Application of the Quantitative Hierarchical Model to Coordinated Ramp Metering

Min Zhi

August 2014

TU Delft Delft University of Technology

Personal information

Author:	Min Zhi
Student number:	4256395

Study information

University:	Delft University of Technology
Faculty:	Technology, Policy and Management (TPM)
Study program:	Engineering & Policy analysis (EPA)
Specialization:	Simulation, Modelling and Gaming

Graduation Committee

Chair:	Prof.dr.ir. A. (Alexander) Verbraeck
	System Engineering and Simulation Section, TPM
First supervisor:	Dr. J.L.M. (Jos) Vrancken
	System Engineering and Simulation Section, TPM
Second supervisor:	Dr. W.M. (Martin) de Jong
	Policy, Organization, Law and Gaming Section, TPM
Extra supervisor:	Dr. Yufei Yuan
	Transport & Planning Section, CEG

Acknowledgement

This thesis finalizes my graduation project as well as my master study life in TPM, Delft University of Technology. Thanks to all those who have helped me during this research experience, I've gained a lot.

First of all, I would like to devote my appreciations for my graduation committee. My first supervisor, Jos Vrancken, has contributed great energy to this project. Besides, he is a very kind-hearted supervisor and has helped me solve many problems: some were even beyond the scope of this thesis. The chair of the committee, Alexander Verbraeck, has given me much supervision and many enlightening feedbacks. I would appreciate my second supervisor, Martin de Jong, for his patience and cooperation from many aspects. Last but not least, I would express my gratitude to Yufei Yuan, who is my extra supervisor. He has given me many technical supports and he can always solve my problems quickly.

I would appreciate my family and friends for their support and encouragement during this period, especially my parents and my boyfriend. Thanks to my parents for their permanent support and care for me. It is them who are always there to share my success or failure, joy or frustration. Thanks to my boyfriend for giving me technical support on computer. I would also appreciate him for his understanding, encouragement, endurance and consideration, especially when I am down in spirits.

Min Zhi
Delft, August 2014

Summary

Transportation is a basic necessity in human society and it has gained increasing importance during the last decades. The subsequent effect of this development is traffic congestion caused by the tension between expanding demand for transportation and limited infrastructure capacity. At present, the most effective way to alleviate traffic congestion is to fully utilize the available resources via appropriate traffic control measures. Ramp metering is considered as the most efficient approach to the control of freeway networks and coordinated ramp metering (CRM) is the prevalent strategy. Current implemented CRM strategies are based on heuristic rule-based approaches, of which the most prevalent algorithm is called HERO. HERO works by balancing the queues of a consecutive series of on-ramps, which lacks flexibility in assigning priorities to certain ramps. Besides, CRM still works locally within a restricted area, but many traffic problems are network related.

A new traffic management framework named Quantitative Hierarchical Model (QHM) inspired from Systems Engineering theory is a potential solution to ramp metering issues. The basic concept of QHM is the network. The key components of this framework are recursive partitioning of networks (hierarchical) and priority settings (quantitative). Therefore, the aim of this thesis is to design a new algorithm by applying the QHM theory to Coordinated Ramp Metering. The research is conducted via simulation. A microscopic traffic simulator, VISSIM, is applied, which is controlled by Matlab via VISSIM COM. The general idea of the algorithm is to distribute inflows among different entries based on the allowed outflow, then examine whether the actual outflow follows the allowed value. Meanwhile, the network should still maintain a desired speed.

The main discovery of this research is the feasibility of QHM to CRM in our system settings. To be specific, the distribution of priorities among different entries is possible and the real inflow conforms to the corresponding priority. Beside, by distributing priorities, the allowed outflow can be achieved, while the network can still maintain the desired speed.

Though the research objective is achieved in this case, it is still far to go to draw the conclusion that QHM can be a substitute to current CRM strategies. In my research, many assumptions and simplifications have been made, which may deviate from reality. In future research, more realistic system settings should be added and a stepwise bigger network should be built. Moreover, feasibility of this framework in practical deployment should also be investigated.

Key words: Coordinated Ramp Metering (CRM), Quantitative Hierarchical Method (QHM), HERO algorithm, priority distribution

Table of contents

Figures

Chapter 1 Introduction

1.1 Problem statement

Transportation is a basic necessity in human society and it has gained increasing importance during the last three decades (Gregurić, Buntić, Ivanjko & Mandžuka, 2013). The subsequent effect of this development is traffic congestion caused by the tension between expanding demand for transportation and limited infrastructure capacity. Traffic congestion has detrimental effects, such as loss of time, reduced safety, more emissions and degraded infrastructure utilization. Some authorities focus on brute force such as expansion of the road infrastructure to tackle this issue. However, the more effective way is to fully utilize the available resources via appropriate traffic control measures (Papageorgiou, Diakaki, Dinopoulou, Kotsialos & Wang, 2003).

Typical control measures employed in freeway networks are ramp metering, link control, driver information and route guidance systems (Papageorgiou et al., 2003). Ramp metering is considered as the most efficient approach to the control of freeway networks (Papamichail & Papageorgiou, 2008). It was developed in the 1960's (Bogenberger & May, 1999) and aims at improving the traffic conditions by regulating the inflow from the on-ramps to the freeway mainstream via traffic lights installed at on-ramps or freeway interchanges. Though ramp metering is widely implemented, it has a number of serious limitations, including the congestion on freeway and on-ramps still being common.

1.2 Research problem

Ramp metering can be divided into two categories, i.e. fixed time (or pre-timed) control and traffic responsive (or adaptive) control (Chu, Liu, Recker & Zhang, 2004). As opposed to the pre-timed strategy relying on historical data, traffic responsive ramp meters are based on real-time measurements from sensors installed in the traffic network and incorporate two types of strategies: local and coordinated (Papamichail & Papageorgiou, 2008). Local ramp metering algorithms only take into account traffic conditions near a single ramp, therefore it lack coordination of on-ramps and fails to achieve the optimization of traffic facilities. By contrast, coordinated algorithms make use of measures at a network level with all ramps included therein (Scariza, 2003). Up to now, the field implemented control strategies for coordinated ramp metering (CRM) are based on heuristic rule-based approaches (Papamichail, Kotsialos, Margonis & Papageorgiou, 2010). The rule-based strategies make real-time decisions by checking heuristic rules and activating specific regulators at local on-ramps (Yuan, 2008). An extensive overview of most heuristic algorithms was presented by Bogenberger & May (1999).

The most prevalent heuristic algorithm is named HERO (Heuristic Ramp metering coOrdination), which in essence strives at balancing the queues on the on-ramps, by making ramp metering systems A and B (Fig. 1.1) more restrictive than they would be when operating purely locally. This form of coordination certainly helps, but still the capabilities of this form of coordination are limited. For instance, if authorities would like to assign different levels of priority to the different on-ramps, this will be hard to implement with queue balancing (priorities may be such that queues are not balanced). Moreover, the motorway traffic is not touched by the queue balancing, which essentially means that the motorway has infinite priority over the on-ramps. Traffic policies may deviate from this as policy scenarios should involve various kinds of on-site situations and stakeholders. Thus, the number of different urban and motorway traffic policies that can be supported by queue balancing is limited. The root cause of this is that HERO coordination takes the existing local ramp metering systems as starting point, and aims at coordinating their effects on traffic, which is inherently a hard problem as the ramp metering systems were not originally designed to function in a setting with coordination. Moreover, the ramp metering systems focus on the borders between motorway and on-ramp, whereas the combined effect of the three on-ramps on its environment is rather determined by what happens on the outer borders of area T (the borders at S, E, F, G and U).

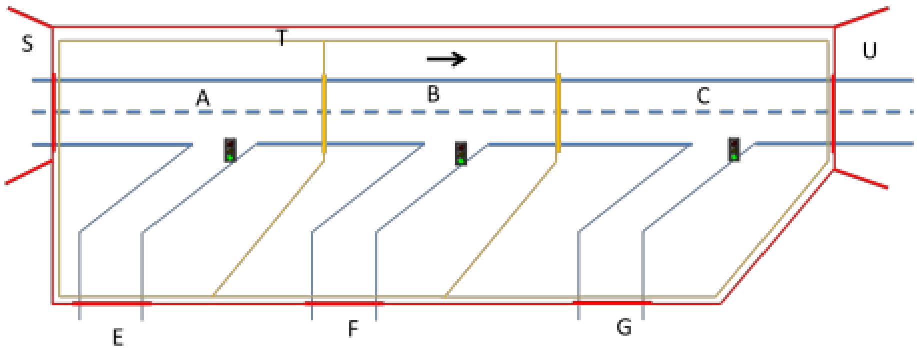


Figure 1.1 Part of a motorway with three on-ramps

A more fundamental approach to ramp metering coordination takes these outer borders of area T as the starting point and tries to manage traffic inside T such that the effects on these borders are in accordance with the traffic policy, which may assign various levels of priority to the motorway and to each of the on-ramps. Because A, B and C are subareas of area T, this is a two-level hierarchy, for which reason this approach is called hierarchical. The hierarchy may be further extended to include an even bigger area, as described by Vrancken, Wang & van Schuppen (2013). The QHM framework decomposes a large network into lower-level sub-networks in a recursive way, likewise the control strategy (Vrancken, Wang & van Schuppen, 2013). Each management instance has a limited, manageable amount of complexity to deal with, thus, QHM can be applied to networks of any size. However, this framework is still generally formulated and some subtle parts, like the exact relationship between entry-exit priorities and on-ramp priorities, still need further research. Possible options to control the flow on the freeway like lane closure or speed limits are discussed by Vrancken, Brokx, Olsthoorn, Schreuders & Valé (2012).

1.3 Research objective and research questions

There are two basic principles in traffic control: the gating principle and the fairness principle. The gating principle means that the vehicles allowed in a network should be as much as that being allowed out. This principle is to keep the volume in the network constant. The fairness principle indicates that drivers at different entries should be treated equally. In HERO, this principle is violated in two aspects as mentioned above: one is the fairness between the motorway and the on-ramps; the other is the fairness within the on-ramps.

The main research objective is to show, in a traffic simulation setting, the feasibility of this approach to CRM, where feasibility means effectiveness in traffic control, to be specific, whether the gating principle and the fairness principle can be implemented. Although the performance of real-life implementations and whether there is a need by the traffic authorities are also important, our aim is to explore the theoretical feasibility in this first step. Hereby the research question is:

Will the Quantitative Hierarchical Model be feasible for Coordinated Ramp Metering?

Sub-questions are:

1. What are useful traffic performance measures for the target control area?
2. What are effective algorithms for traffic control for the motorway and on-ramps, given the chosen performance measures? This includes performance under unpredictable variations in traffic demand on all entries and supply (allowed outflow) at the exit.
3. Can the Gating Principle be implemented with the proposed algorithm?
4. Can the Fairness Principle be implemented and how well is this maintained?

If the answer to the main research question is as expected, the problem of HERO, that it can't assign priority to certain ramp meters or restrict the mainstream, will be solved fundamentally. This is because QHM is inspired by the system engineering theory, which is a totally different perspective from traditional regional control and fits network management well. The designed sub-questions are a decomposition of the main question and will be solved progressively step by step.

1.4 Research method

The method applied for this research is simulation, where VISSIM and Matlab are combined: VISSIM is used as the simulator and Matlab is responsible for controlling it. To control VISSIM by Matlab, an external control interface is needed, VISSIM COM. The interface reads data from VISSIM and transfers it to the controller (Matlab), which then calculates the algorithm and sends control information back. VISSIM is a professional software in traffic modelling, while Matlab is a powerful tool for programming and data processing. A successful example (Yuan, 2008) has demonstrated the combination of these two. The limitations of this method mainly lie in VISSIM, which is difficult to interface with, making the interface with Matlab a bit complex. Moreover, some traffic behaviour (merging behaviour, lane change, etc.) in VISSIM is not so realistically simulated.

1.5 Outline of the thesis

The outline of the final thesis is based on the division of the project. The introduction presents the thesis topic, including the background, research problem, research goal & questions, as well as the research method. The second section is a literature review: an overview of the ramp metering development is given and the gap with current knowledge is addressed. Section 3 gives a description of the methodology applied in this research, involving QHM, VISSIM modelling and Matlab controlling. The model design part (Section 4) involves system investigation, the conceptual model, the simulation model, and an interlude of our failure in building a flow controller via Variable Speed Limit (VSL). Then the experiments are designed in the next section. In Section 6, the simulation results and analysis are presented, followed by verification (Section 6.2) and validation (Section 6.3) of the model. In the following section, the conclusion of the research work and recommendation for future research are addressed. Finally, Section 8 gives a reflection on the whole project.

Chapter 2 Literature Review

This literature review briefly summarizes the development of the prevalent traffic control strategy—ramp metering. The focus is on the most widely applied method—the heuristic rule-based method and a prevalent algorithm: HERO. Although HERO outperforms many other coordinated ramp metering approaches, it still has some drawbacks. The reasons leading to the shortcomings of HERO are analyzed explicitly for various aspects. The gaps in existing research are addressed, followed by a possible solution at the end.

2.1 Ramp Metering

Ramp metering is deemed the most efficient method for freeway traffic control (Papamichail & Papageorgiou, 2008). It can be divided into two broad categories, local (or isolated) and coordinated (or area-wide) (Scariza, 2003). Local ramp metering strategies make use of measurements from the vicinity of a single ramp (Papageorgiou et al., 2003). The most prevalent local ramp metering control algorithm is ALINEA. ALINEA is a feedback control approach based on the linear quadric feedback law (Scariza, 2003). Uncoordinated ALINEA at each ramp may ameliorate the traffic conditions compared to the uncontrolled situation, but cannot always prevent congestion or minimize its subsequent effects (Papamichail et al., 2010).

In view of this, the coordinated ramp metering (CRM) has been developed. CRM is designed to optimize traffic flow at the network level rather than on a single ramp. CRM has three categories of strategies, namely multivariable control strategies, optimal control strategies and heuristic rule-based algorithms (Papamichail et al., 2010). The field implemented strategies are based on the heuristic rule-based ones.

2.2 Heuristic rule-based CRM approaches

2.2.1. Heuristic approaches

The heuristic (=rule-based) CRM strategies make real-time decisions by checking related heuristic rules and activating specific local on-ramps. The field implementation on approaches, complexity, calibration and efficiency would differ a lot from each other between different heuristic rule-based strategies, due to lack of a common general method (Yuan, 2008), even though rule-based approaches are still the basis of current

CRM strategies. The main reason for this may be that an accurate numerical algorithm is a burden for field application (Papamichail et al., 2010). A number of algorithms have been designed and the well-known used ones are ZONE in Minnesota (Thompson & Greene, 1997), HELPER in Denver (Lipp, Corcoran & Hickman, 1991), BOTTLENECK in Seattle & Washington (Jacobson, Henry & Mehyar, 1989), Fuzzy Logic Algorithm in Seattle, Washington & the Netherlands (Bogenberger & Keller, 2001), METALINE in Paris , Amsterdam, etc. (Papageorgiou, Blosseville & Hadj-Salem, 1990; Taale & Van Velzen, 1996) and SWARP in California (Paesani, Kerr, Perovich & Khosravi, 1997). The common drawbacks of these algorithms are (Papamichail et al., 2010):

- Most schemes apply a feed-forward approach, which may lead to increased sensitivity to disturbances. Feed-forward schemes are based on the traffic state upstream of the ramp and control actions are determined off-line for a limited number of such states. Extreme and exceptional states (disturbances) are often not covered and the response is then sub-optimal. Contrary to this, feedback regulators are based on the traffic state, downstream of the ramp (Smaragdis, Papageorgiou & Kosmatopoulos, 2004), i.e. the actual result of the control actions, and therefore can handle a larger set of traffic states.

- All these algorithms assume a value for the flow capacity of the road, which in reality varies with varying circumstances. This may result in an overload or underutilization of the network.

In view of these drawbacks, a heuristic traffic responsive feedback strategy for CRM was developed, the HERO (Heuristic Ramp metering coOrdination) algorithm with the ALINEA regulator (Papageorgiou, Hadj-Salem & Blosseville, 1991) employed at the local level.

2.2.2 HERO Algorithm

Introduction to HERO

The HERO algorithm was developed by Papamichail & Papageorgiou (2008). This scheme targets the critical occupancy rather than a pre-specified capacity value for throughput maximization and this parameter setting is more robust (Papamichail & Papageorgiou, 2010). The local ramp metering strategy ALINEA is incorporated into the HERO scheme and the basic philosophy of this algorithm is described below (Yuan, 2008; Papamichail & Papageorgiou, 2010).

HERO will identify potential mainstream bottlenecks. All on-ramps process the traffic control independently using ALINEA to maximize the local mainstream throughput. The needed information such as speed or flow on the motorway is restricted to the merge area, i.e. the upstream and downstream areas are not considered. Each ramp has a predefined maximum queue length value and when this threshold is reached, the upstream on-ramps (slave-ramps) of this concerned one (master-ramp) are recruited increasingly by HERO to defer or avoid mainstream congestion. Actually the inner mechanism for this is to increase the storage capacity of the master-ramp. When the mainstream occupancy of the bottleneck or the queue length of the master ramp decreases to a sufficiently low level, the formed cluster of ramps will be dissolved.

The central control system is responsible for communication and coordination between local controllers. It gets up-to-date data about local controllers and conducts the algorithm calculation. When one ramp becomes a master-ramp, the coordination controller will recruit and deploy successive slave-ramps. Another important task for the central controller is to calculate the cycle time for traffic signals or updating parameter values like minimum queue length. The cycle time is flexibly determined by the real-time traffic condition and the implemented policy.

Notice that:

- The ALINEA continues to operate during the coordination process.
- HERO will set the appropriate minimum ramp queue length occasionally for specific ramps and if the slave-ramp queue length is lower than this value, the cycle time will be established higher for the queue to accumulate to this minimum level. On the other hand, the slave-ramps also have maximum queue length restrictions.

Advantages of HERO

The simulation and field implementation results prove that HERO outperforms the local ramp metering strategy and approaches the performance of some complex algorithms. Almost all the advantages have been mentioned above. Here is a summary of them according to Papamichail & Papageorgiou (2010).

