A Framework for the Modelling and Ex-ante Evaluation of Coordinated Network Management

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Summary

Since the second half of last century, traffic congestion on road network has become a predominant phenomenon due to the rapid increases in transport demand and number of vehicles. It starts to become clear until later that century traffic congestion cannot be solved single-handedly by expansions of road network. During peak hours, besides recurrent congestion caused by insatiable demand, non-recurrent congestion caused by incidents, adverse weather conditions and work zones, are becoming more problematic with their temporary disturbances causing traffic breakdowns. Developments and deployments of traffic control strategies come into effect to solve recurrent and non-recurrent congestions with a synthesis combining technologies, traffic theories, mathematics and kinematics. Although ITS control measures are relatively new, they transform into the backbones of a prevailing type of traffic management, Dynamic Traffic Management. When coordination and integration between DTM control measures is introduced as the advanced approach to restore the utilization of road network, great hope is placed on Coordinated Network Management to improve the effectiveness of traffic management. The Field Test Integrated Traffic Management Amsterdam aims at investigating the effect and the control concept of coordinated network wide traffic management for the implementation in 2013. The graduation project is to develop an assessment methodology framework for modelling and ex-ante evaluation of CNM. This methodology is applied to the kidney shaped network of southern Amsterdam region in order to perform ex-ante evaluation on realizing and testing dynamic coordinated network management. Evaluations and validations of the above modelling are presented to show the effect of individual DTM and coordinated DTM, also known as CNM, under recurrent and non-recurrent congestions. A test solution towards advanced deployment strategies and methodologies based on an incident-induced empirical case is contrived later using Matlab. Simulation results are also presented in order to assess this test solution and the effect of CNM under its coordination strategies and methodologies. Finally, findings, conclusions, recommendations and future directions are drawn to bring the thesis project to completion. Hopefully, this thesis work could be referred to for the future implementation of CNM in the PPA project and it could be informative to other CNM related researches.

Acknowledgement

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Dedication

To my father

And

My family

List of Acronyms and Terms

PPA: The Field Test Traffic Management Trial Amsterdam.

PoC: Proof of concept showing the feasibility of the PPA project.

FOT: Field operational test

SAA: Schipol-Amsterdam-Almere project.

MFD: Macroscopic Fundamental Diagram

NFD: Network Fundamental Diagram

DTM: Dynamic Traffic Management

CTM: Coordinated Traffic Management is basically the coordination between the same kind of control measure, for example, coordination of traffic signals at intersections (SCOOT), coordination of ramp metering on a freeway on-ramps, etc.

CNM/INM: Coordinated Network Management/ Integrated Network Management are the coordination between individual DTM, referring in particular to heterogeneous control measures (route guidance, ramp-metering, intersection control and dynamic speed limits, etc.) on the network level [1].

STEP: Short-Term Traffic Prediction Model.

DSS: Decision Support System

MPC: Model Predictive Control

AMOC: Advanced Motorway Optimal Control adopts macroscopic freeway traffic model METANET as optimization model. So, AMOC is a control system based on optimal control theory.

HERO: Heuristic Ramp-metering coordination is a rule-based coordinated ramp-metering strategy that applies ALINEA for the local regulators

ITS: Intelligent Transportation System

VMS: Variable Message Sign. VMS includes a variety of control measures in this thesis.

DRIP: Dynamic Route Information Panels

VS: Variable speed limit

RI: Route information via VMS. It refers to congestion warning VMS in Dynasmart-P.

RA: Route advice via VMS. It refers to optional detour VMS in Dynasmart-P.

LRM: Local ramp metering. LRM in this thesis project mostly uses ALINEA control.

CRM: Coordinated ramp metering.

HOV: High Occupancy Vehicle

LOV: Low Occupancy Vehicle

HOT lane: High Occupancy Toll-charge lane

HOV lane: High Occupancy Vehicle lane

MOE: Measure of Effectiveness, criterion for the evaluation of the effect of traffic management.

MPSM: Macro Particle Simulation Model

DSP: DYNASMART-P (Dynamic Network Assignment Simulation Model for Advanced Road Telematics) version 1.4 is the modelling tool chosen for the thesis project to evaluate CNM effect on a network. Other versions of DSP are being developed. DynusT is derived from DSP and DSPEd. DynusT is suitable for DTA assignments.

DSPEd: Dynasmart-P editor is a user interface to layout and build networks as well as evaluation and analysis for DSP. DynaBuilder is used to prepare input data for DSP.

Questor-DSP: An advanced and adjusted version of DSP designed in the Netherlands (DHV). Questor is a package of building traffic models; its basic functions are similar to a combination of DynaBuilder and DSPEd; it is a static model with a dynamic coating and the ability to perform dynamic simulation and DTA.

K-Shortest Path (K-SP) Computation: This algorithm is used in the path processing component of DYNASMART to solve for the K best paths from all origin nodes to each given destination node for a given set of link travel times.

MUC: Multiple User Class. Based on the route selection behaviours, DSP has five MUC.

MVC: Multiple Vehicle Class. Based on the information availabilities and vehicle types, DSP has seven MVC.

SA: Saturation Flow Rate applies to downstream vehicles discharging from a queue, with the unit vehicle per hour per lane in DSP.

SF: Maximum Service Flow Rate is maximum capacity of moving vehicles along a given lane, and provides an upper bound on the flow rate through a section under any condition. The unit is pc per hour per lane in DSP.

CIA: Capaciteitswaarden Infrastructuur Autosnelwegen

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Part I: Introductions

1 Introduction

Traffic congestions on a road transport network can be explained as a mismatch between the supply and demand characteristics of the road network. Dynamic traffic management applies control measures that can adjust and synchronize the traffic demand and supply on a road network. As a family member of DTM, integration and coordination of network management aims at getting the most out of DTM control measures. The concept of CNM is not new but its potential is far from be fully understood and practiced. Amsterdam regional network has been on the frontline of coordinated optimal control [2]. Researches and practices of CNM are still going on step by step on this network.

1.1 Background

In Northern Holland, the five main motorways A10, A9, A2, A1, and A4 connect each other around the south and east parts of Amsterdam region. The city of Amsterdam is circled by A10 ring road and an open A9 ring, which forms a half outer ring outside A10 ring. In the southern Amsterdam region, the A2, A1, and A4 southbound, northbound together with the A10 and A9 westbound, eastbound were constructed into a kidney-shaped road network. The kidney shape is hardly an exaggerate metaphor of how vital they are to the northern region, to the Randstad area and to the entire country. The Amsterdam road network has one of the busiest traffic in the country. Recurrent and non-recurrent congestions are often found in this region at multiple potential bottlenecks during extended morning peak and extended evening peak [3]. A project called Field Test Integrated Traffic Management Trial Amsterdam (in Dutch: "Praktijkproef Verkeersmanagement Amsterdam") was planned and the proof of concept for this project was established in 2009 [4]. A set of traffic management measures have been introduced to the Amsterdam network in this proof of concept [5]. The PPA project focuses on improving the traffic situation and the reliability of the traffic assignments on the Amsterdam network using coordinated network traffic management so that accessibility and capacity of the network can be restored and maintained. The overall approach of the PPA project is based on smart integration of established concepts, theories and state of practice coordinated DTM. A large-scale operational field test of integration and coordination will be performed and evaluated on the PPA network [1].

Previous research showed that coordinated traffic control measures have some advantages compared with local traffic control measures. An ex ante estimation of the effects of the set of measures on the PPA project was given using Regional Traffic Management Explorer. The results clearly showed that the scenario of coordinated TMT (traffic management trial) has the best performance in alleviating the congestion on A10 ring of Amsterdam. But

under non-recurrent congestions, the estimated effect of coordinated TMT became insignificant or non-existing [6].

While the PPA project is moving forward to the phase of investigating the control of concept, the current pressing goal of this thesis project is to develop an assessment methodology and simulate the effects of CNM on the case study of the PPA network. From evaluating and validating the results under recurrent and non-recurrent conditions, the future pressing goal is to attempt extrapolating suitable strategies and methodologies for the advanced deployment of CNM on a heuristic CNM trial, for example, the coordination of dynamic traffic control measures under an incident-induced traffic jam.

1.2 Problem statement

As a dominant form of dynamic traffic management, isolated operation of ITS control measure has deemed to be effective on increasing effective capacity, preventing spill-back and distribute traffic demand in space and time on a road network [7]. Rationally, people are interested in the potential benefits of coordination between various ITS control measures on a network level. There are mainly three reasons for this need: First, installations of different types of dynamic control measures on one network can cause conflicts which can underutilize these control measures or even worsen the traffic situation [8]. Second, non-recurrent congestions are severe and the effect of local control measure renders insignificant under non-recurrent congestions such as a severe incident or inclement weather condition. Third, coordination enables us to increase the duration of deploying effective measures so that capacity drop and congestion spillback can be prevented longer. Although coordination of DTM control measures is regarded as a promising solution for congested traffic network, it is a complicated matter that is still going under study.

The two circumstances that are still lacking and also need to be tackled with in the PPA project:

1. The coordination of heterogeneous ITS control measures, such as ramp metering, VMS route guidance, lane control and signal control etc., especially under non-recurrent congestion;
2. CNM practice on a large scale network, especially operations in field [1];

This thesis will identify the specific problems and design assessment methodology to study and evaluate the effects of CNM. The assessment methodology is applied to a case study in the scope of the PPA project under these two circumstances. Then, the proposed assessment methodology is applied to an empirical case. Evaluations of the assessment methodology and the effects of CNM are shown.

1.3 Research objectives and research questions

1.3.1 Research objectives

The first research objective of this thesis project is to develop and apply an assessment methodology which can be used for the modelling and ex-ante evaluation of DTM/CNM. The second objective is to gain some lessons from scrutinizing the assessment methodology with the results after applying it to the case study. The third objective is to design a test solution for the advanced deployment of CNM, which could give some perspectives to the proposed assessment methodology and the future development of CNM.

1.3.2 Research questions

To achieve the objectives given in section 1.3.1, this thesis research can be interpreted as to answer the following questions:

1. What is the state-of-the-art CNM and how is the practice of CNM important?
2. What could be the proper assessment methodology and modelling tool for CNM in the case study?
3. How should the experiments of case study be carried out under recurrent and non-recurrent conditions to test the effects of CNM and the proposed assessment methodology?
4. According to the simulation results of the experiments, what are the effects of DTM and CNM and how could the simulation results be interpreted?
5. How did the proposed assessment methodology and modelling tool perform during testing? What impacts and implications have been put to the CNM practice in the case study?
6. What can be learned from the case study? In order to evaluate the assessment methodology, how to design an enhancement application with test solution for CNM?
7. What are the main findings, recommendations and future directions of CNM?

From chapter 2 to chapter 8, each chapter will sequentially answer one of the above questions.

1.4 Research plans and methods

As an acknowledged promising solution, an assessment methodology is proposed for modelling and ex-ante evlaution of CNM. Effects of CNM will be studied when applying this assessment methodology to a case study network in the scope of the PPA project.

1.4.1 Research plans

Research plan of this thesis project contains two stages. The first stage is the investigation of isolated dynamic traffic management, nominally, different types of ITS control measure and the coordination between them using the proposed assessment methodology. The second stage is the extrapolation and design of a test solution for modelling CNM according to the proposed assessment methodology, and the evaluation of this test solution.

Stage one:

According to the proposed assessment methodology, dynamic traffic management, nominally different types of ITS control measures such as ramp metering and VMS will be investigated. Their underlying theories and mechanism will be examined. With the above studies, the assessment methodology is applied to a case study to study the effect of CNM. Contol designs of the case study are modelled with hierarchical scenarios aiming at comparisons between isolated and coordinated network management. First, separate ITS control measure is studied and tuned as element of collaborated dynamic traffic management. Second, different types of ITS control measure are installed hierarchically to perform basic coordination.

Stage two:

Modelling results of the aforementioned case study control designs will be exported for analysis and evaluation. The limitations and effects of the assessment methodology for modelling and ex-ante evaluation of CNM will be shown. Then, this thesis project will focus on creating a testt solution for the advanced deployment CNM that can enable the beneficial essence of the assessment methodology. Advanced coordination scheme and heuristic algorithms of CNM will be synthesized as the test solution in Matlab. Applying the proposed assessment methodology, this test solution will model the impacts of network-wide CNM. Together with the assessment methodology, the test solution and its simulation results are also validated and evaluated.

1.4.2 Research methods

The research methods can be explained in three-fold, namely, pre-work, modeling and simulation with results analysis and improvement solution with assessment. These three different methods not only constitute the general research methods but also point out the solution directions and organization of this thesis project. The detailed process can be mapped in Flow chart 1-1.

Part one: Preparation work

This part contains literature review, software study and problem statement. Since CNM is a complicated system of many related components, literature review of CNM needs to proceed in constructive order so that the state of

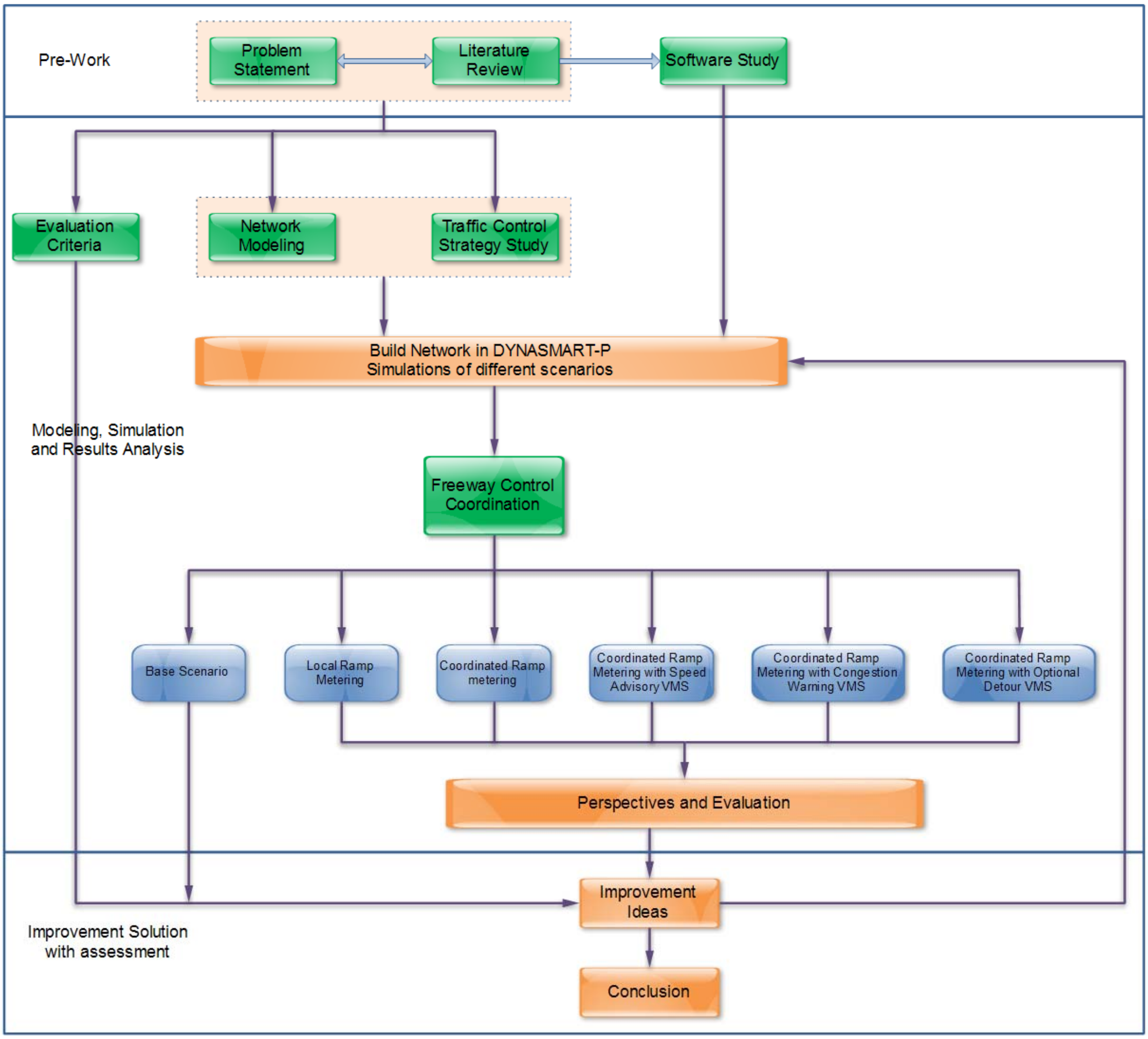
the art CNM can be summarized. First, components that are related to CNM need to be described. Traffic control measures, especially ITS control measures that are usually applied in DTM are described. Then, a general description of these isolated traffic control measures and related theories that have relevance to coordination of traffic management are presented. Also, there are quite a few researches concerning the theoretical studies of CNM, which are part of the fundamental resources to this thesis project. The PPA project must be considered during pre-work period so that experiments of the case study can be identified and designed accordingly. Second, software study of Dynasmart-P should be carried out both in operation level and in theory level, especially in the aspects of CNM that are related to the case study. Third, an assessment methodology for CNM is formed and presented after pre-work study.

Part two: modelling and simulation with results analysis

This part is the major content of simulating work and performing modelling runs with Dynasmart-P. From pre-work knowledge, a wide range of information on a variety of network traffic control strategies and their theories are obtained. The state of the art CNM is also discussed. Dynarsmart-P was chosen to perform modelling tasks for the case study. In this part, the experiments of case study are carried out according to the assessment methodology. Freeway traffic management is chosen from the broad scope of traffic management. The selection fundamentally determines the different scenarios in network traffic simulation later on. For both recurrent and non-recurrent traffic conditions, deployments of freeway traffic control, such as ramp metering and VMS are applied. Modelling runs are performed and simulation results are studied so that the effect of CNM under recurrent and non-recurrent traffic conditions can be interpreted and evaluated. Then, the assessment methodology is evaluated with the application of the case study as well as the validity checking of the modelling tool and its implication to the case study. Simulation results are summarized and shown graphically on both local and network levels.

Part three: Improvement Solution with assessment

This part mainly focuses on creating advanced deployment ideas of CNM. Improvement solution for CNM deployment is created by learning from the precious lessons. Then it is used to model CNM according to the assessment methodology on an empirical case. First, with the assessment of previous case study, the most pressing solution is to create and design a network-wide CNM deployment solution that can model CNM properly. Second, this solution must be implemented and evaluated using enhancement tests before CNM can be deployed. Then, CNM control designs are deployed and simulation results are evaluated and validated together with the proposed assessment methodology. Main findings, conclusions and recommendations can be drawn finally.



Flow chart 1-1 Research method

1.5 Research applicability

This thesis research is applicable in both scientific and practical aspects. For future reference only, the relevance of each aspect is generally listed in this chapter.

1.5.1 Scientific relevance

The scholastic relevance of this thesis is listed as follows:

1. Through this thesis, the definitions, working principles and performances of the prevailing dynamic traffic management control strategies will be studied. Therefore, this thesis provides insight in these related control

strategies and the coordination between them.

2. Meanwhile, based on the existing network, the performances of several DTM and CNM scenarios will be evaluated with Dynasmart-P, theoretically. The effects of CNM could be quoted for future traffic management research.

3. By evaluating the modelling results, the assessment methodology and the modelling tool, the limitation and implication are represented. According to these limitations and implications, a test solution of coordination between multiple ramp-meters and detour VMS under incident-induced traffic jam is proposed. The test solution helps to properly apply the assessment methodology on an empirical case. Modelling results from Matlab are evaluated to show the effecs of CNM and the effectiveness of the assessment methodology. Hopely, it is referred to for the future research and deployment of coordination network management.

1.5.2 Practical relevance

The operational relevance of this thesis is listed as follows:

1. This thesis serves in the scope of the project "Praktijkproef Verkeersmanagement Amsterdam". The simulation results in this thesis provide some perspectives for the further implementation of the control strategies on this network.

2. This thesis also deals with various control strategies systematically and with a certain priority. Therefore, this thesis also tried to provide an assessment methodology of design strategies and methodologies to on-going projects.

3. This thesis proposes a coordination test solution at the end and its simulation performance is tested and evaluated. The test solution and the assessment methodology can be referred to in the future operational cases of CNM.

1.6 Thesis outline

This thesis report is organized with eight chapters depicting three periods of the thesis project, which is also corresponding to the research method. Flow Chart 1-2 indicates structurally the outlines of this report. This section can be used as a reading guide of this thesis report.

Chapter 1

This chapter is a brief introduction to the thesis work. First, the background of this thesis project is presented. Second, the problems of CNM are stated. Third, the research objectives and research questions are defined.

Fourth, the research method and approach are introduced. Fifth, the thesis outline is presented. Finally, the research applicability of this thesis project is stated.

Chapter 2

This chapter gives a brief introduction to DTM, focusing on the development of CNM. The state-of-the-art best practice of CNM will be presented.

Chapter 3

This chapter is to provide an assessment methodology of CNM. The content can be divided into two parts. The first part is to present the overall assessment methodology of CNM evaluation. The second part gives an introduction to the modelling tool, Dynasmart-P, focusing on the aspects which can relate and potentially implicate the effect of CNM.

Chapter 4

In this chapter, using the proposed assessment methodology, several control designs are set up to evaluate the effect of CNM under recurrent and non-recurrent conditions. First, the network of the case study is described. Selection and deployments of ITS control are discussed, focusing on their functions, advantages and disadvantages. Finally, the control designs of CNM are listed.

Chapter 5

This chapter presents all the simulation results of Chapter 4. The results are evaluated to give some perspectives of CNM on the case study and the applicability of the assessment methodology. Since simulation results could be inconsistent and uninformative, an across-the-board validity checking is the most critical task at hand.

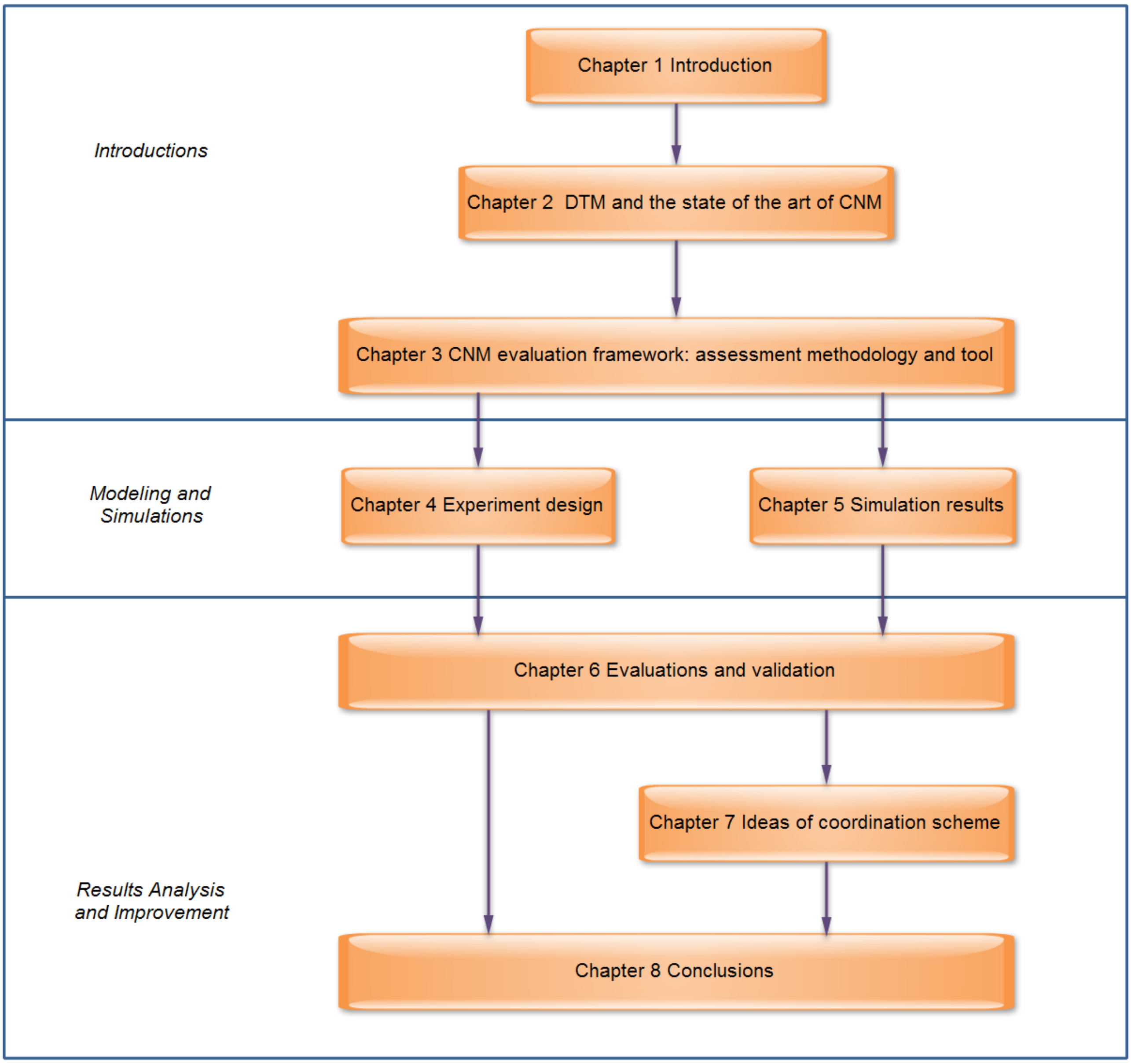
Chapter 6

This chapter includes a roundly checking of validity, both for the assessment methodology and the case study results, focusing on the implication from the modelling tool and the basic network. The intention of this critical evaluation is to learn lessons regarding CNM deployment in order to make improvements later.

