network at low demand levels



In the following, the MFDs of sub-networks are derived to learn whether the MFDs maintain similar shapes in a smaller network. The whole study area is divided into several sub-networks based on both types of roads and the geographic pattern (Figure 3.7). Two sub-networks, Amsterdam centre and A10 beltway have been chosen to investigate MFDs in a small area composed of the similar types of roads.

Figure 3.7: Subdivision of Amsterdam network in the RBV model



The sub-network Amsterdam centre (the central subarea in the Figure 3.7) contains 208 links, covering the city centre of Amsterdam. The links are all urban roads with speed limits of either 50 or 70 km/h. At most intersections, signals are installed to control the traffic. The congestion level is almost evenly distributed in the network, considering its small size. The MFD of this sub-network is illustrated in Figure 3.8, in which similar patterns as the MFD of the whole network can be observed. The difference of flows between the morning and the evening period is more significant.

Figure 3.8: MFD of Amsterdam centre sub-network at different demand levels

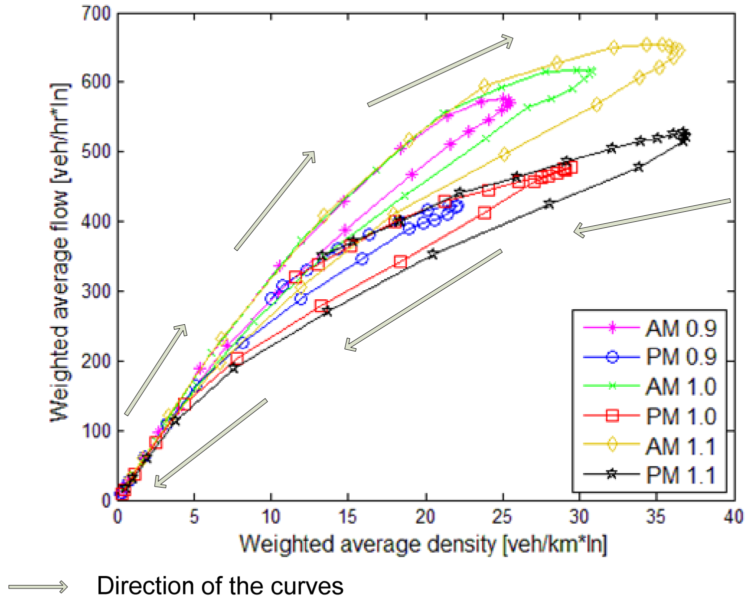
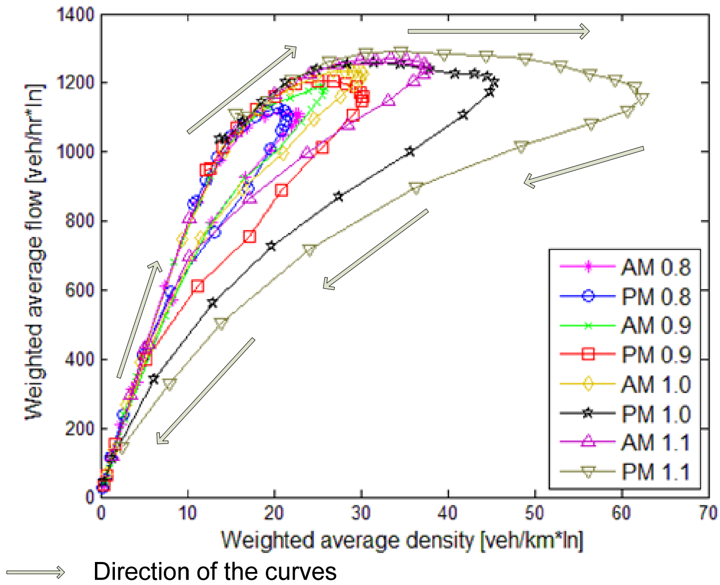


Figure 3.9 shows the situation on the A10 beltway, the ring road around the city of Amsterdam. 121 links, with speed limits of 80 or 100 km/h, compose the network. It can be found that traffic builds up along the same shape and reaches almost the same maximum flow, about 1250 veh/hr*ln, for different demands. However, the flow becomes much lower at the same density when congestion dissolves, which is also shown in the case of the whole network. The shape of a theoretical fundamental diagram is not observed in MFDs derived from the RBV model.

Figure 3.9: MFD of A10 beltway sub-network at different demand levels



Unlike the situation in the Amsterdam centre sub-network, the congestion levels of the links in the A10 beltway are quite different. During the peak hour, some links are totally congested while other links still remain in free flow state. When only data from congested links are considered, the shape of MFD is similar to that of the whole A10 beltway sub-network (see Figure 3.10). The maximum density increases dramatically from 35 to about 95 veh/km*ln and the maximum flow is decreased by about 150 veh/h*ln.

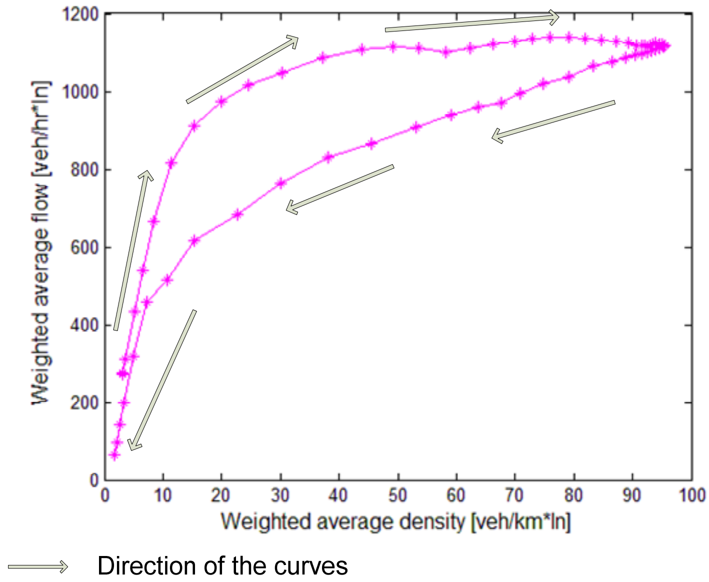


Figure 3.10: MFD of congested links on A10 beltway sub-network (AM 1.0)

3.4 Explanation of the shape of MFD derived from RBV

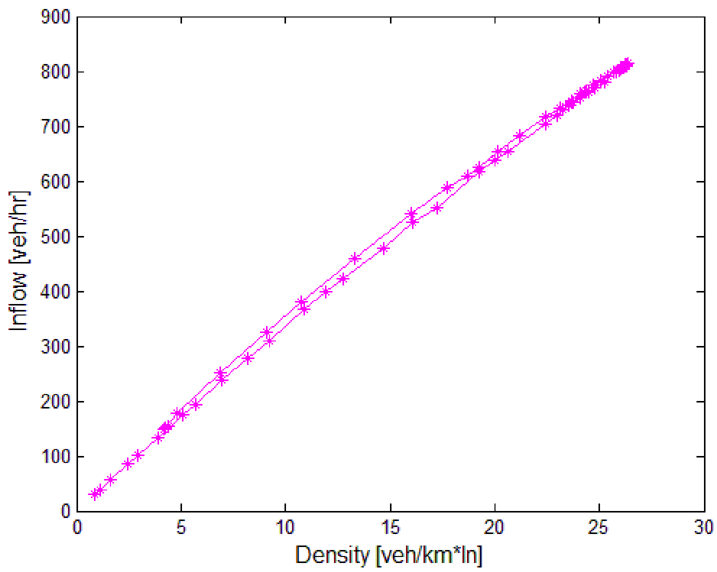
In last section, the MFDs in different sub-networks under various traffic demand levels are derived by using the RBV model. In these diagrams, some common patterns can be observed. Firstly, it is likely that drops of flows between the onset and the resolving of the congestion will always exist in the RBV model, regardless of the size and the type of the network. Furthermore, the congestion branch of a conventional fundamental diagram is not shown in the MFDs obtained from the RBV model. The results are quite different from the MFDs in previous studies, which have been derived from the empirical data. In those cases, the shape of the MFDs is similar to a conventional link fundamental diagram.

Hence, in this section, analysis is made on the reason why the shape of MFDs derived from the RBV model is quite different to those derived from the real traffic data. The focus is shifted to the link level because the situation on one link during one time period is obviously homogenous. Then the reasons causing the shapes of the MFDs derived by RBV are found, which are the ways of measuring the traffic variables and loading the vehicles through the network in the RBV model. The detailed explanations are given as follows.

In the study area, several links are selected, from both urban roads and motorways, to derive link fundamental diagrams. Whatever the length and type of link is, the link fundamental diagrams show two shapes in general. If a link is always free during the simulation period, its fundamental diagram is a straight line. However, if queues are observed on a link, the shape of the link fundamental diagram is quite strange, with a loop during the congestion period. In this section, two links are selected to describe two shapes in more detail.

Figure 3.11 demonstrates the fundamental diagram of link 693, a 550 meters long link in the sub-network of the Amsterdam centre. It has a speed limit of 50 km/h. During the simulation period, travellers can always pass the link at a high speed. The average speed varies between 30 km/h and 36 km/h and no queues are recorded on this link. The fundamental diagram of this link also reflects these characteristics. Only the free flow state of a conventional fundamental diagram is seen in Figure 3.11 and the slope of the line approximately equals the average speed.

Figure 3.11: Fundamental diagram of link 693 at average demand level



The other type of the link fundamental diagram shows a totally different pattern. Link 2171 is a part of the A10 beltway near the junction of the A10 and A1 motorways (see Figure 3.12). Drivers are allowed to pass this 769.3 meters long link at a speed no higher than 100 km/h. It is composed of four lanes with a total saturation flow of 8000 veh/h. This link has two downstream links, one of which (link 873) is a bottleneck. The saturation flows of these two links are 2800 veh/h and 4000 veh/h respectively.

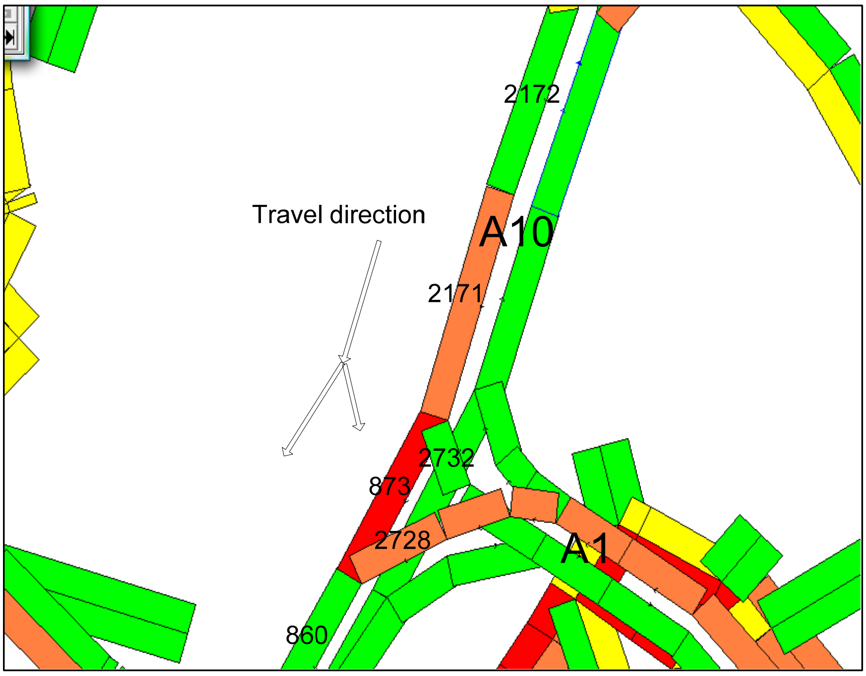


Figure 3.12: Layout of junction the A10 beltway and A1motorway

Figure 3.13 and Figure 3.14 demonstrate the queue length on link 2171 and the link fundamental diagram respectively. The numbers in the diagram represent different traffic states through the simulation period. When traffic is low, the fundamental diagram follows a straight line (state 1 of Figure 3.14). However, after the queue appears, it indicates a pattern which is not shown in a conventional fundamental diagram (state 2). While the density is rising dramatically, the flow is increasing to about 7200 veh/h for 4 lanes. Then the flow declines slightly to 6800 veh/h, the sum of the saturation flow of two downstream links. The density reaches the maximum, 127.2 veh/km (state 3). Considering the space occupied by a vehicle including both vehicle length and the average headway (7.5 meters in the RBV model), the link is almost full of vehicles at the maximum density. State 3 lasts about 2 hours so that the spot on the most right side in Figure 3.14 is actually made up of 24 spots overlapping altogether. When traffic volume decreases, both density and flow decline but the curve does not go back along the shape when congestion built up (state 4). A significant drop of flow at the same density is observed. When the queue has totally disappeared from the link, the curve enters state 5 and returns to the zero point along the same straight line in state 1.

Figure 3.13: Queue length on link 2171 during the morning period in the RBV model

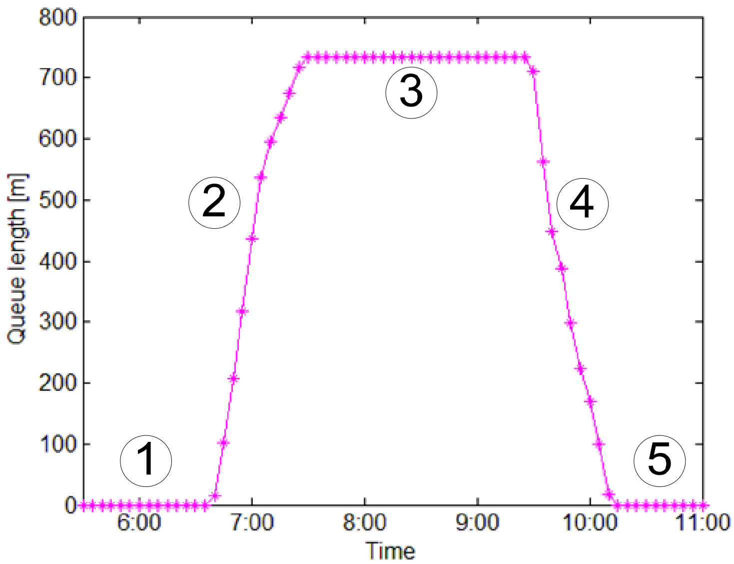


Figure 3.14: Fundamental diagram of link 2171 at the average demand level

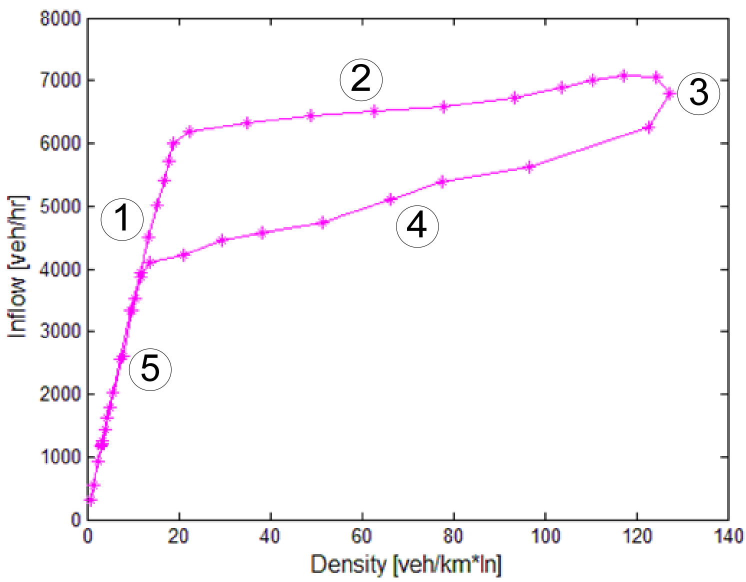


Figure 3.14 reveals that a drop of flow between building up and resolving congestion exists in the link fundamental diagram. Furthermore, the curve does not bend down at high densities. The MFDs in Figure 3.5 are expected when aggregating traffic data of all links containing similar patterns. The shape of the link fundamental diagram also implies that the cause of the shape of MFD is the modelling of traffic within RBV model.