- Like its rule-based counterparts, the HERO algorithm is simple and transparent.
- It targets the critical occupancy, which is more stable than flow capacity.
- The algorithm is feedback-based, with reduced sensitivity to unexpected disturbance compared to most feed-forward predecessors.
- It is generic without a need for parameter calibration or fine-tuning;
- It is reactive without a need for disturbance prediction or real-time model involvement.

2.2.3 Shortcomings of heuristic rule-based algorithms and potential solutions

Being the prevalent strategy applied in current traffic control, heuristic rule-based CRM approaches ameliorate traffic performance tremendously. All the research on this algorithm presents significant improvements in the mainstream throughput, the total travel time and the mean speed, etc. Traffic congestion is still common, especially when the traffic demand increases unexpectedly or unexpected disturbances occur, indicating that these algorithms are still not robust enough. Except for deviations in field implementation, these algorithms have their inherent drawbacks. Three aspects of shortcomings will be discussed in a hierarchical manner: the intrinsic limitations of a specific algorithm (taking HERO as an example), the features of heuristic rule-based strategies and the restrictions of CRM. These gaps are detected either by summary of existing research or by confrontation of different articles.

The intrinsic limitations of HERO

The HERO algorithm was designed to be generic so that no cumbersome parameter calibration is needed (Papamichail & Papageorgiou, 2010). However, in field implementation, the optimization of parameters is still unavoidable (Yuan, 2008) and the most efficient combination of parameters is usually not invariable. There is always a need for configuration and calibration to achieve a local optimum.

The other obvious shortcoming of HERO is equal treatment for all the on-ramps in the controlled network, which is not always desirable in reality. HERO cannot deal with the situation where some on-ramps need priority. Besides, the motorway is not touched in queue balancing, which essentially means that the motorway has infinite priority over the on-ramps. A solution to this problem, proposed by Yuan (2008), was that the prioritized ramps can be treated as “master” ramps then the original algorithm of HERO can be invoked. Meanwhile, he claimed that this is still insufficient as there is only one master in a control string according to the control algorithm. If the downstream ramp becomes the controller, the prioritized ramp will be forced to be “slave-ramp”. He further suggested to make some changes to the control algorithm in order to allow for different masters simultaneously. The proposed solution may be a good method to tackle the priority issue among ramps. Nevertheless, the motorway is still excluded from the regulation and only one solution has been proposed so far, the Quantitative Hierarchical Model (QHM) (Vrancken, Wang & van Schuppen, 2013).

QHM is a hierarchical control approach for network management, using a recursive decomposition of the road network and a recursive, agent-based control strategy. It does not target the coordination of the existing local ramp metering systems, but considers the part of the network covered by such systems and manages the outer boundary of this network, not the inner interfaces between ramp and motorway (which are still managed locally by the local ramp metering systems). In this way, QHM can handle priority settings for ramps and for the motorway together. QHM is a recent proposal, which in this thesis is being tested by means of traffic simulation. The aforementioned publication of 2013 covers CRM as an example.

Drawbacks of “heuristic” and “rule-based’

Currently the CRM has three categories of strategies, namely multivariable control strategies, optimal control strategies and heuristic algorithms (Papamichail et al., 2010). Multivariable regulators are derived from linearization of a nonlinear traffic flow model, so the efficiency is limited in case of heavy congestion; relatively sophisticated numerical calculation in optimal control strategies may be a burden for field implementation (Papamichail & Papageorgiou, 2010). Therefore, the implemented CRM approaches are based on heuristic rule-based algorithms, which apply appropriate heuristic rules to approximate optimal settings (Yuan, Daamen, Hoogendoorn & Vrancken, 2009). The "appropriate" and "approximate" are quite vague terms, meaning that heuristic rule-based measures have a large space for tuning. Therefore, control strategies should apply powerful and systematic methods of optimization rather than questionable heuristics (Papageorgiou et al, 2003).But in the same article he pointed out that due to a lack of quantified impact analysis and a corresponding validated mathematical model, some control systems can only be based on heuristic. Very few articles talk about how to tackle this problem. A possible solution would be the integration of different methods and this is also discussed in the next part.

Limitations of CRM

On-ramps have limited capacities, so the CRM approach should be switched off to avoid traffic spilling back to the arterials when there is a high on-ramp demand. This shows the restriction of CRM. In view of this, Lu et al. (2011) proposed to combine CRM with variable speed limits (VSL) (Lu, Varaiya, Horowitz, Su & Shladover, 2011). Papageorgiou & Kotsialos (2003) also talked about an integration of different control strategies. An example of such a strategy is AMOC, a combination of ramp metering and route guidance (Kotsialos, Papageorgiou & Messmer, 1999).

2.3 Conclusion

This literature review is an overview of the heuristic rule-based traffic control strategies based on the HERO algorithm. A brief introduction to ramp metering is given first. Then an overview of heuristic, rule-based CRM approaches is given with a more detailed description of the philosophy and the pros and cons of the current state-of-the-art algorithm, HERO. It has been implemented in a number of places and proves to outperform the local ramp metering and approaches the performance of some sophisticated algorithms. The main drawback of HERO is that the queue balancing strategy is deemed unfair and cannot deal with the need for assigning priorities to specific ramps. The reason is that HERO still uses ALINEA as local control. Possible solutions could be treating the prioritized ramp as a master-ramp to invoke the existing HERO algorithm. Also, the "one master controller in one control string" algorithm should be changed accordingly. The other solution is the QHM framework, which solves the problem more fundamentally via hierarchical control theory.

The rigid drawbacks of heuristic rule-based traffic control strategies for CRM are also mentioned. Heuristic rule-based approaches are not as accurate as numerical methods; then fine-tuning is usually needed. Integration of methods, development of mathematical models and systematic methodology are possible solutions suggested for this issue.

Chapter 3 Methodology for research

In this chapter, the methodology applied for this research is discussed from both theoretical and practical aspects. Section 3.1 describes the QHM framework and gives an example to illustrate how this framework can be applied in this research. Section 3.2 focuses on introduction of a microscopic simulator for traffic modelling, VISSIM. In addition, for extensive investigations of some scenarios, there is an interface between VISSIM and other controllers, VISSIM COM interface, is described as well. The controller implemented in this research is Matlab and the principle for interaction between VISSIM and Matlab is addressed in Section 3.3.

3.1 Quantitative Hierarchical Model

This section contains a summary of QHM (Quantitative Hierarchical Model). For a more extensive description, we refer to (Vrancken, Wang & van Schuppen, 2013).

Current traffic control is still mostly local, even Coordinated Ramp Metering, which still aims at a series of on-ramps in restricted area. However, most problems in traffic are network related. In this regard, control of traffic needs to be lifted to the network level. This is often called Network Management (NM). A new method for NM, named Quantitative Hierarchical Model (QHM), was proposed recently (Vrancken, Wang & van Schuppen, 2013). The QHM is a framework inspired from the hierarchical way the government of countries is organized and from Systems Engineering (SE) theory, which is able to manage system complexity effectively. The core concept of SE is to distinguish between the system and the environment, which interact mutually via the system's boundary. For the road network, any subnetwork can be considered as a system, with the entries and exits as the boundary of this system. For a given network N, the traffic behavior inside N, as seen from the environment (the surrounding network) can be abstracted to behavior of traffic on the boundary of N, which is a finite set of points (entry and exit points, i.e. cross sections through a road in one driving direction). This is a tremendous complexity reduction. Another important notion in SE is that a system can be divided into sub-systems in a recursive way. Similarly, control of traffic inside a given network N can be decomposed into the control of sub-networks of N. Effectively, N only needs to manage the boundary behavior of its subnetworks. The internals of each subnetwork can be delegated to the subnetwork and are not a concern for N.

QHM has four main components:

- Recursive partitioning of a network
- General road network properties

- General control principles
- Hierarchical (i.e. recursive) control strategy

3.1.1 Recursive partitioning

All current approaches to NM involve a geographic splitup of a given network N into parts. But just a splitup is not enough. It has to be done recursively. If N is a big network, then one level of splitup results in either too many subnetworks, which means management of N is still too complex, or there are few subnetworks but then the subnetworks are still too big to be managed directly, without further splitup. The obvious, and probably only, solution to this is to apply the splitup recursively: N is split up into few big subnetworks, and each of these is further split up into smaller ones.This partitioning process can continue recursively down to the level of individual road segments and nodes, resulting in a tree structure of networks. The subnetworks below a network N are called its children and N is called the parent. The first level below N are called the direct children. The complexity of traffic management of N is now reduced to the boundary behavior of the direct children (and they are only few). In this way, in principle NM becomes feasible for networks of virtually any size.

The recursive splitup introduces boundary points that are boundary points of several networks in the tree, at different levels. These are called multi-border points. Each internal boundary point within N has a stack of networks for which it is an entry point and a stack of networks for which it is exit point. The two stacks have a common parent, which means the highest networks on these two stacks are direct children of the same parent.

3.1.2 General network properties

In QHM, the network is the basic unit of control. A network is a network of smaller networks, which is essentially different from regarding a network as a network of roads. The latter is not scalable from the point of view of complexity: a bigger network means more roads, means an increasingly complex control problem. Seen as a network of networks, the number of subnetworks can be kept limited (even the number of boundary points can be kept limited, but that is outside the scope of this description), and therefore the control problem's complexity can be kept limited.

For an arbitrary network N, we can distinguish four types of traffic, depending on whether the origin and destination are inside or outside of N. For instance, OO-traffic is traffic from outside N going to a destination outside N. This is the kind of traffic which is most relevant for this research: CRM considers a network with only OO traffic. The other kinds are IO, OI and II traffic, but the description below will be restricted to OO-traffic.

The behavior of traffic on the boundary of a network N can be described by referring to any properties of traffic or of an individual vehicle in a point. These are first of all speed, density and flow. The flow can be further distinguished into partial flows towards the different exits of N (the final destination of a vehicle is not relevant for N). For operational control, other properties of a vehicle may be relevant, for instance whether the vehicle is a truck with hazardous goods (an entry may be closed for hazardous goods).

All in all, the boundary behavior is a tremendous simplification compared to the internal behavior of N, but it can still be rather complex.

3.1.3 General control principles

Control of an arbitrary network can be described qualitatively by means of a number of guiding principles and trade-offs to be made.

The Modularity Principle (MP)

The MP, described earlier, implies that control of a network N can be split up into control of the boundary of N and control of the internals of N. This decoupling of internal control from the control of the surrounding network, via agreements on the boundary, means that internal control has a great deal of freedom. It is a difficult problem to find a near optimal way to manage the internals, which is essentially a never ending learning process. Optimal performance has to be determined for a large number of different circumstances (weather, season, day/night, composition of traffic, different demand patterns, etc.). But this problem can be studied in relative isolation. As long as the boundary agreement is fulfilled, management of the surrounding network will not be made more complex, but will only profit from the better performance of N.

The Gating Principle (GP)

The Gating Principle is a consequence of the fact that any network can be overloaded and will then perform badly (the flow collapse caused by congestion). It is sometimes expressed by means of the notion of *critical density*. Which density should be considered critical is a hard problem (just like optimal performance, it is dependent on circumstances, demand patterns, etc.), but it obvious that, for given circumstances and other factors that play a role, there is a critical density, related to the amount of vehicles in the network. The Gating Principle states that, on average and as long as circumstances don't change, one should allow in just as much traffic as is allowed to flow out. In this way, the amount of traffic is kept more or less constant, which means that the average density remains the same and below critical density. In other words, one of the key control decisions to be made is about the amount of traffic allowed in. GP says that the amount allowed out is an important factor in this decision.

At first sight, it may seem to be a problem that the distribution of the vehicles in a network plays an important role (the same amount of cars may be spread evenly and not cause any congestion, or may be huddled together in a small part of the network and definitely cause congestion), but this is handled by the recursive application of the principle: if all the children of N apply this principle, then a subcritical amount of cars will be subcritical all over N.

Fairness Principle (FP)

The third principle that plays a key role in controlling a network is the Fairness Principle. In states that any minute of delay of any vehicle is just as bad as a minute of delay of any other vehicle. In other words, control should aim at reducing delay for all cars in total. It does not mean that each individual car is treated equally, because the treatment of an individual car is dependent on its position in the network. Congestion on a belt road may cause delay for many other cars, whereas a car at the exit of a parking lot, does not. For a given network N, the FP results in flow priority settings on the entries of N. N itself is not aware of, and cannot take into account the vehicles outside N, so this priority setting is essentially done in interaction with N's parent, the parent of N's parent, etc, who have a broader view of traffic conditions. This is again a recursive process.

Trade-offs

For a given network N, there are two obvious performance criteria: throughput and travel time. All other things being the same, then more throughput (amount of cars allowed in per unit of time at the entries of N) is better, as is a shorter travel time for an individual car. This makes the performance of a network a multi-objective optimization problem. Other factors, such as safety and enviromental damage, may lead to additional objectives, but for simplicity's sake, we limit ourselves here to throughput and travel time. These two factors are related, for a point (flow = speed times density and the Fundamental Diagram) as well as for a network (Macroscopic Fundamental Diagram). Initially, a higher speed serves both a shorter travel time and higher throughput, but above a certain limit, the flow will be reduced and a trade-off between travel time and throughput will have to be made in the traffic policy for the network. An important factor that plays a role here is the variance of demand and supply (= allowed outflow) of the network. A high variance, for instance in supply, means that the network can suffer a sudden decrease of supply. If the network is close to critical density, this means that density will go above critical density and performance will suffer. Therefore, the optimal density is determined, among other things, by the expected variance in supply, which can be considered as part of the expected traffic pattern. Variance is bad in a sense. High variance makes control harder, reduces throughput and increases travel times. Therefore, each network should try to dampen variance. This means that the optimal density is also determined by the variance in demand. The buffer space within a network is used to dampen this variance.

3.1.4 The Hierarchical Control Strategy

When the demand at the entry points of a network N is higher than the allowed outflow at the exit points, a network has to limit the inflow. This requires a priority setting for all the entry points. Traffic policies may be such that just equal priorities for all entries are not always optimal. Some roads are far more important for the overall performance of a network than others. Moreover, the priorities apply to partial flows: the entry flow towards one exit may be given a higher priority than to another exit. This results in a matrix of priorities, with the rows corresponding with network entries and the columns with exits.

Priority matrices must be recursively consistent: a multiborder point must be assigned a priority setting that is consistent for all the networks (at the different levels) involved. For the details we refer to (Vrancken, Wang & van Schuppen, 2013).

Traffic is seen as a combination of an expected pattern (for instance the morning rush hour traffic, or the traffic generated by a sports event), unpredictable variations on this expected pattern, and exceptional, unpredictable events (mainly accidents). The expected pattern is derived from historical data plus filtering techniques using fresh data (see Wang, van Schuppen & Vrancken, 2013).
The expected pattern is translated into a network configuration, which is mainly a recursively consistent setting of priority matrices. This is done by parent - child interaction. The network configuration, which maybe dynamic according to the dynamics in the expected traffic pattern, is set on a time scale of half an hour to hours.

The unpredictable variations on the expected pattern, can only be handled reactively. This is done by means of peer-to-peer interaction between neighboring networks, also known as multi-agent control. If one network A is confronted with a reduction of allowed outflow at one of its entries, it has to reduce its inflow (this may be done with a delay, depending on how close A is to critical density, but it has to be done at some point in time). Therefore A determines which partial flows at which entry points have to be reduced and sends maximal-inflow requests to the neighboring networks at these entry points. In this way, a problem at one place results in a chain reaction of reduce-inflow requests through the whole tree of networks. In order to avoid cyclic request storms, networks also have a priority setting, in the sense that the direct children of each network can be compared on priority. In this way, excess traffic is pushed back from high to low priority areas, such as residential areas or parking lots, which results in the core network being kept fluid and congestion, in principle, occurring only in low priority areas.

Exceptional events are seen as changes in the network. For instance a car accident blocks a segment or node for a certain amount of time. This can best be handled by a network reconfiguration. The demand hasn't changed but the network itself has changed.

3.1.5 Priority settings in CRM

Here is an example of illustration for the method of entry-exit priority setting. Below is a figure of part of a motorway stretch with three on-ramps. T is the target network, while S, U, E, F and G are the boundaries of T. T can be decomposed into three sub-networks, namely, A, B and C. The flow direction is from the left to the right, as indicated by the arrow. Without coordination, C would be the most restrictive area as all vehicles from upstream accumulate here. But if traffic policy prescribes that, the three on-ramps should be treated equally and they should contribute to 30% in total to the outflow, with the remaining 70% comes from S, then the priority matrix for inflow to T is defined as T=[70%, 10%, 10%, 10%]. If the 'parent' T wants to distribute priorities among its children: A, B and C, the priority matrices are as follows (in a backward sequence): C= [90%, 10%], B= [88.9%, 11.1%], A= [87.5%, 12.5%].

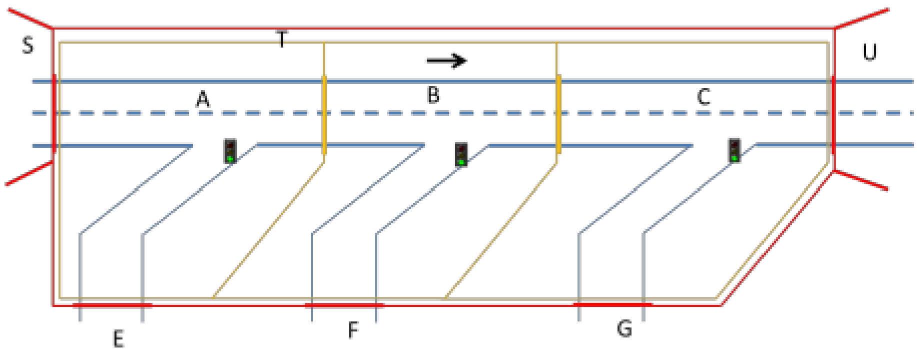


Fig. 3.1: Part of a motorway with three on-ramps

3.2 VISSIM and VISSIM COM

3.2.1 VISSIM

In contrast to macroscopic traffic models, which restrict to the collective vehicle dynamics in terms of the spatial vehicle density and the average velocity as functions of the freeway location and time, microscopic models delineate the position and velocity of all interacting vehicles (Helbing, Hennecke, Shvetsov & Treiber, 2000). They give a comprehensive representation of traffic and arrive at more detailed and reliable simulation results. Therefore, the microscopic modelling is chosen for this research. VISSIM is one of the best microscopic simulators for traffic simulation. It can be applied as a useful tool in a variety of transportation problem settings, including vehicle composition, signal control, speed detection, etc. The simulation package VISSIM is internally consisted of two components, exchanging detector calls and signal status through an interface.