Chapter 7

This chapter moves towards advanced deployment focusing on creating test solutions for CNM. Section 7.1 describes the lessons from previous part. Section 7.2 introduced the test solution. Section 7.3 presents the process of the test solution applying the proposed assessment methodology. The details of this test solution are introduced in the coordination scheme and the mathematic modelling. Section 7.4 starts the enhancement tests of the modelling. Section 7.5 lists the control designs for the application of the assessment methodology and test

solution on an empirical case. Section 7.6 shows the simulation results using the test solution.



Flow Chart 1-2 Thesis Project Structure

Chapter 8

This chapter summarizes the main findings and answers the research questions in 1.3.2. Conclusions of this thesis project are drawn. Recommendations and future directions for CNM practice are given.

2 Dynamic traffic management and coordinated network management

Traffic processes are collective human behaviours that eventually lead to stochastic, dynamic/variable, instable, non-linear and hysteretic features of the traffic process [7]. The dynamics of traffic flow characteristics such as headway distribution, relationship between density, speed and capacity distributions, etc., more or less represent these five features of a traffic process [9]. Axiomatically, network production deterioration, network performance degradation, uneven distributions of traffic, bottleneck capacity drop and congestion spill-backs/gridlocks are also correlated and can be seen as the phenomena of these five features [10]. In this thesis research, studies of effective DTM, especially CNM are motivated by these undesired phenomena of a road network.

This chapter is an introduction and review to the DTM and the state-of-the-art practices of CNM, focusing on the need of CNM. Section 2.1 is an introduction of DTM. Section 2.2 gives a general definition and introduction of CNM. Focusing on the need of CNM, the underlying motivations to study CNM in the scope of the PPA project are given. Section 2.3.1 tries to review the state of the art CNM in Europe and in Oceania. Section 2.3.2 introduces the CNM projects in the Netherlands focusing on the PPA project, which is the scope of the case study in part two of this thesis project.

2.1 Dynamic traffic management

The necessity of dynamic traffic management can be explained in three-fold. First, traffic flow is the collective human behaviours and only self-organized provided there is not much congestion on the road，which is considered to be inefficient [7]. Second, road traffic network undergoes self-degradation once it becomes oversaturated. Third, the relationship, see Figure 2-1, between the number of traffic participants (demand characteristics) and productivity (supply characteristics) is why effective intervention from traffic management is needed, especially proactive traffic management [7, 11].

Dynamic traffic management can be proactive, supported by effective traffic control strategies with ITS (acronym for Intelligent Transportation System) control measures. ITS control measures are traffic control strategies collaborating with innovative telematics ideas and operations. They are capable of providing real-time information of transport network conditions by adapting the synergy of data processing, sensor and communications technologies [12]. In many theoretical studies, efficient and proactive dynamic traffic management using ITS control strategies are proven to be influential on full utilization and degradation prevention of available road network [1, 13].

ITS is a control process that can both affect the demand and the supply characteristics of the traffic networks; DTM primarily affects the supply characteristics of the traffic networks. In this thesis research, the ITS applications fall into the category of traffic management because they are used to dynamically control the supply characteristics of the traffic networks [7]. There are many ITS control measures that can be straightforwardly classified into Intelligence Vehicle and Intelligence Infrastructure by looking at the application area [14]. For the latter category, freeway management is chosen for the case study of DTM-ITS control measures in this thesis research.

For freeway management, typical DTM control measures include ramp metering, dynamic unravelling control, peak hour lane control (shoulder running) and different applications of Variable Message Sign (VMS) information display with dynamic speed control, route information, route advice and route guidance.

Ramp metering is a classic DTM [7]. It is often used to delay or shift congestions in time and space by keeping the freeway in high capacity regime until there is no more space to temporarily store traffic [10]. Ramp metering may not solve the traffic congestion completely. Nevertheless, it is one of the most effective controls to increase effective capacity, prevent and postpone traffic breakdowns and congestion spill-backs [15]. Other beneficial "side-effects" may also include improving traffic safety, merging behaviour and so on [12].

As mentioned earlier, VMS has many applications in DTM. As a control system, it receives traffic data from sensor and function according to different strategies and objectives of the application; then, it sends control instructions to the actuator- the VMS display (road-side, in-car, via interfaces such as radio, TV and internet, etc.). Travellers receive and react to the information and therefore, the traffic process is controlled by VMS with its feedback loop [7]. In short term, VMS can control and distribute traffic demand as well as prevent or postpone capacity drop and queue spill-back. In the long term, VMS could potentially influence the demand characteristics such as traffic mode and demand, departure time etc. [10].

2.2 Coordinated network management

In a nutshell, coordinated network management (CNM) refers to using all available traffic control and management applications in a road network to improve throughput, prevent congestion and postpone spill-back [7]. As mentioned in the last section, a variety of ITS control measures are deployed on freeways and urban roads. To optimally effectuate improvements in travel time, delay, safety, reliability and predictability, fuel consumption and emission, a prevailing issue is to pursue the dynamic coordination of individual traffic management in a large-scale road network, creating an interconnected system capable of better improving road network performances with network-wide coordinated traffic management [7].

On the one hand, studies have shown the effectiveness of some individual ITS control measures and coordinated ITS control measures implemented in Amsterdam region to alleviate various traffic problems. Results from ex-ante researches and ex-post evaluations are also optimistic comparing the case with isolated controls to the case without control and comparing the case with coordinated controls to the case with only isolated controls [2, 16]. On the other hand, as different types of dependently designed, locally tuned ITS control measures thriving on the road networks, it is involuntarily to presume that conflicts can arise between them. These conflicts may impair the utilization of those measures and produce counteractive results. Last but not least, the pioneering work of Daganzo and Geroliminis shows the existence of the Network Fundamental Diagram (NFD). As see in Figure 2-1 [15], the NFD reveals network production deteriorates once the number of vehicles in the network has surpassed the critical accumulation. Since effective isolated controls can keep or delay the number of vehicles at local level from surpassing the critical accumulation, many experts are proposing more effective coordination and integration of isolated controls that can longer keep or delay the number of vehicles on the whole network from deviating from the "sweet spot". Hence, the underlying causes of NFD property provides both solution principles and control methodologies for the design and operation of effective CNM [15, 17]. From the three layers of analysis above, the necessity and the enhanced position of CNM in the field of traffic management are irreplaceable as far as concerned.

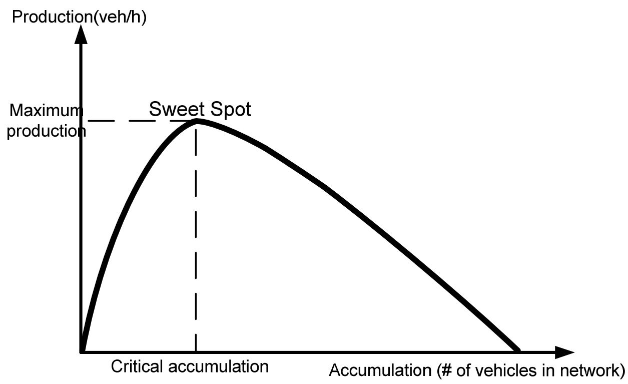


Figure 2-1 Example Network Fundamental Diagram

Keeping the NFD in mind, coordination network management of the PPA project is motivated to avoid aforementioned conflicts and exploit synergetic functionality. More attentions are paid to the CNM practices in the PPA project in section 2.3.2.

2.3 The state-of-the-art CNM practices

Nowadays, more and more agencies and authorities in different countries are realizing that CNM is needed to relieve traffic congestions. While most of the CNM research are theoretically showing the impacts of CNM in

small cases, limited projects of CNM practice can be found around the world [1]. Due to the complexity of CNM, some of these CNM practices are still under planning and some of them are heading towards testing or operational phase [18]. In this section, the state-of-the-art CNM will be presented using cases of CNM projects. Section 2.3.1 introduces the state-of-the-art CNM practices around the world. Section 2.3.2 introduces the state-of-the-art CNM in the Netherlands, focusing on the PPA project. This section contains confidential information and proprietary intellectual property. It should not be directly or indirectly quoted without consent from the original parties [18].

2.3.1 CNM practices around the world

It is clear that CNM practices will continue in the future. In this section, an overall vision of the state-of-the-art CNM is given with several cases of CNM practices in Europe and Oceania.

1. Several state-of-the-art CNM practices in European countries, such as Germany, Italy and United Kingdom, are summarized as shown in Table 2-1. In order to better understand the state-of-the-art CNM, these cases are analysed and concluded according to the core elements of Short-Term Traffic Prediction model in CNM [18]:

Data collection [18]

Data collection is a complicated issue. Lack of data could be caused by lack of devices (or properly working devices) and lack of integration protocol across different data collection systems. Lack of data compromises the capability of most modelling software when dealing with Floating Car Data (FCD). However, those data issues were not mentioned in most related papers of the cases reviewed. Many related cases, and even the three advanced cases in Table 2-1, show that data collection method is limited. Loop detector, video detector and vehicle counts at toll station are mainly used in data collection for traffic management.

Cases	Dusseldorf, Germany	London, UK	Naples, Italy
Objectives	Provide info: Estimation and prediction of future traffic states. Traffic system control & management.	Provide info: Estimation and prediction of future traffic states. Traffic system control & management.	Provide info: Estimation and prediction of future traffic states. Detect incidents.
Time line	Currently operational	Currently in testing phase	Currently operational.

Network	Urban, cover 217 km^2, 29,000 links, 560 zones	Urban, cover 21,5 km^2	Motorway, 100 km stretch
DSS techniques	Model-Based	Model-Based, namely, IDS	Model-Based
Tools	PTV Traffic Platform. Future, replaced by OPTIMA	PTV, TSS and IBM trial testing. PTV (OPTIMA)	RENAISSANCE
Data collection	560 loop detectors. Flows, speeds. Signal information. Incident information.	Loop detectors. Pre-defined signal plans (only historical information).	Video detectors. Flow, speed. Number of vehicles by toll stations.
CNM scenarios generation algorithms	Simulate incident scenarios in real-time, either accidental or generated as a control measure.	Manually selected based on events, demand or signal plans. E.g. proposing different combinations of signal plans using SCOOT control system.	Focus on providing info instead of control strategies. Single prediction, based on current state.
Prediction horizon	60 min	30 min	10 min
Practice intervention	Info to public via website. Prediction results to the authority. Real-time info via website used prediction model.	Nothing on-line yet, as the different software is now being tested.	No information was found regarding the current procedure.
Validated	Unknown	No, system not operational yet	Unknown

Table 2-1 State-of-the-art CNM practices in Europe [18]

Control strategies [18]

The design and assessment of control strategies, according to the control methodologies adopted, can be classified into different categories, for example, optimal control approaches, Model Predictive Control (MPC) approaches, rule-based approaches, case-based approaches and network MFD-based approaches. However, coordinated traffic control strategies are not found in all the cases listed in Table 2-1, nor are scenario generation algorithms found in these cases. The fact is that multiple scenarios had to be manually inputted into the system for testing. With the Intelligence Decision Support system developed for the FREEFLOW(FF) project in London, UK, one could speculate that the control strategies of this project is an extension based on rule-based and case-based approaches by adding a pattern matching component [19].

Decision Support System (DSS) [18]

The purpose of a Decision Support System (DSS) is to aid traffic operators to select appropriate traffic control measures under different control strategies. Most existing DTM/CNM applications choose a specific technique for decision support system. It seems that the three cases in Table 2-1 used model-based technique to select control measures from a pre-defined set of possible DTM/CNM. This technique responds to demand profile change and prediction of DTM impact under non-recurrent condition.

Miscellaneous [18]

Current applications of CNM cover motorway links, motorway networks and urban networks. No apparent bias towards a specific type of network was found. But none of the cases mentioned have practiced large-scale integrated regional networks. Evidently, large-scale CNM field tests are lacking in practice.

In addition, we can observe from Table 2-1 that validation efforts of CNM frameworks and control strategies are very few. Validation of CNM impact is only speculated when anomalies appear in ad hoc observations concerning traffic estimations and predictions.

2. In Oceania, there are also successful CNM practices. Monash freeway is an urban freeway in Victoria, Australia, linking Melbourne's Central Business District to its southeastern suburbs and the Gippsland region [20]. In the early 2008, VicRoads, the responsible road authority of Australia, piloted a project to address the heavy traffic congestion on Monash Freeway.

The objective of this pilot project is to maximize the throughput and reduce the travel time by deploying coordinated ITS measures, such as ramp metering and VMS. To achieve the coordination between local ramps, VicRoads implemented HERO (HEuristic Ramp metering coordination) at six consecutive inbound on-ramps of the Monash Freeway. HERO is a rule-based coordinated ramp-metering control strategy that applies ALINEA

for local regulators, based on a master-slave ramp metering coordination algorithm. Once the queue on master ramp (normally the last ramp in a string of successive ramps) exceeds a threshold length, coordinated control actions are then taken at the slave ramps (the upstream ramps). The slave ramps then hold back some traffic to release the pressure at the master ramp, therefore prevent or postpone the onset of congestion on freeway. In this way, the queue lengths of the slave ramps and the master ramp can be kept in balance. The HERO-based coordinated ramp metering control strategy is shown to have better performance than uncoordinated local ramp metering and approximate efficiency as the optimal control schemes (e.g. AMOC), without the effort for real-time modelling calculations or external disturbance prediction [18, 20]. If the queue length on the master ramp decreases below the threshold, then the control of the slave ramp metering is released.

The field experimental results show an increase of traffic throughput and a reduction of travel times and the economic payback period was 11 days [20]. Due to the successful field test implementation of HERO, VicRoads carried out the project ‘Monash-CityLink-West Gate Upgrade’ (MCWU) during 2009/2010, aiming at implementation of HERO at 63 sites along the entire 75-km route. According VicRoads, a 4.7% increase in average flow and a 24.5% increase in average speed (over the previous system) have been achieved during the morning peak; an 8.4% increase in average flow and a 58.6% increase in average speed have been achieved during the evening peak.

2.3.2 CNM practices in the Netherlands

From the installation of electronic systems-DRIPs in the 1980s to the ambitious network-wide PPA project mentioned in chapter 1, the Netherlands have been very active in the field of traffic management. One reason is that the use of road network has grown constantly with a percentage higher than 31% from 1995 to 2009. Another reason is that traffic management reduces the increase of road congestion (measured in vehicle hour delay) by 25% from the years 1996 to year 2005 [6, 21]. Two cases of DTM/CNM practices in the Netherlands are discussed, focusing on the restarted and on-going project-PPA.

1. AMOC application on A10 ring-road

Amsterdam, the largest city in the Netherlands is embraced by the A10 ring-road. It serves local, regional and inter-regional traffic and acts as a hub for traffic entering and exiting North Holland [22]. A10 ring-road is connected with four other freeways, A1 in the South-East, A2 in the South, A4 in the South-West and A8 in the North. The counter-clockwise A10 ring has a total length of 32 km, equipped with 21 on-ramps and 20 off-ramps.

To test the effect of coordinated ramp metering on relieving traffic congestion, Kotsialos and Papageorgiou

proposed the application of a network-wide ramp metering coordination approach, AMOC (Advanced Motorway Optimal Control), as the traffic control strategy on A10-ring road [22]. AMOC is an Optimal Control coordinated traffic control strategy aimed at optimizing the cost function of the whole freeway network based on a network model for a certain future time horizon. It can coordinate the freeway network in a centralized structure, not just control measures on different locations and time points but also different types of control measures (e.g. between ramp metering and VMS). The model parameters for Amsterdam network were determined from validation of the network traffic flow model against real data taken from the motorways, provided by Rijkswaterstaat. The simulation ran with a 4 hours timing horizon during evening peak hour, from 16:00 until 20:00, using realistic historical demands from site. The results showed that with AMOC coordinated traffic control strategy, the total time spent is 33.2% improved compared to the case without control [22].

2. Operational Test Integrated Network Management Amsterdam (PPA)

The Dutch Ministry of Transport, Public Works and Water Management commissioned the PPA project. The proof of concept (PoC) and the ex-ante evaluation were carried out in 2009. The project was restarted in 2011. The basic idea of this project is to investigate the potential of CNM in reality.

Network

In the PoC, the operation network of the PPA project was divided into five sub-networks, as shown in Figure 2-2. The Amsterdam field test area covers about 175 km2, including over 40 ramp-metering and 4 intersection controllers that regulate the inflow towards the motorway, and 75 (variable) message signs.

Project objectives

The objectives of the PPA project are two-fold. First, by gaining experience about CNM from the Amsterdam region field test, a working prototype of network-wide CNM is created. From the PPA project, conditions for successful implementation of CNM elsewhere in the Netherlands should be determined. Second, the PPA project should serve the regional policy objectives, improves the accessibility and utilization (by improving traffic flow) of the network with CNM. Besides CNM with roadsides control measures, the future direction of CNM in the PPA project includes coordination via roadside DTM measures and individual in-car traffic information [5, 23].

Project timeline

The plan for this large-scale field operational test was about four years, from 2009 to 2012, including design and development, implementation and evaluation, considering the motorways, urban ring roads and arterials [1]. The PoC and ex-ante evaluation phase has finished. From 2009 to 2012, road-side Integrated Network Management is carried out to improve and optimize traffic flow on the local level (A10) and on network level [23].

The field operation was re-started in 2011. From 2011 to 2015, an Integrated Network Management system will be put into operation to continue optimizing traffic flow on network level. In the new coordinated traffic control network, adaptive control based upon real-time and short-term traffic flows prediction will also be adopted. However, the specific information such as short-term traffic flow prediction model and decision support system and control are unknown yet.

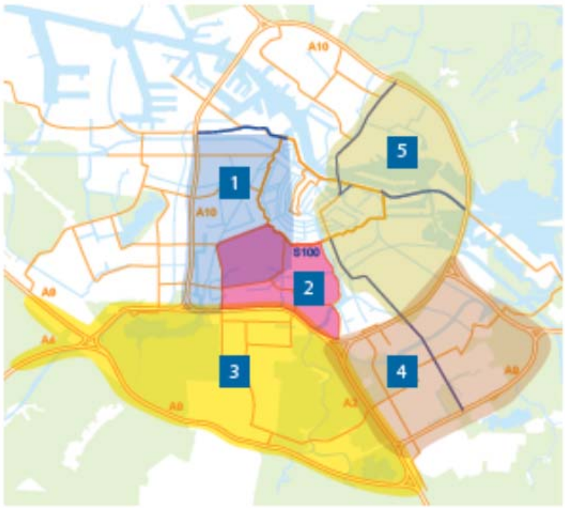


Figure 2-2 Network of the PPA project in PoC study [5]

Figure 2-2 shows the network of the PPA project. The network is divided into five sub networks. The reason for this kind of zoning is based on the traffic characteristics and traffic control strategy of the PPA project. And to the author's arbitrary interpretation, it is an application of "From divide and conquer to unite and prosper" proposed by SunTzu around 512BC [24].

According to the recent plan of Rijkswaterstaat, the PPA project implementation is planned as such [25]:

Phase 1: Implementation INM on parts of A10 city ring and a connecting urban corridor, including an ex post evaluation (spring/autumn 2013). Estimated cost is 3.7 Million euro.

Phase 2: Implementation INM scale-up on a larger part of the comprehensive network (2014)

Phase 3: Full scale implementation on the comprehensive network (2015)

In addition, a new in-car traffic information system will be integrated with roadside traffic control measures according to the objective. The in-car system is aimed at providing reliable individual traffic information for drivers. This system has a planning implementation period of three years, from 2012 to 2014, including stages of preparation, execution and project wrap-up [23].

Control strategy

A coordinated control strategy based on distributed hierarchical control methodology was proposed for the PPA project [15]. From the highest to the lowest, the hierarchy of this control methodology is composed of coordination on the network, the sub-networks and the arterial levels as well as the local management. The underlying principles of this control strategy are:

i. First, from local management to network coordination, more coordination should be included hierarchically when they are necessary to solve congestion.

ii. When congestion cannot be prevented or solved, the network performance is allowed to deteriorate according to the priorities and functions of the roads.

iii. When problems become more severe, tougher measures should be applied.

To sum up, the PPA is a promotive field test for CNM practice. However, there are still a lot of work needs to be done to operate and test the cost efficiency of this prototype.

2.4 Conclusion

This chapter is provided an introduction and review of traffic management embodying ITS control measures. The realization and practice of traffic management has evolved from isolated dynamic traffic management to coordinated traffic management, and heading towards coordinated network management.

On top of the overview of traffic management, this chapter also tries to describe the characteristics of traffic individual, traffic flow and traffic network in order to show the causes and solution directions of traffic management. The importance of effective CNM is stated here. The limited cases showed in this chapter indicate the lack of operation and practice of CNM. Most of the state-of-the-art CNM cases didn’t include a demonstrative or detailed strategy framework, nor did any structural methodology for implementation. In a sense, the limited projects and ambiguous operation of CNM show the extent of complexity, both on the scientific level and the practical level. In fact, the complexity of CNM could be a main reason why the PPA project has been halted. As far as described, the PPA project is one of the most comprehensive and innovative CNM practice. The re-launching of the PPA project is inevitable. With the proposed control strategy and methodology for the PPA project [1, 15], the core of this thesis project is to simulate and evaluate the effect of CNM in the scope of the PPA project as well as assess the proposed CNM assessment methodology that are used in this thesis project. Needless to say, this thesis project is motivated by and contributed to the future completion of the PPA project in the Netherlands.

Part II: Assessment methodology framework and a case study

In an attempt to achieve the goal of developing a framework for modelling and ex-ante evaluation of CNM, Part II and Part III of this thesis project are reported from chapter 3 to chapter 8, as shown in Figure II-1. To consider all aspects of modelling and ex-ante evaluation of CNM, a coordinated assessment methodology framework is introduced in chapter 3. Using this framework, an assessment methodology is proposed in section 3.1. To illustrate the application of the proposed assessment methodology, the case study in the scope of the PPA project is carried out using this assessment methodology in chapter 4 and chapter 5. A modelling tool for applying the methodology onto a case study is selected and introduced in section 3.2. To identify the strengths and weaknesses of the proposed assessment methodology, chapter 6 evaluates its application on the case study with the application results. The unreliable validities of the case study provide several lessons from part II. To avoid these pitfalls and properly identify the strengths and weaknesses of the proposed assessment methodology, the assessment methodology is applied to an empirical case with a coordinated test solution which amends these lessons. At last, the thesis project with answers to the research questions is synthesized in chapter 8.

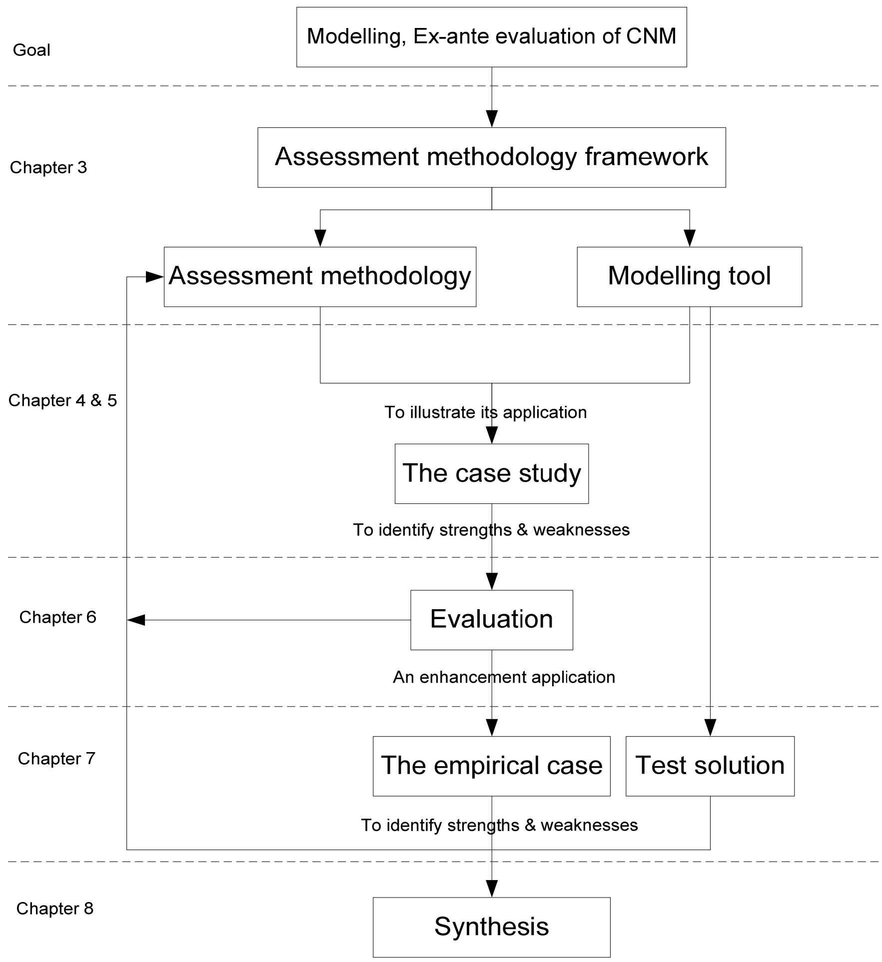


Figure II-1 Approaches of developing the framework for modelling and ex-ante evaluation of CNM

3 Assessment methodology framework

This chapter introduces a proposed assessment methodology framework for modelling and ex-ante evaluation of CNM. As introduced in section 2.2, to corporately improve network performance, the trends in traffic management in the Netherlands are towards coordinated, network-wide dynamic traffic management [26]. From the reviews of the state of art CNM practice, a suitable assessment methodology is required to gain insights into the modelling and ex-ante evaluation of CNM and it should provide a coordinated framework for all aspects of modelling and ex-ante evaluation of CNM. With this framework, an assessment methodology is proposed in section 3.1. The key elements of this assessment methodology include objectives, principles and process, which are described in section 3.1.1, section 3.1.2 and section 3.1.3 respectively. The process of the assessment methodology is introduced in section 3.1.3, which shows the process of modelling and ex-ante evaluation of CNM. Section 3.2 introduces Dynasmart-P, the modelling tool chosen for the case study, mainly focusing on the traffic flow model, the conceptual design and the control measures related to practicing CNM on the case study using the proposed assessment methodology.