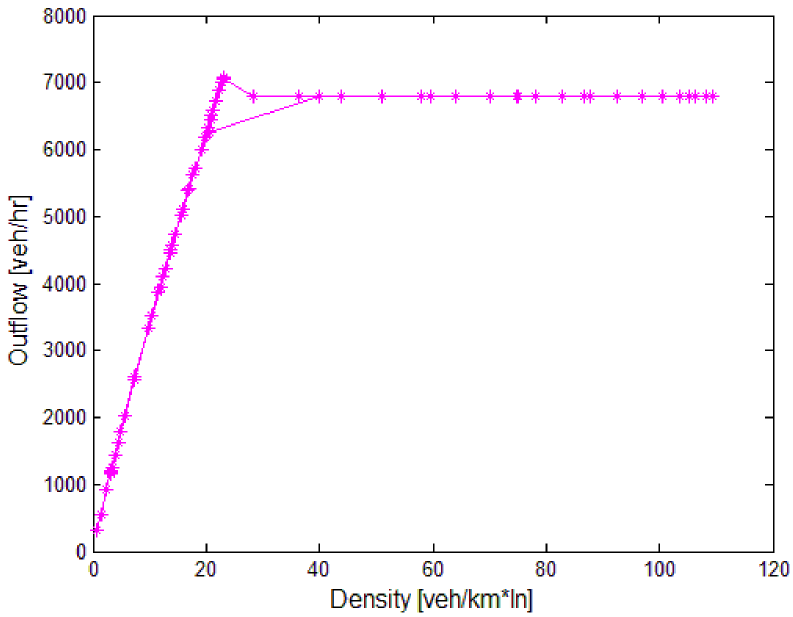
In the RBV model, the density is determined by the number of vehicles on the link and the link length. It reflects the traffic situation on the whole link. However, the flow is the inflow of a link, which is calculated by counting the number of vehicles entering the link in one time period. It can be regarded as a local traffic variable measured by a detector installed at the beginning of the link. When the traffic is low, vehicles are assumed to be evenly distributed over the link so that the traffic situation in the beginning of the link is the same as that on other parts of the link. Hence, a straight line is obtained in the link fundamental diagram as in a conventional fundamental diagram (state 1 in Figure 3.14), even though density and flow are collected at different locations. However, when a queue appears, the RBV models suppose a constant outflow. The vehicles can continue entering the link during the congestion period. Hence, the flow is still growing slightly when density experiences a significant increase (state 2), until the inflow equals the outflow, which is the saturation flow of the downstream link (state 3). During the congestion period, this high value of the link flow is constant in the RBV model. By contrast, in reality, the flow measured on a link decreases greatly when the link is congested so that the congestion branch is shown in the MFDs based on empirical data. Hence, large difference is observed between the MFDs from the RBV model and those based on real traffic data.

In the RBV model, a horizontal queue model is applied and shock waves are not considered. During the congestion period, a queue is generated from the end of a link and develops upstream. More vehicles gather at the end of the link while the beginning part is relatively sparsely occupied. So a large amount of vehicles are still allowed to enter the link from the upstream link until the maximum link density is reached. When the peak hour passes, the queue dissolves from its beginning part to the end of the link. Many vehicles are in the queue at the end of the link because the downstream link, as a bottleneck, is still fully congested. Due to the relatively large number of vehicles on the link, the link density is high as well. However, the inflow becomes low due to lower demand after the peak hour. Fewer vehicles are willing to enter the link even if it is less congested. Hence, a drop of flow is seen between state 2 and 4 at the same link density in Figure 3.14.

It can be concluded that in the RBV model, the density combines the congestion and free flow state on the link. However, the inflow of a flow does not take congestion into account because it is measured at the beginning of the link. Especially when the congestion is dissolving, the inflow is much lower than that in congestion period while the density remains high due to the queue at the end of the link.

A solution could be found to relate outflow rather than inflow with density so that the influence of the queue can be considered during both onset and resolving of congestion. It appears to work for some links, for example, link 2372, an upstream link of link 2171 (see Figure 3.15). However, the flow does still not decrease when density is high as a conventional fundamental diagram due to the assumption of constant outflow during the congestion period in the RBV model.

Figure 3.15: Fundamental diagram of link 2172 (outflow vs. density)



Moreover, this shape of fundamental diagram does not hold for all links. Relating outflow and density of link 2171, a drop of flow is still seen, but the shape of the fundamental diagram is completely different (see Figure 3.16).

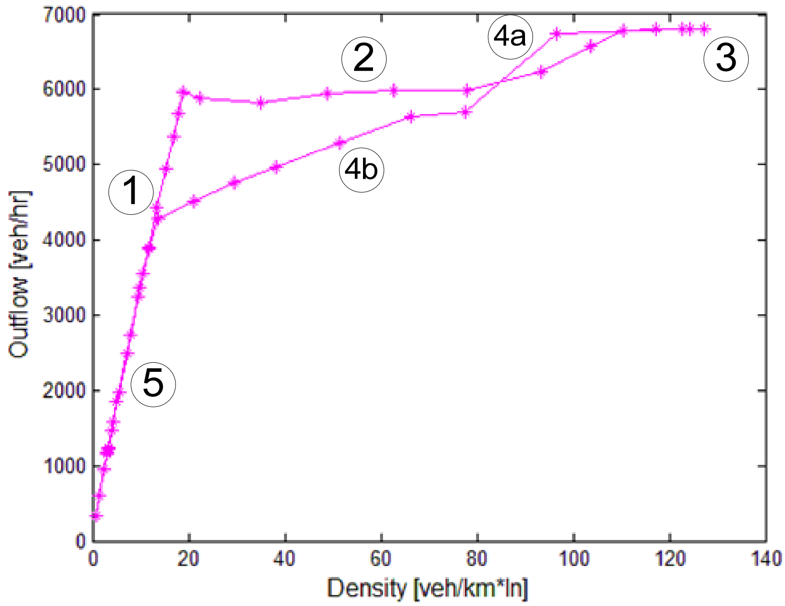


Figure 3.16: Fundamental diagram of link 2171 (outflow vs. density)

The different shapes of link fundamental diagrams in Figure 3.15 and Figure 3.16 result from the layout of the links. Considering the change of link queue length as well (see Figure 3.13), the shape of the MFD relating outflow and density can be explained. Actually, the outflow of a link equals the sum of the inflow into its downstream links. Link 2172 only has one downstream link while link 2171 has two (see the layout of the links in Figure 3.12). In the junction of the motorway A10 and A1, link 860 is a bottleneck. The saturation flow of link 873 and link 2728 are both 4000 veh/h while link 860 only has a capacity of 5600 veh/h. During the morning peak hour, the number of vehicles travelling from link 873 or 2728 to link 860 exceeds its capacity. Assuming a polite driving behaviour, the maximum number of vehicles travelling from link 873 to link 860 is the half of the allowed inflow of link 860, which is 2800 veh/hr. So the queue appears from the end of link 873 and 2728 and it develops upstream. Hence, for link 2171, one downstream link (link 873) is more congested than the other (link 2732). When the traffic is low, the curve of fundamental diagram goes along a straight line until the flow reaches about 6000 veh/hr (state 1). At that moment, the queue starts to spill back from link 873. On the other hand, the flow from link 2171 to link 2732 continues to increase in the following 40 minutes (state 2). Afterwards, the traffic on link 2732 also reaches its capacity of 4000 veh/hr so that the outflow of link 2171 is restricted to 6800 veh/hr. The queue also grows to the start of the link 2171 and the whole link is full of vehicles (state 3). This situation lasts about 2 hours. Comparing the link fundamental diagram to the one relating inflow and density in Figure 3.14, the most obvious difference in Figure 3.16 is state 4a. At that time the demand begins to reduce so that the queue dissolves from the start of the link and the density becomes lower. However, the outflow of the link keeps the on saturation flow because there are still many vehicles on the queue waiting to enter the downstream links. After that, while the link 873 is still crowded for a long time, the queue on link 2732 starts to dissolve. Due to the lower demand, fewer vehicles enter link 2732, leading to a lower outflow of link 2171. But the density of link 2171 is still high because of a queue spilling back from link 873 (state 4b). After the traffic on the link is totally recovered from congestion, the queue disappears on link 2171 and it returns to the free flow state (state 5).

Hence, it can be concluded that the characteristics of the RBV model cause the drop in link fundamental diagram. The location where the flow is measured determines the flow is a local variable rather than a space or time mean average. The attempt on relating outflow and density leads to the similar MFDs as those relating inflow and density. Only for the links having one downstream link, the curves of fundamental diagram will return along the same trajectory when congestion dissolves. Unfortunately, they only account for a small part in the whole network so that the idea of relating outflow and density is not useful to derive MFD. Moreover, the decrease of the flow at higher densities in a conventional fundamental diagram is still not observed in the fundamental diagrams of these links.

3.5 Conclusions

In this chapter, an attempt is made to derive MFDs for the Amsterdam network by applying the RBV model. However, the shape of the MFD is quite different from those obtained by using empirical data in previous researches. Firstly, the congestion branch is missing on MFD. Secondly, there is a drop of flow between the onset and the resolving of congestion. After analyzing the link fundamental diagram and the principles of the RBV model, the causes of these two strange findings in MFD are indicated. The RBV model supposes a constant link outflow during congestion period, which is the saturation flow of the downstream links. So the link inflow does not decrease, even at high densities. In terms of the drop of flow, it results from the fact that the density and flow used to derive MFD are not corresponding spatially. Density is the average value on the entire link, while the flow is a local variable.

The drop of the flow seems not so important because it can also reflect the different traffic state through the simulation period. However, the missing congestion branch makes it impossible to read the value of the sweet spot, one of the most important variables in the MFD. Due to the modelling principles of the RBV model, this drawback cannot be solved easily. Therefore, the RBV model is not suited for deriving MFD.

4. Application of the microscopic model VISSIM

In this chapter, the application of VISSIM in the thesis project is described. In section 4.1, some basic information of VISSIM is presented. Then a basic scenario, in which no DTM measures are applied, is created for VISSIM to derive MFD. In section 4.3, the MFDs in the different conditions are obtained. Afterwards, the shapes of the MFDs derived from the VISSIM model are discussed in section 4.4. Finally the suitability of the VISSIM model for deriving the MFD is put forward.

4.1 The VISSIM simulation model

VISSIM is a microscopic traffic flow simulation software developed by PTV Planung Transport Verkehr AG in Karlsruhe, Germany. The simulation system VISSIM is composed of two different parts, the traffic flow model and the signal control model (Fellendorf, 1994). A detailed description of the system architecture of VISSIM can be found in Appendix. By traffic flow model involved in VISSIM, dynamic traffic assignment (DTA) can be made to simulate the multi-modal city traffic. The VISSIM model is able to generate different output files according to the requirements of the user. In this section, the process of the dynamic traffic assignment and the performance measures in the VISSIM model are provided.

- Dynamic traffic assignment (DTA)

In reality, traffic demand varies greatly over the time. In addition, the infrastructure characteristics may not be constant. In order to provide more accurate information and traffic forecasts, dynamic assignment models are required to capture the true dynamic nature of traffic.

The dynamic traffic assignment is one of the important points in VISSIM to consider time dependencies in reality. In VISSIM, the assignment is done dynamically over time by an iterated application of the microscopic traffic flow simulation. When using DTA, an abstract network is built represented by nodes and edges for the DTA to reduce the complexity of the model. In addition, unlike using vehicle input on selected links with a given value, travel demand is specified in the form of an OD matrix in DTA. To cover the changes of traffic demand over time, the total simulation period is divided into several time periods ranging from 5 to 30 minutes. An OD matrix is set for each time period.

During a simulation, travel times are measured for each edge in the network. To model a growing experience of travel time, the times from all preceding iterations should be considered. The method of successive averages (MSA) is applied to compute the smoothed travel costs.

$$T_i^{n,k} = (1 - \frac{1}{N+n}) \bullet T_i^{n-1,k} + \frac{1}{N+n} \bullet TO_i^{n,k} \qquad (4.1)$$

where $T_i^{n,k}$ and $TO_i^{n,k}$ are the measured and the expected travel time on edge i for period k in iteration n respectively. $\frac{1}{N+n}$ represents the variable smoothing factor resulting from user defined value N and the index of the iteration n.

The general costs influencing route choice include several factors. It is calculated by the following formula.

$$C = \alpha \bullet TT + \beta \bullet TD + \gamma \bullet FC + S \qquad (4.2)$$

TT and *TD* denote the travel time and the travel distance respectively. *FC* and *S* both represent other final costs such as tolls and petrol expenses. However, the previous one is weighted by factor γ but the latter one is calculated by just adding costs on the link. The coefficients α, β and γ are user defined factors, specific to vehicle types. Hence, driver groups may have different opinion on general costs, leading to a various route choice behaviour.

The general costs of a route are defined as the sum of the general costs of all edges on this route. Vehicles driving from a specific OD pair make route choice based on costs of all alternative routes. The Kirchhoff distribution formula is applied in VISSIM to determine the percentage of drivers using a route

$$p(R_j) = \frac{U_j^k}{\sum_i U_i^k} = \frac{e^{k \bullet \log U_j}}{\sum_i e^{k \bullet \log U_i}} = \frac{e^{-k \bullet \log C_j}}{\sum_i e^{-k \bullet \log C_i}} \quad (4.3)$$

where U_j is the utility of a route, which is defined as the reciprocal of the general cost C_j. The sensitivity k in the exponent determines how much influence the difference in utility has.

The routes which vehicles will choose are searched during the simulation. For each OD pair in each iteration of DTA, the best route with lowest travel costs is looked for and added to the set of alternative routes. Since the travel costs change from iteration to iteration, the different routes will be found throughout the simulation. If the number of iterations is large enough, drivers can have several choices from an origin to a destination.

From the above explanation on DTA in VISSIM, it can be found that the drivers have determined the route to the destinations before they starts from the origins. They are not able to change the route during the trip based on instantaneous traffic information. Even the delay on the route is extremely long, the vehicles will still stay on this route rather than choose another less congested one. However, the long travel time on the route will result in a high general costs for the next iteration so that fewer vehicles will choose the route. It also proves that the sufficient number of iterations is necessary to reach a stable traffic situation in VISSIM.

The DTA will be stopped if the traffic situation becomes stable, which means the travel times and volumes of all routes do not change greatly between two successive iterations. The usual convergence criteria include route travel times and edge flows.

- VISSIM performance measures

The VISSIM model is able to generate several kinds of output files. The typical simulation results include travel time, speed, delay for the network, every route as well as an individual vehicle. Besides, VISSIM can offer traffic information on the link level. The link evaluation features allows the user to gather traffic variables on a link, such as flow, density, speed and emission, the first two of which are paid attention to in this thesis project. As in the RBV model, flow is the actual number of vehicles that can pass through a given section of roadway with a period of time (Wilbur Smith Associates, 2007). However, the ways of calculating speed and density in VISSIM are quite different from those in the RBV model. In the VISSIM model, the traffic variables of each individual vehicle are recorded. The link speed is the average speed of all vehicles on the link. However, the link density is not measured from the network directly. It is calculated as the flow divided by the average speed on the link.

4.2 The Amsterdam network in the VISSIM model

The part of the Amsterdam network that has been modelled in VISSIM is shown in Figure 4.1. It consists of the A10 west, part of the A10 south and the A4 motorways, and nearby urban roads. This model contains nearly 1706 links, among which nearly 1600 are in the urban network and the other links are motorways.