3.2.2 VISSIM COM

In some simulations, extensive pre- or post-processing or numerous scenarios need investigation. For these cases VISSIM can be run from within other applications serving as a toolbox for transportation planning algorithms. Access to model data and simulations is provided through a COM interface, which allows VISSIM to work as an Automation Server and to export the objects, methods and properties. To get access to VISSIM via VISSIM COM interface, the entities or elements in VISSIM are treated as objects, like VISSIM, Net, Simulation, etc. The object model is based on a strict object hierarchy. Fig. 3.2 is an overview of the hierarchical object model (PTV, 2011). VISSIM is the highest object; all other objects belong to VISSIM. To get access to a lower-level object, e.g. a Link object, you should follow the hierarchy: VISSIM -> Net -> Links -> Link. The objects in plural form like Links are collections, a special object type, serve as a container for single objects and are used to enumerate network elements.

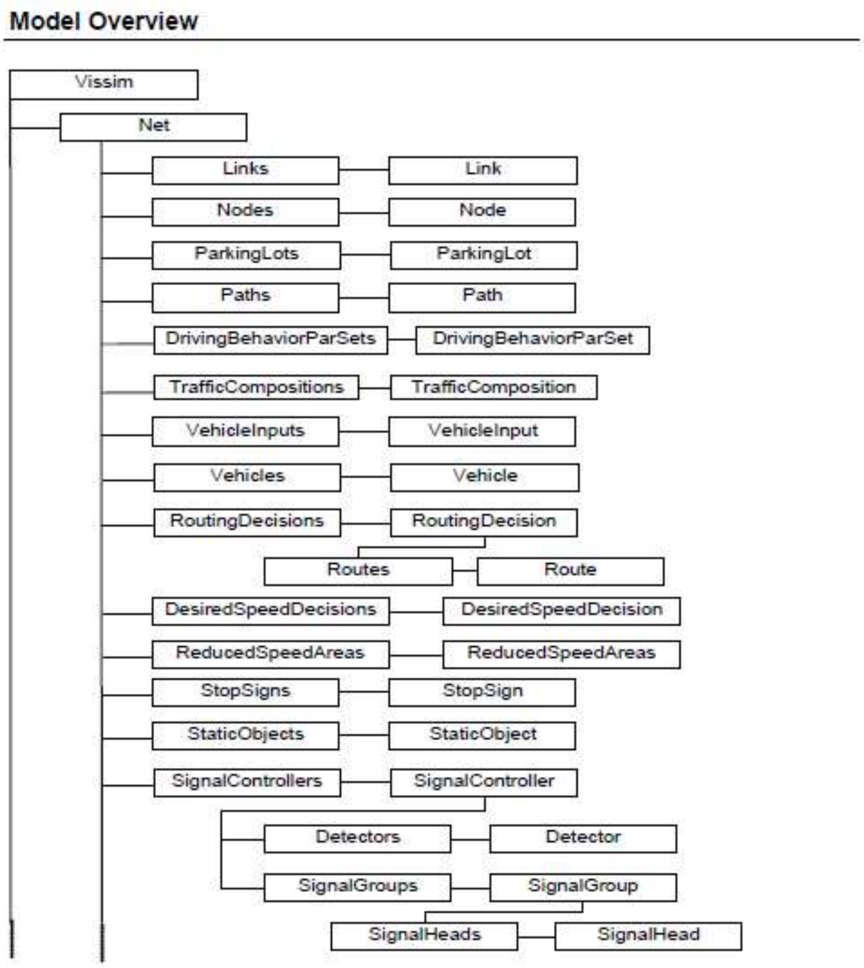


Figure3.2: the model overview of hierarchical objects in VISSIM COM (PTV, 2011)

3.3 VISSIM and Matlab

Except for VISSIM, another simulation tool applied here is Matlab. Matlab is a multi-paradigm numerical computing environment, allows interfacing with programs written in other languages. In this research, VISSIM works as the simulator, responsible for building a traffic model and visualising the simulation process; while Matlab takes the role of controller and manages the simulation process via the VISSIM COM interface, in which case VISSIM works as an Automation Server to export needed information. The interface reads data from VISSIM and transfers it to the controller (Matlab), which then executes the algorithm and sends control information back (Fig. 3.3). This communication process is just like a feedback loop.

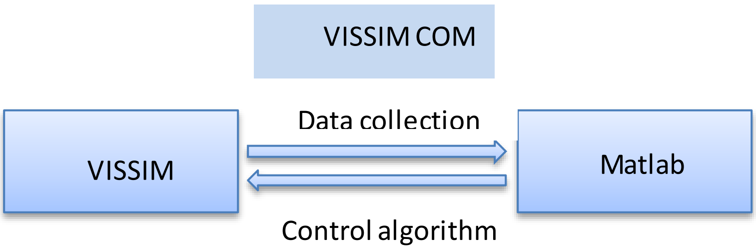


Figure3.3: the communicating process of VISSIM and Matlab

3.4 Conclusion

This chapter illustrated the methodology applied in this research. For the theoretical aspect, QHM has been introduced as a new framework that may solve the problems of current CRM. The four components of QHM framework have been addressed: recursive partitioning of road networks, general network properties, general control principles and hierarchical control strategy. The core concept in QHM is network and the control is in a network level rather than roads, so that complexity is reduced. For the execution part, VISSIM and Matlab will be combined for the simulation, where VISSIM works as the simulator and Matlab as the controller. To bridge these two tools, an interface called VISSIM COM needs to be invoked.

After introducing the methodology of this research, next chapter will discuss the model design process.

Chapter 4 Model design

This chapter is a description of model design process. Firstly, characteristics of the system are investigated from the aspects of system boundary, system goal, environment and interdependency relationships between the dependent and independent variables. This is followed by model formulation, to envision the conceptual model of the specified system. The final stage of model design is model representation, to translate the conceptual model into an executable model with appropriate tools. In this chapter, model representation is displayed in two parts. One part is the VISSIM model with a visualized road network and some important parameter configurations. The other part is the code description regarding Matlab: flow chart and pseudo code are used to explain the controlling algorithm.

4.1 System investigation

Characteristics of the system which contains the research problem are investigated in this part. Delineation of the system is mainly from four aspects: system boundary, system goal, environment and interdependency.

4.1.1 System boundary

According to the research objective and research problem, the research system should meet the following requirements.

- The system should be a medium-sized road network, which is part of a bigger network and can be de-composed into subnetworks as well. Being part of a higher level network enables interaction with the peer network or the environment, while a possibility of decomposition can realize the recursive partitioning of a network.
- The system should include several entries and at least one exit so that we can distribute priorities among different entries and check the influence on the outflow.
- The system should be equipped with some transportation facilities like signal controllers and detectors where necessary. The signal controllers help to restrict inflow to a network and detectors are used for data collection, for instance, speed, flow, queue length, etc.
- In this system, our focus is mainly on the collective behavior of vehicles, like the mean speed, inflow, outflow, etc. The behavior of a single vehicle or the drivers'

behavior is beyond our research boundary in general. But if there is a need for specification, some microscopic parameters may still be investigated.

4.1.2 System goal

The goal of our research is to achieve the allowed outflow, which depends on the adjacent network downstream in real deployment, while we can still keep the system above a desired speed level. Moreover, the system should distribute inflow according to priority settings from traffic policy and investigate whether it is feasible to control the outflow by priority distribution.

4.1.3 Environment

The 'environment' is an important concept in System Engineering as opposed to 'system'. A system's environment consists of all input variables that can affect its state significantly (Balci, 1998). In this research, the input variables from the environment are as follows:

- *Vehicle input*: the time variable traffic volumes to enter the network, also called demand of the network;
- *Outflow*: the allowed maximum outflow, which is decided by the adjacent downstream network in real deployment;
- *Priority matrix:* the distributed priority of inflow of different entries derived from the traffic policy.

4.1.4 Interdependency

The interdependency is the relationship between variables in the system. These variables are categorized into two types: independent and dependent ones.
The inputs described in the *environment* part: vehicle input, maximum outflow and priority matrix, are independent variables. Besides, some more independent variables are introduced below:

- *Loop time*: The loop time is the control time step or the time interval that the control measure changes. In this research, the control measure is the cycle time (which will be introduced later). The loop time has an influence on the stability of traffic behavior, as the shorter loop time, the more drastic fluctuation in traffic behavior. Besides, the system needs a period of buffer time to transform from one control measure to another, so the loop time should not be too short. Also, it cannot be too long, otherwise control of the system will not be timely. The loop time is set as a constant value here based on experience.

- *Speed limit*: The speed limit is the defined speed of vehicles in the network. The achivievable speed in VISSIM submits to a distribution in a range of possible values: for instance, if the speed limit is set as 100km/h, then the achievable speed of vehicles may vary in [88, 130] km/h. The speed limit has a significant influence on road capacity, the throughput and the travel time. Usually, it is set based on reality.

The dependent variables and determinacy are described below.

- *Actual inflow*: The actual inflow is the real inflow allowed into the network, which is different from vehicle input, the demand decided by the environment.
The actual inflow of every entry depends on the maximum allowed outflow and the priority of this particular entry.

- *Actual outflow*: Though the desirable outflow is set and traffic control strategy is designed to achieve that value, the real outflow may deviate from this. Three reasons account for this phenomenon. Firstly, traffic behavior fluctuates all the time, for instance, the speed distribution. The speed limit we set in VISSIM is not a constant, which may vary in a range during the simulation. Secondly, there is a time delay in the control process. To be specific, the inflow depends on the immediate outflow at the exit, but it takes time for the inflow to arrive at the exit, leading to a delay effect. Moreover, the time to arrive the exit varies between inflows from different entries, while control of inflow is executed simultaneously based on the same outflow. This is one reason that the achievable flow deviates from the desirable one. Thirdly, the allowed outflow changes instantaneously, but it takes a while for the road to transfer from one state to another. The transitory stage is the transient state of the road from one steady state to the next.

The actual outflow is determined by the allowed outflow, loop time and some minor factors which may influence the traffic state.

- *Speed*: The speed varies with the location in the network and the time. It plays a crucial role in traffic performance. For a fixed location, the speed depends on the speed limit, road density and car following behavior.

- *Cycle time*: It is the duration of every signal control cycle, which usually consists of green time, amber time and red time. The cycle time has a decisive effect on the actual inflow. It is determined directly by the allowed inflow, which depends on the allowed outflow and the priority matrix in this research.

4.2 Conceptual model

The system was abstracted as a hypothetical 1.35-km-long two lane motorway stretch as shown in Fig. 4.1. A two lane motorway is of the right complexity for our research objective: more lanes are not necessary and fewer lanes (one lane) may be unrealistic for motorway. The length of this stretch depends on the number of onramps. There are three 0.25-km-long on-ramps, which are distributed along the motorway every other 0.5 km. A 0.5 km interval is enough for the flow to recover from disturbance at the merge area. T is the target network, while S, E, F, G and U are the environment area. The demand for this network is determined by inflow at S, E, F and G, while the supply (allowed outflow) is restricted by U. To embed QHM framework into this system, four points are addressed as follows:

- S and U are the peer networks of T and T can be decomposed into three subnetworks in further steps, namely, A, B and C.

- If control is executed from the network level of T, traffic behavior inside T can be abstracted to the boundary behavior of the four entries and one exit. Moreover, the traffic type of T is O-O, which means that the origin and destination of all the vehicles inside network T come from outside.

- The objective of control is to allow maximum outflow dependent on U keep T while still maintain a desired speed level. In this research, the allowed outflow is set manually as U is only a hypothetical network here. Control of T equals to control of inflow from the four areas, S, E, F and G.

- There is a desirable outflow at the exit of U, and priority will be distributed among the entries of S, E, F and G. There are two kinds of priorities in QHM, the entry-exit priority and children priority. In this network, distribution of priority among A, B and C is possible. But as T is a simple network, the entry-exit priority assignment is enough.

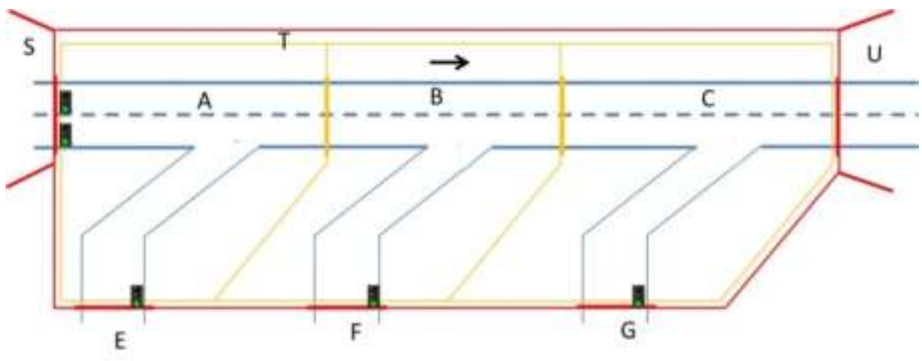


Fig. 4.1: Part of a motorway with three on-ramps

Unlike normal CRM system, where traffic signals are placed at the end of on-ramps, the traffic signals are placed at all the entries in this system instead. It is because in other CRM control measures, the traffic lights are used to control inflow to the motorway, but in our algorithm, they are applied to restrict inflow to the target network. Besides, there are traffic signals on the boundary of S and T to restrict the inflow from S as well.

It's worth noticing that traffic signals are unrealistic on motorway and the commonly applied method to control flow on motorway is VSL (variable speed limit). Actually, a flow controller via VSL has been tried, but the outcomes were not satisfactory. It is really difficult to control the flow via speed limits as it involves learning the exact relationship between the VSL at the upstream and the effect on the flow downstream. Additionally, to control the flow well also requires precise prediction of flow based on the traffic behavior. The influence of VSL on the flow by fuzzy logic has been tried, of which the idea was to derive several patterns of traffic behavior by learning from large amount of simulation data. However, the derived patterns were very sensitive to disturbance and once a pattern was recognized, the execution of control might leads to new problems like a rebound of all the restraining flow.

Recent work by Carlson, Papamichail & Papageorgiou (2010) introduced a MTFC (main stream flow control) local feedback strategy, which was claimed to be effective and practicable. Unfortunately, attempts to replicate the model were not successful. An expert with rich experience in VSL pointed out some flaws in the assumption of Carlson etc.'s work. Additionally, he has discussed the simulation results with the authors, who admitted the validity of the results needed further investigation. Therefore, the trial of building a flow controller via VSL was terminated and the research focus was shifted to priority settings. Instead, restriction of flow was achieved by traffic signals, which is unrealistic on motorway but can realize our goal of limiting the inflow easily. After all, this research is to investigate the feasibility of QHM and a practicable motorway flow controller via VSL is beyond the scope here.

4.3 Simulation model

4.3.1 VISSIM model

Building a traffic model in VISSIM was the first step for the simulation. According to the conceptual model in Section 4.2, a road network can be quickly constructed in VISSIM (Fig. 4.2). Despite of the network elements mentioned above, another important setting is data collection points for collecting data during simulation, as marked by blue dots in Fig. 4.2. The sensors for motorway data collection were put close to the intersection of the motorway and the onramps at a distance of 30m, approximately. In this location, any influence from the merge behavior can be detected almost simultaneously. The data collection points on the onramps were placed at the end of each onramp. Some important parameter configuration is displayed as follows, with an extensive description of the VISSIM model in Appendix A.

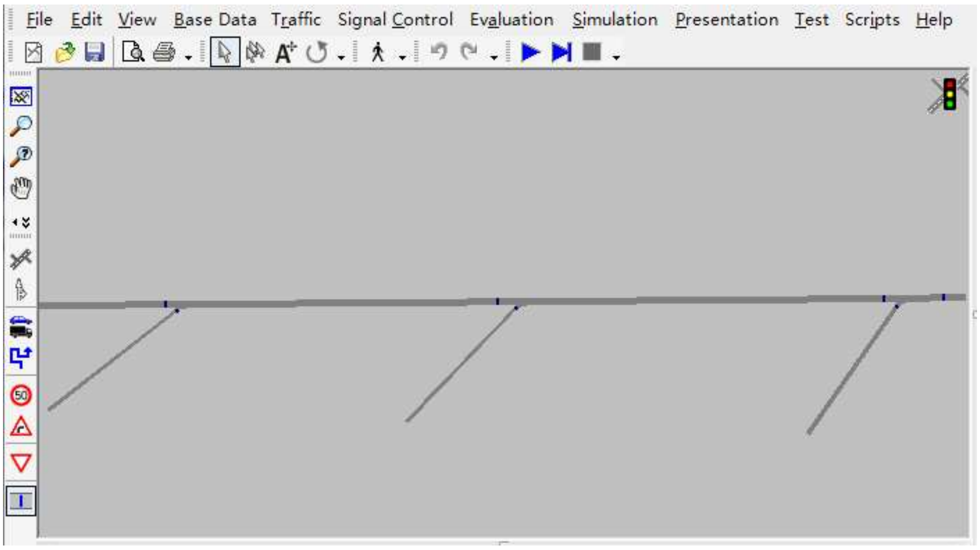


Fig. 4.2: The road network in VISSIM

Vehicle composition

In this model, only two types of vehicles were defined, Car and HGV (heavy goods vehicle), occupying 90% and 10% percentage of the total flow, respectively. As this is a theoretical model with no real cases for references, the vehicle composition has no requirements. Here the composition was an arbitrary set and it remained unchanged during the whole study. The parameters related to selected vehicle types were left default. The interface configuration of the vehicle composition is displayed in Appendix A (A1).

Signal controller

The traffic signals here only involved interleaved red and green lights, without amber light in-between. Usually the amber time is 0.5 seconds, the influence of which to traffic behavior can be neglected in simulation. The signal type was defined as fixed time control in VISSIM, but actually the traffic signals were controlled by the external controller (Matlab) during the simulation. Configurations of signal controllers are displayed in Appendix A (A3).