3.1 Assessment methodology

Regarding the complexity of coordination on a network level, the proposed assessment methodology for CNM aims at providing a coordinated framework which considers all aspects of modelling and ex-ante evaluation of CNM, including sub-elements of the modelling phase, the ex-ante evaluation phase and the predictive operation phase. Thus, the proposed assessment methodology is developed on principle-based, modelling-based and predictive operation-based approaches. The objectives of the proposed assessment methodology are introduced in section 3.1.1. Section 3.1.2 introduces the principles for the principle-based approach. After the preparation of these two sections, section 3.1.3 depicts the process of the proposed assessment methodology for modelling, ex-ante evaluation and predictive control operation that links modelling and ex-ante evaluation together.

3.1.1 Objectives

To develop a suitable assessment methodology for modelling and ex-ante evaluation of CNM, the objectives of modelling and ex-ante evaluation need to be defined clearly. The objectives of the proposed assessment methodology are defined as:

- Assess the function and effect of DTM control measures and the impacts of DTM/CNM control designs using these control measures, by comparing the modelling results with the desired traffic situation (frame of reference). Gain insights about the interrelations and different impacts between local/isolated DTM and

CNM control designs.

- Provide information of the current state monitoring (focusing on identifying active bottlenecks) to CNM control designs using hierarchal controller to achieve predictive control operation, linking the modelling and the ex-ante evaluation of CNM together. While this control operation is performed predictively on models using simulations, it is also expected to be transferable to field operation deployment in the future researches.

The above objectives of the assessment methodology take the common initiatives of CNM into account. Sub-objectives can be developed according to a project specific study when applying the assessment methodology to a specific case. For example, when applying the proposed assessment methodology to the case study in chapter 4 and 5, the control objectives are detailed in section 4.1.

3.1.2 Principles

The assessment methodology takes a principle-based approach. Principles-based approach means relying on principles that embodies the outcomes of the traffic response to the CNM control design and the methods to control these responses as a global means to achieve the desired objectives. The principles of the assessment methodology are adopted from the core philosophy of CNM design and implementation [1].

1) Expand coordination to a higher level when lower level coordination is insufficient.

   To illustrate its application on the case study, it means the CNM practice starts with isolated control on locations, then coordination along a string, then coordination in the sub network, finally coordination in the network to the end of effectively improving the network performance.

2) Increase the degree of control measures when reinforcement from hard control measures is needed.

   One application of this principle is the increasing compliance rates of various variable message signs. When congestion is starting to form, route information with congestion warning could be sufficient. As the severity of congestion grows, route advice, route guidance or even perimeter control can be applied. Another application is the ramp metering control, increasing the degree of control can be achieved by reducing the desired occupancy rate or even closure of the on-ramp.

3) Let go of some controls and allow some network performance degeneration according to road functions and priorities or other specific plans.

   Compromises have to be made when congestion cannot be solved. In this case, the function and priorities of roads are the direct factors that determine the grade of concessions. Priorities of roads are often related to

functions of roads. For example, in the case study, the priorities of roads decrease from primary road network to supporting road network and the functions of roads follow the order of freeways, urban belt-way urban axis, regional connecting roads and supporting roads.

For individual applications, some adjustments to the principles can be made to fit the project specific study. But, the principles for a project need to be made explicit in order to apply this principle-based assessment methodology on the project.

3.1.3 Process

The assessment methodology for modelling and ex-ante evaluation of CNM is demonstrated in this section. This assessment methodology is based on the principle-based approach, the modelling-based approach and the predictive operation-based approach. This assessment methodology accumulates ideas of several previous frameworks for DTM/CNM practice, namely, the GGB+ (gebiedsgericht benutten) approach, the control cycle approach, the control scenario workbook 2005 and the PoC of the PPA project 2009.

The GGB+ approach provides method for setting up traffic management from a combined vision on the network but it hardly demonstrates how to operationally deploy these measures [27, 28]. The control cycle approach provides a scheme for the operational deployment of traffic management [7]. The control scenario workbook 2005 is scenario-based and provides a flowchart of steps for carring out traffic management [29]. The PoC of the PPA project was completed in 2009 and the feasbility of the PPA project was proven. It provides strategic and tactical choices for CNM and three control principles that point out the control method directions [4]. These frameworks all provided methods for traffic management practice but none of them fully covers the process of an assessment methodology for modelling, ex-ante evaluation of CNM and the linkage (predictive control operation) between them. Therefore, the proposed assessment methodology tries to provide a process that covers modelling, ex-ante evaluation and predictive control operation of CNM on a given project, taking the complexity of any CNM project into account.

The **process** of this assessment methodology is shown in Figure 3-1. From the starting point,

Network build-up: Gathered information of the project network is interpreted into a model. Road networks are interpreted into node, link and zone on a grid. Splits of traffic demand and corresponding route choice are determined.

Control objectives: The objectives of this assessment methodology were introduced in section 3.1.1, which can be detailed for a specific project case. From a practical aspect, the goal of CNM practice on the project network is to achieve the desired control objectives. To this end, this assessment methodology combines the

principle-based, model-based and predictive operation-based approaches. They are explained within this process.

Frame of reference: After the network build-up and the control objectives, the desired traffic situation concerning the use of the project network is painted. Therefore, the frame of reference depicts a desired situation where the quality requirements for each part/function of the network are set [27]. For instance, the road function map and road priory map are set and a ranking is thus provided. Degradation of the network performance is also based on frame of reference.

Network data: Network build-up and control objectives provide basic input to the chosen model (a model for simulation, such as DSP). The basic input should include road networks, demand, route and the scenario of interest.

Modelling: With sufficient network data, the base scenario of the project network can be modelled. The simulation results that are used as the measures of effectiveness can be outputted to describe the current state.

Ex-ante evaluation: The direct outputs above provide basis for the actual situation, which are compared with the desired situation (frame of reference). The comparison results are the ex-ante evaluation results which contribute to the estimated outcomes of the current state monitoring module.

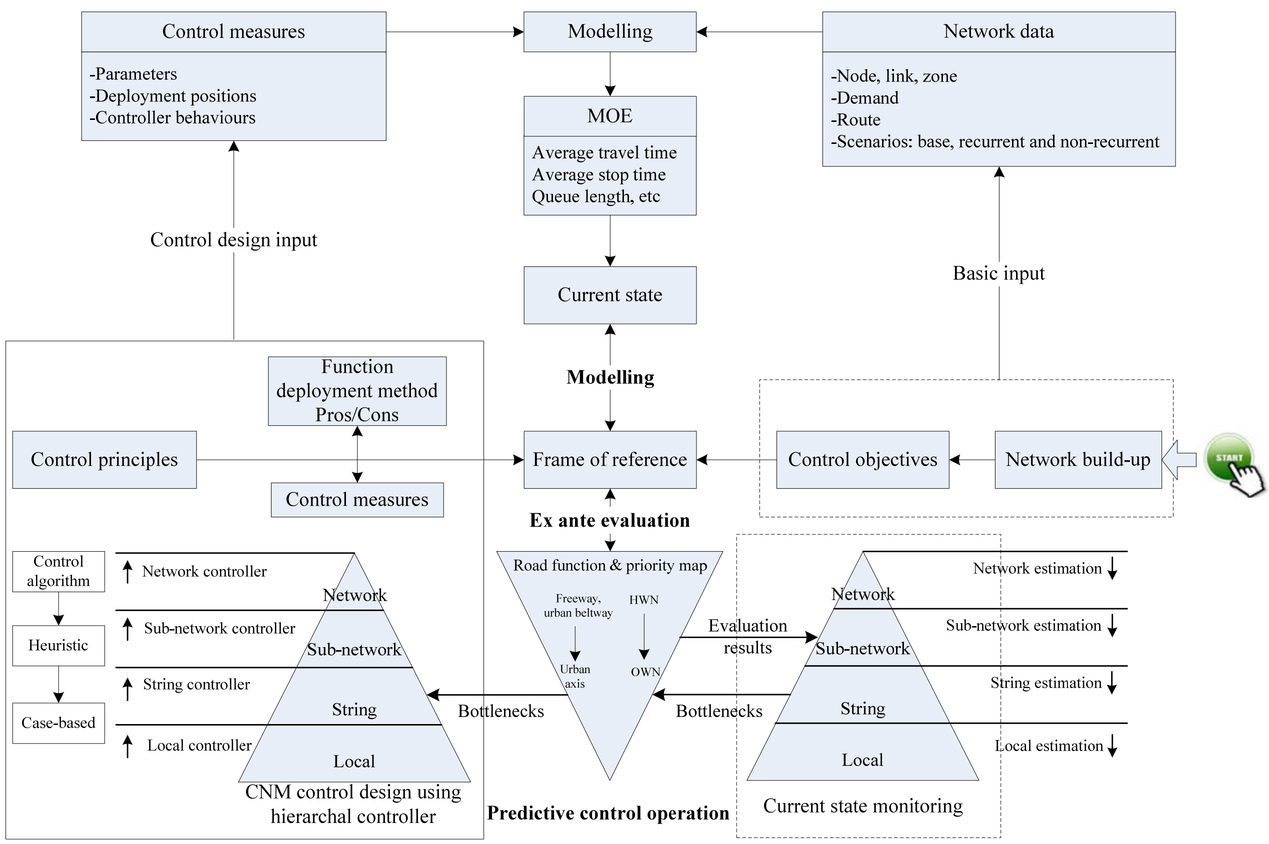


Figure 3-1 Assessment methodology for modelling and ex-ante evaluation CNM

Predictive control operation: Predictive control operation is comprised of the three triangles at the bottom of Figure 3-1. It has the functions of identifying bottlenecks and forecasting CNM control designs during control operation. The horizontal communications between the three triangle modules show the steps predictive control operation; the hierarchical communications between layers within each module illustrate the decision making process based on the objectives and principles.

Current state monitoring: This module is constructed based on a distributed hierarchical architecture [15]. The monitoring module is responsible for identifying current state traffic condition and diagnosing bottlenecks. In this module, the outcomes of current traffic states such as macroscopic traffic characteristics are estimated from the top to the bottom, according to the sequence of network, sub-networks, strings and locations. Thus, traffic problems at hand start with bottlenecks at locations.

While the current state is based on simulation here, this module is also applicable in field operation. In field operation, monitoring involves the automatic collection and processing of all data, which include traffic measurements such as speeds, flows, densities and also additional information. Diagnosis, as implied by the name, pertains to the description and identification of the bottleneck location, type and causes with the data collected during monitoring.

Ex-ante evaluation: The diagnosed bottlenecks from the current state monitoring module are ranked according to the same way as the frame of reference in ex-ante evaluation. The "bone to pick" bottlenecks are sent to the CNM control design module.

CNM control design using hierarchical controller: The CNM design module is responsible for forecasting control designs using hierarchical controller which behaves according to the control principles. As mentioned, the assessment methodology is principle-based and the principles were introduced in section 3.1.2. These principles point out the solution directions of CNM design and they are also in accordance with the frame of reference. Specific control principles are developed for each given project. The starting point is to find the traffic management control measures that match the solution directions. This includes assessing the function, deployment method and pros/cons of the control measure based on predictive effects and theories.

This module is also constructed based on a distributed hierarchical architecture [15]. Hierarchical communications of the controllers at different levels are made between CNM design layers. The control design starts from local level and harder control measures are used if needed. If bottlenecks are not solved within its own layer, then the corresponding level controller will communicate to the upper level controller and hand over the CNM control design task to the upper level, namely, in the order of string level, sub-network level and finally network level,

Control design input: A control design is suggested by the CNM control design module and related information of the control design, such as parameters, deployment positions and controller behaviours are sent to *modelling* (controller behaviours can be explicitly categorized according to the control algorithms, such as heuristic, case-based etc.).

Modelling: Together with the basic input of network data, control design input is also realized through modelling. Direct outputs of simulation results are used as the current state. Thus, one cycle of the process finishes and the next one starts.

Technically speaking, the assessment methodology for modelling and ex-ante evaluation of CNM is organized through the process. An application of the assessment methodology is introduced in chapter 4 and chapter 5. The operational details of the process will be discussed in section 6.1. Another application of the assessment methodology is described in chapter 7. The process of proposed assessment methodology is also reflected.

3.1.4 Summary

The assessment methodology for modelling and ex-ante evaluation of CNM is generally introduced in section 3.1. This proposed assessment methodology is applied to a case study in chapter 4 and chapter 5 in order to determine the strengths and weaknesses of this proposal. In chapter 6, a general evaluation of the assessment methodology is given after the case study.

3.2 Modelling tool

In this section, a brief introduction to Dynasmart-P, the assessment software used in the case study (an application of the assessment methodology), will be presented, focusing on the basic theories, simulation concepts and dynamic traffic control measures that are relevant to the case study. A more comprehensive design and operation of DSP and DSPEd should refer to the design manual of DSP and the user guide of DSPEd [30, 31]. In this section, DSP is introduced from both macroscopic and microscopic views. Since the author tentatively thinks the microscopic aspect of DSP is not an unambiguous term, section 3.2.1 introduces the macroscopic traffic flow model used in DSP and section 3.2.2 presents the mesoscopic network operation of DSP based on the traffic flow model in section 3.2.1. These two sections will also be discussed in section 0 for the modelling tool verification. Section 3.2.3 describes route choice component in DSP, which can be explained with user behaviour (route switching model) and path processing (k-shortest path). Section 3.2.4 and section 3.2.5 generally describe the traffic control measures which will be later used in the case study. Section 3.3 gives a preliminary judgment on whether DSP is applicable for the case study.

3.2.1 Macroscopic traffic flow model

The most common classification for traffic flow models is the distinction between microscopic and macroscopic traffic flow modeling approaches [9]. However, with the existence of hybrid models, this classification doesn't sound complete. Considering the distinguished traffic entities and the description level of these entities, three main types of traffic models, namely microscopic, mesoscopic and macroscopic are classified by Hoogendoorn [32]. This classification can be further interpreted as:

A traffic flow model can be classified by the underlying behavioral theory, whether it is based on characteristics of the flow (macroscopic), or individual drivers (microscopic behavior), or an integration of both (mesoscopic); and the representation of the traffic flow in terms of flows (macroscopic), groups of drivers (mesoscopic), or individual drivers (microscopic) [9].

Dynasmart-P is usually being classified as mesoscopic simulation software because it combines ideas of both microscopic and macroscopic simulation models. In particular, DSP uses established macroscopic traffic flow models (modified Greenshield, conservation law of traffic) and relationships to model the flow of vehicles through a network. And, DSP moves vehicles in a group or individually, while keeping a record of the locations and itineraries of each vehicle.

From a macroscopic aspect, this section introduces the theoretical foundation-the macroscopic fundamental traffic flow model of Dynasmart-P. Like most macroscopic traffic flow models, DSP is also based on kinematic wave theory proposed by Lighthill and Whitham [33]and Richards [34]. The basic macroscopic equation of traffic resembles the fluid conservation equation that characterizes compressible flow, that is:

$$\frac{\partial k(x,t)}{\partial t}+\frac{\partial q(x,t)}{\partial x}=g(x,t) \tag{3.1}$$

Where,

$q(x,t)$= flow (vehicles/hour)

$k(x,t)$= concentration or density (vehicles/mile)

$g(x,t)$= net vehicle generation rate

x= location

t= time

The above partial differential equation is used to represent the conservation law of traffic: the fact that a vehicle can never be lost or created on a roadway.

Conventional macroscopic models usually couple equation (3.1) with a speed-density relationship and the identity, which is expressed with the following equation:

$$q(x,t)=k(x,t)\times v(x,t) \qquad (3.2)$$

Where,

$v(x,t)$= velocity (mile/hour)

Theoretically, given a fundamental diagram and homogeneous initial and boundary conditions, a solution or characteristic line from equation (3.1) and equation (3.2) can be drawn. Combining these characteristic lines of different vehicles or vehicle packages with certain traffic conditions, such as the density variation on a road, closure of a lane, or the propagation of the traffic flow, can be analysed. Practically, continuous differential equation (3.1) coupled with the speed-density relationship and the identity of equation (3.2) can be solved numerically by discrete time steps and discretized road segments [35].

However, Dynasmart-P avoids using equation (3.2) to find the link-to-link flux in order to solve equation(3.1). The prevailing density of each link is the updated density at the beginning of every time step, which is calculated according to the discretized form of equation (3.1) using density, inflow and outflow of the link in the previous time step. Vehicles, which are considered as non-compressible macroparticals in DSP, are moved in a link according to the mean link speed using the prevailing density and the v-k relationship of modified Greenshield model. The link-to-link flux (difference between inflow and outflow) is determined by the number of vehicles reaching the link boundary (using vehicles positions, kept as the distances from the end of the link) and the movement constraints at the link boundary. Then, the vehicle positions are updated in a straightforward manner.

The original Greenshield model bases on the assumption that, under uninterrupted flow conditions, speed and density are linearly related. This relationship is shown graphically in Figure 3-2.

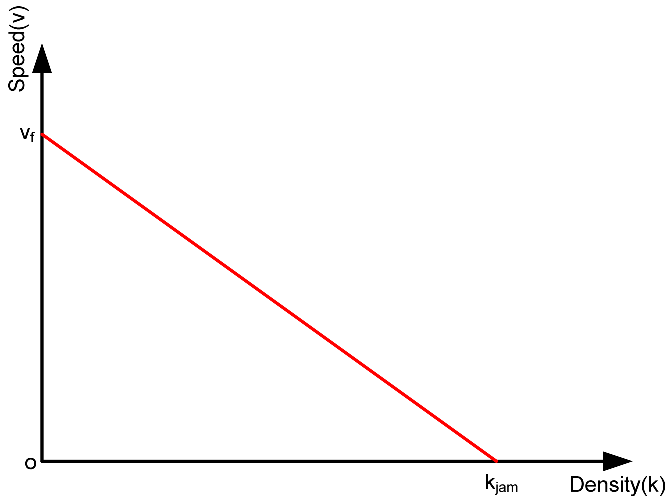


Figure 3-2 Greenshield speed-density relationship

Dynasmart-P uses two types of modified Greenshield models as the speed-density relationship for traffic propagation.

As shown in equation (3.3) and Figure 3-3, type one modified Greenshield is a dual-regime model in which constant free-flow speed is specified for the free-flow conditions (1st regime) and a modified Greenshield model is specified for congested-flow conditions (2nd regime) [30]. Given the density (concentration), inflows and outflows of the previous time-step, the current section's speed (V_i^t) can be calculated with the current density according to a speed-density relationship as follows:

$$V_i^t = \begin{cases} v_f & , \quad 0 \le k_i^t \le k_b \\ (v_{intercept} - v_{\min}) \times (1 - k_i^t / k_{jam})^{\alpha} + v_{\min} & , \quad k_b \le k_i^t \end{cases} \qquad (3.3)$$

Where,

V_i^t=mean speed on link i during the tth time step

v_f=free flow speed on link i

$v_{intercept}$=speed intercept

v_{min}=the minimum (jam) speed

k_{jam}=jam density

α=a parameter used to capture the sensitivity of speed to the density (the shape of the curve) and

k_b=break point density, the density k_i^t when $v_f = (v_{intercept} - v_{min}) \times (1 - k_i^t/k_{jam})^{\alpha} + v_{min}$

Example

Here is an example in which the above parameters are assigned with practical values.

The values are given in the following table:

v_f	$v_{intercept}$	v_{min}	k_{jam}	α
80km/h	100km/h	5km/h	150pc/km	5.37

Table 3-1 Assigned parameters of a practical example

With equation (3.3) and the parameters in Table 3-1, the speed-density relationship can be plotted as the blue-solid curve in Figure 3-3.

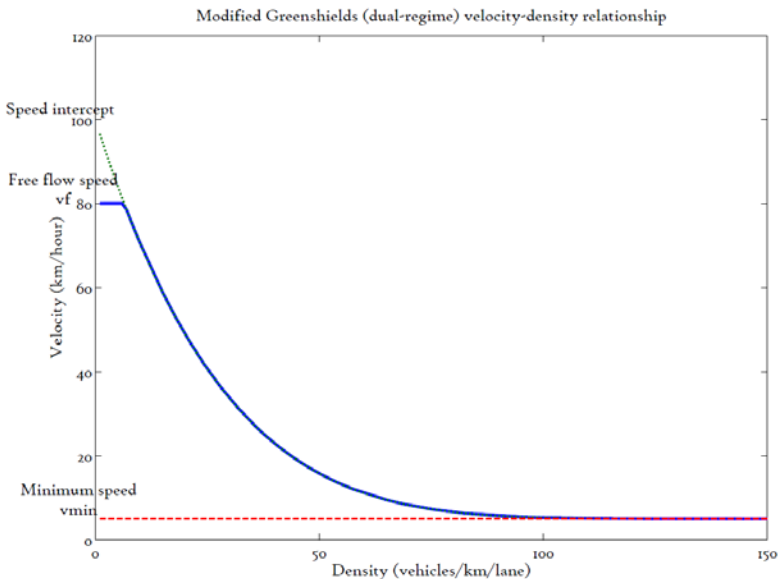


Figure 3-3 Type 1: modified Greenshield model, dual-regime model

As shown in equation (3.4) and Figure 3-4, type two modified Greenshield uses a single-regime to model traffic relations for both free- and congested-flow conditions and the modified Greenshield model is applicable for the whole regime.

$$v_i^t = (v_{intercept} - v_{\min}) \times (1 - k_i^t / k_{jam})^{\alpha} + v_{\min} \qquad (3.4)$$

All the terms in equation (3.4) have the same definitions as those in equation(3.3). These parameters are assigned with the same values as those in the previous example and the speed-density relationship for type two can be expressed as the blue curve in Figure 3-4.

In Dynasmart, dual-regime model is applied to freeways, whereas single-regime model is applied to arterials. The reason is that freeways have typically more capacity than arterials and can accommodate dense traffic (up to 2300 pc/hour/lane) at near free-flow speeds. In addition, arterials have signalized intersections, meaning that even if such a phenomenon of free-flow can occur on arterials, it may be short-lived.

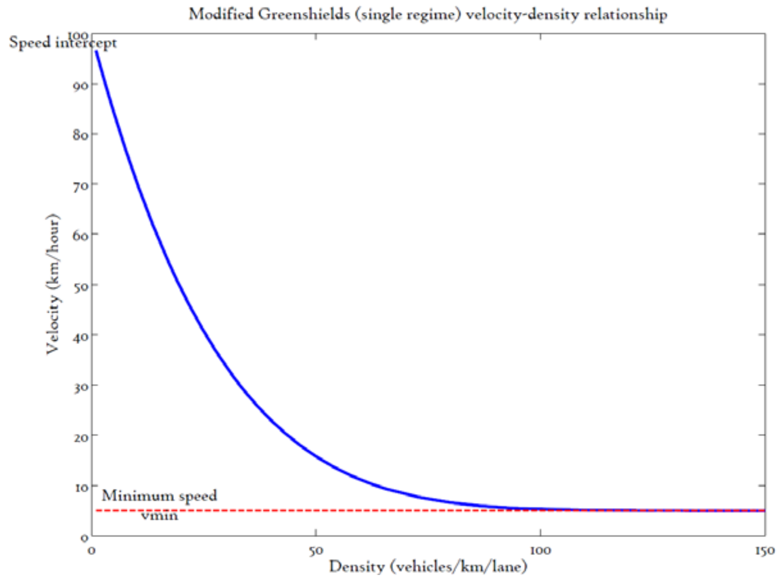


Figure 3-4 Type 2: modified Greenshield model, single-regime model

Hence, a slight increase of traffic would cause more deterioration in prevailing speed than in the case of freeways. Therefore, arterial traffic relations are better expressed using a single-regime model [36].