Figure 4.1: A10 west network modelled in VISSIM

The original OD matrix of the model was derived from a static model, aiming to simulate the traffic during evening peak hour between 15:30

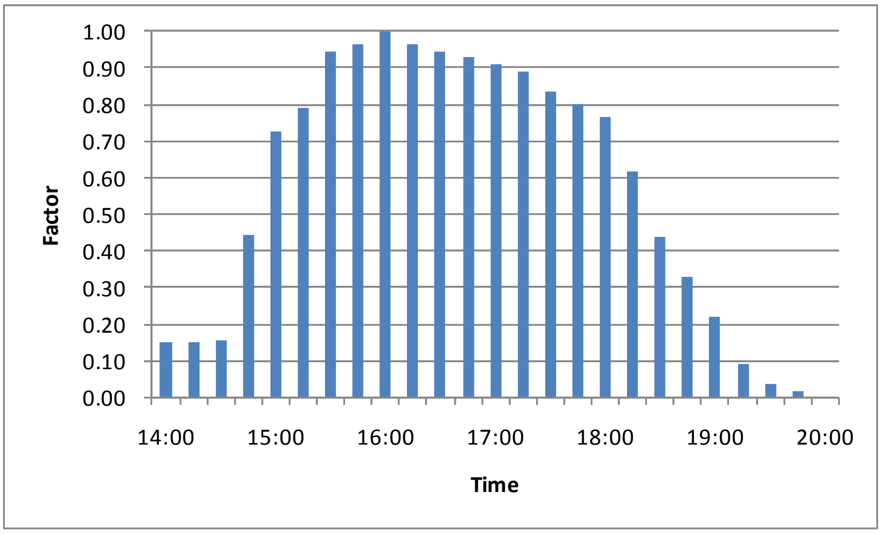
and 18:00 (Taale, 2008). The two-hour matrix was transferred into 10 separate matrices for every 15 minutes. Using real traffic data gathered from the motorways, the model has been calibrated to reflect traffic situation on the A10 west with the average demand for the year 2000. The model was further modified by Yuan (2008) regarding route choice and lane change behaviour. The illogical routes were eliminated by closing certain edges in the VISSIM model. In addition, the lane changing decision distances at certain locations are set long enough before the merging points to provide sufficient distance for lane changing. Hence, the unrealistic blocking in the merging sections in VISSIM has been partly rectified.

In this thesis project, a complete MFD is necessary for analyzing the characteristics of the MFD during both peak hour and off peak hour. Since the existing OD matrix only covers the peak hour of 150 minutes, it needs to be extended. In this case, the OD matrix is defined as

$$q_{ij}(t) = a(t) \bullet q_{ij} \tag{4.4}$$

where $q_{ij}(t)$ denotes the demand from origin *i* to destination *j* at time *t*, and $a(t)$ is a step function changing with time every 15 minutes. q_{ij} is the reference OD matrix between origin *i* and destination *j*. It is the OD demand from 16:00 to 16:15 used in Yuan's project, representing the most congested period during the evening peak hour. Multiplying factors no larger than one, the dynamic OD matrixes of the whole simulation period can be obtained. The factors used during the simulation period are shown as Figure 4.2, which is recommended by the calibrated RBV model. The simulation period in this project is set as 6 hours to cover both peak and off-peak hour. The first half hour is the warm-up period because the VISSIM model needs some time to distribute vehicles from origins to the whole network.

Figure 4.2: Time step function for deriving dynamic OD matrix



Therefore, the distribution of traffic demand over origins and destinations remains same during the whole simulation period. In this case, the aim is not to create a model which exactly reflects the real traffic situation. The focus is on the shape of MFD for a large network so that this time dependant OD matrix with the same distribution is applied in the project.

In Yuan's project, the calibration of the two hours simulation has been made. He has compared the simulation results with the empirical data collected on A10 west motorway. It has been proven that if OD demand is multiplied by 65% totally, the traffic situation, represented by congestion level on the roads, in the VISSIM model is almost similar to reality.

In order to reduce the time needed to reach an equilibrium in DTA, several measures have been made. The number of alternative routes is limited up to three for each OD pair. In addition, the convergence criterion is less strict. The convergence is regarded to be reached if the route travel times do not change by more than 30% from one iteration to the next. The later research in this project shows the shape of MFD hardly changes if the sufficient number of iteration has been run in DTA, even though the coarse convergence criterion has not been reached.

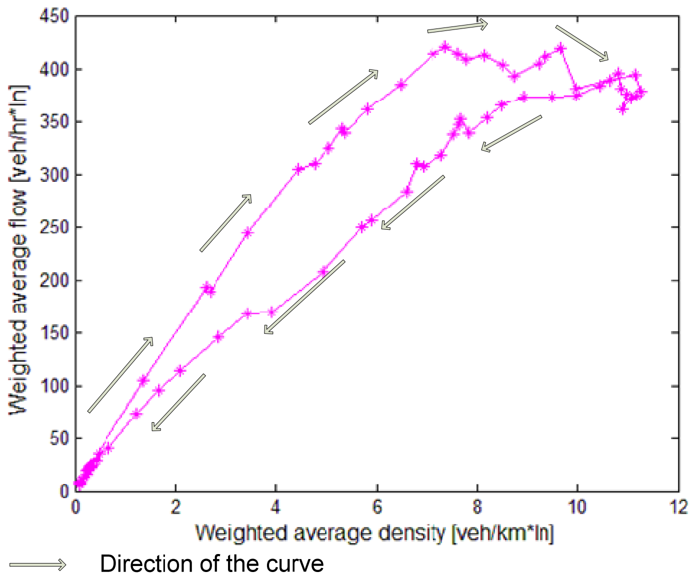
In order to derive the MFDs, the travel variables on each link are measured. The evaluation interval should be lower than frequency the demand changes. On the other hand, too small interval will increase the fluctuation of values. In this project, five-minute periods are used as evaluation interval, being larger than the length of two signal cycles.

4.3 The MFD derived from the VISSIM model

In this section, the MFDs under different conditions are derived by using VISSIM. The original OD demand is globally multiplied by a factor to avoid unrealistic congestion. According to Yuan's study, 60% demand is first used. For this demand level, the dynamic traffic assignment in VISSIM reached equilibrium after 59 iterations. After the simulation, the MFD of the whole A10 west network is derived by using the formula (2.1) and (2.2).

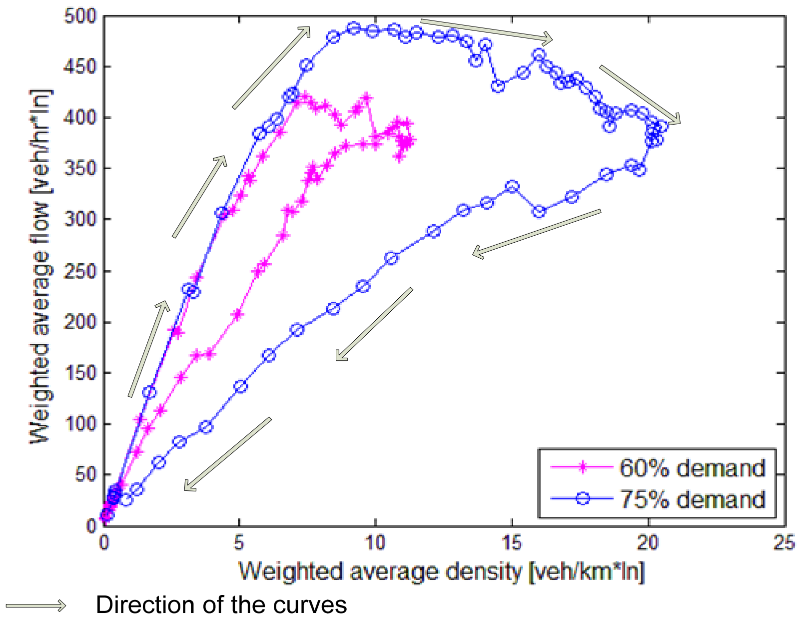
Figure 4.3 demonstrates the MFD at the 60% demand level. The curve develops from the zero point to the maximum average flow of around 420 veh/hr*ln, at the density of about 9 veh/km*ln. However, when congestion is dissolving, the flow is about 150 veh/hr*ln lower at the same density compared to the building up period of congestion. A drop of flow is still observed, as that in the RBV model. In addition, the congestion branch is missing in Figure 4.3 and the spots with the maximum values of flow and density are almost on the most right side of the curve. It is not possible to estimate the value of the sweet spot on this MFD. The low maximum density on the MFD implies that the network does not enter a congestion state at the 60% demand level.

Figure 4.3: MFD for the whole network under 60% demand level



In this project, an MFD covering all traffic states is required to investigate the shape of MFD in different traffic situations. Hence, the demand of the VISSIM model has been increased to 75% of the original OD matrix. After 65 iterations, the dynamic traffic assignment in VISSIM reaches the equilibrium again. Figure 4.4 illustrates the MFDs at both 60% and 75% demand level. When travel demand is increased, the congestion branch is observed on MFD, which means the network does experience the congestion state during the peak period. The maximum flow in the MFD increases to about 480 veh/hr*ln, and the critical density also rises up to about 10 veh/km*ln. The drop of flows between onset and resolving of congestion becomes larger, which corresponds to the findings from the RBV model.

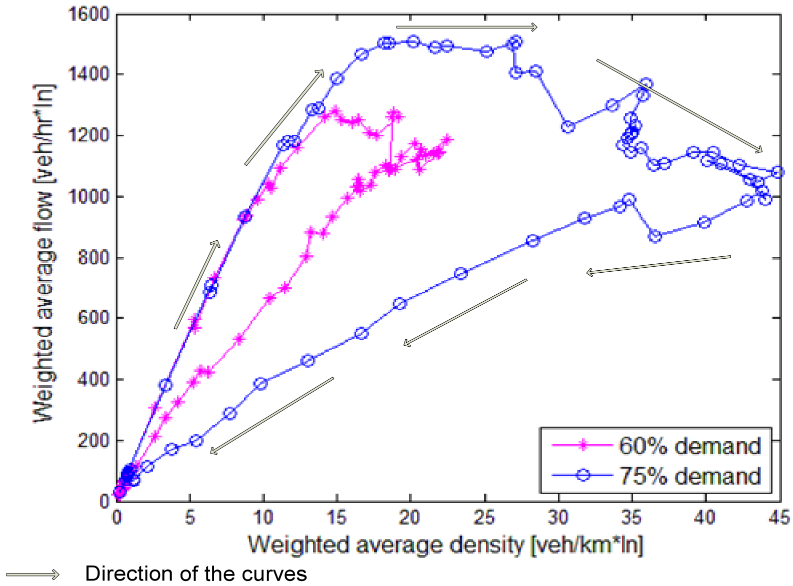
Figure 4.4: MFDs of the whole network at 60% and 75% demand level



According to the study in Toulouse (Buisson & Ladier, 2009), the MFDs in a smaller sub-networks show different characteristics. Considering the various road operators of motorways and the urban roads in the study area, it is worthwhile to analyze the different types of the roads separately. Hence, the whole network is divided into sub-networks, based on the type of links.

Figure 4.5 demonstrates the MFD for motorways under 60% as well as 75% demand level. The similar effects are shown for motorways and the whole network. When congestion is building up, the curves go along the almost same shape under both cases. The curve of 75% demand level bends down when the density is higher than about 20 veh/km*ln, which is the value of the sweet spot. The maximum flow also increases by about 250 veh/hr*ln. However, the drop of flows becomes much larger than that in 60% case.

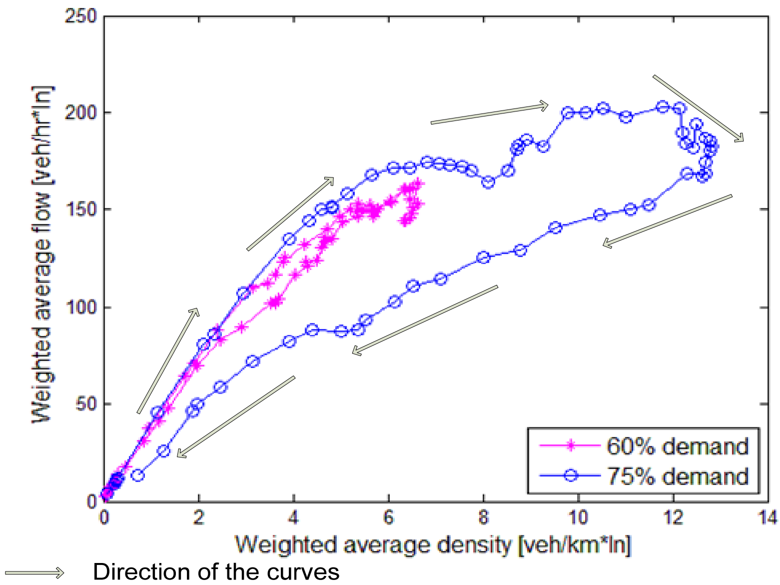
Figure 4.5: MFD of motorways at 60 and 75% demand level



Similar characteristics are shown on MFD of the urban roads (see Figure 4.6). The maximum flow rises from about 160 veh/hr*ln to 200 veh/hr*ln. Besides, a larger drop of flow is observed with the increase of travel demand. However, the traffic situation on urban roads, especially those not connecting to motorways, is much less congested than that on motorways. High densities are mostly observed on the onramps of the motorways during the congestion period. Therefore, only the free flow state is observed on MFD of the urban roads and the critical density cannot be estimated.

In should be noticed that the traffic flow on the urban roads is quite lower than the real situation in this area because the VISSIM model is calibrated based on empirical data on motorways only. However, the focus of the thesis project is how the MFD changes after DTM measures implementation. The exact reflection of traffic situation in the study area is not emphasized. Hence, VISSIM will be used for the further research.

Figure 4.6: MFD of the urban roads at 60% and 75% demand level



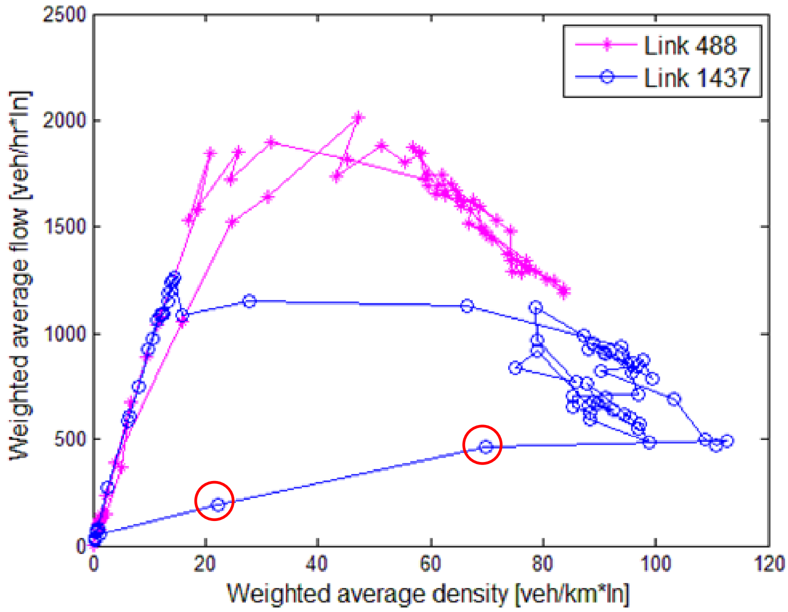
In summary, compared to the RBV model, the congestion state is modelled more realistic in VISSIM. The congestion branch does occur in the MFD derived from the VISSIM model. However, a drop between flows between onset and resolving of congestion appears to always exist in VISSIM. When the congestion dissolves, the MFD moves toward zero point directly, rather than along the shape generated during the period of congestion building up. The more congested the traffic situation, the larger drop on MFD. In the next section, the cause of the drop is discussed.

4.4 Explanations on the shape of MFD derived from VISSIM

Unlike the RBV model, VISSIM is a microscopic model, which has a totally different way modelling the traffic. Using the same procedure as for the RBV model, the link fundamental diagrams are investigated to find the explanations of the drop on the MFD. Having checked the fundamental diagram of many links in VISSIM, it can be found that the reason resulting in the drop on the MFD in VISSIM model is similar to that in the RBV model. When congestion is dissolving, the combination of low link inflow and high density on the whole link leads to an unrealistic part on the MFD. The analysis also indicates that the dramatic decrease of demand in the simulation model is the radical cause of the drop on the MFD. The detailed explanations are given as follows.