Data collection

To collect data, data collection points (Fig. 4.2 above) should be defined in the model first, followed by configuration of some parameters. Configuration interface of data collection is shown in Appendix A (A4). The data to be collected was *mean speed* and *number of vehicles*. Instead of *number of vehicles*, what was needed is the flow, therefore, a conversion should be made from vehicle number to flow in the algorithm. The time interval for data collection was 60s (Carlson, Papamichail & Papageorgiou, 2010), which is a commonly applied value for traffic control.

Simulation parameters

The parameter settings are displayed in Appendix A (A5). The simulation period was set as 1800 simulation seconds, as the loop time was 5 minutes (300s) and 6 loops were required. Resolution is the number of times the vehicle's position is calculated in one simulation second, also known as time step. The value ranges from 1 to 10 simulation seconds, while the higher resolution, the more smoothly vehicles will move during the simulation and the lower the simulation speed (Yuan, 2008). Here the resolution was set as 1 because the time step in the control algorithm was 1 simulation second. Though different seeds can lead to different results, these results won't have a substantiate difference. In this research, the result of every scenario was chosen for one run rather than several runs of different seeds. The maximum simulation speed was chosen to reduce the real simulation time.

4.3.2 Code description

After completion of VISSIM model, the control algorithm should be coded in the external controller, Matlab. In this sub-chapter, assumptions of the algorithm are addressed first, then two methods for model narrative are applied to describe the code. For the original Matlab, please refer to Appendix B.

The algorithm is divided into two parts in general: the interfacing with VISSIM COM and the real-time control of simulation. For the control part, fixed priorities were assigned to different entries and these priorities remained unchanged during the same simulation. The priorities were defined by a priority matrix in the code. Likewise, the allowed outflows were varied by assigning an outflow array. Deployment of each value in the arrays was realized by checking the loop number as these values change every loop. As the outflow and priorities were predefined, the cycle time for every signal controller of different entries were set accordingly.

Assumptions

- In reality the cycle time of the metering system is between 4-20 seconds (Yuan, 2008). The typical green time is 2 seconds and the minimum red time is 2 seconds as well, so the minimum cycle time is 4 seconds. The maximum cycle time of 20 seconds is to ensure that vehicles on any ramp do not wait too long. However, in order to fully realize the allowed inflow, the applied cycle time here was merely based on calculation (with round-off numbers). The restriction of minimum or maximum cycle time is not a concern here.

- In the Netherlands, only one vehicle per lane is allowed to pass the signal per green time, known as one-car-per-green realization. In reality, the green time depends largely on the reaction time of drivers and the acceleration time. Typically, it is 2.0 seconds as mentioned before, but in our simulation, it was set as 1.0 simulation second according to the tests in VISSIM.

- In VISSIM, a traffic signal controller can only control one lane. As the motorway has two lanes here, two signal controllers were placed at the entry of the motorway. In order to make the algorithm simpler, the number of entries was set as 5 rather than 4, where the two lanes of the motorway were treated separately.

- To evaluate the merge behavior, speed is a key performance indicator. The mean speed at a certain point in the merge area (about 30m upstream of the intersection) is collected every 60 seconds based on the assumption that if the average speed in this period is above the critical value, congestion will not occur. Here the critical value is set as 30 km/h, which dose not mean that the congestion is marked by this particular value, but that speed above 30 km/h is considered as acceptable in our study. After all, the internal performance is not our primary concern here, but the boundary behavior instead.

Flow chart

The process of the control algorithm is described generally as follows.

1. Enable interfacing with VISSIM COM and set some global variables and parameters;
2. Set the priority matrix and allowed outflow array;
3. Calculate the cycle time matrix;

$$cycletime = round(\frac{3600}{I\_in})$$

4. For every simulation second, check if it is integral multiples of 60 seconds: if so, collect the needed data; if not, go to step 6;
5. Check which loop it is currently;
6. For every entry, decide the elapsed time of every cycle and set the traffic signal state accordingly.

Below is the flow chart of the whole simulation process.

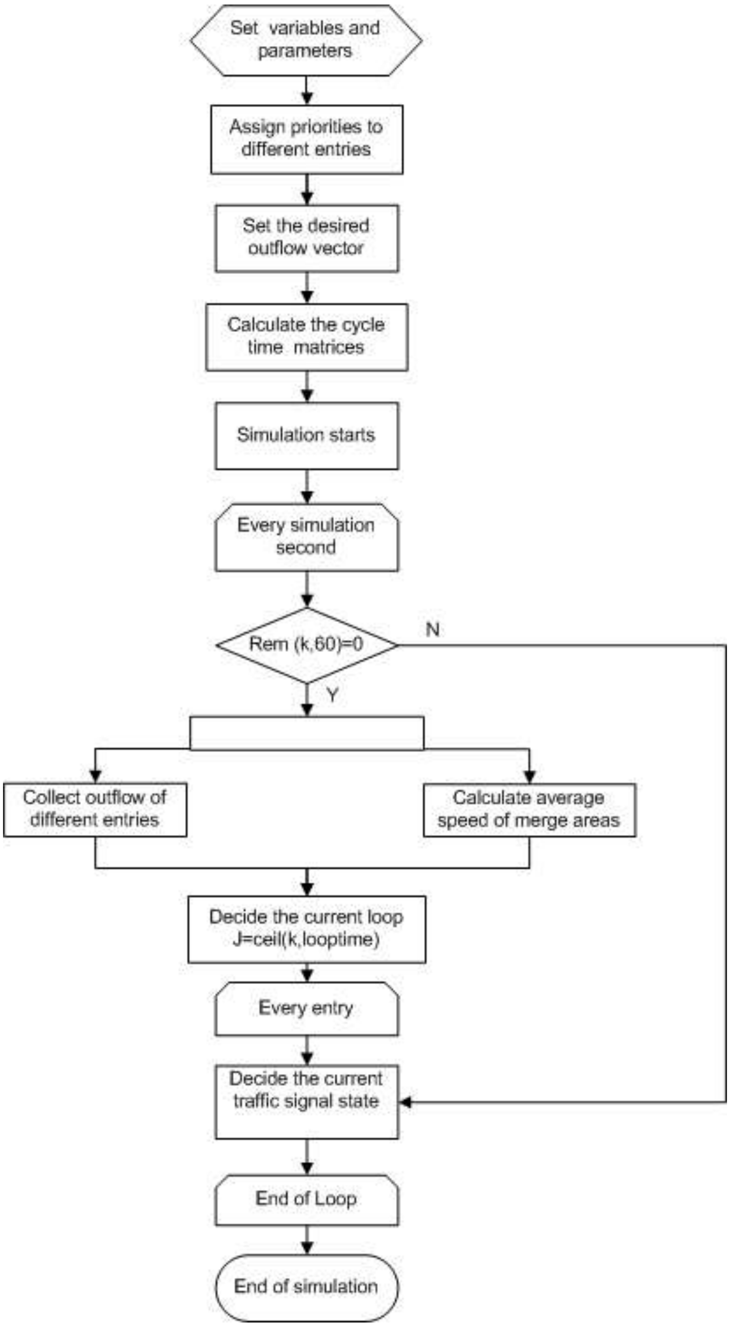


Fig.4.3: Flow chart of the control algorithm

Pseudo code

To be more explicit, pseudo code is displayed to represent the algorithm.

Step 1: Set some parameters for getting access to VISSIM

Step 2: Set some global variables

Set NumberofEntry=5;
Set TotalSimulationTime;

Set data collection interval TimeInterval;
Set GreenTime=1s;
Set the duration time for every outflow LoopTime=300s;
Assign a vector of allowed outflow I_out;
Assign a priority matrix T;

Step 3: Generate matrices for some variables
Generate the real outflow matrix I_realout;
Generate the outflow matrices for three on-ramps: I_ramp1, I_ramp2, I_ramp3;
Generate average speed on three merge areas: v_1, v_2, v_3;

Step 4: Decide the cycle time matrix
Set inflow of each entries Inflow =I_out * T;
Set CycleTime =round (3600/Inflow);

Step 5: Simulation

```
For every simulation second k
   Do while k <TotalTime;

      If k/60=integer
       Calculate flow of on-ramps: I_ramp1, I_ramp2, I_ramp3;
       Calculate flow of the motorway exit: I_realout;
       Calculate the speed in three merge areas: v_1, v_2, v_3;
End if

  Decide the current loop j=ceil (k/LoopTime);

For each entry
     Calculate the elapsed time since the current loop starts: t1=rem (k, LoopTime);
     Calculate the elapsed time since the current cycle: t2=rem (t1, CycleTime);
     If t2<= GreenTime
        Set signal controller Green;
     Else
        Set signal controller Red;
     End if
End for
End while
End for
```

4.4 Conclusion

This chapter has delineated the model design process, from the system specification to the conceptual model, and at last the simulation model.

In the system specification section, system boundary, system goal, environment and interdependency relationships were described, respectively. The system boundary defined inclusion and exclusion of elements of our system. Our system goal is to keep the system free from congestion while achieving allowed outflow, which is the allowed inflow to the adjacent network downstream, and this goal should be achieved under the QHM framework. The environment of the system described the variables that beyond the system but have a significant influence on it. Here three variables are included in the environment, the vehicle input, the allowed outflow and the priority matrix. The interdependency is the relationship between dependent and independent variables. The independent variables are the vehicle input, allowed outflow, priority matrix, loop time and speed limit; the dependent variables are actual inflow, actual outflow, actual speed and cycle time. The reasons of why these variables were set as independent or dependent and the influence have been addressed as well.

In the conceptual model, a hypothetical road network was described. What should be noticed is that all the entries in this network were equipped with a traffic signal, which deviates from reality. This is to control the inflow to the network. Though a motorway flow controller via VSL was tried, the results were not satisfactory. Instead, traffic signals were placed on the motorway. As our aim is to investigate the feasibility of priority distribution among entries to control the outflow, the method of how the inflow is achieved does not influence this goal.

In the simulation model part, the VISSIM model and the Matlab algorithm were introduced. The VISSIM model involved a road network interface in VISSIM and important configuration of parameters. For the Matlab algorithm, some assumptions have been made. The model narrative part was delineated in flow chart and pseudo code.

After building up the models, experiments will be set up in the next chapter.

Chapter 5 Experiments design

This chapter focuses on setup of experiments: the system Key Performance Indicators (KPIs) are presented first, then the relating inputs and parameters are introduced based on the KPIs, followed by description of three scenarios to discover the preliminary feasibility of the proposed algorithm.

5.1 KPIs

The research question is: will the Quantitative Hierarchical Model be feasible for Coordinated Ramp Metering? To answer this question, the first step is to define useful traffic performance measures for the target control area. Below are the key performance indicators for this case.

- Actual outflow: As the main objective is to restrict outflow of a network by distributing priorities among the entries, the actual outflow is a critical criterion. If the algorithm works well, the actual outflow should follow the allowed value.

- Priority conformance: Priority assignment is a breakthrough in QHM and it is one of the main goals of our research. The achievable flow from different entries should conform to their priorities.

- Merge area speed: Though in QHM, traffic behaviour can be abstracted to the behaviour at the boundaries as seen from outside of a given network, the fundamental internal objective is to keep the network free from congestion, which requires detection of some parameters or variables inside the network. In a network with intersections, merge behaviour is very crucial for traffic performance evaluation. The merge behaviour can be indicated by speed: usually there is a rule of thumb for critical speed to judge whether the road is congested. In this case, the speed above 30km/h is considered as acceptable.

Usually, for network performance evaluation, total throughput and total delay are key measures. However, these two parameters are not our direct targets in this project. Besides, total throughput has an overlap with the actual outflow, the accumulation of which is just the total throughput. For total delay, merge area speed can be regarded as a substitute. Because congestion mostly happens in merge area or starts from merge area, leading to the delay. Therefore, these two parameters will not be evaluated for traffic performance.

5.2 Inputs and parameters

After defining the KPIs, possible variables that may affect these performance measures should be investigated. These variables are some of the inputs and parameters that can be varied in VISSIM or Matlab. Three input variables which have been introduced before are important here as well, namely, traffic demand, priority matrix and allowed outflow. Allowed outflow and priority matrix are to be assigned in the code, while traffic demand is set in VISSIM. In all the experiments, the traffic demand values are set big enough for any desired input, so there will always be vehicles entering the network when traffic signals turn green. These three input variables are closely related to the actual outflow. Also, they may have some effects on the merge behaviour, which is to be investigated in the experiments as well. Besides, there are two more parameters that may influence the outcomes, speed limit and gap acceptance.

- Speed limit: it refers to the speed defined of all the vehicles in VISSIM. The speed limit has a direct influence on the network throughput: generally, the higher speed limit, the bigger throughput in a fixed time without any congestion. For different speed limits, the critical speed for congestion definition should be adjusted accordingly. In addition, change in speed limit may lead to different traffic behaviours, which is to be investigated in the experiments.

- Gap acceptance: in traffic it happens frequently that a participant (a car driver, a pedestrian, a cyclist) has to use a gap in another traffic stream to carry out a manoeuvre (Hoogendoorn, 2014). This parameter has a decisive effect on the merge behaviour. The principle of gap acceptance theory is that a driver assesses an offered gap and compares it with the critical gap, which varies with different drivers in reality. In VISSIM, this parameter is based on a relatively simple model and it is user-definable (Marczak, Daamen & Buisson, 2013). In this research, the way to change this parameter was by changing the “minimum headway”, the time gap between two vehicles, which is equal to gap acceptance in this case.

5.3 Scenario description

Several scenarios have been designed to investigate whether the proposed QHM-based algorithm is effective for controlling the traffic. The difference between different scenarios lies in the priority matrices or the allowed outflow or both.

- Scenario 0: This is the base scenario without any coordination between the onramps: there is not any restriction of the allowed outflow and no priority distribution among all the onramps. This scenario is the reference for checking our control measures.

- Scenarios 1: This is the first scenario and the focus is whether the algorithm works. All the on-ramps are distributed with the same priority and the values in the outflow array increase incrementally within the road capacity. The actual outflow will be compared with the allowed outflow. Besides, the flow from different entries will be checked for the conformance of the priority settings. Moreover, merge area speed will also be collected to check if there is any congestion.

- Scenario 2: In this scenario, the priory matrix is changed to check whether different priority settings work well in the algorithm. The KPIs to be evaluated are the same with Scenario 1.

- Scenario 3: In this scenario, the main objective is to check if the model is robust enough with unpredictable variation situations. Therefore, the maximum outflow fluctuates drastically. The priority settings remain almost the same as in Scenario 2.

Table 5.1 presents the settings of all the scenarios described above.

Scenario	Priortiy matrix /T	I_out (veh/h)
0	NA	NA
1	[0.35,0.35,0.1,0.1,0.1]	[1500,2000,2500,3000,4000,2500]
2	[0.25,0.25,0.1,0.15,0.25]	[1500,2000,2500,3000,4000,2500]
3	[0.25,0.25,0.15,0.1,0.25]	[1500,3000,2500,4000,1500,4000]

Table 5.1: parameter configuration for all the scenarios

Chapter 6 Results and analysis

In this chapter, firstly, model verification is conducted with some techniques from literature, for instance, animation, structured walkthrough, data relationship correctness. Then face validation is performed involving experts in this field. Hereafter the simulation results of the three scenarios in Section 5.3 are displayed. Then model robustness is investigated, with the focus on the sensitivity analysis. For sensitivity analysis, the stretch length, speed limit and gap acceptance are varied respectively. In addition, the shortcomings of VISSIM are discussed and the consequences of these defects are also addressed.

6.1 Verification

Sargent (2012) and Balci (1998) described the techniques of verification and validation quite explicitly. For this model, some suitable approaches for verification are applied, which can be divided into two categories, static techniques and dynamic techniques. Static techniques don't require machine execution of the model, but mental execution can be used; dynamic techniques require model execution and are intended for evaluating the model based on its execution behaviour (Balci, 1998).

Static techniques

Structured walkthrough

The VISSIM model and programmed code in Matlab were continuously traced by peer researchers to check if the conceptual model is correct, if the simulation language has been properly implemented and the model has been programmed correctly in the simulation language. With the help and feedback from peer researchers, the model has been verified all the time.

Data dependency analysis

This technique involves the determination of what variables depend on what other variables. As has been addressed before, we have several dependent variables. For instance, the cycle time, which can be determined before the simulation as it is calculated based on the allowed outflow and the priority matrix. Numerical calculation can be performed by Matlab and the matrix of the cycle time can be assessed for correctness.

Structural analysis

Structural analysis is used to examine the model and structure and is conducted by constructing a flow chart of the model structure, which has been done already (Section 4.3).

Symbolic evaluation

Symbolic evaluation is used to assess model accuracy by exercising the model using symbolic values. It is performed by feeding symbolic inputs into the model and producing expression for the output (Balci, 1998). The pseudo code in Section 4.3.2 can be regarded as the first step of this technique. We show an example to illustrate this verification process. Below is part of the pseudo code.

```
  For each entry
 Calculate the elapsed time since the current loop starts: t1=rem (k, LoopTime);
Calculate the elapsed time since the current cycle: t2=rem (t1, CycleTime);
If t2<= GreenTime
Set signal controller Green;
 Else
Set signal controller Red;
 End if
End for
```

Assume that k is 346s currently, then t1=46s (looptime =300s). For simplicity, the cycle time is assumed to be 20 seconds, then t2=6s. As GreenTime is 1s, t2>GreenTime, so the signal should be red.

Dynamic techniques

Animation

During the simulation process, the traffic behaviour was displayed graphically in VISSIM. Some basic achievements were observed: vehicles were running and they followed the traffic signals; 'one car per green' was realized; the cycle time for different entries changed with time and there was an obvious difference between different entries. All the visualized behaviours were as expected except the merging behaviour, which is a well-known problem in VISSIM. This will be shown not to have an influence on the results.

Data relationship correctness

Similar to data dependency analysis in the static part, here the test was performed after the simulation. The results were checked for some pre-defined relationships. For instance, the outflow of the network exit and three on-ramps should conform to their priorities. Besides, the sum of these outflows should be close to the desired value. Except for the first 500 seconds, when VISSIM behaves abnormally, the volume met the relationship in the rest of time.

6.2 Face validation

It is almost impossible to do validation tests in reality for traffic simulations, which is too costly. A common method for traffic model validation is face validation, that is: to display the simulation results to some experts in this domain who review the results based on their experience.