For both types of equilibrium speed equations, v_{min} exists as a pre-specified term corresponding to jam density. Hypothetically speaking, if the density increases to jam density and keeps increasing, the speed is always the minimum speed, which implies an increasing flow after the density is higher than jam density with the equilibrium flow equation q=Q(k). This could be seen as a problematic flaw of the traffic model in DSP. Its implication to CNM practice will be examined in section 6.2.

3.2.2 Mesoscopic traffic flow operation

Dynasmart-P simulates the vehicle movements according to pre-specified speed-density relations, moving vehicles at the prevailing local speeds in a group or individually. Since DSP simulates the microscopic characteristics of traffic, such as car following, platoon dispersion, etc., the author tentatively to address the details of its mesoscopic traffic flow operation, which are discussed in this section [37].

DSP is based on Macroparticle Simulation Model (MPSM) [38], which is the predecessor of DSP. Besides the common assumptions of most macroscopic traffic simulation models, MPSM is a macroscopic traffic simulation

model which models the traffic flow as groups or bunches, so-called macro particle instead of a compressible fluid, like most macroscopic traffic simulation models.

Building on the MPSM model, the initial concept of DYNASMART-P was proposed by [39]. A distinguished improvement from MPSM is that DSP tracks the movements of individual vehicles in a network and vehicle queues in links and another feature is that links in DSP do not have to be divided into smaller segments like MPSM.

How DSP track individual vehicle movement with mesoscopic traffic flow operation is discussed below. The basic structure of DSP is shown in Flow Chart 3-1, a conceptual structure, which uses main module to integrate and call for three other modules: path processor module, traffic simulation module and driver decision modelling module. The main module is in charge of organizing all modules and generating new cycles following constant time increment. Initialization in this module requires the input data of time-dependent OD matrices, which could be loaded either by OD demand table or generated by activity chain. Traffic simulation module is the core of DSP simulation, including link movement (used twice in each time step) and node transfer, which are introduced with more detailed operation steps below. The path processor is responsible for finding and building K-shortest path tree as well as storing and updating trip time for the tree. The driver decision modelling module is responsible for making initial path decision and link after link decision, then sending the decision back to the traffic simulation module.

The communications between these modules can be further explained step by step.

Step one:

Main module initializes the input OD and network data, such as link characteristics and control strategies,

Step two:

The traffic simulation module takes a time-dependent loading pattern and process the movement of vehicles on links with “link pass 1”, as well as the node transfers movement according to the defined control strategies with “node transfer”. Simulation results, such as densities and travelling times etc. are generated after “link pass 2” and output to the path processor.

Step three:

The driver decision modelling module provides all path and route decisions (with the K-shortest path tree built by path processor module) to the traffic simulation module during its processes of link pass and node transfer.

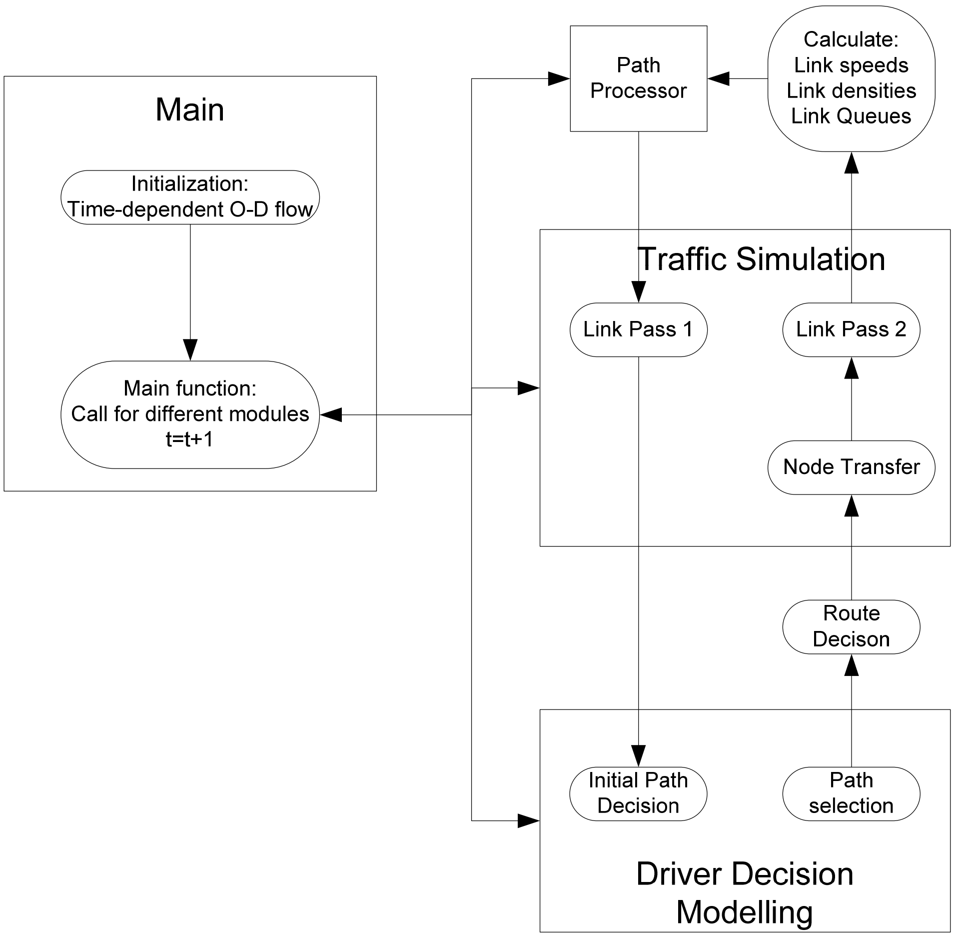
Step four:

The path processor module determines the route-level attributes (e.g. travel time) with the simulation results from the traffic simulation module, which are critical for the calculations of route switching (by path selection component of the driver decision modelling module) in user behaviour component of the driver decision modelling module.

Step five:

The path selection component gives route decision to the node transfer component in the traffic simulation module to direct vehicles to the desired outgoing link. The node transfer component will adjust the link movement by adjusting the number of vehicles allowed to switch to a certain link.

Up to here, DSP finished one simulation time step and the main module will decide whether to start another one (taking in new OD if necessary). To illustrate the operation mechanism, the aforementioned components (link pass and node transfer components) of the traffic simulation module are further discussed with queuing algorithms. The other two modules, namely the path processor module and the driver decision modelling module of DSP will be described in the following sections.



Flow Chart 3-1 Conceptual structure of Dynasmart-P

Dynasmart-P operates and simulates traffic network operation with a segmentalized network and discretized timing horizon, based on a method combining macroscopic theories and mesoscopic operations. The vehicles (particles) movement from upstream link to node, then to downstream link in the traffic simulation module and related queuing model in DSP are presented below [40].

Symbol list:

$k_{i,t}, k_{i,t+1}$: Mean densities in link i, during the t^{th} and $(t+1)^{th}$ time steps.

$q_{i,in}, q_{i,out}$: Inflow and outflow rates of link i, during the t^{th} time step

Δt: Simulation time interval.

l_i: Length of i^{th} link.

nol_i: Number of lanes of i^{th} link.

$NV_{i,t+1}$: Number of vehicles on link i during the $(t+1)^{th}$ time step.

$v_{i,t+1}$: Mean speed in link i, during the $(t+1)^{th}$ time step.

$d_{m,t+1}$: Distance of the vehicle m could travel during the $(t+1)^{th}$ time step.

$R_{i,m,t}, R_{i,m,t+1}$: Distance from vehicle m's current position to the downstream node of link i during the t^{th} and $(t+1)^{th}$ time steps.

$q_{i,t+1}$: Transfer flow from link i to link i+1 during the $(t+1)^{th}$ time step.

$VQ_{i,t}$: Number of vehicles in the queue list of link i during the t^{th} time step.

$VO_{i,t}$: Number of vehicles exit link i during the t^{th} time step.

Step1: density update

The discrete form of conservation equation (3.1) is formed in equation (3.5).

$$\frac{\Delta k(x,t)}{\Delta t} + \frac{\Delta q(x,t)}{\Delta x} = g(x,t) \tag{3.5}$$

Equation (3.5) can be further expressed as equation (3.6), during a simulation step.

$$\frac{k_{i,t+1} - k_{i,t}}{\Delta t} = \frac{q_{i,in} - q_{i,out}}{l_i \times nol_i} \tag{3.6}$$

The density in link i at the $(t+1)^{th}$ time step can be expressed as equation (3.7).

$$k_{i,t+1} = \frac{NV_{i,t+1}}{\Delta x} \tag{3.7}$$

Where,

$NV_{i,t+1} = k_{i,t} \times l_i \times nol_i + (q_{i,in} - q_{i,out}) \times \Delta T$

Step 2: Link speed calculation

Link speed can be calculated with updated density $k_{i,t+1}$ with equation (3.3) or equation (3.4).

Step 3: Vehicle location estimation

$$d_{m,t+1} = t \times v_{i,t+1} \tag{3.8}$$

If $R_{i,m,t} \geq d_{m,t+1}$, then

$$R_{i,m,t+1} = R_{i,m,t} - d_{m,t+1} \tag{3.9}$$

Else, add vehicle m to the queue list in link i.

Step4: Transfer flow from link i to link i+1

$$q_{i,t+1} = Min\left\{VQ_{i,t}, \left[k_j \times l_{i+1} \times nol_{i+1} - (NV_{i+1,t} - VO_{i+1,t})\right], k_j \times l_i \times nol_i\right\} \tag{3.10}$$

Step5: Update vehicle location and queue list

If the order of the vehicles in the queue list is no more than $q_{i,t+1}$, then

$$R'_{i+1,m,t+1} = [\Delta t - (R_{i,m,t} / v_{i,t+1})] \times v_{i+1,t+1} \tag{3.11}$$

Else,

$$R_{i,m,t+1} = 0 \tag{3.12}$$

The queue propagation in DSP will be further examined in section 6.2.

3.2.3 Route choice

As shown in Flow Chart 3-1, Dynasmart-P simulator makes route choice during the simulation with two modules: driver decision modelling and path processor. In this section, they are discussed separately. Since they provide different solutions to different classes of users, before discussing these two modules, the classifications of users and vehicles, MUC and MVC respectively, are introduced first.

MUC and MVC

1. Multiple User Classes

Based on the route selection behaviours, DSP categorizes vehicles into five user classes. Table 3-2 shows the multiple user classes in DSP and their basic descriptions.

User Class	User Class Name	Description
1	Unresponsive	Vehicles that follow their given paths and do not respond to en-route guidance devices such as VMS
2	System Optimal (SO)	Vehicles following paths with SO objective
3	User Equilibrium (UE)	Vehicles following paths with UE objective
4	En-route info	Vehicles that receive real-time en-route information via in-vehicle equipment, and are allowed to re-route at any intersection. Re-routing is based on the bounded rationality behaviour mechanism.
5	VMS-responsive	Vehicles that follow their given paths; however, they are capable of responding to real-time en-route information via external guidance devices such as VMS. Re-routing is possible at the VMS link.

Table 3-2 Classification of multiple user classes [36]

2. MVC

Based on the information availabilities and vehicle types, Dynasmart-P categorizes the vehicles into seven vehicle classes. They are non-equipped passenger car, non-equipped truck, non-equipped high occupancy passenger car, equipped passenger car, equipped truck, equipped high occupancy passenger car and bus. Because this multiple vehicle classification is not considered later in the case study, details of MVC can refer to the DSP user guide [30].

Driver decision modelling [36]

The driver decision modelling module basically has two functions. The first function is to decide and store the initial paths of vehicles, which are new-generated on a link at a certain time interval, before the calculation of the vehicles movement during the same time interval on the same link. The second function is link movement and node transfer. The simulator calculates the trip time to the destination for the vehicles on current path and compares to the previous k-shortest path. Then the simulator selects the route based on a "Bounded Rationality"

rule and returns to the main function with the number of the link to move to. It is assumed that the basic information available to the drivers include the travel times on alternative routes, for different information supply systems. In this case, the best route available will be brought to the drivers but they are not required to follow the suggested route. Thus behavioural rules determining drivers' decisions should be incorporated. Dynasmart-P has the option of using the "Bounded Rationality" rule in its route choice component, which means drivers look for gains only outside a threshold. Within which the results are satisfying and sufficing for them. This can be translated into the following route switching model:

$$\delta_j(k) = \begin{cases} 1 & ,if \quad TTC_j(k) - TTB_j(k) > \max(\eta_j \cdot TTC_j(k), \tau_j) \\ 0 & , \quad otherwise \end{cases} \tag{3.13}$$

Where, for vehicle j:

$\delta_j(k)$: 1, indicates a route switch; 0, no switch at node k.

$TTC_j(k)$: Trip time from node k to destination on current path.

$TTB_j(k)$: Trip time along the best path.

η_j: Relative indifference threshold.

τ_j: Minimum improvement needed for a switch.

The threshold level can reflect preferential indifference, perceptual factors, or aversion to switch and persistence. The term η_j decides users' responses to the supplied information and their propensity to switch. In Dynasmart-P, η_j is assumed to follow a triangular distribution, with a mean η and a range $\eta/2$. The minimum improvement τ_j is taken to be identical across a traffic network according to the defined values and should be calibrated with field experiments.

Alternatively，Dynasmart-P can also model route choice at a node according to a probabilistic discrete choice function, for example, according to the Logit form. As behavioural research improves user response models, these can be incorporated within the Dynasmart-P framework relatively easily because of its modularity and flexibility provided by the path processing capabilities.

Path processor [36]

With the link-level attributes from the simulator, the path processor component determines the route-level attributes used in the user behaviour component. For this purpose, a multiple-user-class k-shortest path algorithm with movement penalties is interfaced with the simulation model to calculate k different paths for every origin-destination (OD) pair. However, in order to improve the model's computational performance by cutting

the use of computation time and machine memory, the k-shortest paths are not updated every simulation time step, but only at pre-specified intervals. During the simulation, the travel times on k current paths are updated using the prevailing link travel times at each simulation time step, or every few steps to further reduce computational requirements. The path information is necessary for the following calculations:

1. Initial routes

At the beginning of trips, non-equipped drivers need to be assigned to initial routes. But the process for assigning initial routes is not universally agreed upon. In DSP, initial routes are modelled in the way of allocating drivers to the k-shortest paths according to a pre-specified rule. When DSP is used as a simulator in conjunction with an algorithmic search procedure, initial paths may be determined by the search. In practice, such assignments for some vehicles may also be available from historical information based on actual measurements.

2. Current path update

Current path update is the basis of driver path choice decisions at every node according to the user behaviour component module. In DSP, only current trip times are available to drivers. The current path information is used in equipped vehicles as well as in Variable Message Signs (VMS) route control module. A real-time k-shortest path routine has also been developed and could be incorporated within Dynasmart-P to simulate anticipatory information supply strategies. Such "anticipatory" strategies are now provided with the system optimal, user equilibrium or multiple user class assignment algorithms. Additional anticipatory strategies with predicted real-time trip times can also be easily implemented if a data fusion and prediction function is provided (in separate module).

3.2.4 Freeway dynamic traffic management

The following features are related for simulating coordinated network management using ITS control measures in the case study. In this section, the network operations in DSP will be introduced by discussing these features. Table 3-3 is a list of the basic traffic control elements used in DSP. The major element for surface street system is signal control and the major elements for freeway system are ramp metering and variable message signs (VMS). These elements are addressed in detail hereafter.

	Surface Street	Freeway System
I. Control Types	a. No Control	a. Ramp control
	b. Yield Control	b. Variable message signs

	c. Stop signs	c. HOV
	d. Signal Control	
II. Geometric Configurations	a. Saturation Flow Rate	a. Number of lanes
	b. Number of Lanes	b. Capacity
	c. Number of Approaches	c. HOV lanes
III. Measure of Effectiveness	a. Average Speed	a. Average Speed
	b. Average Travel Time	b. Average Density
	c. Average Delay	c. Average Ramp Queue Length

Table 3-3 Traffic Control Strategies in Dynasmart-P [30]

In this thesis, only the coordination of dynamic traffic management controls on freeway is considered. The most frequently used control elements for freeway system control are ramp metering and variable message signs (VMS). Freeway controls are normally categorized as capacity management control and demand control. Capacity control is aiming to maximize throughput and keep a certain level of service, for example, ramp control and variable speed control. Two elements, ramp control and variable message signs (VMS), are implemented for coordination purpose on freeway in the case study. It is worth mentioning that traffic management with different types of VMS can as well be used for surface street traffic control.

Ramp metering control

Ramps are designed to limit the number of vehicles entering or exiting a freeway in order to keep the freeway or the connecting arterials within the capacity limit. Only entrance ramp controls are modelled in DSP because exit ramp controls are seldom used and not in accordance to the situation of the case study. DSP has three types of entrance ramp control models: closure, ramp metering and traffic-responsive metering.

Closure

Drivers need to select alternative routes to their destinations when a ramp is closed. For equipped vehicles, they can make a decision to the alternative route before the closed ramp. For un-equipped vehicles, they can only make a decision when they reach the closed ramp. Nowadays, more and more VMS are applied to arterial streets

and freeways at the decision points upstream of the closure ramp. Therefore, people can be informed with the ramp closure and normally follow their second best route to the destination. In Dynasmart-P, a flexible way diverting the non-equipped vehicles allows users to define a k-th best path number or to randomly choose a path from database.

Pre-set ramp metering

In pre-set ramp metering, a fixed ramp rate or variable ramp rate is defined to limit the number of vehicles joining the freeway. This ramp rate is determined by the capacity calculations during a specified time period. Because it is not event-responsible, it is only effective when dealing with recurrent traffic congestion.

Traffic-responsive ramp metering

Traffic-responsive metering is modelled according to the flow conditions during the metering period. ALINEA [41] is implemented in Dynasmart-P. ALINEA is a local feedback control law for on-ramp metering and Figure 3-5 shows the principle of the feedback.

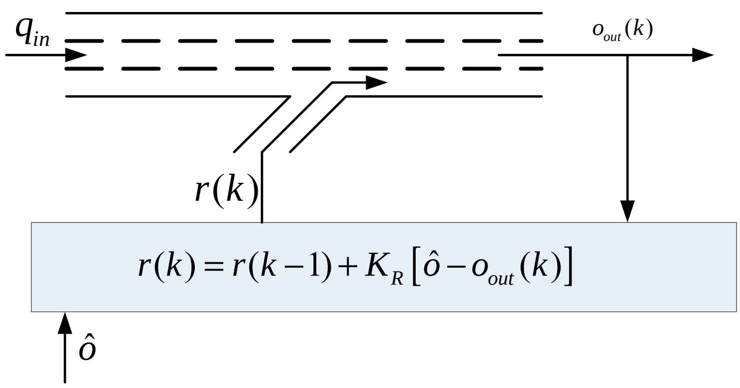


Figure 3-5 ALINEA: a local feedback control law for on-ramp metering

The basic feedback function is:

$$r(k) = r(k-1) + K_R\left[\hat{o} - o_{out}(k)\right] \tag{3.14}$$

Where,

$r(k)$ and $r(k-1)$: the ramp flow at kth and (k-1)th simulation time interval respectively.

$\hat{o}$: A set value for downstream occupancy. Default value is 0.2 in Dynasmart-P.

K_R: A regulator parameter. 70 vehicle/ hour give good results in real-life experiments.

$o_{out}(k)$: Downstream occupancy at kth time interval. This term can be defined with the equation as follows:

$$o_{out}(k) = \left(\sum_{i=1}^{N(k)} t_i \right) \Bigg/ T \tag{3.15}$$

Where,

T is the total observation period.

t_i is the time occupied by vehicle i, which can be defined as follows:

$$t_i = L_i / v_i \tag{3.16}$$

Where,

L_i is the length of the vehicle i.

v_i is the velocity of the vehicle i.

$N(k)$ is the total number of vehicles passing the observation point during the kth observation period. Therefore, $N(k)$ can be calculated with equation:

$$N(k) = \left[r(k-1) + q_{in}(k-1) \right] \times T \tag{3.17}$$

Assuming the traffic flow has a constant speed v_f, and all the vehicles have the same length, L, then equation (3.17) can be simplified as follows:

$$o_{out}(k) = \frac{\left[r(k-1) + q_{in}(k-1) \right] \times L}{v} \tag{3.18}$$

Therefore, equation (3.18) now can also be expressed as:

$$r(k) = r(k-1) + K_R \left[\hat{o} - \frac{\left[r(k-1) + q_{in}(k-1) \right] \times L}{v} \right] \tag{3.19}$$

ALINEA has a certain advantage compared with demand-capacity strategy. In demand-capacity strategy, the ramp flow is calibrated only when the downstream occupancy exceeds a certain threshold value, which makes the control rough. In contrast, equation (3.14) shows that ALINEA reacts more smoothly to a small difference between the real downstream flow at kth interval and the desired value, which helps solve congestion by stabilizing the traffic flow at high flow rate.

Example

Here an example is given with the mathematical implementation of ALINEA with Matlab. One assumption is that there is no HOV vehicle in the simulation and all the vehicles have an identical length and velocity. The parameters used in the simulation have the same meaning as in equation (3.19).

K_R	ô	q_{in}	L	v	$r(o)$
70 pc/h	0.2	1000 pc/h	5 m	80 km/h	0 pc/h

Table 3-4 the values of the parameters used in the simulation

The difference between the measured (simulated) downstream occupancy $o_{out}(k)$, and the desired downstream occupancy ô is used to evaluate the algorithm. The simulation result is shown in Figure 3-6. The residual error between $o_{out}(k)$ and ô is approaching zero with the increase of simulation step, which means given enough time, $o_{out}(k)$ will reach the desired value ô. The error can settle down because of the 1st order feedback control theory behind ALINEA. The settling speed in this example is a little slow because the gain factor K_R is set low. Increasing K_R can increase the settling speed of this residual error; but, if K_R is set too large, there will be oscillation at the end. Some discussions on the selection criterion of K_R are given in chapter 7.

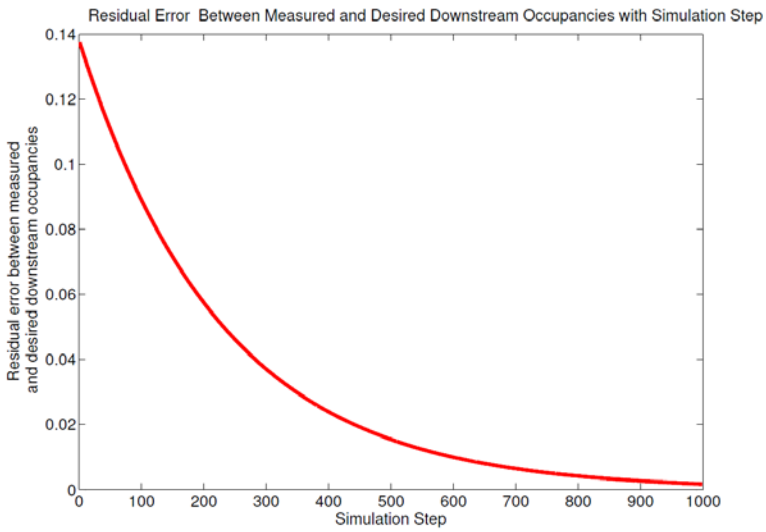


Figure 3-6 Residual error, difference between measured and desired downstream occupancies rate

Variable Message Signs

VMS is a dynamic way to provide real-time traffic information to the on-road vehicles, especially to the un-equipped vehicles, normally presented on a LED board on the roadside or gantry. They can provide current traffic conditions such as congestions, accidents and closure of entrance or exit. Meanwhile, on some VMS

information board, alternative route, advisory speed and predicted travel time can be given. However, vehicle compliancy to VMS is different from the ramp metering control and HOV control. Drivers are not required to follow all the information from VMS. Therefore, in DSP, the VMS module should be used with consideration of driver behaviour. The VMS module in DSP includes four types of VMS: speed advisory, mandatory and optional detour (route advisory) and congestion warning. Most of them will be applied in the simulations in chapter 4 and chapter 5.

Speed advisory

Speed advisory VMS informs users to increase or decrease speed by a certain percentage when below or above a certain threshold.

Mandatory detour

Mandatory detour VMS informs vehicles of lane closures or congestions, and compels all vehicles to follow user-specified sub-path in the vicinity.

Congestion warning

Congestion warning is used to warn vehicles about the traffic congestion on the link. In Dynasmart-P, percentage of VMS responsive vehicles can be defined on how to react to congestion warning.

Optional detour

Similar to the mandatory detour VMS, optional detour VMS also informs vehicles about traffic congestions. However, optional detour gives vehicles the option to follow the detour path or keep original path, based on the bounded rational decision rule.

Depends on the VMS types and VMS pre-emption mode, different user classes have different responsive behaviours to VMS control. These behaviours are related to the analysis in the following chapters and therefore they are given in Table 3-5.