In VISSIM, the fundamental diagrams of some links have a shape like a conventional one and all spots are distributed close to the theoretical curve (see the curve for link 488 in Figure 4.7). On the other hand, other links have a total different pattern (see the curve for link 1437 in Figure 4.7). In the Amsterdam network in VISSIM, link 488 and link 1437 are parts of the A10 west motorways, where vehicles move from south to north. The downstream link of link 1437 is a bottleneck on the A10 west motorway so that the heavy congestion is witnessed on this link. When congestion is dissolving, the flow is extremely low whiles the density is still large. This period occurs during the last hour of the simulation, on which the demand had already decreased. Like the RBV model, VISSIM determines the link flow as the number of vehicles entering the link and the density reflects the traffic situation on the whole link. If the demand decreases quickly, a low flow with high density is seen (red cycles in Figure 4.7). By contrast, the density of link 488 during the congestion period is nearly 40 veh/km*ln lower than that of link 1437. The congestion starts to dissolves at around 18:00 and the MFD returns to the zero point along the shape when congestion is building up.

Figure 4.7: Fundamental diagrams of link 488 and link 1437 in VISSIM



Each link in the VISSIM model has one of two types of fundamental diagram shown in Figure 4.7. Taking all links into account, a network fundamental diagram unlike a conventional one is derived (see Figure 4.6). The drop of the flow in the MFD results from the fundamental diagram of some links, on which the traffic situation return to free flow state very late, when the demand has decreased dramatically. The more links having this kind of fundamental diagram, the larger drop will be shown on the MFD. If the congestion period finishes earlier, the traffic demand will be still high on the link. If the demand is lower than the capacity, the flow will also remain high and the curve of an MFD will return to the free flow state like a conventional link fundamental diagram. Hence, the size of the drop on MFD can be regarded as an index of congestion level in this project, although it is not observed in other studies. A small drop indicates the drivers experience a less congestion period.

However, the MFDs derived from empirical data do not show such a drop (Geroliminis & Daganzo, 2008; Buisson & Ladier, 2009). In chapter 2, it has been pointed out that the fast change of traffic during the onset and resolving of congestion will lead to high scatter in a MFD. Hence, a possible reason of the drop shown in VISSIM is that the input of the VISSIM model is not realistic, especially in the onset and resolving of congestion. Because the direct cause of the drop is the dramatic decrease of flow during the resolving of congestion, the flows on the link from reality as well as the simulation model are compared. The aim is to see whether the significant decline of flow is also indicated in the real traffic situation.

Figure 4.8 illustrates the traffic flow on one road section on A10 west motorway in the north direction (corresponding to link 1437 in VISSIM), derived from the empirical data and the simulation model based on 6 hours created OD matrix. The empirical data is collected on an ordinary workday (Tuesday, 10 March 2009) by the detectors on the motorway automatically for every minute. In Figure 4.8, the biggest difference between two curves is the period of congestion dissolving. In simulation, the flow declines extremely fast. It only takes about one and half hour to decrease from the peak value to zero. Hence, the inflow is very low when the density is still high, which is the direct cause of the drop on the link fundamental diagram and the MFD. In reality, this process takes about seven hours. When congestion is dissolving, the inflow decreases gradually, corresponding to the decline of density. Therefore, the MFD goes back to zero point along the curve when congestion is building up, which has been shown in the previous studies. Hence, based on the empirical data, the drop was not shown or at least it was not so large.

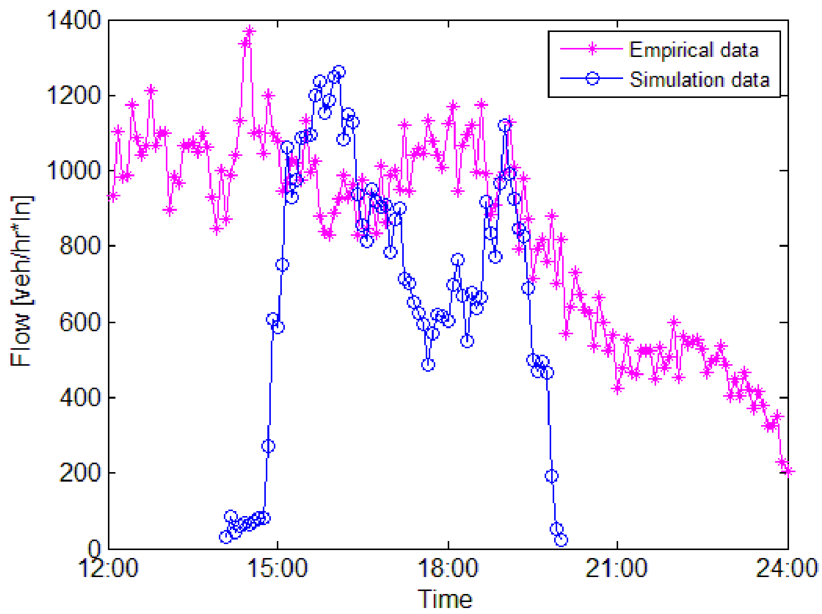


Figure 4.8: Flows on link 1437 for empirical data and simulation data

Hence, the rapid change of the demand results in the unrealistic low inflow during the congestion dissolving period. The ways of measuring the traffic variables in VISSIM make the MFD to reflect this problem clearly, which is the drop of flows. However, the drop does not affect the analysis on the characteristics of the MFD. If the congestion branch is included in MFD, the most important patterns of an MFD, the value of the sweet spot and the corresponding maximum flow, can be estimated from the diagram. Hence, it is not necessary to extend the simulation period, which will lead to extremely long computing time.

4.5 Conclusions

In summary, the A10 west network has been modelled using the microscopic simulation tool VISSIM. The simulation period was extended by originally 2.5 hours to 6 hours, trying to cover both peak and off peak hour. The corresponding dynamic OD matrix was created using a reference OD matrix multiplying by time step values.

After about 60 iterations, the dynamic traffic assignment in VISSIM reached the equilibrium. The link traffic variables were generated to derive MFD. In this project, 60% demand level was first attempted. However it was proven not suitable because the congestion branch was missing on MFD. Then the demand was increase to 75% level and the congestion state was observed. The curve of MFD bent down at high density. The performance of the network reduces when the network is overloaded.

However, a drop of flow between the onset and the resolving of congestion still exists. The created OD matrix leads to dramatic decrease of demand in the end of the simulation period. If the congestion period finishes late, the flow on a link reduces fast due to low demand, although the density still remains high. Hence, compared to the onset of the congestion, the flow is lower at the same density. Nevertheless, this drop does not affect recognizing the patterns of an MFD. The important values such as the critical density and the maximum flow can be easily read from the MFD.

Therefore, the MFD derived from VISSIM model is a good representation of the overview performance of the study area. 75% demands are applied as input of the model and the simulation period is 6 hours, including 30 minutes warming up period. The MFDs derived at 75% demand level will be used as a basic scenario to be compared with other MFDs after the implementation of dynamic traffic measures in the next chapter.

5. Effects of dynamic traffic management on MFD

In this chapter, the effects of dynamic traffic management on the shape of the macroscopic fundamental diagram are discussed. Firstly, the main dynamic traffic measures applied in the Netherlands are reviewed. Based on the feasibility of the simulation model VISSIM and the real situation of the Amsterdam network, the dynamic traffic measures to be tested in this project are determined in section 5.1. Afterwards, the scenarios with and without DTM measures are simulated in the model. Finally, the results are compared to investigate how MFDs change after the implementation of the DTM measures.

5.1 Dynamic traffic management in the Netherlands

Nowadays, traffic management plays an important role in the Dutch policy to meet the increasing traffic demand. The objective of traffic measures is to use the existing infrastructure more efficiently and to reduce the potential needs for building new roads. Table 5.1 gives an overview of dynamic traffic measure applied in the Netherlands.

Table 5.1: Overview traffic management measures (Taale, et al., 2004)

	number	km.
Motorway Traffic Management		997
Dynamic Route Information	103	
Ramp Metering Systems	46	
Peak Hour Lanes		43
Plus Lanes		6
Truck Lanes	6	12
Bus Services	31	78
Overtaking prohibition trucks		2413

In the project Praktijkproef Amsterdam, different dynamic traffic measures will be tested to improve the traffic situation. Ramp metering systems and hard shoulder use (peak hour lane and/or plus lane) are the two most important DTM measures which will be implemented widely on A10 beltway in the near future. Tests have been made to analyze the effects of ramp metering and peak lanes, but not from the view of MFD. The changes of the shape of the MFD resulted from these DTM measures are not clear. In addition, ramp metering installation and hard shoulder use can be implemented in VISSIM. Hence, these DTM measures are selected in this project to investigate their influence on MFD. The application of ramp metering installation and hard shoulder use, including both peak hour lanes and plus lanes, in the Netherlands is reviewed as follows.

- Ramp metering system

Ramp metering is the control of a traffic stream from an on-ramp merging on the motorway. The traffic conditions on the motorway are improved by limiting too many vehicles entering it from the on-ramp. Ramp metering is typically applied in the following situations (Taale & Middelham, 2000).

– On-ramps close to a bottleneck;
– On-ramps which cause disruptions in the traffic stream on the motorway due to the merging process, for example caused by platoons of vehicles coming from a signalised intersection.

The first ramp metering system was implemented in 1990 in the Netherlands. By 2004, 46 ramp metering systems had been installed with another 24 planned (Taale, 2006). Several assessment studies have been performed, proving that the capacity increases by up to 5% in general. In addition, ramp metering has positive effects on the increase of speed on motorways, major reduction of shockwaves, and substantial reduction of 'rat-runners', which means the drivers exiting the facility for a short distance to avoid congestion on the motorway (Middelham, 2006).

- Peak hour lanes

Motorway hard shoulders provide valuable existing road space that is normally only available as a refuge for broken down vehicles, vehicles that have been involved in an incident and for access by emergency services or maintenance vehicles. Road operators have made several attempts to open hard shoulder running for all vehicles during the peak hour to reduce congestion. In the Netherlands, peak hour lanes were first introduced in 2003. According to the indication from overhead lane control signals, the drivers are allowed to use hard shoulder temporarily during the peak hour, depending on the prevailing flow on the main road. The effects of peak lanes have been assessed, revealing that overall capacity rises by 7 to 22 percent (depending on usage levels). Meanwhile, the travel time is decreased by 1 to 3 minutes and 7 percent more vehicles are induced onto motorways with peak lanes during the congestion periods (Mirshahi et al., 2007).

However, temporary use of hard shoulder may reduce the reliability of the motorway when an incident occurs. Hence, several measures have been taken to increase the safety on the motorways. For example (Helleman, 2006):

- Motorway traffic management system (Overhead lane signs)
- Speed reduction during times of hard shoulder running
- Variable route signs at junctions
- Advanced incident detection
- CCTV surveillance
- Incident management
- Public lighting
- Emergency refuge areas with automatic vehicle detection

In April 2010, 6 peak hour lanes will be implemented on the A10 beltway. All of them will be on A10 south and the adjacent roads on the nearby motorways like A2 and A4. This number will further increase in the coming years because of an optimistic expectation on effects of peak hour lanes based on previous studies (Middelham, 2006; Mirshahi et al., 2007). The open of peak hour lanes will be triggered when the flow on these road sections is higher than 1500 veh/hr*ln (Helleman, 2009).

- Plus lanes

Similar to peak hour lanes, plus lanes use the potential of hard shoulders. The lane width of each lane is changed to add a new lane without road expansion. For instance, the lane widths are reduced from 3x3.25m with hard shoulder to 2.7m, 3.0m, 3.25m and 3.0 m for each lane and a narrower hard shoulder (Mendoza, 2006). The left lane is narrow so that it is only available for personal cars. When plus lanes are implemented, similar traffic measurements as mentioned in the case of peak lanes are applied to ensure the road safety.

In summary, DTM measures of ramp metering and hard shoulder use have been proven effective in the previous studies. They are and will be implemented widely in the Netherlands. It is meaningful to investigate the effects of these two dynamic traffic measures by using MFD because the shape of MFD may changes in the different traffic conditions. In this project, three scenarios have been set up. Scenario 0 is the basic scenario, the situation of which has been demonstrated in Chapter 4. Scenario 1 describes the application of ramp metering. Since the coordination of ramp metering is not expected to have significant improvements on traffic situation, the ramp metering devices all work locally in scenario 1. Scenario 2 applies hard shoulder use to improve the traffic situation. VISSIM cannot block a single lane on one link temporarily so that an extra lane will open or close for the whole simulation period. Several sub-scenarios, in which the locations of the extra lane and speed limit during implementation are varied, have been made for analysis. The simulation results are cross-compared to investigate the effects of DTM measures on the shape of MFD, which are shown in the following sections.

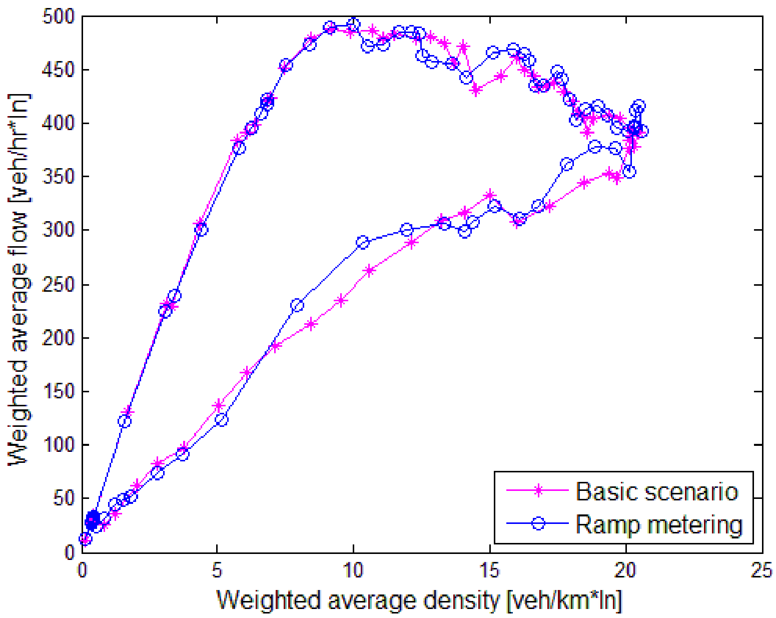
5.2 Application of ramp metering

In scenario 1, four ramp metering devices are installed on the on-ramps near urban main roads S105, S104, S102 and S101 respectively (see Figure 5.1), in the northern direction. The ramp metering systems work locally and each of them only considers the traffic situation on the nearby motorway section. The number of vehicles from the urban roads is restricted when the flow on upstream motorways is high. The critical flow values for each ramp metering installation to start or stop metering are about 75% and 68% with respect to the road capacity (Yuan, 2008).