For this research, the model was verified and validated by experts from both faculties of TBM and Civil Engineering. The validation was conducted in the form of an informal interview based on discussion and followed the life cycle of modelling: conceptual model, simulation process, the results and verification and validation process.

The conceptual model was introduced first and the reliability of putting traffic signals on the motorway was doubted. As explained before, building a motorway traffic control via VSL needs much more research, which was not our concern. Besides, a flow controller with traffic signals is more effective in this case. Then animation of the simulation was displayed and the verification test regarding this part was examined again. As the model performed within expectations, it can be inferred that the model was probably built right. The further step is to validate the results of the simulations, which are the most important. In this step, except for the recognition of the realization of the two main objectives, some questions and suggestion were raised as well.

- The phenomenon of traffic breakdown in the merge area upstream was more serious than that downstream, which was confusing. Here the breakdown was indicated by the speed. One of the experts pointed out that there were mainly two influences on the decrease of speed at merge area: the merging behaviour and over loading of the road. Usually, an obvious speed decrease at the downstream is caused by over loading, while the upstream by merging behaviour. In this research, the speed of the upstream merge area were always lower than that of the downstream and there was an obvious gradient decline of speed from upstream to downstream among the three merge areas, in whichever scenario. In some scenarios, the allowed flow was apparently below the road capacity, therefore, some other reason(s) should account for the speed decrease. One possible explanation is that the traffic upstream is more sensitive to any disturbances or changes downstream. This possibility has a proof that the speed of the three merge areas were always changing in the same direction, indicating a propagation of traffic behaviour from downstream to upstream.

- In one of the sensitivity tests, the minimum headway value in VISSIM was changed to examine if unrealistic merge behaviour will influence the model performance. Still, some other parameters can be varied as well, for instance, the safety factor, representing the aggression level of the drivers. This parameter can be studied in future research.

- For the validation, further steps should incorporate the detection of capacity breakdown and the test of the fundamental diagram. For evaluation of the internal performance of the network, whether there is a traffic breakdown is very important. However, in our algorithm, the internal flow was almost the same as the allowed outflow, which means that if the allowed outflow is below the capacity, traffic breakdown is not likely to occur inside.

- Another point was that in this thesis, the result for every scenario was presented for only one run. Though different runs have been conducted during the experiments and the results have proven to be almost the same for different replications, it is still necessary to present the results of different replications with different random seeds in the discussion part. Duo to the time limitation, results with different random seeds of only one scenario will be added to Chapter 7 afterwards.

After the face validation, it was confirmed that the research results were convincing and significant. However, there is still some space for improvement and further development.

6.3 Simulation results

The results displayed here are for the scenarios designed in Section 5 that aim to investigate the feasibility of the proposed algorithm. For the base scenario, the figure is not displayed here. It is commonly known that without coordination between onramps, there will be an underutilization of traffic facilities and unfair treatment of different onramps. Besides, in our network settings, the demand was higher than the road capacity, which will definitely lead to a traffic paralysis.

Fig. 6.1 displays the flow of the three scenarios (The red line is the allowed outflow; the black line represents the actual outflow; the green, yellow and purple lines display the outflow of three on-ramps from left to right, respectively. In the following graphs, the line colorings remain the same).

The first thing is to check whether the actual outflow follows the allowed value. It is easy to see that the black line converges with the red line well after 500 seconds. It should be noticed that in the first 500 seconds, the outflow of the exit (black) and the third on-ramp (purple) is unusually high, which may exceeds the allowed outflow. In addition, the two lines seem to overlap each other, indicating that the flow from the third on-ramp contributes the majority of the total outflow. This was caused by weird behaviour of VISSIM, that during the first several hundred seconds, the vehicles on Ramp 3 ignored the red traffic signals. Therefore, the inflow of the third on-ramp is far beyond the allowed value, so is the total outflow. Besides, the third on-ramp is very close to the network exit, so the delay of flow difference can hardly be distinguished, resulting in an overlap of the two lines. This period can be regarded as a warmup for VISSIM and in the following analysis, this ‘start up effect’ will be ignored.

Secondly, the priority conformance is to be examined as well. Demonstration of successful priority distribution can be inferred from the outflow of three on-ramps, that the flow variation trend and amplitude of all the on-ramps are almost the same, except for one segment of the purple line in the third scenario. Meanwhile, the proportion of flow of the three on-ramps conforms to the priority value. For instance, the three lines overlap in the first scenario as the three on-ramps have the same priority.

Another point to be noticed is that the maximum actual outflow cannot reach the desirable value, which is attributed to restrictions of road capacity. Road capacity is not a fixed value but dependent on the traffic situations.

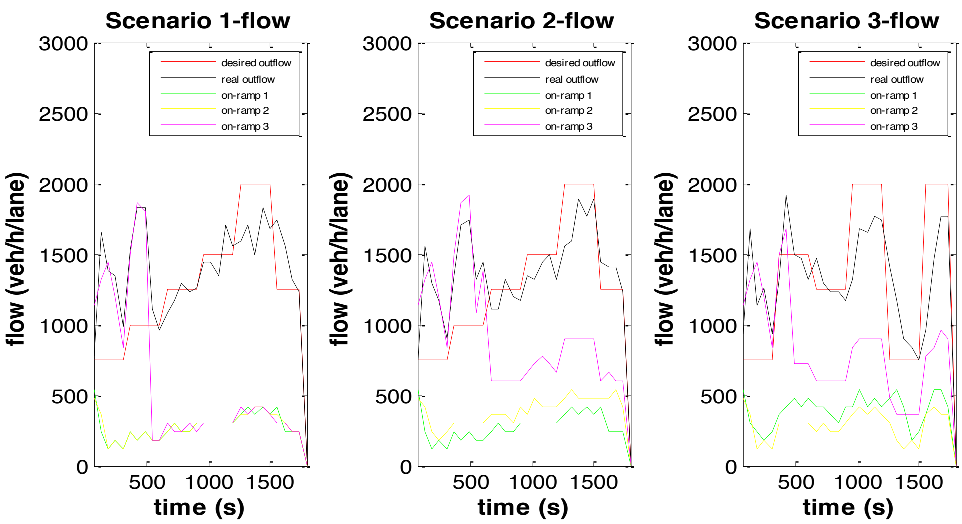


Fig. 6.1: outflow of the motorway and three on-ramps

The graph below shows the speed of three merge areas for every scenario (the red line represents the first merge area; the black line represents the second area while the green one displays the third. The numerical order of the merge areas is consistent with the order of on-ramps from left to right in the network). Besides, the value of the last second was set as 0 due to the artefact of VISSIM that the data of the last simulation second cannot be collected. Some conclusions are derived below.

- The minimum speed of all is about 40 km/h while the speed limit is 100km/h, indicating that there was no congestion (on the basis of a critical speed of 30km/h).

- Speed at the first merge area is much lower than that at the other two, while it is also a bit lower at the second than that at the third merge area. In general, the closer to the network exit, the higher the merge area speed is. This may contradict with the common sense that the downstream has more vehicles as all the vehicles accumulate here, so the last merge area should be the most 'congested'. However, the influence from any delay or emergencies downstream may propagate backwards to upstream, which is related to shock wave theory (Hegyi, Hoogendoorn, Schreuder, Stoelhorst & Viti, 2008). From this point of view, the flow upstream has a higher tendency to be disturbed.

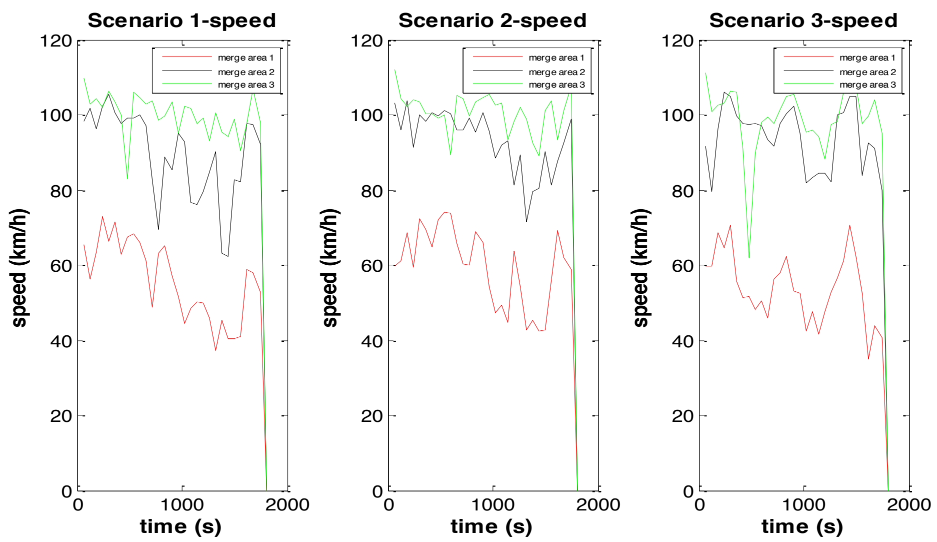


Fig. 6.2: Speed at three merge areas

From the simulation results of the three scenarios above, it is known that the designed model and algorithm worked and QHM is possibly feasible in this specific system. However, whether the conceptual model is reasonable, if the model is accurately transformed from conceptual model to simulation model is not substantiated. Besides, only two variables have been varied before and there are still some other parameters which may change the system behaviour.

6.4 Robustness and sensitivity analysis

6.4.1 Extreme condition test (Scenario 3.1)

This scenario was set as the extreme value test for validation of the model. As a follow-up of Scenario 3, the priority matrix was still the same as in Scenario 3, only one element in the allowed outflow array was changed, which was set beyond the road capacity. The original flow vector was [1500,3000,2500,**4000**,1500,4000] and it was changed to [1500,3000,2500,**5000**,1500,4000].The simulation results are displayed in Fig. 6.3.

Regardless of the first 500 seconds, the actual outflow still follows the desired values in general. However, in this case, the outflow fluctuates more than in the reference scenario, Scenario 3. Moreover, the flow is obviously delayed when the extreme value shows up. On the other hand, the speed declines sharply for all merge areas from the time point of about 1000 seconds and lasts for 300 seconds, when the extreme desirable outflow is applied. In addition, the valley of the speed is as low as 30 km/h, which may be regarded as a congestion situation in motorway.

Though in this extreme condition test, the traffic patterns differ from the case before. The behavior is just as expected: when there is an abrupt increase in the desired supply, the demand will go up simultaneously based on this algorithm. Therefore, the vehicles rush into the network from different entries instantaneously, leading to congestion at all merge areas. The overload of the network will not vanish just as implementation of the extreme outflow stops, but is alleviated gradually, displayed as latency for the actual flow in the flow diagram. This problem can be addressed for each onramp individually, using the subareas A, B and C in Figure 4.1. But this is left for future research.

Another phenomenon to be noticed is that the achievable outflow increases with bigger allowed outflow compared to Scenario 3. In Scenario 3, the maximum allowed outflow is 2000 veh/h/lane and the maximum actual outflow approximates to 1800 veh/h/lane. By contrast, in this scenario, the maximum actual outflow goes up to about 2000 veh/h/lane with the allowed outflow rises to 2500 veh/h/lane.

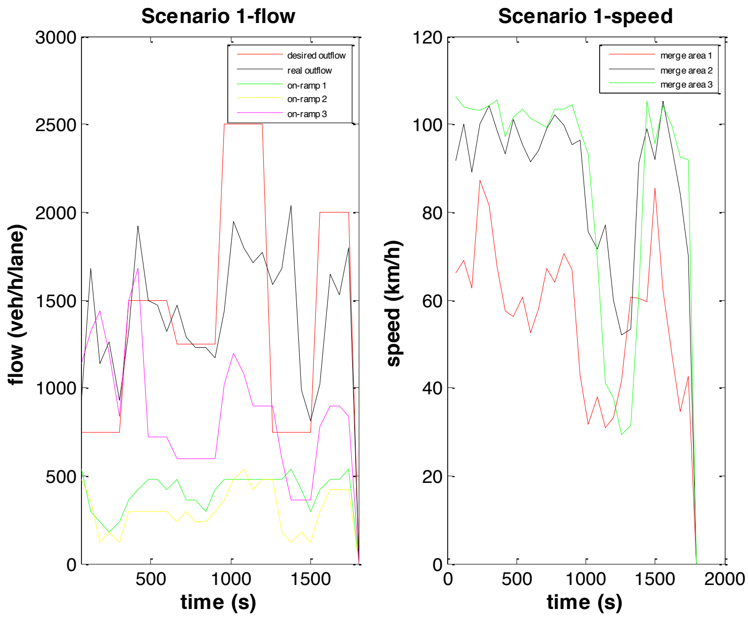


Fig. 6.3: Results of extreme condition test

6.4.2 Sensitivity analysis

Sensitivity analysis was conducted by changing some inputs or parameters of the system over some range of interest and examining the influence on system behavior. Here three common methods for sensitivity analysis have been performed.

The motorway stretch length (Scenario 3.2)

According to the figure displayed in Chapter 6.1, the speed at the first merge area is always lower than the other two. This may be caused by the fact that the length of the motorway from the entry to the first intersection is only 150m, which may not be enough for the vehicles to accelerate to the speed limit level after passing the signals. Therefore, the stretch was extended to 1.75km and the first on-ramp was located at the point where the length is about 0.75km. Such a long stretch is enough for the vehicles to accelerate (Carlson, Papamichail & Papageorgiou, 2010) to the speed limit from the motorway entry to the first merge area.

This new scenario is again a follow-up of Scenario 3 and all the settings remain unchanged except for the stretch length. The results are displayed in the following graph. In comparison with Scenario 3, the average speed at the first merge area increases, but it is still obviously lower than that at the other two merge areas, indicating that the system behavior is only numerically sensitive to the length of the motorway stretch, but not behaviorally sensitive. The same holds for the actual outflow.

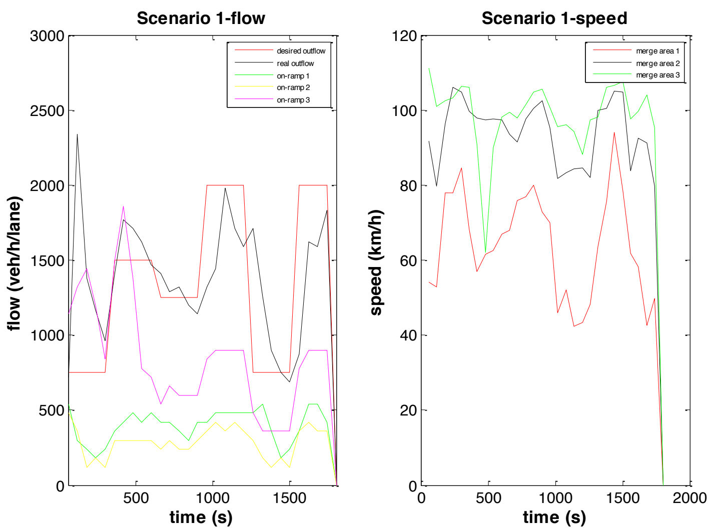


Fig. 6.4: Simulation results of a different-length stretch

Speed limit (Scenario 3.3)

The speed limit set before was 100km/h, which is applied in many countries, also in the Netherlands. In this test, the speed limit of the network was changed to 70 km/h to validate whether the model is sensitive to speed limits. From the following graph, it can be concluded that the flow diagram is almost the same as that of Scenario 3, indicating that it is not sensitive to speed limits. On the other hand, the behaviour pattern of speed at merge area remains unchanged, except for a reduction of average speed, which is in accordance with expectation. An interesting phenomenon is that in this case, the vehicles entering the third on-ramp obey the traffic rules from the beginning.

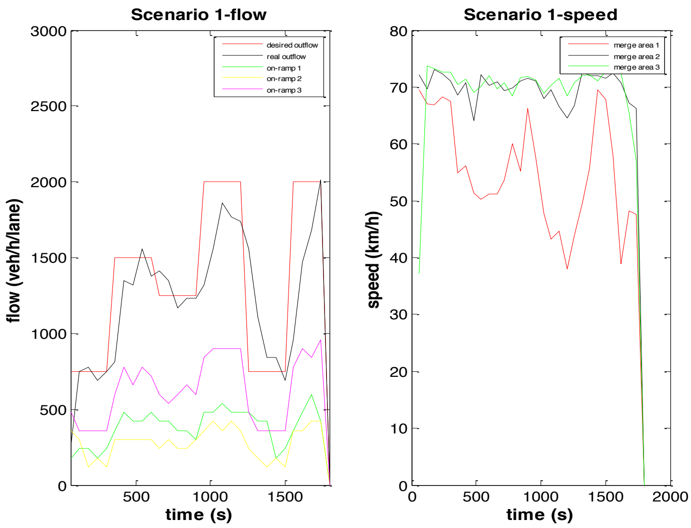


Fig. 6.5: Simulation results of a different speed limit

Gap acceptance (Scenario 3.4)

Gap acceptance is a key parameter for merge behaviour. However, it is still not clear to what extent this parameter will affect traffic behaviour in this model. So this scenario is to examine the robustness of the model to this parameter by changing the headway in the VISSIM configuration, specifically, the 'Min.headway (front/rear)'. The default value of this parameter is 0.5m and in this test, it was set as 0.8m.

Below is the graph of the simulation results and distinctions can hardly be observed between this scenario and the reference case, except for some minor peaks, which is common in traffic simulations. It can be referred that though merge behaviour or lane change behaviour is unrealistic in VISSIM, they have no significant influence on the simulation results regarding this particular research objective.