User Class	VMS Type 1 Speed Advisory	VMS Type 2 Mandatory Detour	VMS Type 3 Congestion Warning	VMS Type 4 Optional Detour
VMS Pre-emption Mode is Off (Default)				
1–non responsive	Responds	Responds	Do not respond	Do not respond

2–system optimal	Responds	Do not respond	Do not respond	Do not respond
3–user equilibrium	Responds	Do not respond	Do not respond	Do not respond
4–enroute info	Responds	Responds	Do not respond	Do not respond
5–vms responsive	Responds	Responds	Responds	Responds
VMS Pre-emption Mode is On				
1–non responsive	Responds	Responds	Do not respond	Do not respond
2–system optimal	Responds	Do not respond	Do not respond	Do not respond
3–user equilibrium	Responds	Do not respond	Do not respond	Do not respond
4–enroute info	Responds	Responds	Responds	Responds
5–vms responsive	Responds	Responds	Responds	Responds

Table 3-5 User classes and their response to various VMS information

3.2.5 Miscellaneous

Incident modelling

Incident modelling in Dynasmart-P includes the modelling of the events such as accidents, bad weather or closure. Users can specify the incident link, time period and severity. Incident can reduce the traffic flow by a great extent or in the worst case, make it zero. In this case, all the vehicles are forbidden to drive on the link with incident and will be diverted with alternative routes when reaching the upstream node of the link. For non-equipped vehicles, they can only be diverted at the incident point, except when VMS is available, in which case they can choose to divert before the incident point. All these calculations are based on the information of the incident specified by the users.

3.3 Applicability of Dynasmart-P on CNM

From the introduction of DSP in section 3.2, it seems that Dynasmart-P can reach a balance between capturing

the traffic complexities, provides essential capabilities for traffic control measures and at the same time, handling the study of large-scale networks. The unique idea of combining macroscopic model with mesoscopic operations gives us hope of successfully finding an appropriate modelling tool. But by taking a second look, the various capabilities of DSP mean that inevitable trade-offs have to be made as any state-of-the-art traffic simulation tool. The advantages of DSP are discussed in section 3.3.1, leading a preliminary decision of its applicability to the case study. The limitation and possible implications of these limitations are roughly predicted in section 3.3.2

3.3.1 Advantages

From the tool capabilities approach, DSP can cover large-scale network, incorporate or emulate the effects of various ITS components (including traffic controls such signalization, ramp metering and many kinds of VMS controls), model various traveller responses and trace individual vehicles trajectories.

From the representation of traffic flow approach, DSP allows a richer representation of traveller behaviour decisions, traffic processes with time-varying properties, and a more complete representation of the network elements, compared to most static tools and some macroscopic tools.

From the simulation-time-efficiency approach, DSP has much higher computation time efficiency than some microscopic simulation software since DSP is based on macroscopic traffic flow model, especially for large-scale network.

3.3.2 Limitations and implications

DSP lacks the ability of automatic coordination between control strategies. In fact, there is no coordination of any kind. Even the signalized intersections can hardly be optimized in DSP, external optimization of signalized intersections are required. This major limitation means that users can only manually set new control strategies from a knowledge-based approach. This limitation renders the validity and sufficiency for the study of coordinated network management, which would lead to serious implications to the CNM effect study. This is also another motive of creating enhancement solution for CNM study in part three of this thesis project.

DSP bases on macroscopic traffic model. Instead of q-k relationship, DSP uses transfer flow at node to predict traffic characteristics with the discretized form of conservation equation. One can speculate that without q-k relationship, the traffic flow on link may not be controlled properly, thus deviate from real traffic condition. And the using link-to-link transfer flow gives us the impression that the results are related and sensitive to the link dynamics. This speculation can also rise from modelling incident by reducing link capacity, yet in fact, computationally reducing link length in DSP.

DSP moves vehicles on links according to a modified Greenshield type speed-density relationship, in the equation, a minimal speed is added to prevent the simulation from shutting down. But this minimum value of speed doesn't exist in real traffic situation. Combining the pre-specified minimum speed with q=kv, one could guess that after density reaches jam density, flow rate will still rise along increasing density. This leads to an eccentric q-k graph which could be problematic for assessing CNM on the case study.

DSP seems to suffer from drawbacks of realism and consistency, which is exacerbated by the implicit and poor representation of queue propagation, especially around bottlenecks. Since the control objectives of the case study include solving bottlenecks with CNM. The results of case study can lose their informative value.

DSP defines many types of user classes. However, the key question remains whether different user classes can be classified in terms of information availability, which is used in DSP. This classification could mean that non-equipped vehicles will keep using the original path even though the downstream links congestion can be observed in sight. This is fundamentally different from the behaviours of drivers, especially drivers without information (unequipped). Since route information and route advice are used in the case study. This limitation may leads to possible overestimation or evenly possible to underestimation of some VMS control measures.

In conclusion, on a certain level, DSP could be a solid simulation tool in some cases considering the fact that there are quite a few cases using DSP, including the case study network in this thesis. But, it could be troublesome for evaluating the coordination effects of ramp metering, VMS and other traffic control strategies on solving traffic bottlenecks.

These implications will be further discussed in chapter 6.2 with simulation results from the case study.

3.4 Conclusion

The goal of this chapter is to develop a feasible assessment methodology framework for modelling and ex-ante evaluation of CNM. The proposed assessment methodology provides a system with methodical process of modelling and ex-ante evaluation of CNM, from setting objectives and principles to modelling, ex-ante evaluating and organizing stepwise predictive control operation. Modelling tool is an auxiliary instrument for CNM modelling and ex-ante evaluation. Dynasmart-P was introduced in this chapter as the modelling tool for the case study. But, from the introduction, we can speculate that the performance of this modelling tool will affect the assessment methodology in the aspects of modelling and ex-ante evaluation. An evaluation of this proposed assessment methodology framework is necessary. After an illustration of the assessment methodology using the case study, chapter 6 gives an evaluation of the proposed assessment methodology framework, mainly based on the case study results.

4 Case study design

The assessment methodology framework in chapter 3 is applied to a case study in this chapter. Based on the description and objectives of the case study network, several control designs to recurrent congestion scenario and non-recurrent congestion scenario are introduced onto the case study network using Dynasmart-P as the simulation model. One purpose of these experiments is to assess the impact of CNM on further solving or relieving recurrent and non-recurrent traffic congestions. The other purpose is to test the proposed assessment methodology framework in order to determine the strengths and weaknesses of the assessment methodology.

According to Figure 3-1, the basic input (network description in section 4.1), control design input (ITS control measures deployment in section 4.2, control designs for two scenario in section 4.3), frame of reference and chosen MOE (measures of effectiveness for modelling in section 4.4) of the case study are described in this chapter. In the next chapter, the simulation results of all experiments in the case study will be presented.

4.1 Network description

This section describes the traffic network of the case study. Firstly, the background and network layout of the case study is introduced from a broad sense. Then, the control objectives of the case study are determined. Traffic flow characteristics are further analysed from a macroscopic approach.

Background

The Netherlands is a small, densely populated country criss-crossed by major rivers and waterways, which is particularly the case for the city of Amsterdam [42]. Circulated and criss-crossed by waterways, the city of Amsterdam has very limited space for road networks. Focusing on multi spatial use and integrated functions, the road network of Amsterdam has been developed over several decades. The opening of the Amsterdam ring road in September, 1990 established the short term effects of the removal of a severe bottleneck in the road network around Amsterdam without inducing too much extra traffic demand [43]. But, the network planning and design is an iterative process. The roads constructed according to the transportation and spatial situations then might not be the most appropriate from the current point of view [44]. Large shifts in time of travel as well as route choice were reported after the opening of Amsterdam ring road [45]. Alterations and adjustments to infrastructures have to be made accordingly. As discussed in chapter 2.3.2, the Netherlands has been and intended to continue applying dynamic traffic management in order to improve road network accessibility and utilizing infrastructure capability, especially in the Amsterdam region. The case study is built on the background and belongs to a part of the state-of-the-art CNM practice, the PPA project. Experiences from the PPA project will serve as a prototype to promote proactive CNM on several other networks in the Netherlands, such as Utrecht, The Hague,

Rotterdam, Eindhoven, Arnhem and Nijmegen to relieve the pressures of these pivot transport hubs.

The research network of the case study is the sub-networks 3 and 4 of Amsterdam region, as shown earlier in Figure 2-2. The desired traffic situation of these two sub-networks is optimizing the network throughput and improving the traffic flows on mainline freeway and their connections as much as possible, respecting road functions and priorities. This is due to the relative importance of a link in relation to the accessibility of the network, which is shown in Figure 4-1.

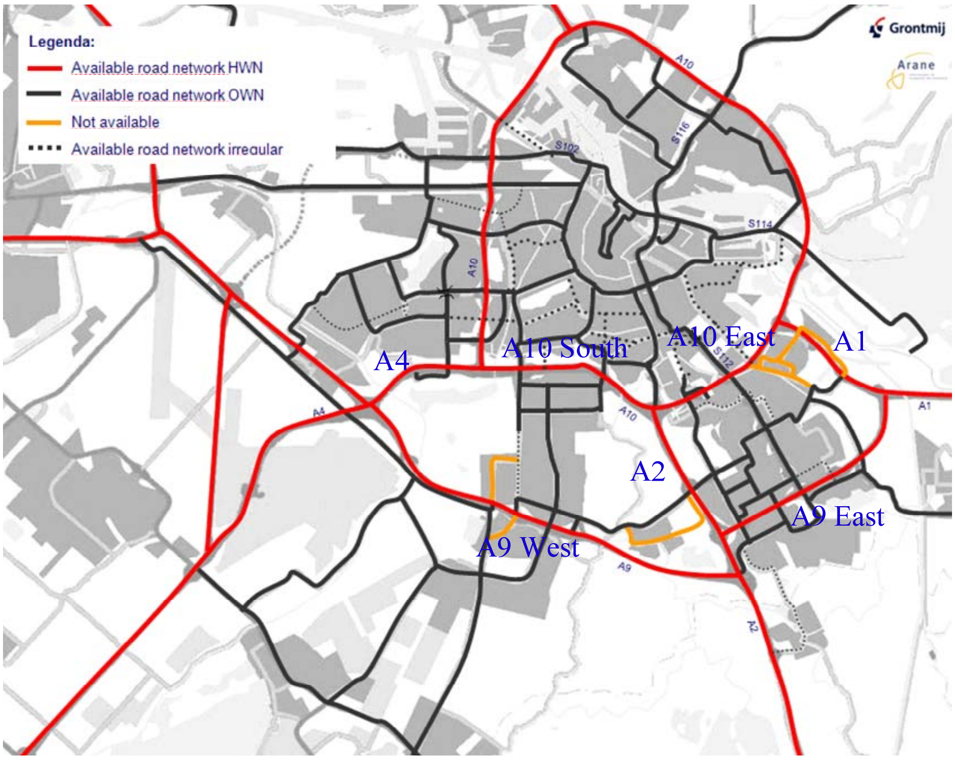


Figure 4-1 Network priority map

From Figure 4-1, the case study area is surrounded by the A1, A2, A4, A9 east, A9 west, A10 east and A10 south freeways. These freeways are crucial to mainlines and connections of the network. For years, many researches and practices are pinpointed in this area. The A2 freeway between Amsterdam and Utrecht has been widened from four-lane two-way road to ten-lane two-way road. A local –express method is applied on A2 near Utrecht, which intends to minimize lane change manoeuvres by assigning three lanes as main lanes for express traffic and two parallel lanes for local (regional) traffic. This method mitigates the drawbacks of complicated weaving basket road construction. And it also avoids the static characteristics of road infrastructure which cannot adjust to dynamic traffic volumes. The functions and priorities of these road sections and the corresponding decisions regarding the function and deployment method of the control measures are further discussed in this section and in section 4.2.

Objectives

The main objectives of the case study are:

First, study the effect of CNM on the case study and gain insights about the effectiveness and sensitivity of coordination between control measures comparing to isolated/local control measures.

Second, by applying the proposed assessment methodology, determine and strengths and weaknesses of the assessment methodology, taking the implications from modelling-based approach, predictive operation-based approach into account.

The specific control objectives describe the goals and the boundaries for modelling and ex-ante evaluation of CNM on the case study. Based on the current state of the case study network, the following control objectives are formed:

1. Develop effective DTM, CTM and CNM designs to improve both recurrent congestion scenario and non-recurrent congestion scenario on the case study network, while keeping the upper level control boundary of no performance deterioration on the network level.
2. Prevent bottlenecks or postpone the onset of bottlenecks layer by layer in order to avoid capacity drop, from locations, in string, in sub network and finally in network with effective designs.
3. Optimize each design within its layer with flexibility. Find out the effect of different control measures and make predictive control operation decision before going up to a higher layer of coordination.
4. Find out which control measures are effective and which are not effective under what conditions, find out if the results are in accordance with the predictions and find out the side effect or disturbances brought by the control measures.
5. Find out which designs are the most effective. Answer the questions of whether coordination designs are superior in terms of delaying the onset of congestion, improving mainline throughput, reducing spill-backs and optimal distributing traffic in both non-recurrent and recurrent congestion scenarios.

Traffic characteristics

Road characteristics

The case study network covers about 55 km^2. Since there are quite a few practice of traffic control measures in this area, as discussed in section 2.3.2. This area already includes over 16 ramp-metering installations and 9 additional ramp-metering installations are planning to undergo implementation. This area also includes over 30 variable message signs. Two existing traffic control centres, one for the freeway network and one for the urban

network, are responsible of monitoring the network and distributing traffic information [1].

Figure 4-2 shows the functions of the roads on the available Amsterdam network [4]. Focusing on the case study area and combining the network priority map of Figure 4-1, the priorities and functions of the roads are explained as follows.

A10 ring road has the highest priority because the first function of A10 can be made to an analogy of a roundabout function. Traffic on the roundabout needs to be kept from congestion as long as possible, so that traffic on the connecting roads (axis) of the roundabout doesn't stop. Another function of A10 is the distribution function [4]. Traffic flows from the city out are distributed into radian freeways such as A1, A2 and A4 to the south or A8 to the north.

The same reasons can be applied to A9 west and A9 east. But due to the "half" and outer ring characteristics, A9 ranks the second in priority.

Urban road such as S112 has a higher priority than the other urban roads such as S108, S109, S111 and S113 because it bears some important diversion or choice points and crosses with three rings, S100, A10 and A9 from inside to outside.

Freeway sections such as A1, A2 and A4, have lower priorities because they could have the function of buffer in the case study.

These road functions and priorities are essential for decision making in traffic management, especially in the case of coordinated traffic controls of a whole network. They are adopted into the decision system module of the assessment methodology in Figure 3-1. In the case study, control measures deployment in section 4.2 and control designs in section 4.3 are based on the road characteristics discussed here. For example, considering CNM designs with variable speed limit control, a plan of implementation details are made beforehand and shown in Table 4-1 [4].

		maximum snelheid	norm	prioriteit 1	prioriteit 2	prioriteit 3	prioriteit 4	prioriteit 5
HWN	Freeway	100 120	1,5	65	60	55		
HWN	Urban belt-way	100	2,0	50	45	40		
OWN	Urban belt-way	50	2,0	25	20	15		
OWN	Regional connecting road	80	1,5			50	45	40
OWN	Urban axis	70	2,0		35	30	25	25
OWN	Urban axis	50	2,0		25	20	15	15

streefsnelheid bijgestelde snelheid

Table 4-1 Variable speed limit according to road function and priority

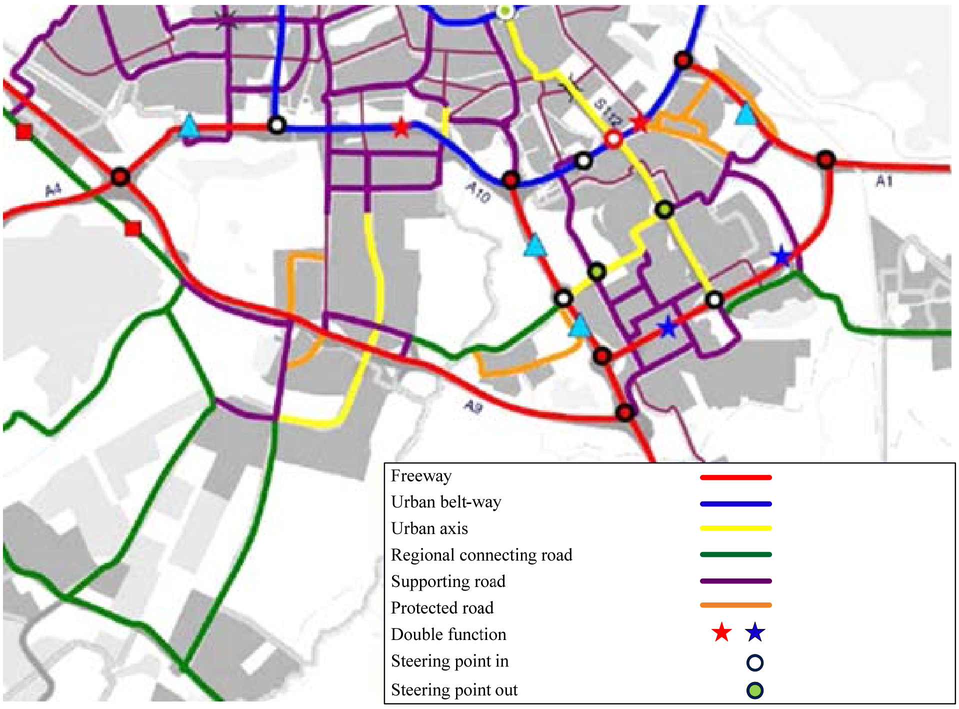


Figure 4-2 Function map of the research area in the case study

A possible way to set the detailed priorities of the road sections is shown in Figure 4-3 [4]. Combining Table 4-1, Figure 4-2 and Figure 4-3, variable speed limit parameters for the case study can be summarized for implementation of dynamic speed control, which is shown in Table 4-2. It is important to know that Table 4-2 provides an example. Adjustments could be made before these parameters are used due to reasons such as changes of traffic characteristics, control objectives, etc.

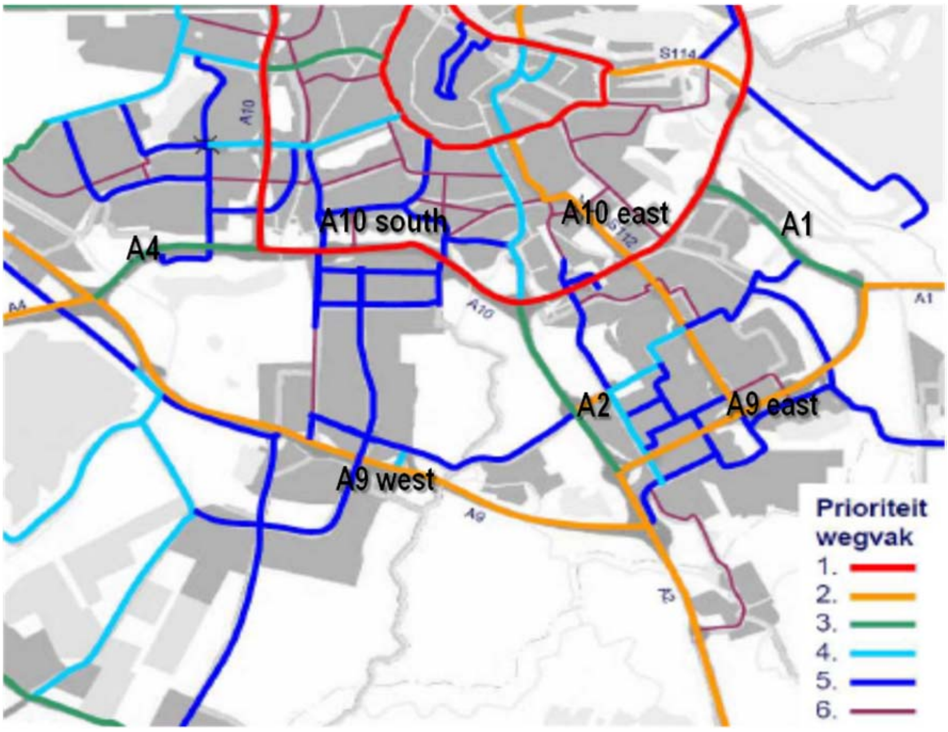


Figure 4-3 Priority map of the research area in the case study

Later in section 4.2, Table 4-2 is used for the parameters of dynamic speed limit control (see Appendix I) and also in chapter 5 for the simulations of the case study.

Road sections	function	Maximum Speed (km/hour)	Priority	Advisory Speed (km/hour)
A10 south	Urban Belt-way	100	1	50
A10 east	Urban Belt-way	100	1	50
A9 west	Freeway	100 or 120	2	60
A9 east	Freeway	100 or 120	2	60
S112	Urban axis	70	2	35
A1	Freeway	100 or 120	3	55
A2	Freeway	100 or 120	3	55
A4	Freeway	100 or 120	3	55
S108	Supporting road	50	5	15
S109	Supporting road	50	5	15
S111	Supporting road	50	5	15

Table 4-2 Summary of dynamic speed limit in the case study

Simulation Networks build-up

The basic network of this case study is converted from the same research area in Questor-Dynasmart of a previous study by DHV and Rijkswaterstaat [46]. Figure 4-4 shows the basic network feature of the case study in DSP. The network is composed of links and nodes. Together there are 948 nodes, 1678 links (usually two links are built between a pair of nodes to simulate two-way traffic) and 102 zones on current build-up. Each link can represent corresponding road characteristics by identifying its road type, length, numbers of lanes, capacities, numbers of approaches, saturation flow rate, etc. The freeways are highlighted in blue; the others links are different types of urban roads. More details about the simulation network build-up and the calibration will be discussed in section 6.2.2.

Figure 4-4 Research area build-up in DYNASMART-P

Traffic demand and evening peak period

Based on the traffic flows obtained from NRM Randstad, the traffic demand is an autonomous traffic demand generated and calibrated for the year 2020. For 102 zones in the case study, the total number of vehicles are 318511, of which the MUC class percentages are 14.79% for non-responsive, 15.23% for en-route information and 69.97% for VMS responsive (0% for UE and SO classes, definitions of each user class are introduced in section 3.2.3). The vehicle type percentages are 95.6% for personal car and 4.4% for truck [46].

The simulation period is the evening peak hours from 15:00 till 19:00 (workday). This evening peak usually undertakes the busiest traffic, especially traffic from inside to outside of the city. Comparing to the current evening peak traffic situation, the traffic demand is higher while the difference of demand distribution for trips is relatively small since it is vague which directions will have demand spurs [46]. The simulation starts at 15:00, in the attempt to prepare and “warm up” traffic. The 240 minutes planning horizon follows a fix value of six

seconds simulation interval, which means positions of vehicles in the network are updated every six seconds, so are the system states.

4.2 ITS control measures deployment

The current situation of the network is described in the previous section and a desired traffic situation is pictured. In order to find solutions for bottlenecks, the corresponding ITS control measures deployment is studied in this section.

In the proof of concept of the PPA project [4], infrastructure adjustments and ITS control measures are the two major categories of traffic managements. Infrastructure adjustment is mostly a static measure, which is basically aimed at solving recurrent congestion. Infrastructure adjustment will not be implemented in this case study due to the technical reason of the modelling tool (macroscopic software, not suitable for investigating most of the infrastructure adjustments). Dynamic traffic management using ITS control measures and their combinations are implementated here to solve recurrent and non-recurrent congestion scenarios and to find out the effect of CNM. In the case study, two categories of ITS control measures, ramp metering and VMS (including dynamic speed limit and dynamic route information / advice/ guidance), are implemented seperately and combined.

Local ramp metering (LRM)

Deployment area

On-ramp metering is normally deployed on the ramp connected to a potentially congested freeway.

Objective and function

The objective of on-ramp metering is to limit the traffic flow from ramp to freeway so that onset of congestion on the freeway is solved or delayed. On one hand, this function reduces the traffic load on the congested freeway. On the other hand, the traffic on freeway is less interrupted by merging behaviour from on-ramp.

Deployment method

There are two types of on-ramp metering: pre-set ramp metering and traffic-responsive ramp metering. Pre-set ramp metering works with a pre-set fixed or variable ramp rate therefore is not suitable for coordination between ITS controls. Traffic-responsive ramp metering can adjust the ramp rate according to the real-time traffic conditions, which means more adaptable and fast response to the congestion in time. There are two popular traffic- responsive ramp metering strategies: demand-capacity and ALINEA. Demand-capacity strategy is based on a feed-forward system and stability can be easily guaranteed. But demand-capacity strategy dynamically determines the ramp rate with the disturbance on freeway and may lead to insufficient performance [7]. ALINEA

is based on a first order feed-back control system, which often results in a better performance. In addition, demand-capacity can only react on measurable disturbances on freeway but ALINEA can also react on un-measurable disturbances if the effects of the disturbances are observable through the system output, e.g. the occupancy rate at the downstream of the ramp. In this thesis project, ALINEA based local ramp metering control is implemented in the case study. The principle of ALINEA can be referred to section 3.2.4.