Figure 5.1: The locations of ramp metering systems on A10 west motorway

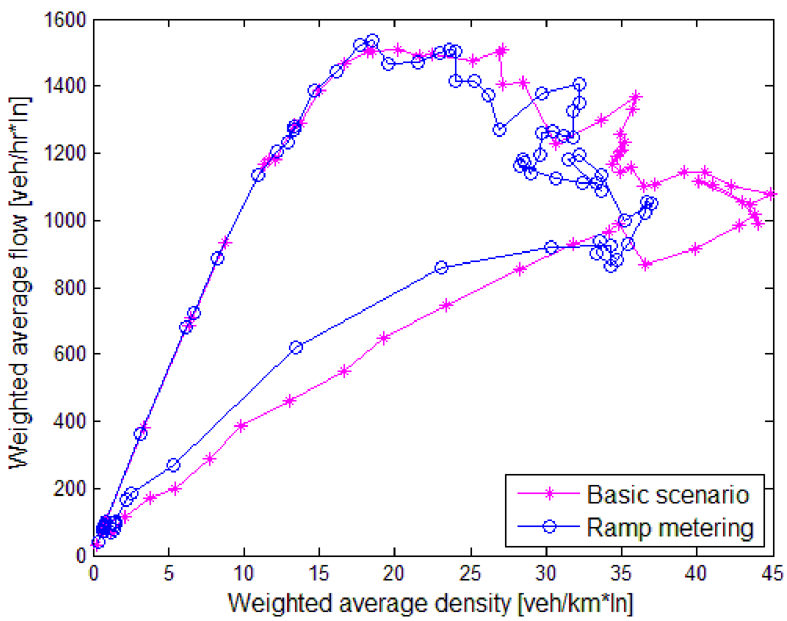
Figure 5.2 show the MFDs of scenario 1 with ramp metering and the basic scenario. It can be seen that the performance of two scenarios has no large difference, from the viewpoint of the whole network. The critical densities and the corresponding maximum flows are almost the same. Besides, the maximum densities during the whole simulation period are about 21 veh/hr*ln in both cases, implying similar congestion levels. When congestion is dissolving, the curve of ramp metering is slightly above the curve of the basic scenario. According to the analysis in section 4.4, it can be concluded that after applying ramp metering, the congestion period finishes a bit earlier.

Figure 5.2: MFD for the whole network with ramp metering implementation



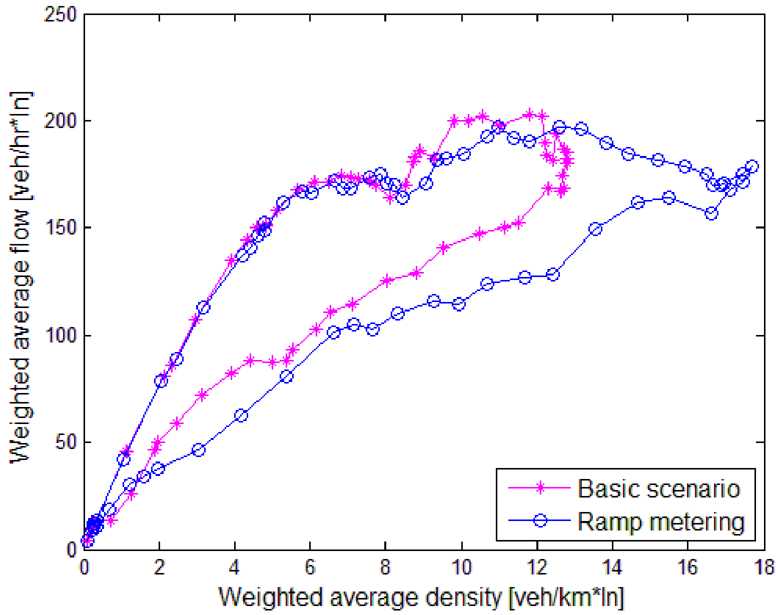
When an MFD is drawn only for the motorways, significant changes can be observed (see Figure 5.3). When traffic is in free flow state, two curves go along the same trajectories until the same maximum flow of about 1550 veh/hr*ln and the same critical density of about 20 veh/km*ln. Then, the traffic situation enters the congestion state and the flow decreases to about 1000 veh/hr*ln. With the implementation of four local ramp metering systems, the maximum density during the congestion period declines from 45 veh/km*ln to 35 veh/km*ln, compared to the basic scenario. It demonstrates that the ramp metering systems are effective on limiting the number of vehicles entering the motorways. The traffic situation afterwards is also better and the congestion dissolves earlier, which is proven by the MFD of scenario 1 going back to the zero point above that of the basic scenario. In addition, it can be also found that fewer points are recorded on the curve with ramp metering than that of the basic scenario, when the MFD return to the zero point. It implies that it costs the motorways less time to recover from the congestion state to nearly empty situation. The ramp metering systems accelerate the process of congestion resolving on the motorways.

Figure 5.3: MFD of the motorway with ramp metering implementation



In terms of urban roads, the situation obviously becomes worse (see Figure 5.4). In the basic scenario, the congestion branch is not really shown on MFD. By contrast, the curve with ramp metering does go down at high densities. Moreover, the maximum observed density is increased to about 18 veh/km*ln. This is logical, because the ramp metering systems prevent too much vehicles entering the motorways. They have to wait on the on ramps and spill back to urban roads. When traffic recovers to the free flow state, the congestion dissolving period lasts longer with ramp metering implementation. The traffic demand has already decreased, leading to lower flows at the similar densities. Hence the curve with ramp metering is below that of the basic scenario when the MFDs move from the observed maximum density towards the zero point.

Figure 5.4: MFD of the urban roads with ramp metering implementation



In conclusion, the shape of the MFD for the whole network hardly changes with ramp metering implementation. Only when the network is divided into sub-network based on the road type, the significance changes are observed. In the MFD for the motorways, the maximum observed density decreases by about 22% while the value of the sweet spot remains the same. In terms of the urban roads, the congestion branch is observed in the MFD. The findings from the MFD reveal that the benefit for motorway traffic is at the cost of local delay on the urban roads. In general, the traffic situation of the whole network seems not to be improved.

5.3 Application of extra lanes

In this project, the use of an extra lane on motorways is described in three scenarios. In reality, there is a plan of hard shoulder use on the A10 south and part of the A4 motorway (ProRail & Rijkswaterstaat, 2007). The hard shoulder, which is designed for emergency parking originally, is now applied as an extra lane during the peak hours. Therefore, several measures have to be taken to ensure the safety level, among which one of the most important actions is to lower the speed limit when the hard shoulder is used. Scenario 2.1 describes this situation. An extra lane is added on A10 south and A4 for both directions in the VISSIM model. Meanwhile, the speed limit on these road sections is decreased from the original 120 km/h to 100 km/h. In VISSIM, the change of the speed limit can be realized by modifying the desired speed of the vehicles on specific road sections. Scenario 2.2 and 2.3 are contributed to two possible future scenarios, applying extra lane on all motorway sections. The difference of these two scenarios is the speed limit on the A10 west motorway. Currently, the A10 west is one of the busiest motorways in the Netherlands. Its speed limit is only 100 km/h whiles other sections on the A10 beltway have a speed limit of 120 km/h. Hence, it is necessary to include this pattern into the VISSIM model. In scenario 2.2, the speed limit is 100 km/h on all roads. In scenario 2.3, vehicles on A10 west are not allowed to drive faster than 80 km/h, although they can increase speed to 100 km/h on other motorways. In summary, the overview of three scenarios with respect to extra lane application is shown in Table 5.2. In each sub-scenario, a new DTA equilibrium has to be reached because the drivers will change their route choice after the implementation of the extra lane.

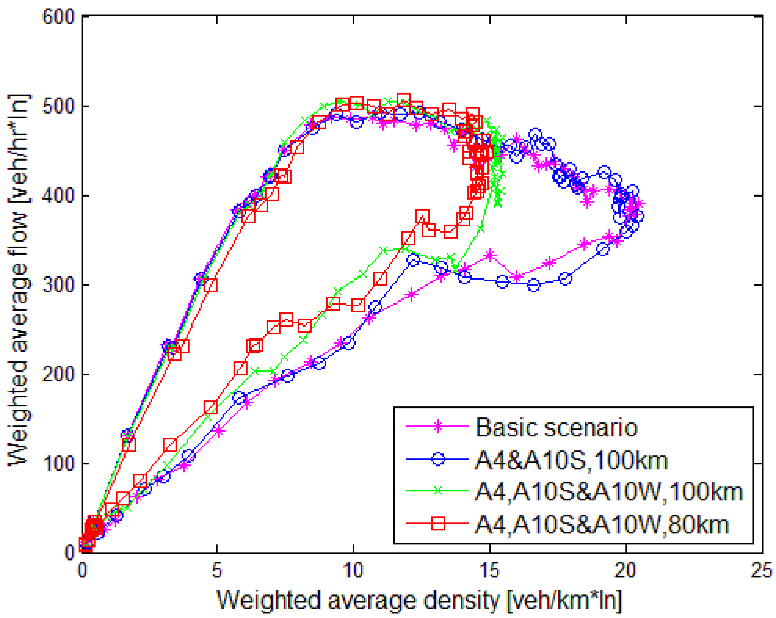
Table 5.2: Overview of scenarios about extra lane application

Scenario	Location	Speed limit
2.1	A4 & A10S	100 km/h
2.2	A4, A10S & A10W	100 km/h
2.3	A4, A10S & A10W	A10W: 80 km/h, Others: 100 km/h

Figure 5.5 illustrates the MFD of the whole network for all scenarios. It can be concluded that the extra lane application does improve the traffic situation, except for scenario 2.1. The MFDs of scenario 0 and scenario 2.1 generally go along the same trajectory. It implies that the

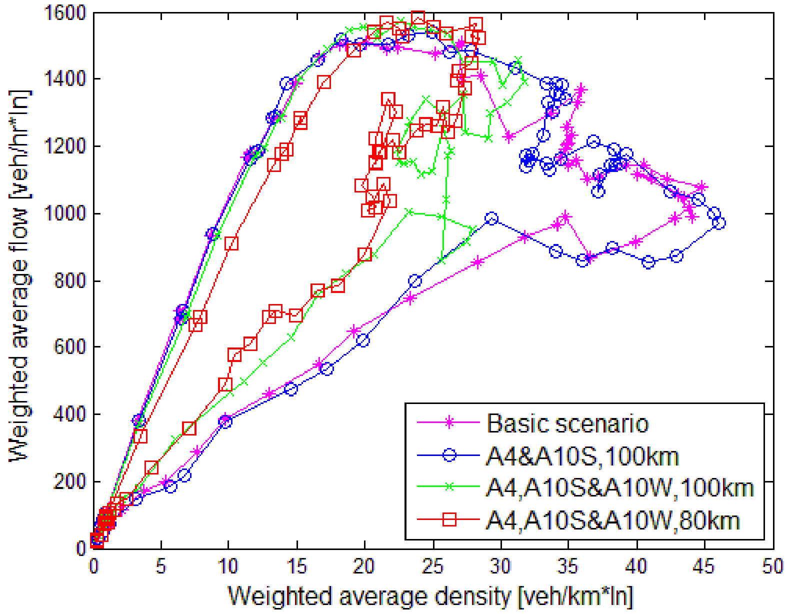
A10 west is the bottleneck of the network and the capacity extension on other road sections does not improve the situation. In scenario 2.2 and 2.3, significant changes in the MFDs are shown. During the peak hour, the maximum densities are decreased from 20 veh/km*ln to 15 veh/km*ln in these two scenarios, compared to the basic scenario. By adding an extra lane, the bottleneck is solved and the vehicles can pass the A10 west motorway more smoothly. Hence, the congestion is relieved, leading to a lower observed maximum density. When congestion is dissolving, scenario 2.2 and 2.3 also demonstrate a better traffic situation because the MFDs of these two scenarios are above the curve of the basic scenario, which implies the congestion period finishes much earlier. In addition, the maximum flows in scenario 2.2 and 2.3 slightly increase at the same critical density as that in the scenario 0, implying a more smooth traffic situation at the optimal state. Besides, the slope of the curve of scenario 2.3 during the free flow state is a bit smaller than other three curves due to the lower speed limit.

Figure 5.5: MFD of the whole network with extra lane implementation



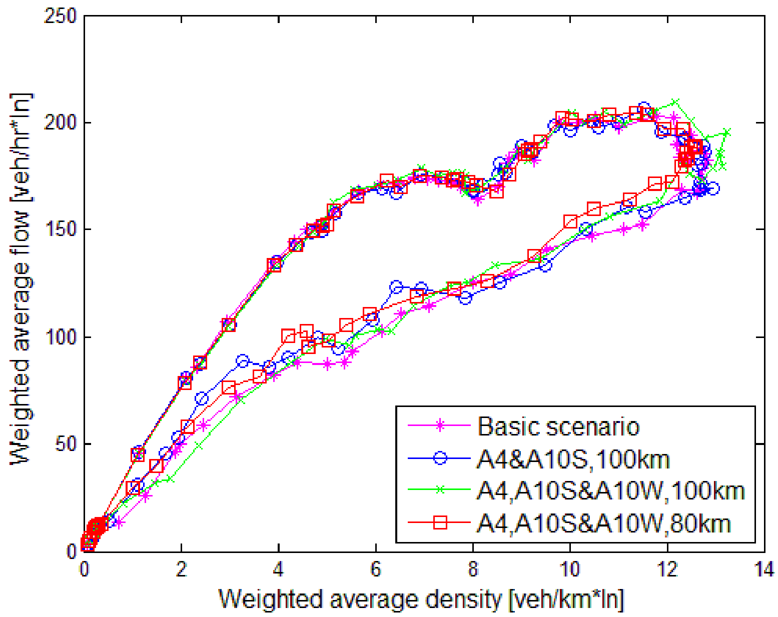
When only the motorways are analyzed, the shapes of the MFDs are similar to those of the whole network (see Figure 5.6). Although scenario 2.1 has little effect on the shape of MFD, scenario 2.2 and 2.3 do improve the traffic situation. The critical density increases from about 18 veh/km*ln to 23 veh/km*ln and the corresponding maximum flow also goes up from about 1500 veh/hr*ln to nearly 1600 veh/hr*ln. Moreover, the congestion branch is missing on these two MFDs. The curves go back towards the zero point when they reach the density of about 33 veh/km*ln and 28 veh/km*ln respectively. The changes in the MFDs prove that the A10 west motorway is the bottleneck and the expansion on this section will solve the traffic problem greatly.

Figure 5.6: MFD of the motorway with extra lane implementation



On the other hand, the urban network is hardly affected by application of extra lane on the roads (see Figure 5.7). Four curves almost overlap completely, showing similar situations on urban roads in all scenarios.

Figure 5.7: MFD of the urban roads with extra lane implementation



5.4 Conclusions

In this project, ramp metering and hard shoulder use are selected to analyze the effects of the DTM measures on the MFD. The shape of the MFD appears to change when different DTM measures are implemented in the study area.

Scenario 1 includes four ramp metering systems installed on the on-ramps of the A10 west motorway. Although the MFD of the whole network is almost the same as that in the basic scenario, the MFD of the motorway witnesses a smaller maximum density. The figure reveals the fact that ramp metering is able to limit the number of vehicles entering the motorway and prevents traffic from congestion. However, the urban network experiences a worse situation because vehicles have to wait on onramp and spill back further to the urban roads.

The scenario 2 introduces three situations with respect to the application of hard shoulder use. Due to the limitations of VISSIM, an extra lane is added through the whole simulation period instead of only during the peak hours. It has been proven that only when road expansion is made on the bottleneck of the network, A10 west motorways, significant changes are observed in the MFD. If the speed limit is decreased from 100 km/h to 80 km/h, the improvement is even larger. The extra lane is applied on the motorway directly and it has little impact on the urban roads. The MFD of the urban network remains same under all scenarios as expected.

In conclusion, MFD is able to reflect the effects of the DTM measures. In some cases, the effects are not visible in the MFD of the whole network. However, when the network is divided into several sub-networks, the changes of the shapes of the MFD, resulting from the implementations of DTM measures, are revealed. Nevertheless, the accuracy of the DTM measure evaluation by MFD is not tested. Therefore, the conventional method for traffic evaluation will be introduced in the next chapter, in which the potential of using MFD for assessing the DTM measures will be quantified.

6. Assessment of the methods on DTM measures evaluation

In chapter 5, the effects of DTM measures are revealed by the changes of the shape of the MFD. It appears that the MFD will be a useful method for the road operators on DTM measures evaluation. In this chapter, the prospect of the MFD as a traffic evaluation method is investigated. Firstly, the evaluation criteria in the conventional method to assess DTM measures are defined, followed by their evaluation results on the DTM measures. In section 6.3, a multi-criteria analysis (MCA) is made to compare the MFD with the conventional method. Using the results of MCA, the advantages and disadvantages of MFD are discussed and the potential of using MFDs for DTM measures evaluation is demonstrated.