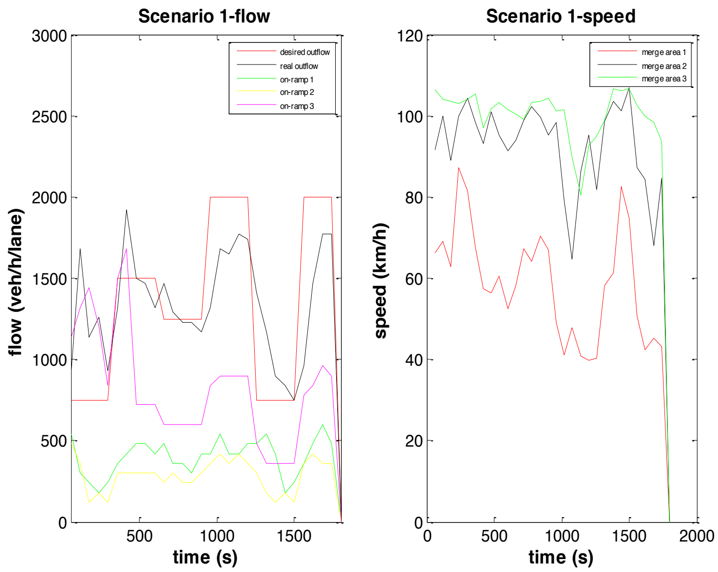


Fig. 6.6: simulation results with a different gap acceptance

6.4 Some defects discovered about VISSIM

Though VISSIM is conceived as one of the best microscopic simulators, it still showed some shortcomings during the simulation. Firstly, the merge behavior is unrealistic in VISSIM (Fig. 6.7). When we didn't have a merge lane on the merge area, vehicles from different directions may crash or go through one another. But when there was a merger for buffering, vehicles may just stay in the merger for quite a long period, which is not the case in reality. Secondly, the vehicles entering the network from the third on-ramp, did not follow the traffic signals at the first several hundred simulation seconds (usually 500), but behaved normally afterwards. This phenomenon happened for the third on-ramp only and appears only recently. The coding and VSSIM configuration has been checked many times to ensure this is not a coding mistake. After the verification and validation tests with various methods, it can be concluded that the unrealistic behavior in VISSIM may have an effect on the simulation results, but they do not influence the verification and validation of this model.

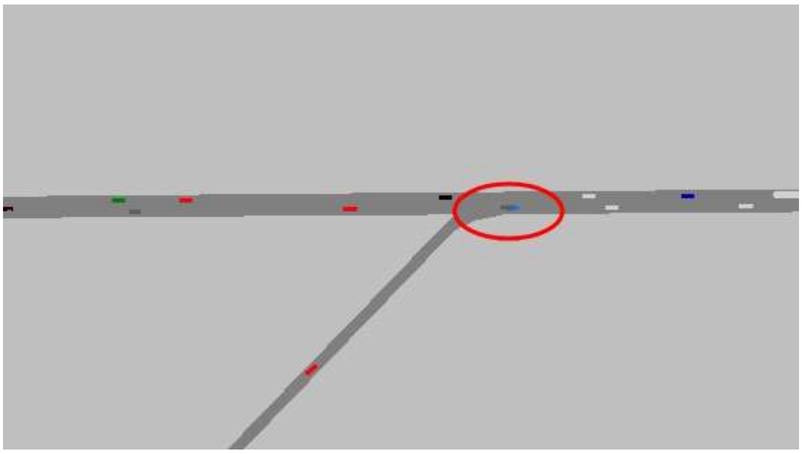


Fig. 6.7: unrealistic merge behavior in VISSIM

6.5 Conclusion

This chapter gave a detailed description of verification and face validation tests, followed by analysis of the simulation results. Then robustness and sensitivity analysis of the model were performed. At last, the problems of VISSIM during the simulation and their consequences were addressed.

In Section 6.1, Verification was performed first. A number of verification techniques have been addressed. The techniques were divided into two types, static and dynamic techniques. For the static type, structured walkthrough, data dependency analysis, structural analysis and symbolic evaluation were conducted. For the dynamic type, animation, data relationship correction and debugging were addressed. Verification of the model is to ensure the accuracy of transformation from real system to conceptual model, and further simulation model.

After verification, a face validation test was conducted involving experts in this field. The test was conducted in the form of discussion with traffic experts. Except for confirmation of the simulation results, they have given many suggestions for improvement and further development as well.

Next, simulation results of the four scenarios defined in Section 5 were presented. The main discoveries are just as expected: the actual outflow follows the allowed value; distribution of priority among entries is executable and effective; the network is free from congestion. Moreover, there is a new discovery that the closer the merge area to the exit, the lower the speed is. This may be explained as the merge area upstream is more likely to be influenced by that on the downstream.

Afterwards, model robustness was examined, while the focus was on sensitivity analysis. Firstly, an extreme condition test was conducted by changing the allowed outflow to a high value beyond the road capacity. The system behaviour changed within expectation. Then sensitivity tests were performed by varying some parameters, namely, the strength length, the speed limit and the gap acceptance. It can be concluded that the model is not behaviourally sensitive to any of the proposed parameters, only numerically sensitive to motorway stretch length.

Section 6.4 discussed the shortcomings of VISSIM as well as some consequences. Some simulation behavior in VISSIM is unrealistic, like lane change, merge behavior, etc. As validated in Section 6.4, unrealistic lane change or merge behavior is not a concern regarding our research objective.

In general, though VISSIM is not a perfect simulator, the defects have minor influence on our research. The research goal to investigate the feasibility of QHM has been achieved in our network settings. Still, the significance of the simulation results remains to be examined in further steps, which will be discussed in the next chapter.

Chapter 7 Discussion

This algorithm based on QHM was proposed to tackle the problem that current heuristic methods of which HERO is the best known representative, fail to solve. In comparison with HERO, QHM is a functionally different strategy, that it exerts control by distributing priorities among the network entries, so the inflow at the entries are restricted by the allowed outflow and the priority of each entry; while in HERO, the algorithm works by balancing the queues of all the onramps in the target network and it is not able to assign priorities to different onramps. This is the fundamental difference between QHM and HERO.

The simulation results in Chapter 6 have shown that our algorithm has realized the intended functionality. However, the results displayed above were all of one run for each scenario. During the simulation, randomness of the input may influence the results to a certain extent, which leads to deviations from a certain mean value of different replications. Therefore, in the chapter, the results of different replications with different random seeds will be displayed for Scenario 3 (for all the scenarios, different replications have been performed, only the results of Scenario 3 will be shown here), to show the stochasticity of the simulation results. In addition, whether the results were significant or not remain to be investigated. In this chapter, statistical tests will be performed for all the scenarios. There are two objectives that need to be confirmed: one is whether the actual outflow follows the allowed outflow; the other is if the inflow of each onramp obeys the priority distribution. Results of the statistical tests will be discussed in two groups according to the two objectives.

7.1 Results of different replications

For all the scenarios, they have been simulated with different random seeds to exclude the possible errors caused by any randomness. Due to limitation of time, only the results of Scenario 3 are displayed here. In the two graphs below, for every collected data, results of three runs were displayed ('RS' is abbreviation for 'random seed'). It can be easily seen from the figures that: except for the warmup period, the lines converge with each other well, indicating that the results with different random seeds have no obvious difference. Hence, the influence of adopting only one run result to the significance of our conclusion can be neglected.

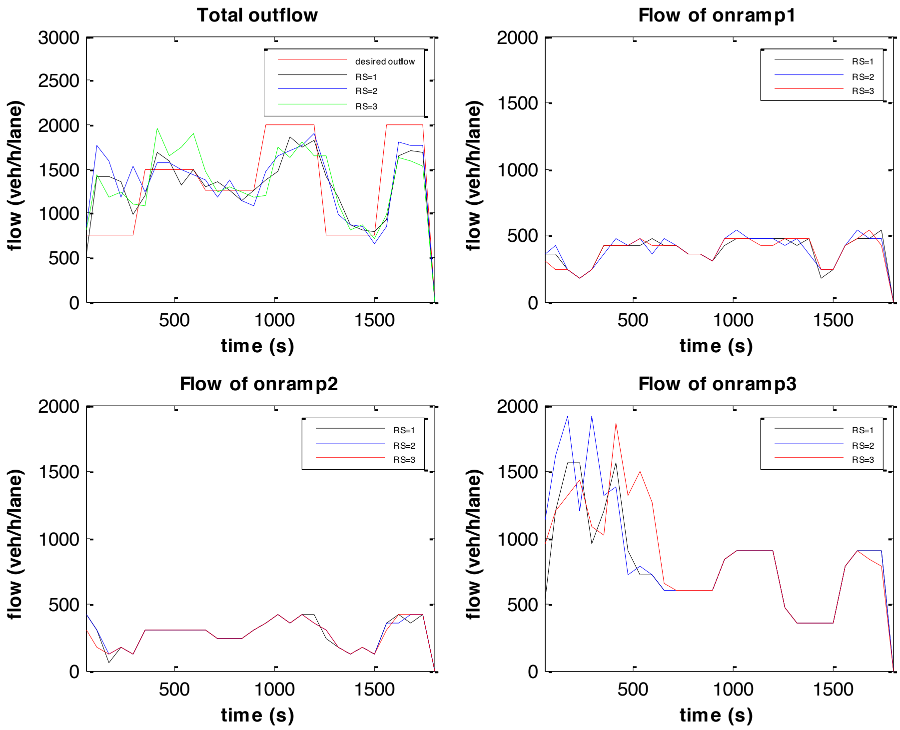


Fig. 7.1: Flow of different replications for Scenario 3

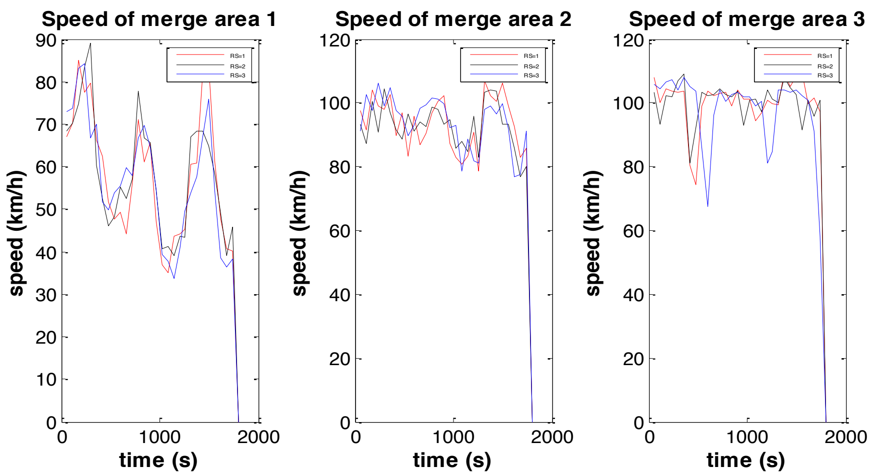


Fig. 7.2: Speed of different replications for Scenario 3

7.2 Outflow test

As the sample size is small (less than 30), and the distribution of the data is unknown, the Wilcoxon rank sum test was applied here for comparison between the allowed outflow and the actual outflow. This test method is a non-parametric statistical hypothesis test used when comparing two related samples.

Table 7.1 displays the Wilcoxon Tests for the 6 scenarios. There are two variables in the table: h and p. The 'h' indicates if the null hypothesis (there is no median difference between the two groups of data) is accepted. The result h=1 ($p< 0.05$) indicates a rejection of the null hypothesis, and h=0 ($p\geq 0.05$) indicates a failure to reject the null hypothesis at the 5% significance level. Therefore, as shown in the table, both h=0 and the p-value indicate that there is not enough evidence to reject the null hypothesis and conclude that the actual outflow follows the allowed outflow at the significance level of 5% for all the scenarios.

Scenario	h	p-value
1	0	0.9495
2	0	0.4345
3	0	0.3379
3.1	0	0.4175
3.2	0	0.6391
3.3	0	0.4437
3.4	0	0.3379

Table 7.1: Wilcoxon tests for outflow comparison

7.3 Priority test

For checking the priority distribution, we have three pairs of data of three onramps in each scenario. Hereby the counterpart of Wilcoxon test was applied: Kruskal-Wallis test， which is an extension of the Wilcoxon rank sum test to more than two groups.

Before performing the tests, the data were processed. The flow detected on each onramp was divided by their priorities, therefore the three groups of data could be compared directly by the Kruskal-Wallis test. Table 7.2 displays the results of Kruskal-Wallis tests for all the scenarios. The only variable here is the 'p'. Again, the critical p-value is chosen as 0.05: if the p-value is less than 0.05, this casts doubt on the null hypothesis that at least one sample median is significantly different from the others. As the p-values of the tests are all considerably larger than 0.05, the null hypothesis cannot be rejected. It can be concluded that the inflow of the onramps has followed the priority distribution.

Scenario	p-value
1	0.9926
2	0.4758
3	0.5863
3.1	0.5570
3.2	0.7312
3.3	0.6016

3.4	0.5863

Table 7.2: Kruskal-Wallis tests for checking priority distribution

7.4 Conclusion

In this chapter, firstly, the functional comparison between QHM and HERO was briefly addressed. Then results of different replications of Scenario 3 were displayed to exclude the influence of randomness on the simulation results. It can be concluded that though small deviations exist between different runs with different random seeds, the effect can be neglected and the choice of using the result of one run for every scenario was valid. At last, statistical tests have been performed to ensure that the simulation results were significant for the conclusion of realization of the two objectives: the actual outflow followed the allowed outflow and the priority distribution was realized. As a result, they have been confirmed and our results are significant with these tests.

Chapter 8 Conclusion and recommendations

The main research objective is to show, in a traffic simulation setting, the feasibility of implementing the QHM framework to tackle the problems of current CRM systems, where feasibility means effectiveness in traffic control theoretically. This objective has been achieved in our network settings. This chapter will first summarize the whole research process, then answers to the research questions will be given, and the research gaps will be addressed, resulting in recommendations for future research.

8.1 Summary of research process

Coordinated ramp metering is a much desired measure for freeway traffic control. However, current applied CRM strategies fail to assign priorities to particular on-ramps and a new framework named QHM could be a potential solution. So the research objective is to investigate the feasibility of QHM to CRM in a simulation setting.

Regarding the methodology of this research, the supporting theory is QHM and the research tools are VISSIM and Matlab. The core idea of QHM is to exert traffic control at the network level and network is the basic concept in this framework. Control of a network should distinguish between boundary control and internal control. This research is the boundary control. For the simulation realization, VISSIM worked as the simulator and Matlab was used as the controller by executing a designed algorithm. Interfacing between Matlab and VISSIM was realized by the VISSIM COM interface, by which VISSIM worked as an automation server.

The target system was set as a hypothetical motorway stretch with three on-ramps. Unlike usual settings, the traffic signals were put at the entries of the system, both the entries of on-ramps and motorway, to restrict inflow of the system. The simulation results have shown that the allowed outflow is achievable by distributing priorities to the entries and the inflow at different on-ramps conforms to their priorities. Meanwhile, we can still keep the network out of congestion. In addition, drawbacks of VISSIM and the consequences have been discussed. Lane change behaviour, merge behaviour and some other unrealistic behaviour may occur during the simulation. Though VISSIM is not a perfect simulator, the defects have minor influence on our research. In all, QHM is a promising method for CRM based on current research, but further investigation is needed.

8.2 Answers to research questions

At the beginning, we raised a main research question and two sub-questions. Hereby the answers to these questions will be addressed.

The main research question: Will Quantitative Hierarchical Model be feasible to Coordinated Ramp Metering?

The simulation results have shown that the allowed outflow is achievable by distributing priorities to the entries and the real flow of different on-ramps conform to their priorities. Priority setting is the quantitative control strategy in QHM. Meanwhile, we can still keep the network free from congestion, which is the fundamental control principle of QHM. Moreover, network is the basic concept of QHM and the behavior of network, as seen from outside, can be abstracted to the behavior on its boundary. In this project, control of the network was executed by control of the entries and exits, which has proven to be effective. In all, QHM is a promising method for CRM based on current research, but further investigation is still needed.

Sub-question 1: What are useful traffic performance measures for the target control area?

Useful performance measures in this case are actual outflow, priority conformance and merge area speed. The actual outflow is to be compared with the allowed outflow to examine whether the allowed outflow is achievable. The priority conformance is evaluated by checking the flow of different on-ramps with their priorities as the reference. The merge area speed is to be examined if it is above the critical speed for congestion.

Sub-question 2: What are effective algorithms for traffic control for the motorway and on-ramps, given the chosen performance measures? This includes performance under unpredictable variations in traffic demand on all entries and supply (allowed outflow) at the exit.

Generally, the algorithm designed here focuses on the entries and the exit of the network. Fixed priorities are assigned to every entry via a priority matrix, which can be derived from historical data or be assigned by the authority in reality. The allowed outflow was also pre-defined, which will change every 5 minutes during the simulation to represent variations of the allowed flow into the adjacent network downstream. Therefore, inflow from every entry is based on the allowed outflow and its priority setting. In this algorithm, control of the inflow is realized by traffic signals for both on-ramps and motorway. Though traffic signals may cause discrete visualization in the flow, it is the most effective method currently available to restrict the inflow precisely.

Sub-question 3: Can the Gating Principle be implemented with the proposed algorithm?

The Gating Principle can be generally described as “allow in as much is allowed out”. In this algorithm, the inflow is decided by the allowed outflow and the priority distribution. Theoretically, the sum of the inflows is equal to the allowed outflow. As a result, the actual outflow followed the allowed outflow regardless of the road capacity influence. Therefore, the Gating Principle has been realized here.

Sub-question 4: can the Fairness Principle be implemented and how well is this maintained?

The fairness is not a unique criterion, but is defined by traffic policies. In our proposed algorithm, fairness is represented by priority. The priority can be assigned by the traffic authority or can be derived from historical data. Based on the simulation results above, the priority distribution was realized. Hereby it can be concluded that the Fairness Principle has been implemented well.

8.3 Gaps and recommendations for future research

In this part, gaps in current research will be described and recommendations for future research will be given accordingly. Development for future research will be proposed based on three aspects: to tackle the problems remaining in this research, to increase complexity for bigger and more realistic network and to implement the algorithm to real situations.

Improvement based on problems of current discoveries

In this control algorithm, there was a delay between the actual and the allowed outflow. The reasons for this effect have been analyzed before. This delay effect may propagate to the network downstream and it may accumulate with the increase of networks involved, which will result in significant retardation of the control. Therefore, this is an important problem to be tackled in future research. Possible solutions could be to fully utilize the recursive tree structure of QHM and to achieve control at a lower level, but this is maybe restricted by the available roadside equipment. Another possible strategy is VSL.

The simulator applied here is VISSIM, which counts as one of the best microscopic simulators currently. Still, some unrealistic traffic behavior was displayed during the simulation. If possible, the simulation may be conducted in a more realistic simulator in the future.