Advantage

The traffic flow from ramp to the congested freeway is limited and freeway throughput is improved by shifting or delaying congestions with utilizing spare spaces of the on-ramp. Meanwhile, the traffic merging behaviour is regulated, which improves the traffic safety. In addition, ramp metering makes freeway a less attractive option than urban street to short-distance travellers, which could affect the demand characteristics on the long run and further reduce the pressure to the recurrent congestion on freeway.

Disadvantage

In case of high amount of traffic volumes on both freeway and ramp, congestion shifted from freeway to the on-ramp could spill back to the urban road and upstream intersections causing gridlocks.

Variable speed limit (VS)

Deployment area

Variable speed limit (dynamic speed limit) is normally deployed along a freeway where is easily congested recurrently during peak hours. It conducts high volumes of traffic with a target speed, preventing breakdowns and capacity drops of the freeway.

Objective

Variable speed limit, with reasonable speed limitation, is usually deployed to alleviate traffic congestions during rush hours by preventing capacity drops or traffic breakdowns on the freeway.

Deployment method

Two approaches are normally used to implement variable speed limit, i.e. 'flat speed limits' and model predictive control approach (MPC). The flat speed limits restrict the vehicles to travel with the same (dynamic) speed over a certain freeway stretch with high traffic demand. With speed limits, the faster vehicles slow down thus the disturbances, such as overtaking and lane changing, could be less. Fewer disturbances help to improve the traffic flow over the freeway stretch, thus avoid traffic breakdowns and reduce accidents. The MPC approach uses an MPC controller for the dynamic speed limits, aiming to remove shockwave congestions. The basic

principles of MPC approach is that limiting the inflow to the shockwave may resolve the shockwave-introduced traffic congestion, and that eliminating a shockwave restores the freeway capacity. For simplicity, the flat speed limit is applied in the case study. The specific speed limit can be referred to Table 4-2 in section 4.1. Implementation of variable speed limit in the case study using DSP simulations can refer to section 3.2.4 speed advisory VMS and Appendix I.

Advantage

Variable speed limit can prevent or delay traffic breakdowns on easily congested freeway stretch and also help to avoid traffic accidents.

Disadvantage

Both flat speed limit approach and MPC approach are incomplete because there may be other causes for traffic congestions on saturated freeways besides speed differences, and there may be other type of traffic congestions besides shockwave congestion. Balancing between the delays cause by the speed limits themselves and the possible traffic breakdowns is difficult. Besides, the traffic flow instability when it is close to road capacity is an intrinsic property of the traffic process itself and cannot be stabilized by reducing the disturbances. Disappointingly, field experiments in the Netherlands show that no significant improvement of measured traffic volume [47], even flat speed limits results in a more stable and safer traffic flow [7].

Route information VMS (RI)

Deployment area

Route information is normally deployed upstream to the road where high volumes of traffic are conducted and traffic congestion is easily formed. Specifically, the route information VMS should be deployed on a diversion point where vehicles can be informed with traffic congestion ahead so that they can choose an alternative route.

Objective

Route information is used to provide warning to vehicles that a certain road is congested in the attempt to divert inflow.

Deployment method

There is a lack of reliable algorithms for route information control measure. For example, the congestion warning VMS is usually engaged when the concentration of downstream link reaches the maximum concentration (traffic congestion happens). In the study case, the congestion warning is deployed according to the existing knowledge of the recurrent traffic conditions. Implementation of congestion warnings in the case

study using DSP simulations can refer to section 3.2.4 congestion warning VMS.

Advantage

It can help to relieve the traffic congestion by diverting in-coming vehicles to alternative routes. Thus the traffic could be redistributed on network level.

Disadvantage

Route information is a relatively "soft" effect and driver compliance rate is difficult to predict. In addition, if only warning of congestion is provided to the drivers, it does not provide any solutions. The diversion function of route information is thus less effective. It also depends on how messages are interpreted by road users. For example, different drivers have different interpretations of the word "congestion", so congestion warnings might be better given in the form of average delay and it would be better to provide alternative routes since most road users are unfamiliar or uninformed about the area.

Route advice VMS (RA)

Deployment area

Route advice VMS is also deployed upstream to the road where high volumes of traffic are conducted and traffic congestion is easily formed. The route advice VMS should be deployed on a diversion point where vehicles can be informed with traffic congestion and alternative routes.

Objective

On one hand, route advice is used to provide alternatives route to vehicles so that they can avoid the traffic congestions. On the other hand, by diverting vehicles to alternative routes, the traffic demand can be better distributed on the network.

Deployment method

The route advice VMS is activated when the downstream road reaches the maximum concentration (traffic congestion happens). On a LED board, the traffic conditions of the roads downstream to the diversion point are available, along with traffic advice. Drivers can choose a proper alternative route to avoid the traffic congestion. In the case study, the route advice VMS is also deployed according to the existing knowledge to the recurrent traffic conditions. Implementation of route advice in the case study using DSP can refer to section 3.2.4 optional detour VMS.

Advantage

Unlike route information VMS, route advice VMS can provide advice such as alternative routes to the drivers so that they are better informed and given optimal alternatives to avoid traffic congestion.

Disadvantage

Compliance rate of route advice VMS is not easy to determine. Some drivers have preference to one route than the other routes. Therefore, they might keep using their preferred route, even there is traffic congestion along the route. Besides, optional alternatives are very hard to optimize considering the dynamics of traffic and it requires prediction models to take future states of the traffic into account. Therefore, the effectiveness of route advice VMS can be limited.

Coordinated ramp metering (CRM)

Objective

One drawback of local ramp metering is that when congestion becomes serious, if one single ramp has been metered for too long, it stops or limits metering so that the queue on the ramp doesn't spill back to the surface streets upstream. Coordinated ramp metering is aimed to further reduce delays by utilizing extra storage spaces, such as coordinating the other (upstream) ramp controls or adjacent intersections with a certain algorithm. Thus, metering duration is increased and delays can be further reduced comparing to local ramp metering.

Approach

Based on different traffic control algorithms, there are several approaches to implement ramp metering coordination. One is the HERO master-slave coordination algorithm based on rule-based traffic control algorithm. The ramp upstream to the bottleneck is defined as the "master" ramp metering and the other ramp meterings are defined as the "slave" ramp meterings. The queue length on the master ramp metering is observed and once its length is over a certain level, triggering controls of the upstream slave ramp meterings. In this way, the extra storge space on the "slave" ramps are bettter utilized and the total metering time is increased. The other approach is based on MPC control algorithm and has a hierachical strucure, comininining AMOC (Advanced Motorway Optimal Control) on network level and ALINEA on local level. The main idea is to find the optimal control measures of the whole freeway network in the future by optimizing the cost function based on a network model for a certain future time horizon [18]. In the case study, a cooridnation approach similar to case-based control strategy is used. Simulations with similar traffic situations are run for multiple times. Solutions are determined with the knowledge gained from previous simulation results.

Advantage

Coordinated ramp metering, according to theoretical researches and field experiments, can further relieve the

traffic congestion on freeway and produce additional reduction of delays meanwhile CRM can prevent the over-growth of queue length on ramps.

Disadvantage

Different impementation approaches have different limitations. For example, AMOC, as most of the optimal control methods, needs effort for real-time modeling calculations or external disturbances prediction. The disadvantage of case-based approach is that the solution is limited by the scale of the case database. Therefore, the disadvantages of the approach for the case study is quite obvious: the efficiency of our solution is limited by our knowledge and research time. Each time when a new case comes up, the case needs to be learnt. Later in part three of this thesis project, the approach of HERO is adopted to develop an enhancement for coordinated ramp metering in the test soluation.

Coordinated DTM (CNM)

Objective

Uncoordinated DTM measures can yield sub-optimal or even counterproductive impacts. The coordination of various DTM measures, including ramp metering, variable speed limit and route information/advice/guidance, is aimed to improve throughput, prevent or delay onset of congestion, control queue spillback and distribute traffic with all available DTM measures [7].

Approach

There are different approaches to CNM deployment. For example, to coordinate ramp metering with congestion warning VMS, an MPC control strategy has been applied in a centralized structure, with METANET algorithm as the predictive model to control and coordinate freeway networks. To suppress shock waves, variable speed limits control is also coordinated. The simulation results show that the MPC controller is effective for coordinating speed limits against shock waves. Experiment results show that the speed limits can complement ramp metering, when the traffic demand is so high that ramp metering alone is not efficient anymore [18]. An overall approach focusing on the developed control framework, based on the principles of escalation, supervision and graceful degradation was put forward [1, 15]. The details can be referred to in section 2.3.2. The coordination strategy can be referred to in section 3.1.

Advantage

CNM is one of the promising solutions for efficient utilization of road networks, by eliminating the sub-optimal and counterproductive impacts due to the large amount of uncoordinated DTM measures.

Disadvantage and Challenge

The concept of coordinated DTM has been put forward for years and theoretical research show the impact with simulation tool. However, coordination between measures on a large-scale has not been carried out extensively yet in practice [1], due to the complexity of the control problems [15]. For the existing control strategies, they all have disadvantages in different aspects. For example, for MPC based control strategy, the real-time computation complexity is a big challenge [18]; a disadvantage of case-based control strategy is that for a new case non-existed in the case database, solution is also absent and needs to be added.

4.3 Control designs for two scenarios

In section 4.2, several ITS control measures are chosen for the deployment in the case study. This section introduces the control designs developed for two scenarios, recurrent and non-recurrent congestion scenarios. The simulations and set-ups of the case study experiments in chapter 5 are carried out according to the control designs here.

The assessment methodology in section 3.1 provides a tactical approach of CNM for both recurrent and non-recurrent scenarios. The control designs here are synthesized layer by layer with the ITS control measures chosen in section 4.2, following the proposed assessment methodology. These control designs are intended to offer some perspectives and provide a sound base for the simulations later.

Following the process of assessment methodology, the study areas of recurrent congestion scenario and non-recurrent congestion scenario are shown in Figure 4-5.

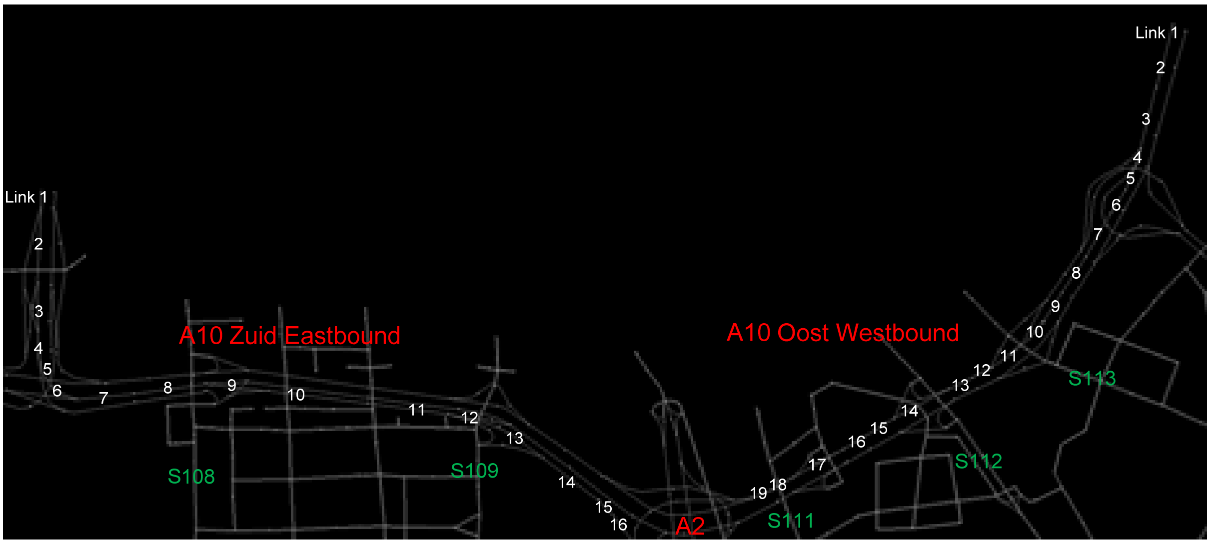


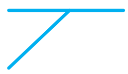
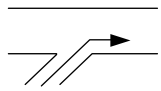
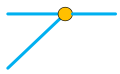
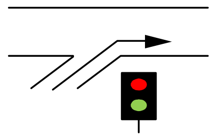
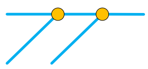
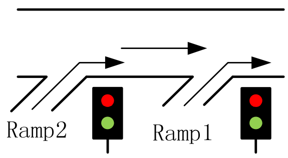
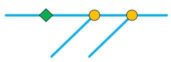
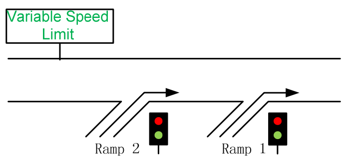
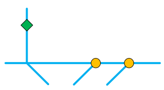
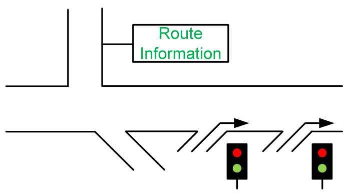
Figure 4-5 Implementation area of control designs for recurrent and non-recurrent congestion scenario

4.3.1 Recurrent traffic scenario

Applying the assessment methodology in section 3.1, the A10 South eastbound is chosen for the recurrent traffic scenario after monitoring the current state of the whole network with base design (D_0) simulations.

Seven control designs for the recurrent traffic scenario are developed and shown in Table 4-3, aiming at study the effect and testing the assessment methodology using the case study.

Each design is further explained with a more detailed description of application area, approach and possible effect prediction.

Control levels	Control design codes	Symbols	Schematics	Control measures
Base	D_0			Do nothing
Local	D_1:LRM			Local Ramp metering
String	D_2:CRM			Coordinated ramp metering
	D_3:CRM+VS			Coordinated ramp metering+ variable speed limit
Sub network	D_4:CRM+RI			Coordinated ramp metering+ route info VMS

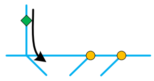
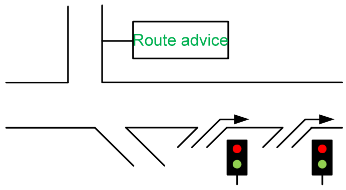
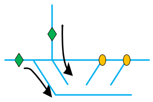
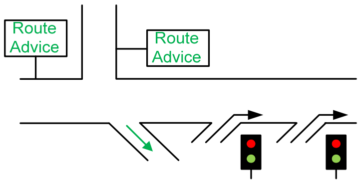
	D_5:CRM+RA			Coordinated ramp metering+ one route advice VMS
Network	D_6:CRM+2RA			Coordinated ramp metering+ two route advice VMS

Table 4-3 Control designs for recurrent congestion scenario in the case study

$D_{0:}$ Base design

From the network descriptions in section 4.1, no extra traffic management is added to the base scenario except for pre-configured signalized intersections calibrated according to the signal control strategies of current network [46]. The base scenario is set to be the benchmark in the case study for comparatively investigating CNM. Therefore, each control design is presented with deployment of ITS control measures on D_0.

$D_{1:}$ Local ramp metering

With the base design simulation results (see Appendix I) and the frame of reference (see section 3.1), current state monitoring module estimates the traffic situation from the network level to the local level and identifies the active bottlenecks. Through ex-ante evaluation, these bottlenecks are forwarded to the CNM control design module. The CNM control design module provides a control design (D_1) based on the established control principles of the assessment methodology. Traffic management starts at local level. This control design provides the control design input to modelling. Together with basic input from the network build-up, the modelling tool-DSP gives simulation results. The control design input contains parameters, deployment positions and controller behaviours (directed by the control algorithms, in the case study, only case-based algorithm is applied manually).

The corresponding control design deployment on control design (D_1) is shown in Figure 4-6. The parameters and deployment positions of this control design in DSP are attached in Appendix I.

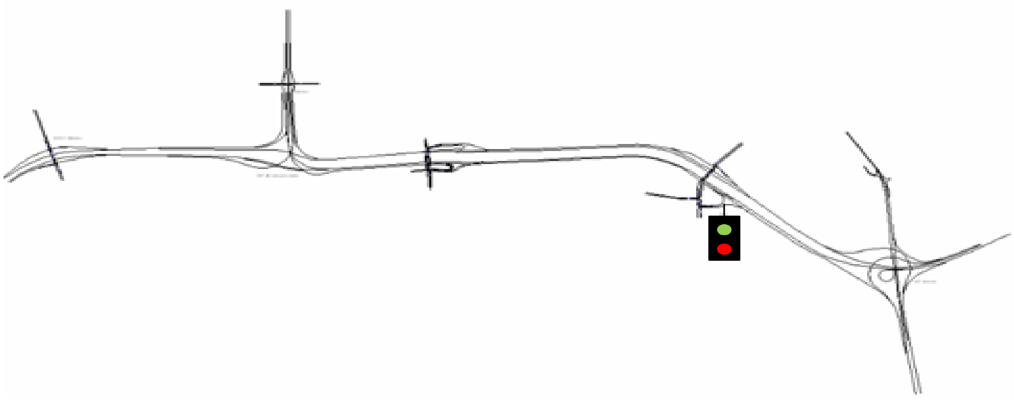


Figure 4-6 $D_{1,}$ Local ramp metering control design

D_2: Coordinated ramp metering

Again, with the D_1 simulation results (see Appendix I and Figure 5-4) and the frame of reference (see section 3.1), current state monitoring module estimates the traffic situation from the network level to the local level and identifies the active bottlenecks after the deployment of D_1. Through ex-ante evaluation, these remaining bottlenecks are forwarded to the CNM control design module. The CNM control design module provides a control design (D_2) based on the established control principles of the assessment methodology. Traffic management starts with coordination of the same type of ITS control measure on the string, then coordination between different types of ITS control measure. This control design provides the control design input to modelling. Together with basic input from the network build-up, the modelling tool-DSP gives simulation results of D_2, coordinated ramp metering.

The corresponding control measures deployment on control design (D_2) is shown in Figure 4-7. The parameters and deployment positions of this control design in DSP are attached in Appendix I.

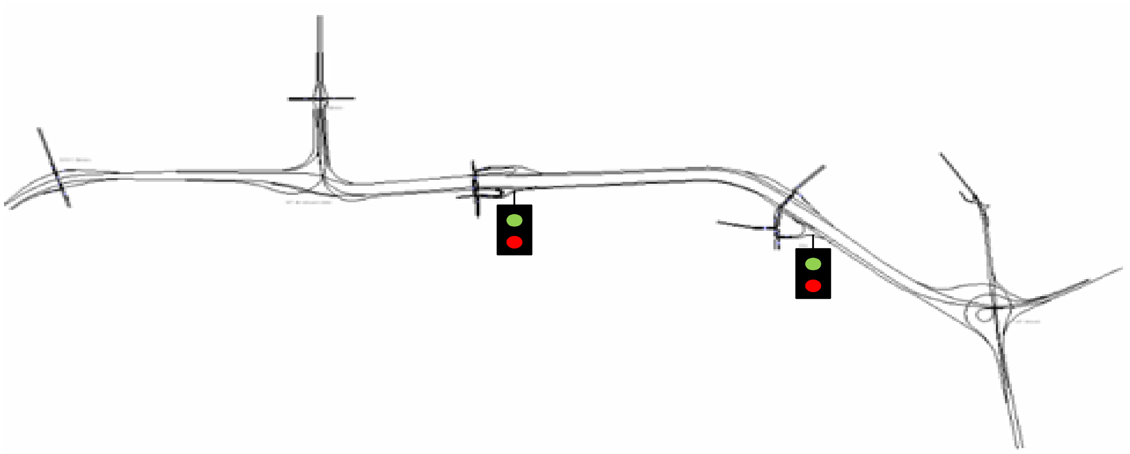


Figure 4-7 $D_{2,}$ Coordinated ramp metering control design

D_3: Coordinated ramp metering and variable speed limit VMS

Again, with the D_2 simulation results (see Appendix I and Figure 5-4) and the frame of reference (see section 3.1), current state monitoring module estimates the traffic situation from the network level to the local level and identifies the active bottlenecks after the deployment of D_2. Through ex-ante evaluation, these remaining bottlenecks are forwarded to the CNM control design module. The CNM control design module provides a control design (D_3) based on the established control principles of the assessment methodology. Since possible ramp metering on the string level is activated, coordination between ramp metering and variable speed limit on the string level starts. This control design provides the control design input to modelling. Together with basic input from the network build-up, the modelling tool-DSP gives simulation results of D_3, coordinated ramp metering and variable speed limit VMS.

The corresponding control measures deployment on control design (D_3) is shown in Figure 4-8. The parameters and deployment positions of this control design in DSP are attached in Appendix I.

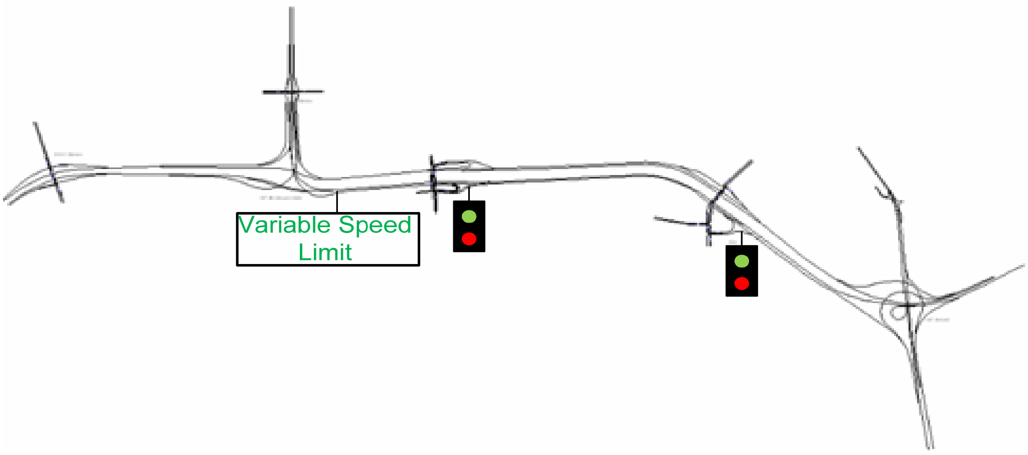


Figure 4-8 $D_{3,}$ Coordinated ramp metering and variable speed limit control design

D_4: Coordinated ramp metering and route information VMS

Again, with the D_3 simulation results (see Appendix I and Figure 5-4) and the frame of reference (see section 3.1), current state monitoring module estimates the traffic situation from the network level to the local level and identifies the active bottlenecks after the deployment of D_3. Through ex-ante evaluation, these remaining bottlenecks are forwarded to the CNM control design module. The CNM control design module provides a control design (D_4) based on the established control principles of the assessment methodology. Coordination between ramp metering and variable speed limit did not show much improvement. Coordination between ramp metering and route information VMS on the sub-network level starts. This control design provides the control design input to modelling. Together with basic input from the network build-up, the modelling tool-DSP gives

simulation results of D_4, coordinated ramp metering and route information VMS.

The corresponding control measures deployment on control design (D_4) is shown in Figure 4-9. The parameters and deployment positions of this control design in DSP are attached in Appendix I.

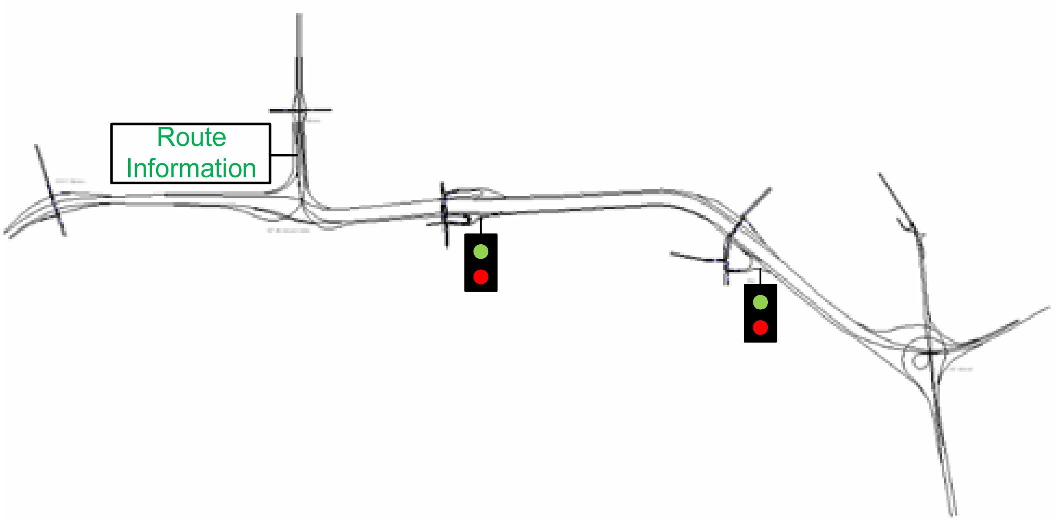


Figure 4-9 $D_{4,}$ Coordinated ramp metering and route information control design

D_5: Coordinated ramp metering and route advice VMS

Again, with the D_4 simulation results (see Appendix I and Figure 5-4), and the frame of reference (see section 3.1), current state monitoring module estimates the traffic situation from the network level to the local level and identifies the active bottlenecks after the deployment of D_4. Through ex-ante evaluation, these remaining bottlenecks are forwarded to the CNM control design module. The CNM control design module provides a control design (D_5) based on the established control principles of the assessment methodology. Since coordination between ramp metering and route information did not show much improvement, coordination between ramp metering and route advice VMS on the sub-network level starts. This control design provides the control design input to modelling. Together with basic input from the network build-up, the modelling tool-DSP gives simulation results of D_5, coordinated ramp metering and route advice VMS.