6.1 Conventional method definition

Although MFD is a new concept, the evaluation of DTM measures has been made for a long time. Many studies have contributed to investigate the effects of ramp metering and hard shoulder use in the Netherlands (Taale & Middelham, 2000; Helleman, 2006; Middelham, 2006; Mirshahi et al., 2007; Yuan, 2008). In these studies, the conventional method consisting of several criteria is applied to evaluate the DTM measures. The chosen criteria rely heavily on the objective of the projects. For example, the emission from the vehicles will be a vital index if the focus is on environmental issues. However, when analyzing road safety, the number of crashes is more important. In this project, the aim of the DTM measures is to improve the effectiveness of the infrastructure so that the following criteria are defined.

The total travel time spent (TTS) by all vehicles reflects the overall performance of the whole network. The lower the TTS in the network, the higher the outflow and the smaller the delays. Usually, the average travel time of an individual vehicle is also a necessary criterion because DTM measures will lead to a change in the total traffic demand of the network and TTS may become even higher under a better traffic situation. However that is not the case in this project. The simulation period in VISSIM is sufficiently long, covering both peak hour and off peak hour, so that all vehicles are able to enter the network. The number of the vehicles entering the model is consistent in all scenarios. Therefore, TTS is an ideal criterion evaluating the general network performance.

Another criterion used in this project is the total travel distance (TTD) travelled by vehicles. Like TTS, TTD is meaningless to reflect the change of traffic demand in this case. Nevertheless, when combing the TTS, TTD can show to what extent the drivers change their route choices and the network performance as well.

Sometimes, other criteria such as the average speed and delay are also considered. However, the evaluation results of them can mostly be represented by those of the travel time and travel distance. For instance, the decrease of TTS indicates a better traffic situation, in which the average speed increases while the delay either in the network or of an individual vehicle declines. Therefore, total travel time and total travel distance are conventional criteria chosen to evaluate the network performance in this case.

However, the criteria of overall performance are not sufficient for the evaluation on a large network consisting of different road types. In the Netherlands, the motorways are monitored by Rijkswaterstaat while the urban roads are controlled by the local government. Special criteria have to be defined on the performance of different types of road sections. Hence, the travel time and travel distance in separated sub-network are measured. Especially, for the local traffic measures, they will bring large changes on the nearby traffic situation. Ramp metering installation analyzed in this project is one of examples. Therefore, the travel time on a specific area will be taken into account.

In summary, the total travel time and the total travel distance are chosen to evaluate the overall performance as well as the situations in the sub-networks. Meanwhile, the travel times on the road sections where the DTM measures are applied are measured to show their direct influence on the nearby roads. The conventional method with these evaluation criteria is applied to assess the effects of DTM measures in the next section.

6.2 Evaluation of DTM measures by the conventional method

In this section, all scenarios discussed in previous chapters are evaluated by the conventional method, composed of criteria mentioned in section 6.1. The results will be an important basis on assessing the evaluation method for the DTM measures.

- Ramp metering installation

Table 6.1 demonstrates the evaluation results of the ramp metering installation by the conventional method. In general, the travel distances almost remain the same in all cases while the travel times vary greatly in different scenarios. With the ramp metering application, the overall performance of the whole network hardly changes but large improvement is seen on the motorways. The total travel time on the motorways decreases by 10.44%. However, the traffic situation on the urban roads become worse, indicated by 7.71% extra travel time.

Table 6.1: Evaluation on ramp metering installation by the conventional method

<table>
<tr><th colspan="3"></th><th>whole network</th><th>motorways</th><th>urban road</th></tr>
<tr><td rowspan="2">Basic scenario</td><td colspan="2">total time (h)</td><td>28343</td><td>11495</td><td>16848</td></tr>
<tr><td colspan="2">total distance (km)</td><td>804597</td><td>474983</td><td>329614</td></tr>
<tr><td rowspan="4">Ramp metering</td><td rowspan="2">total time (h)</td><td>value</td><td>28443</td><td>10296</td><td>18147</td></tr>
<tr><td>change</td><td>0.35%</td><td>-10.44%</td><td>7.71%</td></tr>
<tr><td rowspan="2">total distance (km)</td><td>value</td><td>803722</td><td>481175</td><td>322547</td></tr>
<tr><td>change</td><td>-0.11%</td><td>1.30%</td><td>-2.14%</td></tr>
</table>

If the focus is on the motorways where the ramp metering systems are installed, which is the section from urban main road S105 to S101, the improvement is also demonstrated (see Figure 6.1). During the congestion period, drivers have about 10-minute time saving when passing through this area, compared to the basic scenario.

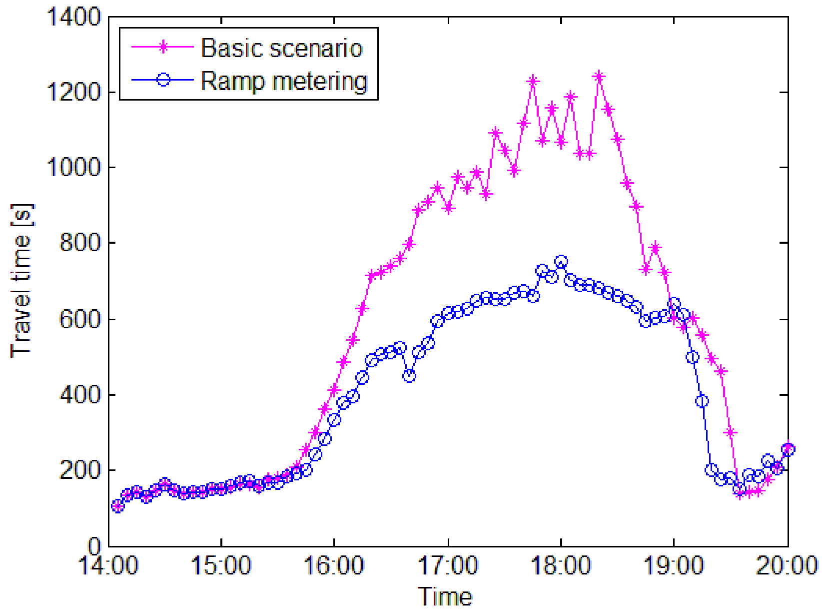


Figure 6.1: Travel time on road section installed ramp metering systems

- Extra lane

Similar to the evaluation results in Table 6.1, with extra lane application, the travel distances hardly change, but the total travel times experience a great variation (See Table 6.2).

Table 6.2: Evaluation on extra lane application by the conventional criteria

			whole network	motorways	urban road
Basic scenario	total time (h)		28343	11495	16848
	total distance (km)		804597	474983	329614
A4&A10S	total time (h)	value	28911	11823	17088
		change	2.00%	2.85%	1.43%
	total distance (km)	value	804366	475627	328739
		change	-0.03%	0.14%	-0.27%
A4, A10S & W 100	total time (h)	value	23416	7752	15664
		change	-17.38%	-32.57%	-7.02%
	total distance (km)	value	805387	478064	327323
		change	0.10%	0.65%	-0.70%
A4, A10S & W 80	total time (h)	value	22716	7652	15064
		change	-19.85%	-33.44%	-10.59%
	total distance (km)	value	805213	476901	328312
		change	0.08%	0.40%	-0.39%

When an extra lane is added on the motorways in the VISSIM model, the great changes on overall performance can be found. If the A4 and

A10 south motorways are expanded by one lane for each direction, the traffic situation of the whole network seems to be worse. It is caused by the characteristics of the VISSIM model. In VISSIM, each zone has a parking lot, at which the trips originating from or ending in this zone can start or end (PTV AG, 2007). If the link connecting a parking lot is full of vehicles, other vehicles going to enter the network will be prevented in the parking lot temporarily and this delay is not calculated for the overall performance. In this case, the bottleneck of the network used in VISSIM is the A10 west motorway. The expansion of the A4 and A10 south motorway alone has no contribution on network improvement. By contrast, it creates more space for containing the vehicles which have to be in the queue before they enter the A10 west motorway. The total travel time of the whole network rises due to the increasing number of the vehicles queuing on the A4 and A10 south motorway.

However, great improvements are observed when expansion is made on the A10 west motorway. If the speed limit is set as 100 km/h on all motorways, the total travel time decreases by about 17%. If a lower speed limit is implemented on A10 west after lane adding, the total time saving increased to 20%. When only considering the motorways, the improvements are even larger. The travel times on the motorways decline by about 33%, in both cases of 80 km/h and 100 km/h speed limit on the A10 west motorway. Meanwhile, the urban roads also benefit from the extra lane. The total travel time on the urban roads decreases by 7.02% in scenario 2.2 and by 10.59% in scenario 2.3 respectively. It does prove that A10 west motorway is the bottleneck of the whole network. The direct road expansion on the bottleneck can improve the network performance dramatically.

In summary, effects of DTM measures, both ramp metering and extra lane, are revealed by the conventional method. In the next section, the results will be compared with findings in Chapter 5, to assess the potential of MFD as an evaluation method.

6.3 Comparison between MFD and the conventional criteria

One of research questions in this project is to investigate the possibility of using MFD as an evaluation method for DTM measures. In the previous sections, the effects of ramp metering and extra lanes have been presented by the MFD as well as the conventional method, which is widely used in the former studies. In this section, the advantages and disadvantages of the MFD are investigated, compared to the conventional method.

In this project, the multi-criteria analysis (MCA) is made, which has several advantages compared to other methods such as the cost-effectiveness analysis (CEA) and the cost-benefit analysis (CBA). Firstly, it is open and explicit, and the translation of the impacts into monetary values is not necessary. Secondly, the criteria that the decision makers use are open to change if they are felt to be inappropriate. In addition, the scores and weights are explicit and are developed according to established techniques. They can be compared and amended if necessary. Furthermore, the performance measurement can be sub-contracted to experts rather than the decision makers themselves.

As is clear from a growing literature, there are many MCA techniques and their number is still rising. Considering the factors including internal consistency, logical soundness, transparency, ease of use, realistic time requirements and ability to provide an audit trail, the MCA recommended by Van Ham is applied in this project. The complete process should include the following seven steps (Van Ham, 2007).

a) Establish the decision context

In this step, the objective of the MCA is determined. In addition, the decision maker and other important actors need to be pointed out. It is obvious that the aim in this case is to assess the potential of the MFD and the conventional method for DTM measures evaluation. Since the study area covers motorways as well as the urban roads, their operators, Rijkswaterstaat and the city of Amsterdam, are both regarded as the decision makers. As the road operators, the main task of

Rijkswaterstaat and the Amsterdam city is to take action to improve the traffic condition on the roads. Therefore, both Rijkswaterstaat and the city of Amsterdam are interested in the traffic measures and the evaluation method which can be used for policy making. However, it is obvious that the focuses of two stakeholders are different. Rijkswaterstaat pays more attention to motorways while the city of Amsterdam cares about the urban roads. The various emphases of two stakeholders will lead to different evaluation results in the following steps.

b) Identify the alternatives

The alternatives to be evaluated should be generated in this step. In this case, there are only two alternatives. One is the MFD and the other is the conventional method, made up of criteria mentioned in section 6.1. In the end of the multi-criteria analysis, whether the MFD outperforms the conventional method for road operators is expected to be revealed.

c) Identify the criteria of MCA

In an MCA, criteria are the measures of performance by which the alternatives are judged. In this case, four criteria are made, which are accuracy on the traffic representation, visualization, feasibility of implementation and low costs of application.

An evaluation method will influence the decision on the choice of the DTM measures so that it must reflect the traffic situation accurately. In addition, a more visual evaluation method with more information will help the road operator to make an appropriate choice easily. Besides, the feasibility of using specific method for DTM measure evaluation should also be taken into account, because technical barriers may prevent their application. Last but not least, costs spent on evaluation are always an important issue. The high costs will obviously decrease the overall performance of an alternative even it is good at other aspects.

d) Describe the performance of each alternative against the criteria (scoring)

In this project, the direct rating is used as an approach to scoring performance on an interval scale because it is difficult to reach an agreed scale of measurement for each criterion in this case. Direct rating uses the judgement to associate a number in the 1 to 5 range with the value of each alternative on that criterion. The scores of 1 to 5 represent "very bad", "bad", "average", "good" and "very good" level of performance respectively. Hence, the pros and cons of two evaluation methods can be revealed in this project, although the MCA is applied in a more qualitative way.

Moreover, different stakeholders are involved in the MCA. Considering different situation on motorways and the urban network in this case, especially the number of detectors on the roads, performance of various alternatives are not the same from the viewpoints of two stakeholders. According to four criteria mentioned in step c, the performance of both the MFD and the conventional method are discussed.

- *Accuracy on the traffic representation*

The evaluation of DTM measures by MFD and the conventional method has been made in the previous sections. In general, the results are similar, implying a reliable evaluation by either alternative. The benefits of the ramp metering on motorways are at the cost of delay on the urban roads. When the extra lanes are applied, only expansion on the A10 west motorway leads to great improvements. It can be concluded that both the MFD and the conventional method are able to reflect the effects of the DTM measures.

But it should be noticed that the MFD is a qualitative evaluation method and it is meaningless to apply the MFD to assess only one scenario. The MFD can tell which scenario is the best, but not to what extend that scenario is good. Furthermore, the division of the sub-networks is quite vital in the MFD application. Road operators should consider several factors such as road types, congestion levels and traffic control measures to partition the network. An inappropriate division will decrease the accuracy of the MFD. Therefore, the conventional method outperforms MFD in the accuracy on the traffic representation, either for the motorways or for the urban roads. The scores of two alternatives against this criterion are 5 and 4 respectively. It should be pointed out that the accuracy of the evaluation method is significant in this case so that a sensitivity analysis will be made to learn the effects of this factor on the final results of MCA in a later step.

- *Visualization*

The MFD is quite visual on showing the traffic variables such as flow and density of the network. The change of the critical density and the maximum density after DTM measures implementation can be clearly demonstrated on one MFD. In addition, other traffic variables are implied by MFDs. The slope of the line connecting any spot of the MFD and the zero point equals the average speed under that traffic condition. The change of the maximum flow also indicates whether the capacity of the network is modified.

On the other hand, the conventional method can provide sufficient traffic information if enough evaluation criteria are involved in the method. But generating conclusions by a conventional method requires more efforts because the evaluation results from different aspects should be integrated.

In summary, the road operator is able to quickly tell the pros and cons of a DTM measure by using the MFD, a really visual evaluation method. The score of the MFD is 5 and that of the conventional method is 4 in this aspect.

- *Feasibility of implementation*

The MFD is derived by aggregating the link traffic data such as flow and density. In an ideal condition, MFDs are obtained based on traffic variables on each link in the network so that the amount of the data is extremely large. However, usually it is not possible, especially when empirical data are used. One of the main restrictions of applying MFD is the availability of the data.

On the other hand, simulation models are possible to simulate the traffic under different scenarios. However, three levels of validity, face validity, construct validity and predictive validity, are required before one can make valid inference with a simulation model (Van Lint et al. 2008). The processes of ensuring that the model has three types of validity are called verification, calibration and validation respectively, which also need empirical data. In the Netherlands, inductive loop detectors have been installed on most motorways (Hoogendoorn, 2008). Traffic data including flow and density are collected automatically for every minute. However, the number of detectors on the urban roads is limited, restricting the feasibility of using a simulation model for a large urban network.

The conventional method for DTM measures evaluation need the empirical traffic data as well. However, they usually focus on the main roads so that the required number of data is much less than the case of the MFD. The traffic data from detectors can be used to calculate the travel time on the motorway. Similarly, the traffic situation on the urban roads can be reflected by measuring the traffic variables on several key points. The travel time on the main urban roads is a good representation of traffic on total urban roads. Of course, if the simulation model is used in a project, the situation will be similar as that of the MFD application. A huge amount of the traffic data is required for model calibration and validation.