Building a more complex model

Though the research objective is achieved in this case, it is still far from the final conclusion that QHM can be a substitute to current CRM strategies. In my research, many assumptions have been made, which may deviate from the reality, for instance, putting traffic signals on the motorway, applying the cycle time merely based on calculation without consideration of minimum or maximum time restrictions, etc. Moreover, in reality, the demand won't be sufficient all the time. Sometimes, one entry of a road network may have more demand than expected, while sometimes the demand is too little and there may be an underutilization of the road. If taking all these into consideration, the control algorithm will be much more complex than the current one.

The network defined in this research is relatively simple and small, with only one-exit and control is exerted over one level of network. In reality, control may be executed over a much bigger and complex network. Then the hierarchical control strategy of QHM will need to be implemented. The next step is to build a stepwise bigger network involving more elements, such as on- and off-ramps.

Real implementation

Now the research is on the theoretical aspect. Field implementation may deviate a lot from theoretical research. The real deployment depends on much more factors, of which many are unpredictable, for instance, the weather, an accident, etc. Besides, application of traffic control strategies may be restricted by transportation infrastructure and the authority's requirements. Therefore, feasible policy scenarios that are acceptable by the authority are to be designed in future research.

Chapter 9 Reflection

Initially, we had an ambitious research goal for the research proposal, that to design a feedback strategy and make the algorithm general, but not to be restricted to limited number of on-ramps. Also, we intended to interview some people from this field, like engineers in companies or traffic policy-makers from the authorities. However, we didn't foresee the complexity of designing such an algorithm and the research time was greatly restricted by my master thesis requirements. Another important reason for this is VISSIM. VISSIM is a highly protected commercial software and has strict requirements on the working environment. It took much time to install VISSIM and get it work: sometimes it was removed from the operating system automatically or refused to operate without obvious cause.

During the research, a considerable length of time was spent on trying to build an effective motorway flow controller via VSL, which distracted us from QHM. Regarding to the flow controller building process, some data analytics techniques were tried to design a predictive method. I was trying to learn the behavior patterns of downstream flow in response to VSL upstream, so that the control of flow can be realized by recognition of traffic behavior and applying different speed limits accordingly. However, classification of traffic behavior patterns failed. Then we tried to find a useful method from literature. A state-of-art strategy, proposed by Carlson, Papamichail & Papageorgiou (2010) was claimed to be effective and practicable. Unfortunately, attempts to reproduce the paper were not successful. Therefore, the trial of building a flow controller via VSL was terminated and the research focus was shifted to priority settings. Still, flow controlling via VSL is a more realistic way than traffic signals on motorway and future research should incorporate this.

Anyhow, this research is still a success in some sense that I started from scratch for this project without any background in a relevant field. With the help from my supervisors, I was able to complete it. Though many difficulties occurred during this process, I finally got here. Trying something new is definitely a challenge, but it is a good chance to develop one's potential as well.

References

Balci, O. (1998). Verification, Validation, and Testing. In B. Jerry (Ed.), *HANDBOOK OF SIMULATION : Principles, Methodology, Advances, Applications, and Practice* (pp. 335-393). New York, US: John Wiley & Sons, Inc.

Bogenberger, K., May, Adolf D. (1999). Advanced Coordinated Traffic Responsive Ramp Metering Strategies. *UC Berkeley: California Partners for Advanced Transit and Highways (PATH)*. Retrieved from: http://escholarship.org/uc/item/3pq977ts

Bogenberger, K., & Keller, H. (2001). An evolutionary fuzzy system for coordinated and traffic responsive ramp metering. *Proceedings of the 34th Annual Hawaii International Conference on System Sciences* (pp. 10-pp), IEEE, 2001.

Carlson, R. C., Papamichail, I., & Papageorgiou, M. (2011). Local Feedback-Based Mainstream Traffic Flow Control on Motorways Using Variable Speed Limits, *IEEE Transactions on intelligent transportation systems*, 12(4), 1261–1276.

Chu, L., Liu, H. X., Recker, W., & Zhang, H. M. (2004). Performance evaluation of adaptive ramp-metering algorithms using microscopic traffic simulation model. *Journal of Transportation Engineering*, 130(3), 330-338.

Gregurić, M., Buntić, M., Ivanjko, E., & Mandžuka, S. (2013). Improvement of Highway Level of Service Using Ramp Metering. I*n 21st International Symposium on Electronics in Transport–ISEP 2013*, ITS in real time.

Hegyi, a., Hoogendoorn, S. P., Schreuder, M., Stoelhorst, H., & Viti, F. (2008). SPECIALIST: A dynamic speed limit control algorithm based on shock wave theory. *2008 11th International IEEE Conference on Intelligent Transportation Systems*, 827–832. doi:10.1109/ITSC.2008.4732611

Helbing, D., Hennecke, A., Shvetsov, V., & Treiber, M. (2002). Micro-and macro-simulation of freeway traffic. *Mathematical and computer modelling*, *35*(5), 517-547.

Hoogendoorn, S. P. (2014). *Traffic Flow Theory and Simulation*, Reader of the course CIE4821, TU Delft, 2014.

Jacobson, L. N., Henry, K. C., & Mehyar, O. (1989). Real-time metering algorithm for centralized control. Transportation Research Record, No. 1232, *Urban Traffic Systems and Operations*, 17-26.

Kotsialos, A., Papageorgiou, M., & Messmer, A. (1999). Optimal co-ordinated and integrated motorway network traffic control. *14th International Symposium on Transportation and Traffic Theory.*

Lipp, L. E., Corcoran, L. J., & Hickman, G. A. (1991). Benefits of central computer control for Denver ramp-metering system, *Transportation Research Record*, No. 1320, 3-6.

Lu, X. Y., Varaiya, P., Horowitz, R., Su, D., & Shladover, S. E. (2011). Novel Freeway Traffic Control with Variable Speed Limit and Coordinated Ramp Metering. *Transportation Research Record: Journal of the Transportation Research Board*, 2229(1), 55-65.

Marczak, F., Daamen, W., & Buisson, C. (2013). Merging behaviour: Empirical comparison between two sites and new theory development. *Transportation Research Part C: Emerging Technologies*, *36*, 530–546. doi:10.1016/j.trc.2013.07.007

Paesani, G., Kerr, J., Perovich, P., & Khosravi, F. E. (1997). System wide adaptive ramp metering (SWARM). *In Merging the Transportation and Communications Revolutions. Abstracts for ITS America Seventh Annual Meeting and Exposition.*

Papageorgiou, M., Blosseville, J. M., & Hadj-Salem, H. (1990). Modelling and real-time control of traffic flow on the southern part of Boulevard Peripherique in Paris: Part I: Modelling. *Transportation Research Part A*: General, 24(5), 345-359.

Papageorgiou, M., Diakaki, C., Dinopoulou, V., Kotsialos, A., & Wang, Y. (2003). Review of road traffic control strategies. *Proceedings of the IEEE*, 91(12), 2043-2067.

Papageorgiou, M., Hadj-Salem, H., & Blosseville, J. M. (1991). ALINEA: A local feedback control law for on-ramp metering. *Transportation Research Record,* (1320), 58-64.

Papamichail, I., Kotsialos, A., Margonis, I., & Papageorgiou, M. (2010). Coordinated ramp metering for freeway networks–A model-predictive hierarchical control approach. *Transportation Research Part C: Emerging Technologies*, 18(3), 311-331.

Papamichail, I., & Papageorgiou, M. (2008). Traffic-responsive linked ramp-metering control. Intelligent Transportation Systems, *IEEE Transactions on*, 9(1), 111-121.

Sargent, R. G. (2012). Verification and validation of simulation models. *Journal of Simulation*, *7*(1), 12–24. doi:10.1057/jos.2012.20

Scariza, J. R. (2003). Evaluation of Coordinated and Local Ramp Metering Algorithms using Microscopic Traffic Simulation (Doctoral dissertation, Massachusetts Institute of Technology).

Smaragdis, E., Papageorgiou, M., & Kosmatopoulos, E. (2004). A flow-maximizing adaptive local ramp metering strategy. *Transportation Research Part B: Methodological*, 38(3), 251–270. doi:10.1016/S0191-2615(03)00012-2

Taale, H., & Van Velzen, G. A. (1996). The assessment of multiple ramp-metering on the ringroad of Amsterdam.

Thompson, N., & Greene, S. (1997). Ramp Metering for the 21st Century: Minnesota's Experience. In *ITS America. Meeting (7th: 1997: Washington, DC.). Merging the transportation and communications revolutions: conference proceedings*.

PTV. (2011). VISSIM 5.30-05 User Manual. *PTV Planung Transport Verkehr AG, Karlsruhe, Germany*.

PTV. (2011). VISSIM 5.30-05 COM Interface Manual. *PTV Planung Transport Verkehr AG, Karlsruhe, Germany*.

Vrancken, J. L., Wang, Y., & van Schuppen, J. H. (2013). QHM: The Quantitative Hierarchical Model for Network-level Traffic Management.

Vrancken, J., Brokx, A., Olsthoorn, R., Schreuders, A., & Valé, M. (2012). DVM-Exchange, the Interoperability Standard for Network Management Systems. In *19th ITS World Congress*.

Wang, Y., van Schuppen, J. H., & Vrancken, J. (2013).Prediction of Traffic Flow at the Boundary of a Motorway Network. *IEEE Transactions on intelligent transportation system*, 15(1), 214–227.

Yuan, Y. (2008). Coordination of ramp metering control in motorway networks. *E. TU Delft, Rijkswaterstaat.*

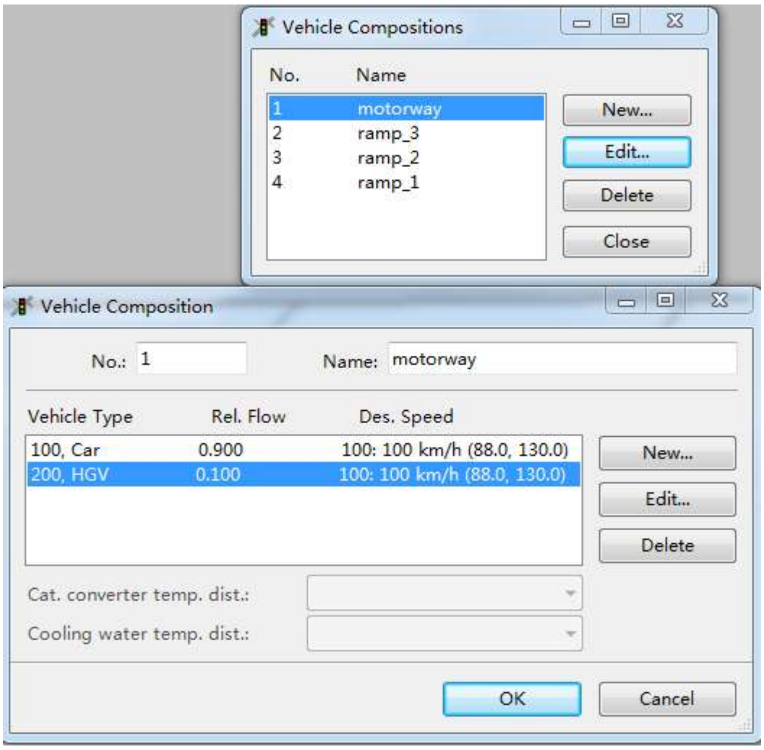
Yuan, Y., Daamen, W., Hoogendoorn, I. S., & Vrancken, J. (2009). Coordination concepts for ramp metering control in a freeway network. In *12th IFAC Symposium on Transportation Systems* , 612-618.

Appendices

Appendix A: configuration of VISSIM model

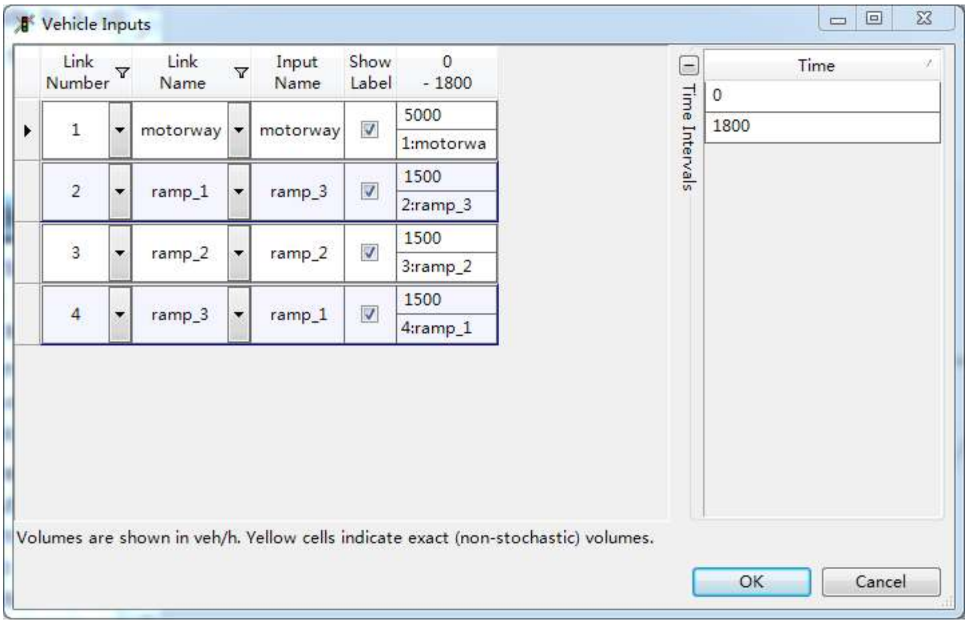
A1: Vehicle Compositions

Two types of vehicles were defined in the model: Car and HGV (Heavy Goods Vehicle), with the occupancy of 90% and 10% of the total flow, respectively. The desired speed was set as 100 km/h. During the simulation, the actual speed will distribute in the range of (88, 133) km/h.



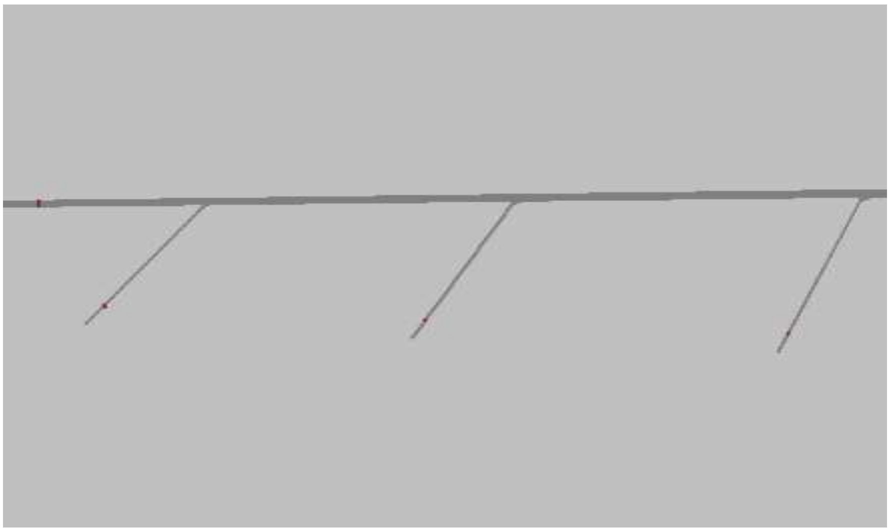
A2：Vehicle Inputs

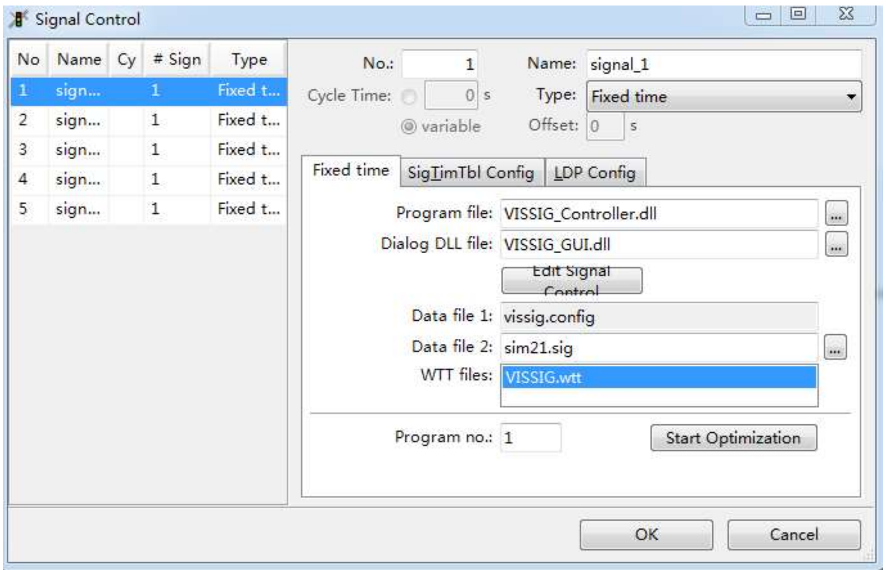
The Vehicle Inputs defines the time variable traffic volumes to enter the network. Traffic volumes are defined for each link and each time interval in vehicles per hour. Within the time interval vehicles enter the link according to a Poisson distribution. In this model, the inputs for four entries (here the motorway was regarded as a single entry) were defined as shown in the following figure. In order to enable sufficient inflow, the inputs were set above the capacities for every road.



A3: signal controller

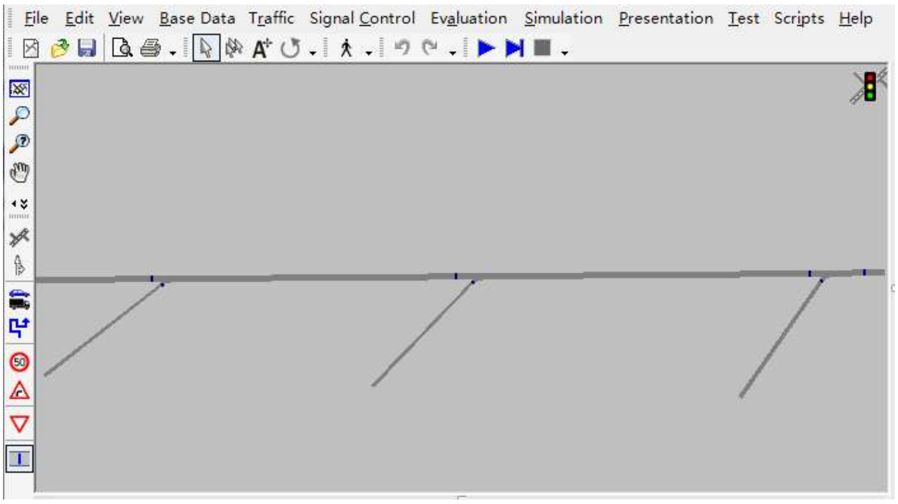
There were five signal controllers defined in the network. These controllers were placed at the entries of the network, as shown in the first figure below (the red dots). For the motorway, there was one for each lane. The second graph displays the configuration window. Though the signal cycle time depends on the control of the algorithm during the simulation, here the type still needs to be set as “Fixed time”. Configuration for “Fixed time” should be defined as well.