The corresponding control measures deployment on control design (D_5) is shown in Figure 4-10. The parameters and deployment positions of this control design in DSP are attached in Appendix I.

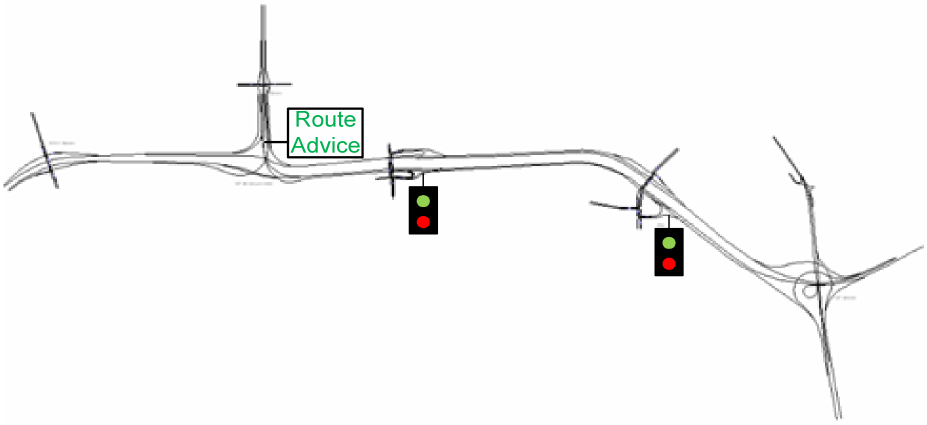


Figure 4-10 $D_{5,}$ Coordinated ramp metering and route advice control design

D_6: Coordinated ramp metering and multiple route advice VMS

Again, with the D_5 simulation results (see Appendix I and Figure 5-4), current state monitoring module estimates the traffic situation from the network level to the local level and identifies the active bottlenecks after the deployment of D_5. Through ex-ante evaluation, these remaining bottlenecks are forwarded to the CNM control design module. The CNM control design module provides a control design (D_6) based on the established control principles of the assessment methodology. Since coordination between ramp metering and route advice VMS on the sub-network level shows promising results, coordination between ramp metering and route advice VMS on the network level starts. This control design provides the control design input to modelling. Together with basic input from the network build-up, the modelling tool-DSP gives simulation results of D_6, coordinated ramp metering and multiple route advice VMS.

The corresponding control measures deployment on control design (D_6) is shown in Figure 4-11. The parameters and deployment positions of this control design in DSP are attached in Appendix I.

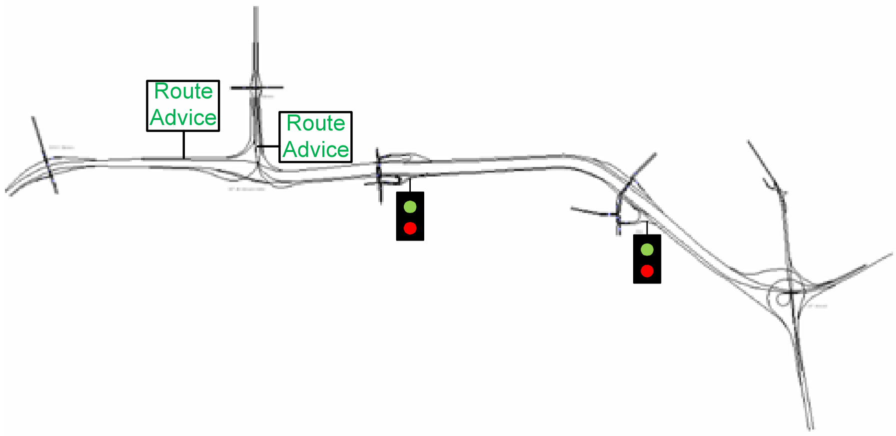


Figure 4-11 $D_{6,}$ Coordinated ramp metering and two route advice control design

Up to here, all types of ITS control measures chosen for the case study is explored regarding recurrent scenario. In DSP, as described early in section 3.2.4, freeway traffic management includes ramp metering and four types of VMS. Notice that route guidance (type two mandatory detour VMS) is also practiced but received unsatisfactory results due to the applicability of the modelling tool, DSP. This is foreseeable since mandatory detour VMS compels all vehicles to take a user-specified path under lane closure, work zone or sever congestions and it is not suitable for recurrent scenario. The pre-specified path cannot be possibility suitable for all vehicles heading to different destinations. So coordination between ramp metering and mandatory detour VMS can hardly get any improvement. Therefore, this design is not shown here.

4.3.2 Non-recurrent traffic scenario

For non-recurrent congestion scenario, the same procedure is carried out step by step according to the assessment methodology. A10 East westbound is chosen as the application area in the case study.

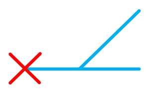
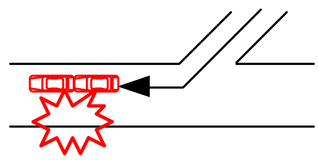
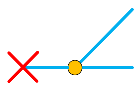
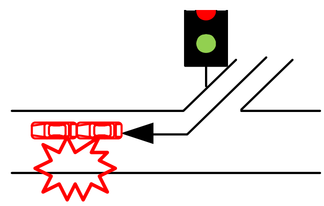
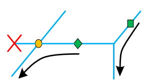
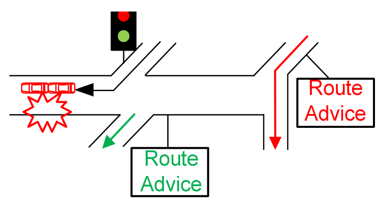
Control levels	Control design codes	Symbols	Schematics	Control measures
Incident base	ID_0			Incident do nothing
Local	ID_1:LRM			Ramp metering
Network	ID_2:LRM+2RA			Coordinated ramp metering+ 2 route advice

Table 4-4 Control designs for non-recurrent congestion scenario in the case study

In Table 4-4, three control designs under incident scenario are listed for the case study. The details of each

design are explained below.

ID_0: Base design with incident

From the network description in section 4.1 and the simulation results of D_0, the base designs with incident is set to be the benchmark in the case study for comparatively investigating CNM under non-recurrent congestion . Therefore, each control design in this section is presented with deployment of ITS control measures on ID_0. The position of incident is shown in Figure 4-12. The reasons for choosing the incident location and its parameters set-up are attached to Appendix I.

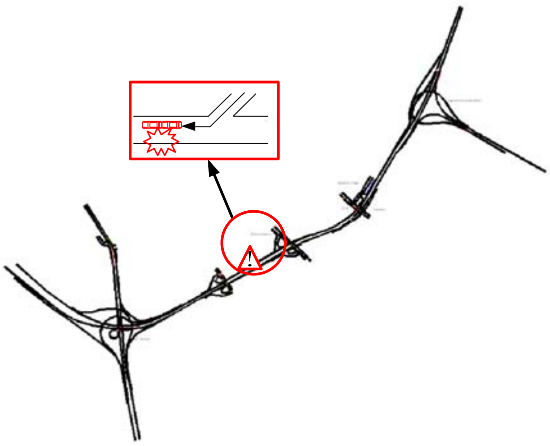


Figure 4-12 ID_0, base design with incident

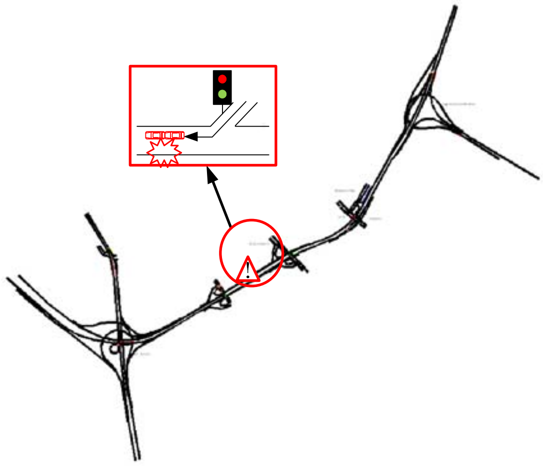


Figure 4-13 ID_1, local ramp metering design

ID_1: Local ramp metering

With the base design simulation results (see Appendix I), current state monitoring module estimates the traffic situation from the network level to the local level and identifies the active bottlenecks after the deployment of ID_0. Apparently, the incident link is chosen to be the active bottleneck. The CNM control design module provides one control design, based on the established control principles. In this design, local ramp metering upstream to the incident location is selected. This control design provides the control design input to modelling. Together with basic input (including the incident input) from the network build-up, the modelling tool-DSP gives simulation results of ID_1, local ramp metering with incident.

The corresponding control design deployment (ID_1) is shown in Figure 4-13. The parameter and deployment positions of this control design in DSP are attached in Appendix I.

ID_2: Coordinated ramp metering and multiple route advice VMS

Again, with the ID_1 simulation results (Appendix I), current state monitoring module estimates the traffic

situation from the network level to the local level and identifies the active bottlenecks after the deployment of ID_1. The CNM control design module provides one control design, based on the established control principles. Since coordination between ramp metering and route advice VMS has received a promising results under recurrent congestion scenario, coordination between ramp metering and multiple route advice VMS on the network level starts in this control design. This control design provides the control design input to modelling. Together with basic input (including the incident input) from the network build-up, the modelling tool-DSP gives simulation results of ID_2, coordinated ramp metering and multiple route advice VMS for incident scenario.

The corresponding control measures deployment on this control design (ID_2) is shown in Figure 4-14. The parameters and deployment positions of this control design in DSP are attached in Appendix I

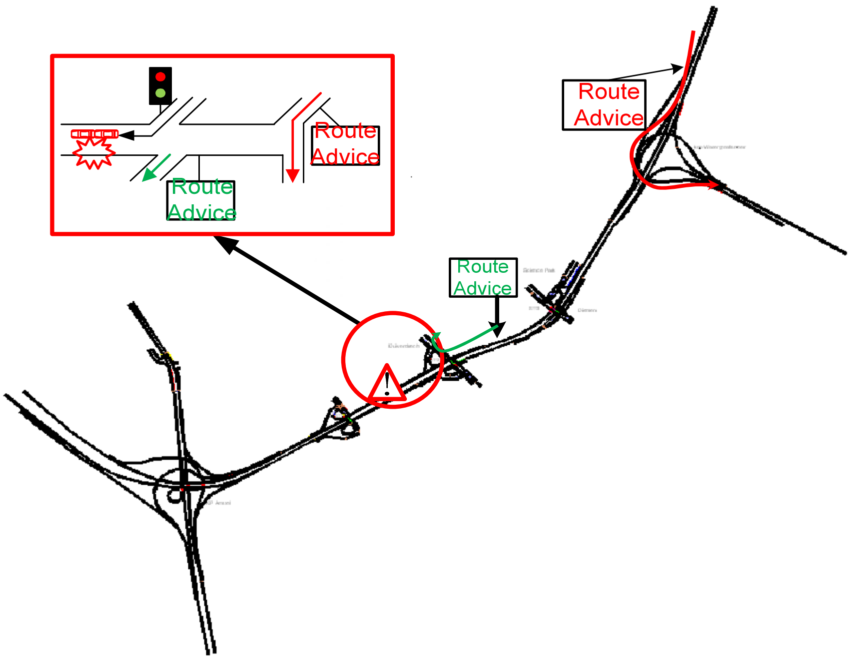


Figure 4-14 ID_2, coordinated ramp metering and multiple route advice VMS for incident scenario

4.4 Performance indicator

One of the research objectives is to develop and apply an assessment methodology framework to assess the impacts of DTM and CNM on traffic flow conditions, on both network level and local (or string) level. The proposed assessment methodology in chapter 3 is applied to the case study and the performance of this assessment methodology on achieving the control objectives can be observed. Therefore, performance indicators are needed to quantify to what extent, the assessment methodology can help to meet the control objects. To this end, two specific questions need to be answered with the help of performance indicators:

1. How do the network qualities, for example, average travel times and average delay times, of the case study network change as the results of CNM practice?

2. What are the impacts of DTM and CNM on the local traffic conditions, such as traffic flow or accessibility, specifically for A10 South and A10 East, where the ITS control measures are deployed?

Corresponding to these two questions, two categories of measures of effectiveness (MOE) are put forward in this section, according to the levels of performance that can be indicated by the MOE. They are network level MOEs, which are used to assess the first question and local network level MOEs, which are used to assess the second question. They are used for presenting the simulation results in chapter 5 and evaluation in chapter 6.

4.4.1 Network level MOE

Five major measures of effectiveness for the evaluation of network traffic situations under different control designs are used in the case study: average travel time, average trip time, average stop time and average trip distance.

Average travel time (mins)

Travel time is the time that vehicles used to travel in the network. Average travel time is the average of travel time per vehicle, including running time and stop time [30].

Average trip time (mins)

Trip time indicates the time from the generation of the vehicles to the exit of the vehicles in the network. Average trip time is the average of trip time per vehicle, including network entry time and travel time [30].

Average stop time (mins)

Stop time is the time that vehicles stop in the network, e.g. waiting in a queue or for a green light and average stop time is the average of stop time per vehicle. It is a good measure for the analysis of vehicle delay [30].

Numbers of in and out of network vehicles

Vehicles can be chosen to be tagged or not, and at the end of simulation, DSP will output the numbers of vehicles in and out of the network. This MOE is useful for evaluating the improvement of network quality under non-recurrent congestion.

Average trip distance (mile)

As suggested by its name, average trip distance is the average of the trip distance per vehicles. Normally it is

used to compare the different responses to various traffic situations and control measures between equipped and non-equipped vehicles [36].

It is important to point out that all five average measures above provide network level effectiveness indications. To be specific, these measures in the case study include all performances of 318511 vehicles during the 240 minutes simulation period.

4.4.2 Local level MOE

Two major measures of effectiveness for the evaluation of freeway stretch on local level under different control designs are used in the case study: average density and average queue length (in percentage of link length).

Average density

DSP reports the average equivalent vehicle density by link (vehicles/mile/lane) [36]. In fact, a more direct indicator for local traffic conditions, such as traffic flow and accessibility would be the average speed on these crucial links (A10 East and A10 South). Due to the doubtful modified Greenshield v=V(k) models in DSP, average speed is not a proper indicator. Relative evaluation using average speed can be found in Appendix I.

Average queue length (in percentage of link length)

Average queue length (in percentage of link length) is defined as the average of the queue length (in percentage of link length) over the simulation period (or a certain length of time) at one certain link (freeway and ramp links are used in the case study). The method for the calculation of average queue length (in percentage of link length) is not explicitly explained by Dynasmart-P.

DSP also provides many other performance indicators. The network MOE and local level MOE chosen here are considered to be more informative by the author. These MOE will be further examined in the validation of evaluation results in section 6.2

4.5 Conclusion

This chapter introduces the case study designs. Section 4.1 provides the basic input for modelling. Scenarios and control designs with selected control measures are developed using the proposed assessment methodology. Questions of assessment criteria choices are raised and corresponding performance indicators are selected. The next chapter presents the simulation results of these case study designs. Judging from the limited MOEs that could be used for indication of performance, the case study simulation and evaluation could have some serious difficulties, which could potential affect the performance of the proposed assessment methodology.

5 Case study simulation results

In this chapter, the case study designs are simulated to show the functioning of the proposed assessment methodology. The simulation results are useful both for ex-ante evaluation and bottlenecks diagnosis. These results are used to preliminarily evaluate the effect of CNM control designs. Further overall evaluations will carried out in chapter 6, where evaluations focus more from the perspectives of assessment methodology and validity of results.

In section 5.1, seven control designs for the recurrent traffic scenario are set up and simulations are run for multiple times. Simulation results are compared from the network level in section 5.1.1 and from the local level (A10 South eastbound freeway stretch) in section 5.1.2. In section 5.2, three control designs for the non-recurrent traffic scenario in the case study are set up and simulations are run for multiple times. Simulation results are compared from the network level in section 5.2.1 and from the local level (A10 East westbound freeway stretch) in section 5.2.2. Both expected and unexpected results are discussed in this chapter.

5.1 Recurrent scenario

Seven control designs with the same basic network input are simulated here with one-shot simulation in DSP. To reaffirm, the seven control designs for recurrent traffic scenario are:

Control levels	Control designs
Base	D_0 = do nothing
Local	D_1=LRM=local ramp metering
String	D_2=CRM=coordinated ramp metering
	D_3=CRM+VS=coordinated (ramp metering + variable speed limit)
Sub network	D_4=CRM+RI=coordinated (ramp metering + route information)
	D_5=CRM+RA=coordinated (ramp metering + route advice)
Network	D_6=CRM+2RA= coordinated (ramp metering + multiple route advice)

Table 5-1 Control designs list for recurrent scenario

5.1.1 Network level

The statistics results (average travel time and average stop time) of the entire network in each control designs obtained from DSP simulations are summarized in Figure 5-1 and Figure 5-2.

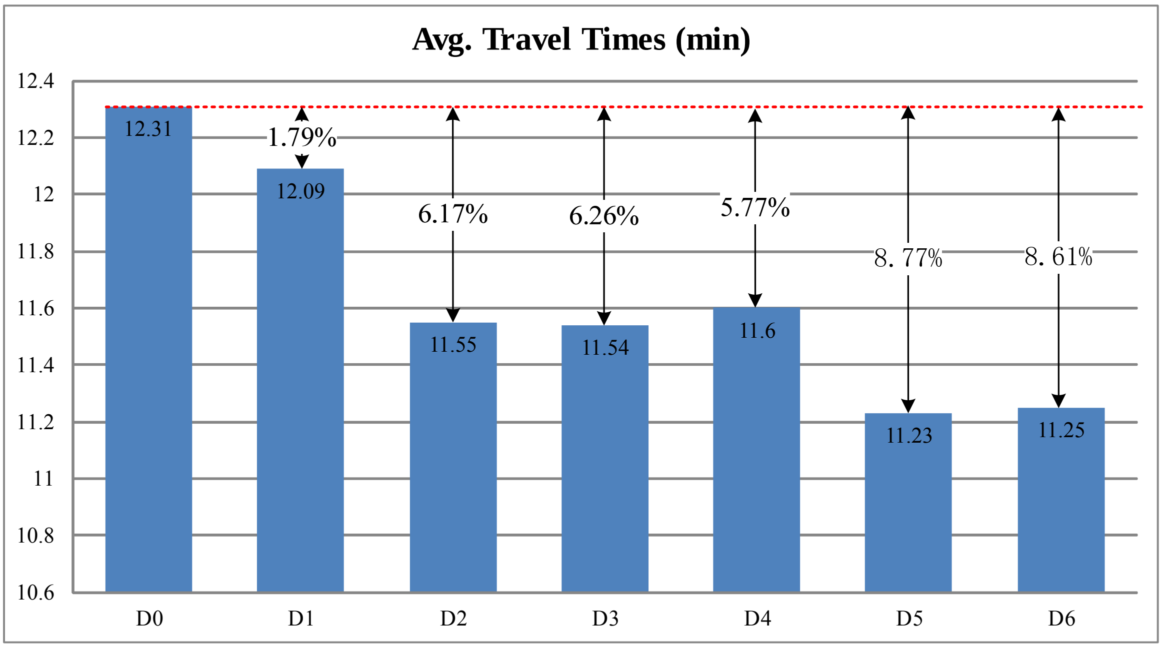


Figure 5-1 Average travel times for each control design in recurrent scenario

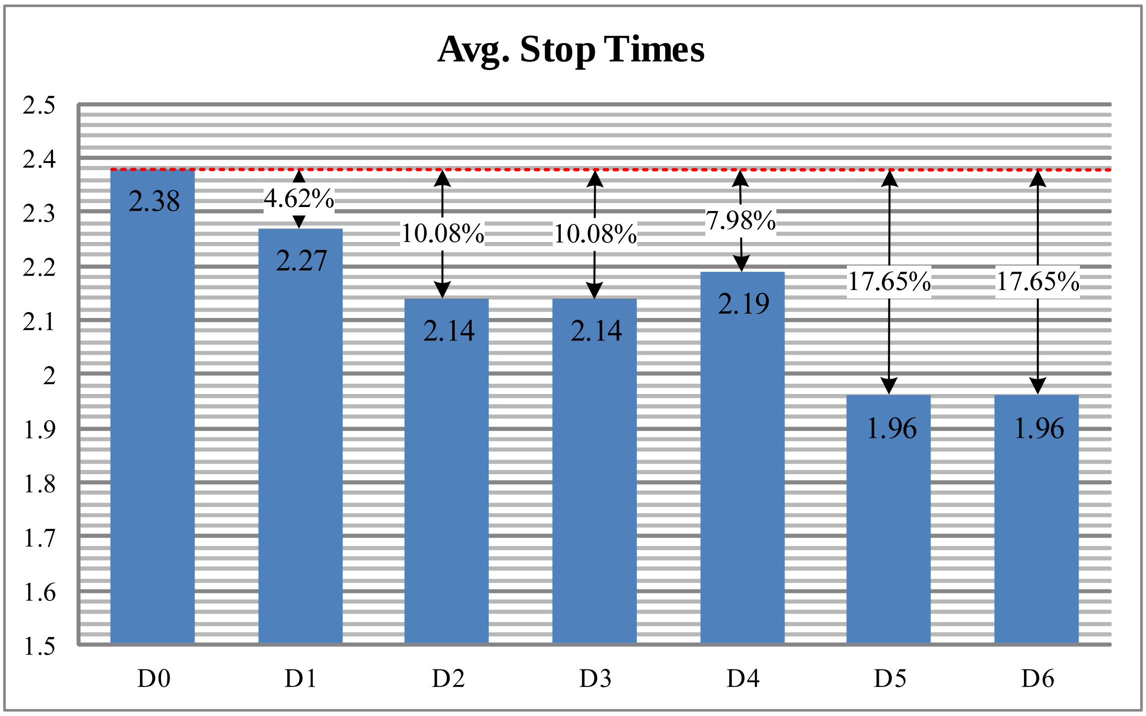


Figure 5-2 Average stop times for each control design in recurrent scenario

$D_{0:}$ do nothing

From the current state monitoring results of base scenario in Appendix I, it can be seen the network in base scenario has a certain level of congestion during peak hour but not too serious. The average travel time of D_0 is 12.31 minute and the average stop time of D_0 is 2.38 minute. Active bottlenecks are observed and the chosen bottleneck is on link 13 and 14 of freeway A10 South eastbound. The position of the bottleneck can be seen in Figure 4-5.

$D_{1:}$ local ramp metering

Local ramp metering on the ramp connecting S109 to link 14 on A10 South eastbound is activated to solve the bottleneck link 13 and 14 on A10 South eastbound, the position of ramp metering is shown in Figure 4-6. Several alternatives of D_1 are simulated and the parameters of the chosen D_1 can refer to Appendix I. The average travel time of D_1 is 12.09 minute, which is 1.79% lower than the average travel time of D_0. The average stop time of D_1 is 2.27 minute, which is 4.62% lower than the average stop time of D_0. The 1.79% improvement on average travel time can lead to saving 1168 hours of total travel time for the 318511 vehicles during simulation period. And the 4.62% improvement on average stop time can lead to saving 584 hours of total queuing time for the 318511 vehicles during simulation period.

$D_{2:}$ coordinated ramp metering

From the current state monitoring results of D_1 in Appendix I, it can be seen bottleneck link 13 and 14 on A10 South eastbound is improved but congestion is not completely relieved and the ramp queue on S109 to link14 (around Amstelpark) is really long and spilling back to the surface street. Therefore, another ramp metering on the upstream on-ramp, from S108 to link10, is coordinated into D_2. The positions of these two ramp meterings are shown in Figure 4-7. Several alternatives of D_2 are simulated and the parameters of the chosen D_2 can refer to Appendix I. The average travel time of D_2 is 11.55 minute, which is 6.17% lower than the average travel time of D_0. The average stop time of D_2 is 2.14 minute, which is 10.08% lower than the average stop time of D_0. The 6.17% improvement on average travel time can lead to saving 4034 hours of total travel time for the 318511 vehicles during simulation period. And the 10.08% improvement on average stop time can lead to saving 1274 hours of total queuing time for the 318511 vehicles during simulation period. The ramp queue lengths (in ramp percentage) of D_1 and D_2 (considering S108 and S109) can refer to the next section.