Hence, the MFD is less feasible on data collection compared to the conventional method. Considering the existing situation on the motorways and the urban roads, MFD and the conventional method can both get the highest score in the opinion of Rijkswaterstaat. However, the city of Amsterdam has to make extra efforts on data collection, especially for the MFD application. So MFD and the conventional method are graded 2 and 4 respectively against the criterion of feasibility.

- *Low costs of application*

When describing the traffic situation, the main costs are spent on data collection. As mentioned above, whether the assessment is made based on the real traffic situation or a simulation model, the empirical data are required. The number of needed traffic data determines the costs of a criterion for traffic evaluation.

The application of MFD requires as many link traffic variables of flow and density as possible, which can be aggregated to generate a network MFD. For a large network, the amount of the data will be extremely huge. In Dutch road network, it is more customary to use two loop detectors to record the traffic variable. The costs of inductive loop detectors vary across districts. For an initial installation, the cost of pull boxes, traffic control, loop detector amplifiers, and motorist delay should be considered. For a six lane motorway sensor station, annualized per-lane sensor costs are about 750 US dollars, supposing a mean working life of 10 years (Klein, Mills, & Gibson, 2006). It should be noticed that the motorways in the Netherlands has been already installed detectors widely. There will be no extra expenses on data collection to derive MFD on Dutch motorways. By contrast, large amounts of detectors are required on the urban roads to measure the traffic variables, which will be a large investment.

For measuring travel times and travel distance, there are two categories of spatial monitoring techniques, automated vehicle identification (AVI) systems and floating sensor systems (Van Lint et al. 2008). The AVI system matches vehicles at two consecutive locations along a particular route and derives traffic variables. The measurement can be realized by the detectors along or on the roads. The costs of these devices are more or less like those of the fixed loop detectors. The floating sensor systems use either in vehicle navigation system or cell phone to determine the positions of a vehicle. Although the unit cost of these systems is low, the number of vehicles installing floating sensor systems should be large to ensure a continuous measurement, which increases the costs dramatically. Furthermore, commercial issue exists on whether the navigation system companies are willing to provide the traffic information. The costs of using floating sensor systems may go up due to purchasing such information.

Therefore, it is difficult to determine the costs of the conventional method. But data like travel time and travel distance can be also estimated by the traffic variables from detectors. Therefore, the costs will be no larger than deriving the MFDs. In general, using the conventional method seems cheaper because fewer number of traffic data needs to be collected. Like the situation in the criterion of feasibility, the Rijkswaterstaat give a high score to both alternatives due to the installed detectors on the motorways. By contrast, in the urban network, the score of the conventional method is mediate and the MFD performs even worse. They are graded 3 and 2 respectively. However, the estimation on the costs of two alternatives is quite rough so that this factor will be investigated in the sensitivity analysis in detail.

In summary, the score cards of evaluation by the MFD and the conventional method in the opinions of Rijkswaterstaat and the city of Amsterdam are presented in Table 6.3 and Table 6.4.

Table 6.3: Score card of evaluation on MFD and conventional criteria from the viewpoint of Rijkswaterstaat

	MFD	conventional methods
Accuracy on traffic representation	4	5
Visualization	5	4
Feasibility of implementation	5	5
Low costs of application	4	4

Table 6.4: Score card of evaluation on MFD and conventional criteria from the viewpoint of the city of Amsterdam

	MFD	conventional methods
Accuracy on traffic representation	4	5
Visualization	5	4
Feasibility of implementation	2	4
Low costs of application	2	3

Legend: 1 – very bad, 2 – bad, 3 – average, 4 – good, 5 – very good

e) Identify the weights of criteria

The weights of the criteria are another important issue in MCA. They reflect how much the decision maker pay attention to the different criteria. The weights also depend on the range of difference in the scores of each criterion, derived in previous step, and on how much the stakeholders care about the difference. Since the number of criteria considered in this case is not large, it is easily to allocate 100 percents against the criteria as weights.

As mentioned above, the accuracy of the evaluation method is the most important issue. The MFD and the conventional method will only be considered if they can correctly represent the traffic situation. Hence, the accuracy should have the largest weights, which accounts for half of the total weights. The better visualization of the method can help the decision maker get the conclusion quickly. It is not so significant because the experienced experts can make an evaluation on DTM measures even the method is not visual. For a DTM measures evaluation in a large network, the decision makers would like to spend more time if the accuracy can be ensured. So the criterion of visualization only gets 10% weights. The feasibility of implementation is also vital because the technical barriers significantly reduce the attraction of the evaluation method. So it is assigned 20% weights. In similar, the decision maker regards the costs of evaluation as an important factor as well and the remaining 20% weights are given to this criterion. Therefore, the weights of criteria in MCA are summarized in Table 6.5.

Table 6.5: Weights of the criteria in MCA

Criteria	Weight (%)
Accuracy on traffic representation	50
Visualization	10
Feasibility of implementation	20
Low costs of application	20

Sometimes the stakeholder involved in the project may have totally different opinions on the weights. In this case, the weights of criteria have little relation with the type of roads so that Rjikswaterstaat and the city of the Amsterdam may have little discrepancy. However, the weights have large influence on the final results of the MCA, especially when the alternatives have respective advantages in different criteria. Hence, the weights will be changed in the sensitivity analysis to get a more reliable conclusion.

f) Calculate the overview value

According to the results in step 4 and step 5, the integrated scores of both alternatives can be calculated. In this MCA, the simple additive method is used, combines the alternative's values into one overall value by multiplying the value score on each criterion by the weight of that criterion. The scores of the MFD and the conventional method are 4.3 and 4.7 respectively, from the viewpoint of Rijkswaterstaat (see Table 6.6). In terms of the city of Amsterdam, the MFD scores 3.3 and the conventional method gets 4.3 (see Table 6.7).

Table 6.6: Overview values of MFD and the conventional method from the viewpoint of Rijkswaterstaat

Criteria	Weight	MFD	Conventional method
Accuracy on traffic representation	50%	4	5
Visualization	10%	5	4
Feasibility of implementation	20%	5	5
Low costs of application	20%	4	4
Overview value		4.3	4.7

Table 6.7: Overview values of MFD and the conventional method from the viewpoint of the city of Amsterdam

Criteria	Weight	MFD	Conventional method
Accuracy on traffic representation	50%	4	5
Visualization	10%	5	4
Feasibility of implementation	20%	2	4
Low costs of application	20%	2	3
Overview value		3.3	4.3

Legend: 1 – very bad, 2 – bad, 3 – average, 4 – good, 5 – very good

g) Sensitivity analysis

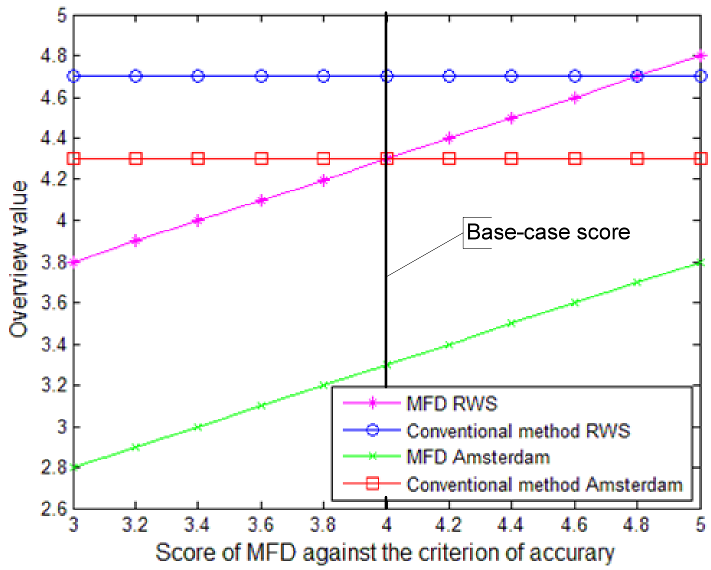
Sensitivity analysis provides a means of examining the extent to which the relative importance weight of each criterion/indicator makes any difference in the final results. Interest groups often differ in their views of the relative importance of the criteria (or weights) and of some scores, though weights are often the subject of more disagreement than scores. In this step, the sensitivity analysis is separated into two phases. The scores and weights of several criteria are changed successively to get more reliable results of the MCA.

As motioned in step d, the scores against two criteria need to be further analyzed. One is the accuracy of MFD, which accounts for the largest amount of weights. The change on the score may affect the overview value greatly. The other factor is the costs of two alternatives on the urban roads. The estimation of costs is quite uncertain so that the analysis on variation of costs is necessary in this step. Hence, the further questions are analyzed:

- What if the accuracy of MFD is changed?
- What if the costs of two alternatives change on the urban roads?

In the previous analysis, the accuracy of the MFD is considered as lower than that of the conventional method due to the difficulty in separating the network. In addition, as a qualitative method, the MFD is not able to tell the exact performance of one scenario. Therefore, the score of the MFD is graded as 4. When the expectation on the accuracy of MFD is even decreased, the MFD will has a lower integrated value and the conventional method will be more attractive (see Figure 6.2). However, with the increasing number of studies on the MFD, the decision maker may generate a more appropriate way for network division to derive the MFD. Besides, the qualitative method is also quite useful in evaluation by comparing several scenarios. Hence, the accuracy of the MFD may increase in the future. Figure 6.2 reveals the impact of this factor on the overview scores. It can be concluded that the final results do not change on the urban roads due to large difference between two alternatives. However, from the viewpoint of Rijkswaterstaat, the small gap of the integrated scores decreases dramatically with the increase of accuracy of MFD. When the value of horizontal axis is large than 4.8, which means quite accurate evaluation results, the total performance of the MFD is even better than that of the conventional criteria.

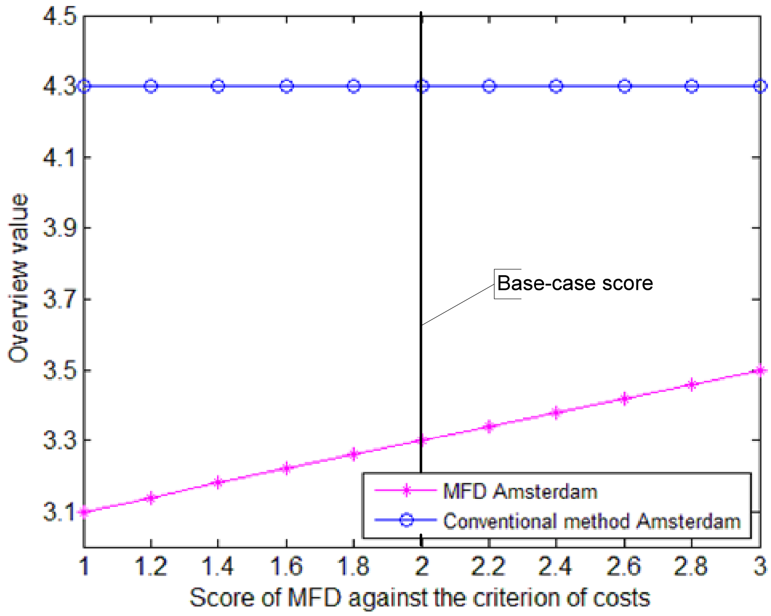
Figure 6.2: Sensitivity analysis on the accuracy of MFD



Legend: 1 – very bad, 2 – bad, 3 – average, 4 – good, 5 – very good

Another uncertainty in the analysis in this project is the costs of two evaluation methods on the urban roads. The costs of conventional method should be not higher than that of MFD because the former method can use the data for deriving MFD to get the results. However, the gap between two methods is difficult to be determined. In the base case showed in step d, the score of MFD is 1 point lower than that of the conventional method. In this sensitivity analysis, the score of the conventional method against the criteria of costs on the urban road is kept the same while that of MFD is varied. The change of overview values under the different estimations on the costs of two alternatives are demonstrated (see Figure 6.3). It can be found that the conventional method always has a better overview performance because it has obvious advantages in other aspects.

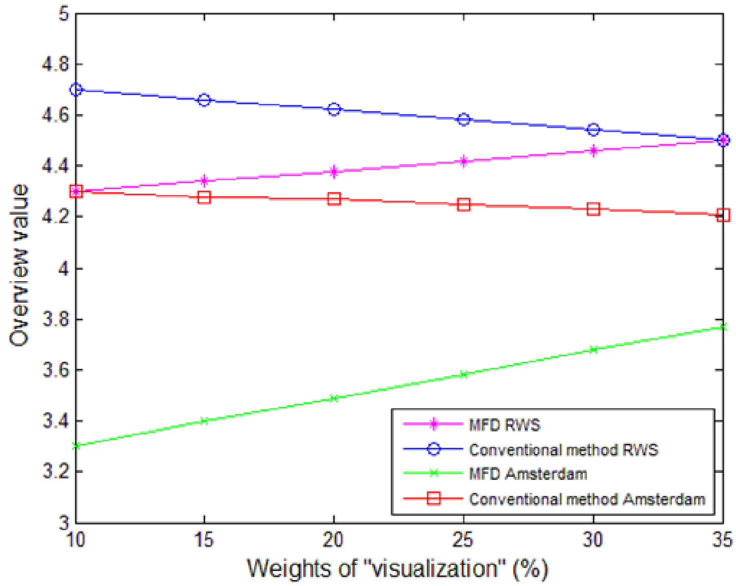
Figure 6.3: Sensitivity analysis on the costs of two alternatives from the viewpoint of the city of Amsterdam



Legend: 1 – very bad, 2 – bad, 3 – average, 4 – good, 5 – very good

Besides the scores, the weights of four criteria are also an important factor influencing the final results. In this project, two sets of weights have been made to reflect the different opinions of two stakeholders, Rijkswaterstaat and the city of Amsterdam. Table 6.6 and Table 6.7 show that the MFD has a worse overview performance on motorways as well as the urban roads, and it only outperforms the conventional method against the criterion of visualization. It is obvious that if the weight of visualization is not increased, the integrated score of MFD will be always lower than that of the conventional method when the score cards remain same. Hence, this sensitively analysis will raise the weight of visualization and investigate how it will change the final results.

Figure 6.4: Sensitivity analysis on the weight of criterion of visualization



Corresponding weights of other criteria

Visualization	10.00%	15.00%	20.00%	25.00%	30.00%	35.00%
Accuracy	50.00%	47.17%	44.25%	41.47%	38.76%	36.10%
Feasibility	20.00%	18.87%	17.70%	16.67%	15.50%	14.44%
Low Costs	20.00%	18.87%	17.70%	16.67%	15.50%	14.44%

The Figure 6.4 indicates the sensitivity analysis on the weight of the criterion of visualization. The analysis increases the weight of this single criterion and keeps the proportion of the weights of other criteria same. It can be found that, from the viewpoint of Rijkswaterstaat, the integrated score of MFD equals that of the conventional method when the weight of visualization reaches 35%. For the city of Amsterdam, MFD needs a much higher weights of visualization to get a better overview performance. However, it is not the case in reality. The visualization of the method is a less important criterion compared to others so that the conventional method is always a better choice if the scores do not change. The results of the MCA are quite robust against the weights of different criteria.

In conclusion, the results of the MCA are generally reliable from the viewpoint of the city of Amsterdam. The MFD is not good at DTM measures evaluation due to the difficulty and high expenses on data collection in the urban network. For the road operator of the Dutch motorway, Rijkswaterstaat, the conventional method also seems better. However, the difference between two alternatives is small so that the minor change on the score or the weights of criteria may change the final results.

6.4 Conclusions

In this chapter, the possibility of using MFD to evaluate the effects of DTM measures is investigated. The MFD is compared with the conventional criteria by using a multi-criteria analysis.

The conventional method is made up of the criteria, travel time and travel distance in the whole network as well as the sub-networks of motorways and the urban roads. It has been shown that the evaluation results by the MFD are similar to those by the conventional method. The DTM measures evaluation is quite reliable if the sufficient data are available and the sub-network division is made appropriately.