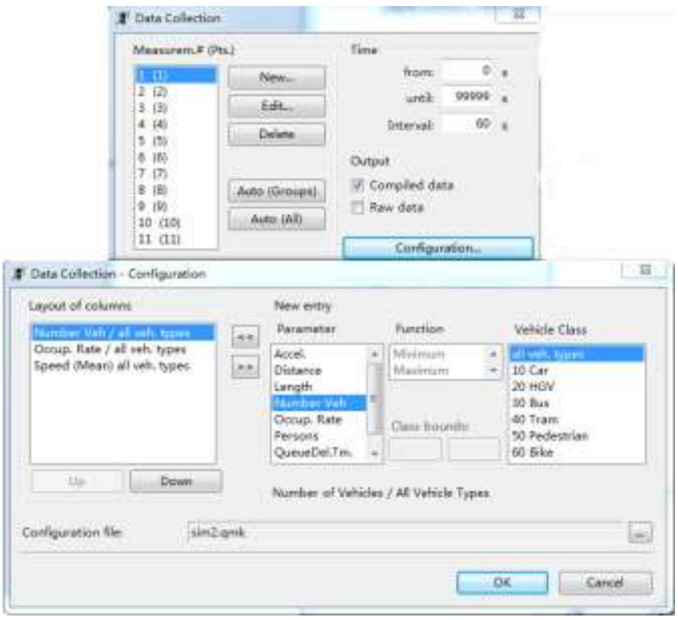


A4: data collection

There were 11 data collection points, marked by blue dots in the first graph below. They were used for collecting data of the merge area, the onramps and the network exit. For the motorway, two detectors were placed in parallel for two lanes at every location.

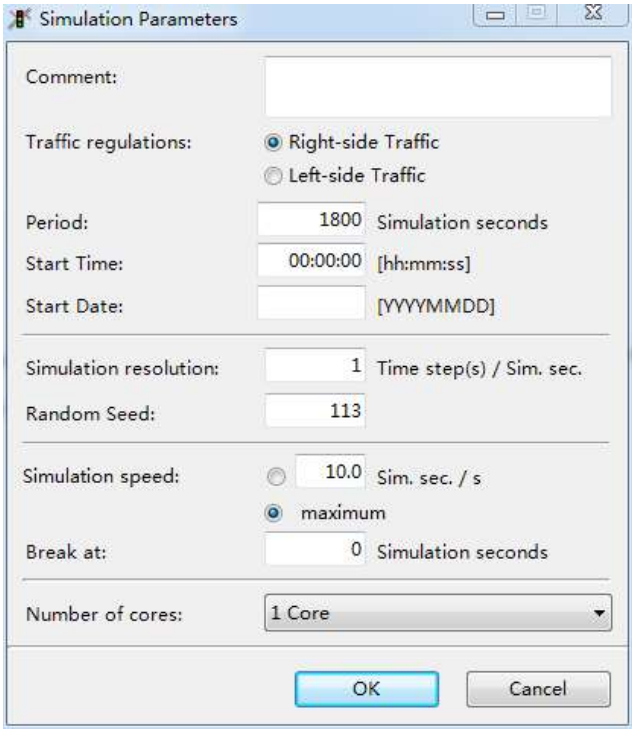


Below is the configuration window for data collection. The time interval for collecting data was set as 60 seconds. For every collection point, number of vehicles, speed and occupancy rate were chosen to be recorded.



A5: simulation parameter settings

The simulation period for every run was 1800 seconds. The simulation resolution was 1 Time step as the algorithm was executed every simulation second. The random seed was set randomly to give an input of the network. Though different seeds can lead to different results, these results won't have a substantiate difference. In this research, the result of every scenario was chosen for one run rather than several runs of different seeds. The simulation speed was set as the maximum to save the simulation time.



Appendix B: Matlab code

```
%Initialization
clear all;
clc;
format compact;

%%
%Declare VISSIM COM types for a Vissim object
h = actxserver('VISSIM.vissim.530');
% load the network and the *inp file
h.LoadNet ('D:\TU Delft\study\graduation\VisSim\with traffic signals\sim2.inp');

%%
% enable datacollection
s=h.Evaluation;
t=s.get('AttValue','DATACOLLECTION');
if t==0
    t=s.set('AttValue','DATACOLLECTION','1');
    t=s.get('AttValue','DATACOLLECTION');
end

%%
% switch of visualisation
s=h.Graphics;
t=s.get('AttValue','VISUALIZATION');
if t==1
    t=s.set('AttValue','VISUALIZATION','0');
    t=s.get('AttValue','VISUALIZATION');
end
clear s t

%%set some external variables
%the number of ramps in the target network
NumofEntry=5;
%the allowed vehicle number per green light, one car per green
n_veh=1;
%assign priority to different entries
T=[0.25,0.25,0.15,0.1,0.25];
%set the time interval of data collection
TimeInterval=60;
%total simulation time in seconds
TotalTime=1800;
%time for green light
```

```
greentime=1;
%set the matrix of allowed outflow to next network
l_out=[1500,3000,2500,4000,1500,4000];
%l_demand: the total demand of all entries
%l_maxout: the maximum allowed outflow

%calculate the inflow matrix
l_in=l_out'*T;
%calculate the signal cycle time
CYCLETIME=round(3600./l_in);
%the time interval for different outflow period
looptime=300;

%% initilization of some variables and matrices
%l_ramp1, l_ramp2, l_ramp3: the real flow of three onramps
l_ramp1=zeros(TotalTime/TimeInterval,NumofRun);
l_ramp2=zeros(TotalTime/TimeInterval,NumofRun);
l_ramp3=zeros(TotalTime/TimeInterval,NumofRun);
% NumVehicle1, NumVehicle2: the number of vehicles passing the detectors of the exit
NumVehicle1=zeros(TotalTime/TimeInterval,NumofRun);
NumVehicle2=zeros(TotalTime/TimeInterval,NumofRun);
%the actual outflow
l_realout=zeros(TotalTime/TimeInterval,NumofRun);
%the allowed inflow
l_desired=zeros(TotalTime/TimeInterval,NumofRun);

%v_1,v_2,v_3: the speed of the three merge areas, respectively
 v_1=zeros(TotalTime/TimeInterval,NumofRun);
 v_2=zeros(TotalTime/TimeInterval,NumofRun);
 v_3=zeros(TotalTime/TimeInterval,NumofRun);

%initialize some simulation values
%declare VISSIM COM type for a Simulation object
s=h.Simulation;
s.RunIndex=0;
s.RandomSeed=0;
NumofRun=1;
timestep=1;
s.Resolution=timestep;


%% simulation starts
for nr=1:NumofRun
    tic;
```

```
RI=s.get('AttValue','RUNINDEX');
RS=s.get('AttValue','RANDOMSEED');
%run simulation continuously
s.RunContinuous;
%declare collections of signal controller object
t=h.net;
scs=t.SignalControllers;

 %% one run
 for k=1:TotalTime
     s.RunSingleStep;
     pause(.05)
    %decide which loop it is now
      j=ceil(k/looptime);

      if k~=TotalTime
          if rem(k,TimeInterval)==0   %when it is the integral multiples of 60s
               l_desired(k/TimeInterval,nr)=l_out(j)./2;
               %declare collections of data collection object
               dc=t.DataCollections;

             %collect the flow of the onramps
               l_ramp1(k/TimeInterval,nr)=dc.GetDataCollectionByNumber(9).GetResult('
               NVEHICLES','SUM',0)*3600/TimeInterval;
                 l_ramp2(k/TimeInterval,nr)=dc.GetDataCollectionByNumber(10).GetResu
                 lt('NVEHICLES','SUM',0)*3600/TimeInterval;
                 l_ramp3(k/TimeInterval,nr)=dc.GetDataCollectionByNumber(11).GetResu
                 lt('NVEHICLES','SUM',0)*3600/TimeInterval;
              %collect the flow of the exit
                  NumVehicle1(k/TimeInterval,nr)=dc.GetDataCollectionByNumber(1).G
                  etResult('NVEHICLES','SUM',0);   %vehicles passing the dectector on
                  downstream of the mainstream
               NumVehicle2(k/TimeInterval,nr)=dc.GetDataCollectionByNumber(2).GetR
               esult('NVEHICLES','SUM',0);
                  l_realout(k/TimeInterval,nr)=(NumVehicle1(k/TimeInterval,nr)+NumVeh
                  icle2(k/TimeInterval,nr))*3600/TimeInterval/2;

                  %collect the merge area speed
                  v_1(k/TimeInterval,nr)=(dc.GetDataCollectionByNumber(3).GetResult('
                  SPEED','MEAN',0)+dc.GetDataCollectionByNumber(4).GetResult('SPE
                  ED','MEAN',0))/2;      %average flow in the 1st merge area
                  v_2(k/TimeInterval,nr)=(dc.GetDataCollectionByNumber(5).GetResult('
                  SPEED','MEAN',0)+dc.GetDataCollectionByNumber(6).GetResult('SPE
                  ED','MEAN',0))/2;      %average flow in the 2nd merge area
```

```
                    v_3(k/TimeInterval,nr)=(dc.GetDataCollectionByNumber(7).GetResult('
                    SPEED','MEAN',0)+dc.GetDataCollectionByNumber(8).GetResult('SPE
                    ED','MEAN',0))/2;       %average  flow in the 3rd merge area
                end

                %decide which loop and which time point it is now
                for i=1:NumofEntry
                    t1=rem(k,looptime);          %the elapsed time since the beginning of every
                                                          loop
                    t2(i)=rem(t1,CYCLETIME(j,i));      %the elapsed time of every  cycle

                %apply traffic  control
                if t2(i)<=greentime  && t2(i)~=0

                scs.GetSignalControllerByNumber(i).SignalGroups.GetSignalGroupByNumber(1
                ).set('State',3);  %GREEN=3
                else
                scs.GetSignalControllerByNumber(i).SignalGroups.GetSignalGroupByNumber(1
                ).set('State',1);  %RED=1
                end
                clear signal;
                end
            end
        end

        h.SaveNet
        h.simulation.Stop
        %set simulation parameters  for  next simulation
        h.Simulation.RunIndex=h.Simulation.RunIndex+1;
        h.Simulation.RandomSeed  = h.Simulation.RandomSeed  + 1;

        pause(10)
        toc
        t=toc;
        disp('t=');
        disp(t);
    end
```

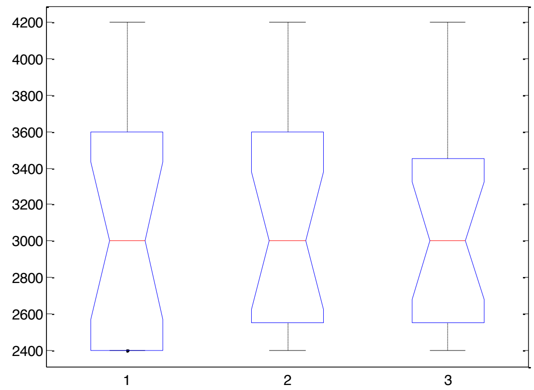
Appendix C: Kruskal-Wallis Tests Results in Matlab

Assumptions for Kruskal-Wallis test:

- All samples come from populations having the same continuous distribution, apart from possibly different locations due to group effects.
- All observations are mutually independent.

The kruskalwallis function in Matlab displays two figures. The first figure is the standard ANOVA table, calculated using the ranks of the data rather than their numeric values. The entries in the ANOVA table are the usual sums of squares, degrees of freedom, and other quantities calculated on the ranks. The usual F statistic is replaced by a chi-square statistic. The p-value measures the significance of the chi-square statistic. The second figure displays box plots of each group of data.

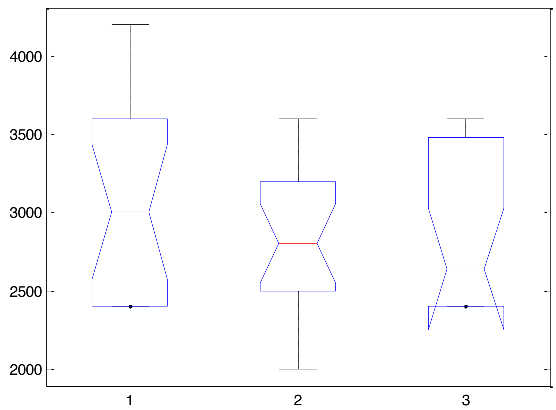
Scenario 1



Scenario 2

Kruskal-Wallis ANOVA Table

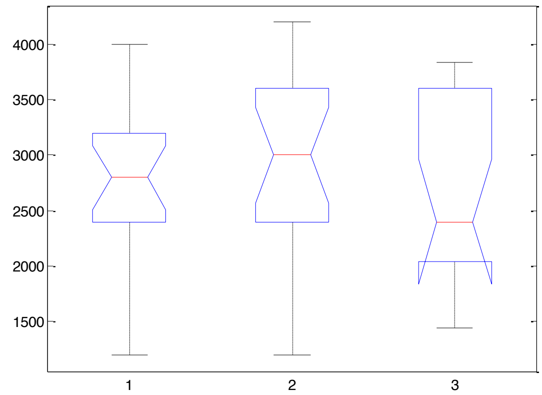
Source	SS	df	MS	Chi-sq	Prob>Chi-sq
Columns	392.4	2	196.197	1.49	0.4758
Error	14398.1	54	266.632		
Total	14790.5	56			



Scenario 3

Kruskal-Wallis ANOVA Table

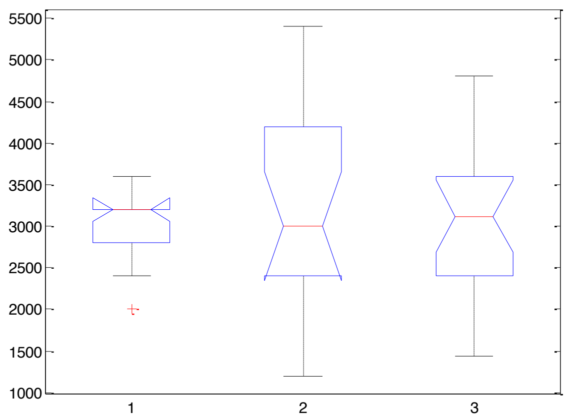
Source	SS	df	MS	Chi-sq	Prob>Chi-sq
Columns	288	2	144	1.07	0.5863
Error	14816	54	274.37		
Total	15104	56			



Scenario 3.1

Kruskal-Wallis ANOVA Table

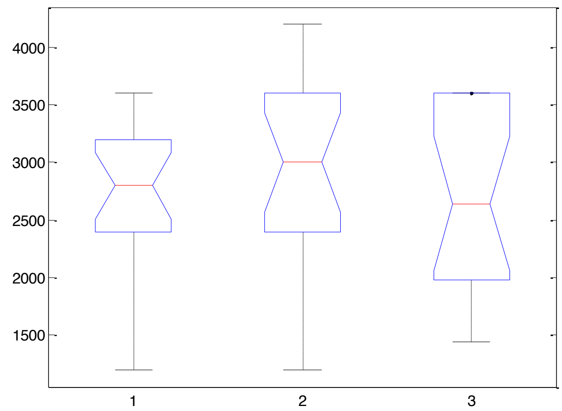
Source	SS	df	MS	Chi-sq	Prob>Chi-sq
Columns	169.7	2	84.842	0.63	0.7312
Error	15606.3	56	277.895		
Total	15776	58			



Scenario 3.2

Kruskal-Wallis ANOVA Table

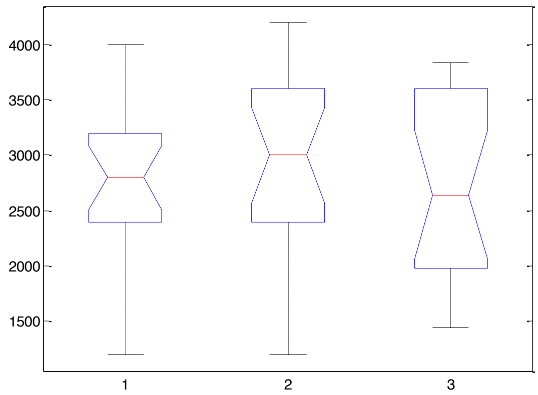
Source	SS	df	MS	Chi-sq	Prob>Chi-sq
Columns	313.4	2	156.721	1.17	0.557
Error	14683.1	54	271.909		
Total	14996.5	56			



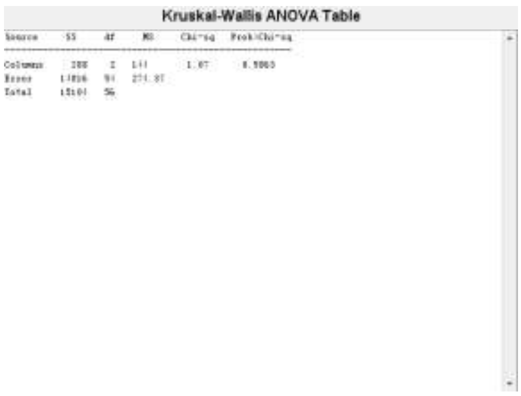
Scenario 3.3

Kruskal-Wallis ANOVA Table

Source	SS	df	MS	Chi-sq	Prob>Chi-sq
Columns	275.8	2	137.882	1.02	0.6016
Error	14918.7	54	276.273		
Total	15194.5	56			



Scenario 3.4



Kruskal-Wallis ANOVA Table

Source	SS	df	MS	Chi-sq	Prob>Chi-sq
Columns	[illegible]	2	[illegible]	1.07	[illegible]
Error	[illegible]	[illegible]	[illegible]		
Total	[illegible]	[illegible]