However, the accuracy is not the only consideration. MCA applied in this project also include other criteria, visualization, feasibility and costs. In this project, Rijkswaterstaat and the city of Amsterdam, the operators of motorways and the urban roads respectively, are two stakeholders. They have different opinions on scoring two alternatives. After seven steps in MCA, the performance of two alternatives, the MFD and the conventional method is revealed. MFD is considered as a worse evaluation method by both Rijkswaterstaat and the city of Amsterdam, represented by a lower integrated score.

Unlike the city of Amsterdam, Rijkswaterstaat gives two close overview values for the MFD and the conventional method. The final results of the MCA may change if the scores and weights for criteria are modified slightly. Hence, Rijkswaterstaat should pay more attention to the method choice. One of possible solutions is to apply the MFD as well as the conventional method. The large number of information hidden in a visual MFD can help the decision maker learn the rough traffic situation fast and clearly. When the technical and financial obstacles of using the

MFD are small, the combination of MFD and the conventional method will bring a more reliable evaluation on the DTM measures evaluation.

7. Conclusions and recommendations

The main objective of this project is to investigate the effects of the DTM measures on the shape of MFD. Meanwhile, the possibility of using MFD as an evaluation method is analyzed. In this chapter, the conclusions related to the research objectives and questions will be presented, and recommendations for the further research are given.

7.1 Summary of research process

First of all, the work which has been done in this thesis project is summarized.

The previous studies regarding the MFD have been reviewed to collect the information for deriving an MFD. The way of obtain MFD by aggregating link traffic data has been introduced and the characteristics of the MFD have been pointed out.

The macroscopic model RBV has been used to derive the MFD for the Amsterdam metropolitan area. After getting the MFD, the principles of the RBV model are analyzed and the explanations on the shape of MFD are revealed. The conclusion has been made that the RBV model is not suitable to derive MFD. The microscopic model VISSIM then has been applied, in which one artificial dynamic OD matrix has been created. The shape of the MFD derived from VISSIM has been studied as well. It has been concluded that the VISSIM model with created OD matrix can be used for the further analysis.

Furthermore, the effects of the DTM measures on the shape of MFD have been investigated. Two measures, ramp metering installation and extra lane application have been selected. Four scenarios have been made with different DTM measures. In each scenario, one MFD has been derived and these MFDs have been compared to show the change of their shape.

Finally, the potential of MFD as an evaluation method is investigated. A multi-criteria analysis has been applied to compare the MFD and the conventional criteria.

7.2 Conclusions

Based on the analysis in the previous chapters, two main research questions, which have been put forward in the beginning of this report, will be answered.

1. What do the MFDs look like in Amsterdam region?

In this project, two simulation tools, the RBV model and the VISSIM model have been applied to derive the MFDs for the Amsterdam region. By using RBV, the flow of an MFD does not decease at high densities. The congestion branch in a conventional fundamental diagram is missing in the MFDs derived from the RBV model, regardless of the different demand levels. Furthermore, a drop of flow between the onset and the resolving of congestion always exists in these MFDs. The cause of the missing congestion branch is that the RBV model assumes a constant outflow during the congestion period. The vehicles are still allowed to enter one link at the saturation flow even the link is totally congested. In terms of the drop of flow, the locations of measuring densities and flows in RBV are not same so that they are not corresponding during the resolving of congestion. Due to these two drawbacks, the RBV model is not suitable to derive the MFDs.

The VISSIM model is able to derive MFDs including congestion branch like a conventional link fundamental diagram. The sweet spot is clearly shown in the MFDs obtained from VISSIM. However, the drop of flow is still observed on these MFDs. The cause is that the dramatically decrease of the demand after the congestion period leads to quick decline of flow on a link when the density is still high. The ways of variables measurement in VISSIM show this problem in the MFD.

Nevertheless, the most vital pattern of an MFD, the value of the sweet spot can be estimated from the MFD and the period of congestion resolving is less important. Therefore, the VISSIM model can be applied to derive the MFDs for the Amsterdam area.

The network of the study area is further divided into two sub-networks, composed of motorways and the urban roads respectively. The MFD of the motorways has the similar shape as that of the whole network. The congestion branch is observed in either MFD. On the contrary, only the free flow state is shown in the MFD of the urban roads.

2. What are the effects of DTM measures on the MFD?
   - How do specific DTM measures affect the MFD?

In this project, two DTM measures are selected for analyzing their effects on the shape of MFD. With the ramp metering application, the MFD of the whole network almost remain the same. Only when the network is separated into sub-networks with different road types, the changes are demonstrated. In the MFD of the motorways, the value of the sweet spot and the maximum flow are the same as those in the basic scenario. However, the maximum density decreased significantly. In terms of the urban roads, the congestion branch is observed, with a higher maximum flow and maximum density.

When the extra lane application is assessed, three scenarios are made. If only the A4 and A10 south motorways are expanded, the changes of the MFD are quite little. When the expansion is also on the A10 west motorway, significant changes are witnessed, regardless of the different speed limits. Both the critical density and the maximum flow increase slightly. In addition, the congestion branch is missing in the MFD because of a much better traffic situation after extra lane application. When extra lanes are implemented on motorways, the speed limit on the road sections are decreased for a safety reason. It results in a more gradual slop of the MFD in the free flow state. When the focus is on the motorway sub-network, similar changes are observed like those of the whole network. By contrast, for the urban sub-network, the changes of the shape of the MFDs are negligible in all scenarios with extra lanes.

   - Is it possible to use the MFD to evaluate the effects of DTM measures?

The MFD is able to evaluate the DTM measures accurately. The effects of the DTM measures can be shown by the changes on the shape of the MFD. However, an MFD requires many link traffic data in a network. Technical and financial barriers decrease the attraction of MFDs. It is more feasible to use MFD when the detectors have been widely installed on the roads and the traffic data are easily collected. Furthermore, MFD can be combined with the conventional criteria to make a more reliable DTM measures evaluation.

7.3 Recommendations for further development

In this section, the recommendations for further improvement of study for MFD in Amsterdam area are presented.

- Traffic network data

Since the empirical data are not available in the study area, the plan of using real data for deriving MFD cannot be realized. Furthermore, due to the drawbacks of the RBV model, VISSIM is finally used in this project. In this case, the emphasis is on the changes of the MFD with the implementation of the DTM measures. An artificial OD matrix has been created to derive MFD in Amsterdam in the VISSIM model.

However, it is always better to use the data which reflect the real traffic situation. The city of Amsterdam plans to install many detectors in the main intersections in the urban network. When these devices start to work, the traffic data on both motorways and urban roads will be available. Hence, it is advised to use empirical data for deriving MFD, which can avoid disadvantages of the simulation models and reflect the real situation in Amsterdam.

- Simulation program

Two simulation programs used in this project both have drawbacks. The main problem of VISSIM is that the computing time is quite long. Many simulation runs are required for each scenario before the convergence is reached. For a large network, the necessary time for simulating the traffic during both peak and off peak hours are extremely long. The dynamic assignment function in VISSIM needs to be improved.

In terms of the existing RBV model, the period of demand decrease should be more gradual to reduce the drop of flow between onset and resolving of congestion. However, the problem of missing congestion branch cannot be easily solved. The dynamic network loading model needs to be redesigned so that the flow will decline at high densities like a conventional fundamental diagram.

- Effects of DTM measures on the MFD

In this case, only ramp metering and extra lanes have been analyzed. In the near future, a ramp metering system will be installed on each onramp of the A10 beltway. Therefore, an updated analysis is required. In addition, an external controller is needed to realize the real temporary hard shoulder use during the peak hours in the VISSIM model.

In addition, the project PPA involves four levels of control concepts, in which many other DTM measures are involved such as dynamic route choice and speed limit reduction. It is worthwhile to assess their effects on the shape of the MFD for a possible real time traffic control by the MFD in the future.

- MFD for simulation model assessment

In this project, two kinds of simulation software, the microscopic model VISSIM and the macroscopic model RBV are applied to derive MFDs. Considering the different situations when deriving the MFDs by two models, it is possible to use the MFDs as a tool to assess the overview performance of the simulation models.

In this project, the number of simulation runs is limited due to long computing time. Hence, more simulations have to be run to obtain more reliable results. In addition, it is better to involve other simulation models as well to have a wider insight on simulation tools by using MFD.

- MFD for traffic control

The main reason that the road operators are interested in MFDs is that they have shown good prospects on real time traffic control. However, effects of using MFD for traffic control in Amsterdam region are not clear now. Hence, it is meaningful to generate a strategy of using MFD for traffic control in this area. The important issues include sub-network division, control measures selection and effects evaluation. Of course, this idea may not be realized until sufficient empirical data or advanced simulation tools are available.

Bibliography

Buisson, C., & Ladier, C. (2009). Exploring the Impact of the Homogeneity of Traffic Measurements on the Existence of Macroscopic Fundamental Diagrams. *the 88th Aunnal Meeting of Transport Research Board.* Washington, DC.

Daganzo, C. (2005). *Imporve city mobility through gridlock control: an approach and some ideas.* Berkeley: UC Berkeley Center for Future Urban Transport, Inst. Trans. Studies, University of California, Berkeley, CA.

Daganzo, C. (2007). Urban gridlock: Macroscopic modeling and mitigation approaches. *Transportation Research Part B , 41* (1), 49-62.

Daganzo, C., & Geroliminis, N. (2008). An analytical approximation for the macroscopic fundamental diagrams of urban traffic. *Transportation Research Part B , 42* (9), 771-781.

Fellendorf, M. (1994). *VISSIM: A microscopic Simulation Tool to Evaluate Actuated Signal Control including Bus Priority.* Dallas: 64th ite Annual Meeting.

Geroliminis, N., & Daganzo, C. (2008). Existence of urban-scale macroscopic fundamental diagram: Some experimental findings. *Transportation Research Part B , 42* (9), 759-770.

Geroliminis, N., & Daganzo, C. (2007). *Macroscopic modeling of traffic in cities.* Washington, D.C.: Transportation Research Board 86th Annual meeting.

Helleman, B. (2009, May 26). Application of peak hour lane on A10 beltway. (X. Qian, Interviewer)

Helleman, B. (2006). *Merged Lanes in the Netherlands: An Overview of TMS Applications.* Rotterdam: AVV Transport Research Centre, Ministry of Transport, Public Works and Water Management.

Hoogendoorn, S. (2008). *Transport Flow Theory and Simulation.* Delft: Delft University of Technology.

Hoogendoorn, S., & Hoogendoorn-Lanser, S. (2009). *Coordinated Dynamic Traffic Management Amsterdam.*

Klein, L., Mills, M., & Gibson, D. (2006). *Traffic Detector Handbook: Third Edition–Volume II.* Federal Highway Administration, US.

Middelham, F. (2006). *Dynamic Traffic Management.* Rotterdam: AVV Transport Research Center, Rijkswaterstaat.

Mirshahi, M., Obenberger, J., Fuhs, C. A., Howard, C. E., Krammes, R. A., Kuhn, B. T., et al. (2007). *Active Traffic Management: The Next Step in Congestion Management.* Washington, DC: Office of International Programs, U.S. Department of Transportation.

ProRail, & Rijkswaterstaat. (2007). *Programma van Eisen Infrastructuur Zuidas.* Amsterdam.

PTV AG. (2007). *VISSIM 5.0 User Manual.* Karlsruhe.

Taale, H. (2008). *Integrated Anticipatory Control of Road networks—A game-theoretical approach.* Delft, the Netherlands: TRAIL.

Taale, H. (2007). *MARPLE Description and Manual (in Dutch).* Delft: Rjikswaterstaat, AVV Transport Research Centre.

Taale, H. (2006). Regional Traffic Management - Method and Tool. *Preprints of the 11th IFAC Symposium on Control in Transportation Systems*, (pp. 457-462). Delft.

Taale, H., & Middelham, F. (2000). Ten years of ramp-metering in the Netherlands. *the 10th International Conference on Road Transport Information and Control.* London.

Taale, H., Westerman, M., Stoelhorst, H., & van Amelsfort, D. (2004). Regional and Sustainable Traffic Management in The Netherlands: Methodology and Applications. *Proceedings of the European Transport Conference 2004.* Strasbourg, France: Association for European Transport.

Van Ham, H. (2007). *Transport Policy.* Delft: Delft University of Technology.

Van Lint, H., Van Zuylen, H., Hoogendoorn, S., Hegyi, A., Bliemer, M., & Pel, A. (2008). *Traffic Theory for Intelligent Transport Systems for Road Transport.* Delft: Delft University of Technology.

Van Zuylen, H., & Muller, T. (2008). *Dynamic Traffic Management I: Traffic Control.* Delft: Delft University of Technology.

Wilbur Smith Associates. (2007). *I-84 / Route 8 Waterbury Interchange Needs Study: The Existing and Future Conditions .*

Yuan, Y. (2008). *Coordination of ramp metering control in the motorway network.* ITS Edulab.

Appendix

System architecture of VISSIM

The simulation system VISSIM is composed of two different parts, the traffic flow model and the signal control model (Fellendorf, 1994). The traffic flow model includes the car following and lane changing logic, and sends detector values to the traffic control model on a time step basis. The signal control model then determines the signals status for the following time step and returns the information to the traffic flow model. During the simulation, the traffic variables on the link level as well as the network level are generated for analysis (see Figure A.1).

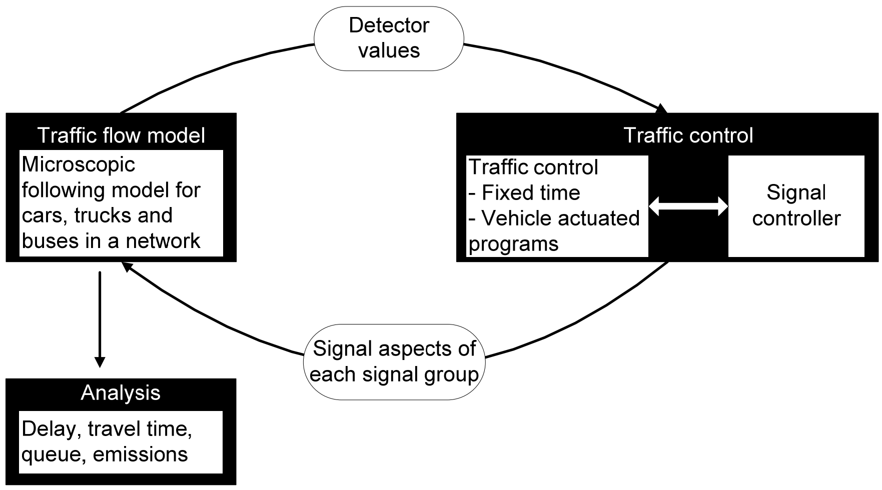


Figure A.1: Communication between the traffic flow model and the signal control model (PTV AG, 2007)

The traffic flow model is the kernel of the VISSIM model, which highly determines the quality of the whole simulation model. Instead of a deterministic car-following model VISSIM uses a psycho-physical model (PTV AG, 2007). Figure A.2 demonstrates the basic principle of this model, in which a curve with numbers shows how a vehicle acts on the road based on the performance of its preceding vehicles. Suppose a faster vehicle is driving behind a slower moving vehicle, the distance between two vehicles continues decreasing due to velocity difference (state 1 in Figure A.2). The fast vehicle begins to decelerate as the driver reaches his or her individual perception threshold to the slower one, which is a function of speed difference and spacing (state 2). Since the driver is not able to exactly determine the speed of the slower vehicle, the fast vehicle will decelerate below the current speed of the preceding one and the distance between two vehicles will become large (state 3). As the driver reaches the opposite perception threshold (state 4), he or she will accelerate again until reaching another perception threshold (state 5). This results in an iterative process of acceleration and deceleration. In order to determine the perception threshold used in VISSIM, continuous measurements of different traffic conditions on motorways and urban streets are made. Hence, the stochastic distributions of speed and spacing thresholds in reality can be introduced to microscopic model VISSIM to generate a realistic car following model.

Figure A.2: Car following logic (PTV AG, 2007)