$D_{3:}$ coordinated (ramp metering + variable speed limit)

From the current state monitoring results of D_2 in Appendix I, it can be seen the previous bottlenecks are improved on A10 South eastbound but another bottleneck on link 7 is observed. From the analysis in Appendix I, a variable speed limit is added to link 7 and coordinated into D_3. The positions of these two ramp meterings and

variable speed limit are shown in Figure 4-8. Several alternatives of D_3 are simulated and the parameters of the chosen D_3 can refer to Appendix I. The average travel time of D_3 is 11.54 minute, which is 6.26% lower than the average travel time of D_0. The average stop time of D_3 is 2.14 minute, which is 10.08% lower than the average stop time of D_0. The 6.26% improvement on average travel time can lead to saving 4087 hours of total travel time for the 318511 vehicles during simulation period. And the 10.08% improvement on average stop time can lead to saving 1274 hours of total queuing time for the 318511 vehicles during simulation period, but unexpectedly, it has almost no improvement compared to D_2.

D_4: coordinated (ramp metering + route information)

From the current state monitoring results of D_2 in Appendix I, it can be seen the previous bottleneck on link 7 is not improved at all. The unexpected results could be due to the macroscopic modelling tool-DSP, which is further evaluated in section 6.2. From the analysis in Appendix I, a congestion warning is added on link 4 and coordinated into D_2. The positions of these two ramp meterings and congestion warning VMS are shown in Figure 4-9. Several alternatives of D_4 are simulated and the parameters of the chosen D_4 can refer to Appendix I. The average travel time of D_4 is 11.6 minute, which is 5.77% lower than the average travel time of D_0. The average stop time of D_4 is 2.19 minute, which is 7.98% lower than the average stop time of D_0. The 5.77% improvement on average travel time can lead to saving 3769 hours of total travel time for the 318511 vehicles during simulation period. And the 7.89% improvement on average stop time can lead to saving 1009 hours of total queuing time for the 318511 vehicles during simulation period.

D_5: coordinated (ramp metering + route advice)

From the current state monitoring results of D_2 in Appendix I, it can be seen coordinating the congestion warning on link 4 worsened the bottleneck even more. The unexpected results could be due to the unreliable route information function of DSP, which is further evaluated in section 6.2. From the analysis in Appendix I, an optional detour VMS is added on link 4 and coordinated into D_5. The positions of these two ramp metering and optional detour VMS are shown in Figure 4-10. Several alternatives of D_5 are simulated and the parameters of the chosen D_5 can refer to Appendix I. The average travel time of D_5 is 11.23 minute, which is 8.77% lower than the average travel time of D_0. The average stop time of D_4 is 1.96 minute, which is 17.65% lower than the average stop time of D_0. The 8.77% improvement on average travel time can lead to saving 5733 hours of total travel time for the 318511 vehicles during simulation period. And the 17.65% improvement on average stop time can lead to saving 2230 hours of total queuing time for the 318511 vehicles during simulation period.

D_6: coordinated (ramp metering + multiple route advice)

From the current state monitoring results of D_5 in Appendix I, it can be seen coordinating the route advice on

link 4 improved the bottleneck. The reasons for the promising results are further evaluated in section 6.2. From the analysis in Appendix I, another optional detour VMS is added on link 2 and coordinated into D_6. The positions of these two ramp meterings and two optional detour VMS are shown in Figure 4-11. Several alternatives of D_6 are simulated and the parameters of the chosen D_6 can refer to Appendix I. The average travel time of D_6 is 11.25 minute, which is 8.61% lower than the average travel time of D_0. The average stop time of D_6 is 1.96 minute, which is 17.65% lower than the average stop time of D_0. The 8.61% improvement on average travel time can lead to saving 5627 hours of total travel time for the 318511 vehicles during simulation period. And the 17.65% improvement on average stop time can lead to saving 2230 hours of total queuing time for the 318511 vehicles during simulation period. The unexpected ordinary performance of CNM on the network level will be further evaluated in section 6.2.

5.1.2 Local level

The local level simulation results of each control design are presented and compared in this section, focusing on the A10 South eastbound freeway stretch since most of the bottlenecks in recurrent scenario are selected in this sub-network. Although the local level results should be studied with the curves of density, flow rate, velocity and queue length characteristics on each link on A10 South eastbound, flow rate and velocity are not appropriate for this analysis and they are not introduced in section 4.4 as performance indicator. The reason for this is due to the implication of the modelling tool-DSP and it will be further explained in section 6.2.

Locally, densities and queue lengths (in percentage of link length) of each link on A10 South eastbound are used as the MOE for comparison of CNM control design effectiveness. Densities and queue lengths (in percentage of link length) are presented in each control design as a function of time and space for a visual representation of traffic characteristic evolvement and an impression perspective to the effectiveness of each control design, as shown in Figure 5-4. The average densities (grouped according to each control design) of different cases are shown as the histograms in Figure 5-5. And ramp queue lengths (in percentage of link length) of the ramps connecting S108 and S109 to freeway A10 South eastbound are compared in an attempt to examine the effect of coordinated ramp metering.

Figure 5-3 is reminded here for the positions of each link on A10 South eastbound freeway stretch.

Figure 5-3 Implementation area of control designs for recurrent scenario

$D_{0:}$ do nothing

From local level perspective, most links of A10 South eastbound are loaded with high traffic demand of peak hours from around 120 minute till the end of simulation and queues are generated on some of the links, as shown in Figure 5-4, row D_0. The first impression is that ring A10 is quite congested, particular for the A10 South. This could be explained by the fact that the network data are calibrated according to evening peak hours when traffic volume is the highest, which puts pressures to the A10 due to its traffic distribution function. The simulation results of density variation on A10 South are shown in Appendix. This figure points out four locations that have the high densities peak starting around 120 minute till the end of the simulation, which suggests that any one of them could, but not necessarily, be a bottleneck.

$D_{1:}$ Local ramp metering

The density and queue length (in percentage of link length) of each link of A10 South eastbound are plotted as a function of time in Figure 5-4, row D_1. The local level improvement cannot be seen explicitly, compared to the results in D_0. The average density can help to exam the local level improvement by local ramp metering. As shown in Figure 5-5, the average densities (over time) on almost all the links of A10 South eastbound in D_1 are lower than those data in D_0. It seems that on the local level, local ramp metering can keep the freeway traffic less interrupted.

$D_{2:}$ coordinated ramp metering

The density and queue length (in percentage of link length) of each link of A10 South eastbound are plotted as a function of time in Figure 5-4, row D_2. The local level improvement is significant, compared to the results in D_1. Both the densities and queue lengths (in percentage of link length) on almost all the links of A10 South eastbound in D_2 are lower than those data in D_1.

D_3: coordinated (ramp metering + variable speed limit)

The density and queue length (in percentage of link length) of each link of A10 South eastbound are plotted as a function of time in Figure 5-4, row D_3. The local level performance has no improvement, compared to the results in D_2, both density and queue length (in percentage of link length). This can also be seen from the comparison of average densities between D_2 and D_3. Average densities on almost all the links of A10 South eastbound are the same or close.

D_4: coordinated (ramp metering + route information)

The density and queue length (in percentage of link length) of each link of A10 South eastbound are plotted as a function of time in Figure 5-4, row D_4. The local level performance has significant improvement, compared to the results in D_2, both density and queue length (in percentage of link length). Also as shown in Figure 5-5, average densities on almost all the links of A10 South eastbound in D_4 are lower than those data in D_2.

D_5: coordinated (ramp metering + route advice)

The density and queue length (in percentage of link length) of each link of A10 South eastbound are plotted as a function of time in Figure 5-4, row D_5. The local level performance also has significant improvement, compared to the results in D_2, both density and queue length (in percentage of link length). Also as shown in Figure 5-5, average densities on almost all the links of A10 South eastbound in D_5 are lower than those data in D_2.

D_6: coordinated (ramp metering + multiple route advice)

The density and queue length (in percentage of link length) of each link of A10 South eastbound are plotted as a function of time in Figure 5-4, row D_6. The local level performance has significant improvement, compared to the results in D_2, both density and queue length (in percentage of link length). Also as shown in Figure 5-5, average densities on almost all the links of A10 South eastbound in D_6 are lower than those data in D_2.

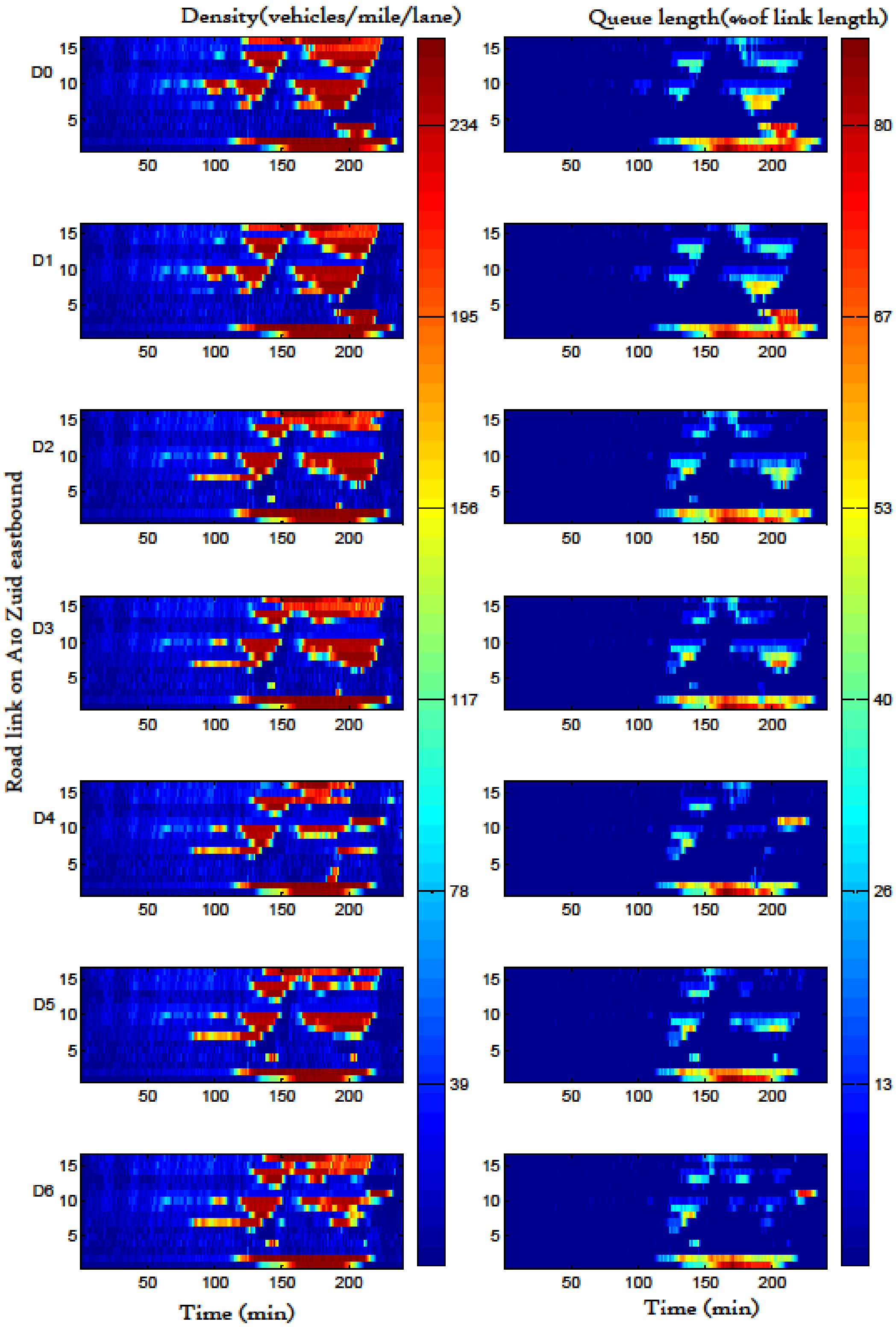


Figure 5-4 Density and queue length (in percentage of link length) on A10 South eastbound of seven control designs in recurrent scenario

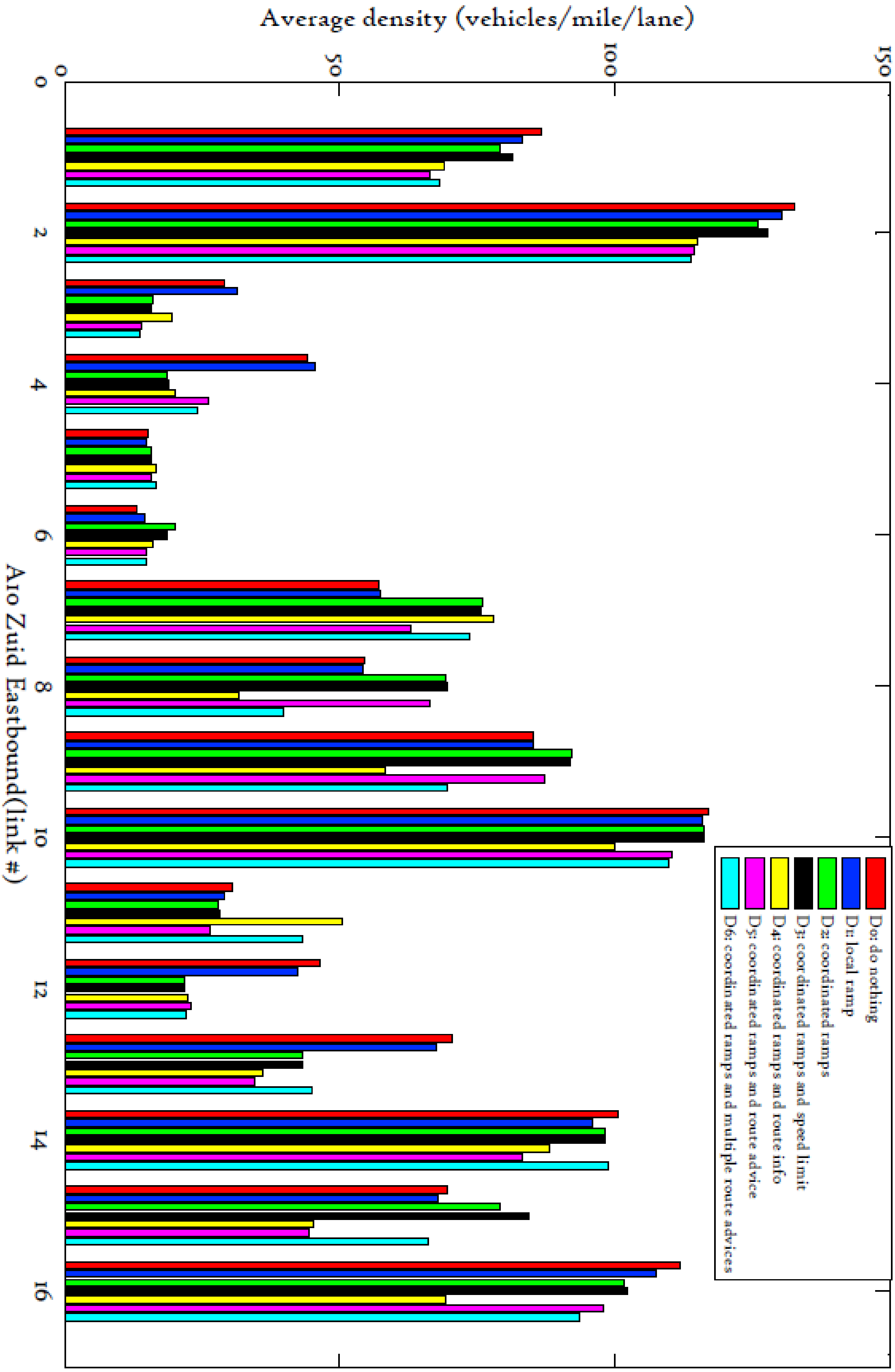


Figure 5-5 Average densities on each link on A10 South eastbound of

seven control designs for recurrent scenario

5.2 Non-recurrent scenario

The purpose of the deployed incident is to study the effect of CNM control designs under non-recurrent traffic condition. From the current state monitoring results of base scenario in Appendix I (also can be observed from Figure 5-9), the sub-network A10 East westbound in base scenario are mostly with smooth traffic during the simulation period, except for the links at the downstream of A10 East. Therefore, an incident is deployed around this possible bottleneck from 60 minute until 180 minute of the simulation period (during evening peak, incident from 16:00 till 18:00) and the severity is set to be 0.8, which means the capacity of the link drops instantly to 20% of its original capacity. The exact position (link 16 on A10 East westbound) of the incident can be seen in Figure 4-12 and a serious non-recurrent congestion is formed (see Figure 5-9).To reaffirm, the four control designs for non-recurrent traffic scenario presentation are:

Control levels	Control designs
Base	D_0 = do nothing
Incident base	ID_0=incident do nothing
Local	ID_1=LRM= local ramp metering for incident scenario
Network	ID_2:LRM+2RA= coordinated (ramp metering + multiple route advice)

Table 5-2 Control designs list for non-recurrent scenario

5.2.1 Network level

The same steps of results presenting and analysis are carried out here as recurrent scenario. The difference is that an incident is set up on a potential bottleneck of a relatively smooth traffic freeway stretch deliberately to study the effect of CNM control designs under non-recurrent traffic condition. It is obvious that the number of control designs is much less than recurrent scenario. This can be explained in two fold. First, the chosen application area, the sub-network A10East, has limited possibilities for implementing ITS control measures. Only two on-ramps are relevant in incident scenario, S112 (connecting to link 15 of A10 East westbound) and S113 (connecting to link 12 of A10 East westbound), and S113 has very few inflows to the freeway. Coordination of both ramps is performed but makes no difference. So this control design was not chosen for discussion. Second, every ITS control measure provided by DSP were studied in recurrent scenario of the case study. Variable speed limits and

route information (also route guidance, which was practiced, but not discussed then either due to software applicability) all received unsatisfactory results. The reasons are mostly due to the defects of the simulation tool. Therefore, these controls won't be repeated in non-recurrent scenario.

The statistics results (average travel time and average stop time) of the entire network in all four control designs are given in Figure 5-6 and Figure 5-7.

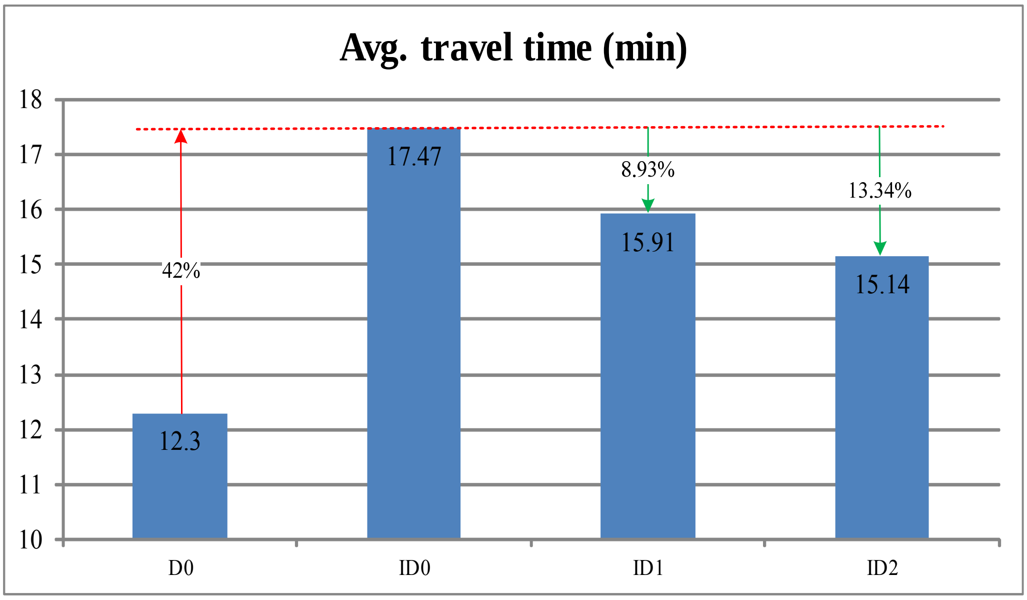


Figure 5-6 Average travel times for each control design in incident scenario

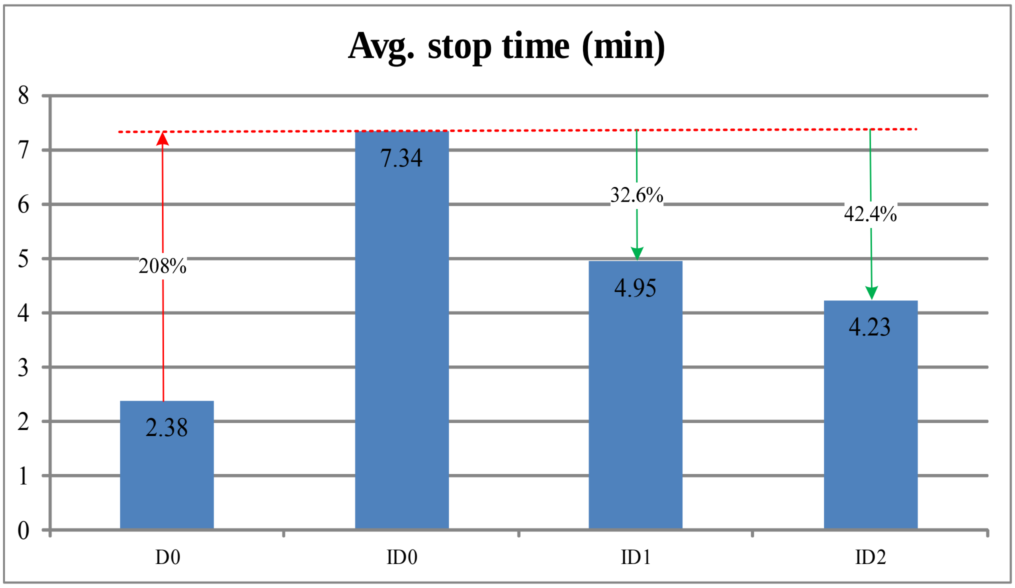


Figure 5-7 Average stop times for each control design in incident scenario

D_0: do nothing

From the current state monitoring results of base scenario in Appendix I, a bottleneck can be identified around the links at the downstream of A10East. The average travel time of D_0 is 12.31 minute and the average stop time of D_0 is 2.38 minute, the same as the base design network statistics in recurrent scenario. Active bottleneck is observed on link 16 of freeway A10East westbound. The position of the bottleneck can be seen in Appendix I and Figure 4-12.

ID_0: incident, do nothing

An incident is set up on the potential bottleneck, link16 of A10East westbound. The parameters of ID_0 can refer to Appendix I. No control is added in ID_0. The average travel time of ID_0 is 17.47 minute, which is 42% higher than the average travel time of D_0. The average stop time of ID_0 is 7.34 minute, which is 208% higher than the average stop time of D_0.

ID_1: local ramp metering

Local ramp metering on S112 (connecting to link 15 of A10 East westbound) was activated during the same time period as the incident to solve the bottleneck link 16 on A10East westbound, the position of ramp metering is shown in Figure 4-13. Several alternatives of ID_1 are simulated and the parameters of the chosen ID_1 can refer to Appendix I. The average travel time of ID_1 is 15.91 minute, which is 8.93% lower than the average travel time of ID_0. The average stop time of ID_1 is 4.95 minute, which is 32.6% lower than the average stop time of ID_0. The 8.93% improvement on average travel time can lead to saving 8281 hours of total travel time for the 318511 vehicles during simulation period, if incident happens as ID_0. And the 32.6% improvement on average stop time can lead to saving 12687 hours of total queuing time for the 318511 vehicles during simulation period, if incident happens as ID_0.

ID_2: coordinated (ramp metering + multiple route advice)

From the current state monitoring results of ID_1 in Appendix I, it can be seen local ramp metering on S112 (connecting to link 15 of A10 East westbound) improved the bottleneck to a great deal. The reasons for the promising results are further evaluated in section 6.2. From the analysis in Appendix I, two optional detour VMS are added on link 3 and link 13 during the incident period in ID_2. The positions of ramp metering and two optional detour VMS are shown in Figure 4-14. Several alternatives of ID_2 are simulated and the parameters of the chosen ID_2 can refer to Appendix I. The average travel time of ID_2 is 15.14 minute, which is 13.34% lower than the average travel time of ID_0. The average stop time of ID_2 is 4.23 minute, which is 42.4% lower than the average stop time of ID_0. The 13.34% improvement on average travel time can lead to saving 12369 hours of total travel time for the 318511 vehicles during simulation period, if incident happens as ID_0. And the 42.4%

improvement on average stop time can lead to saving 16509 hours of total queuing time for the 318511 vehicles during simulation period, if incident happens as ID_0. The satisfactory performance of CNM on the network level will be further evaluated in section 6.2.

5.2.2 Local level

The local level simulation results of each control design in non-recurrent scenario are presented and compared in this section, focusing on the A10 East westbound freeway stretch. Again, the local level results are studied with the density and queue length (in percentage of link length) characteristics on each link on A10 East westbound. Locally, densities and queue lengths (in percentage of link length) of each link on A10 East westbound are used as the MOE for comparison of CNM control design effectiveness. Densities and queue lengths (in percentage of link length) are presented in each control design as a function of time and space for a visual representation of traffic characteristic evolvement and an impression perspective to the effectiveness of each control design, as shown in Figure 5-9. Figure 5-8 is reminded here for the positions of each link on A10 East westbound freeway stretch.

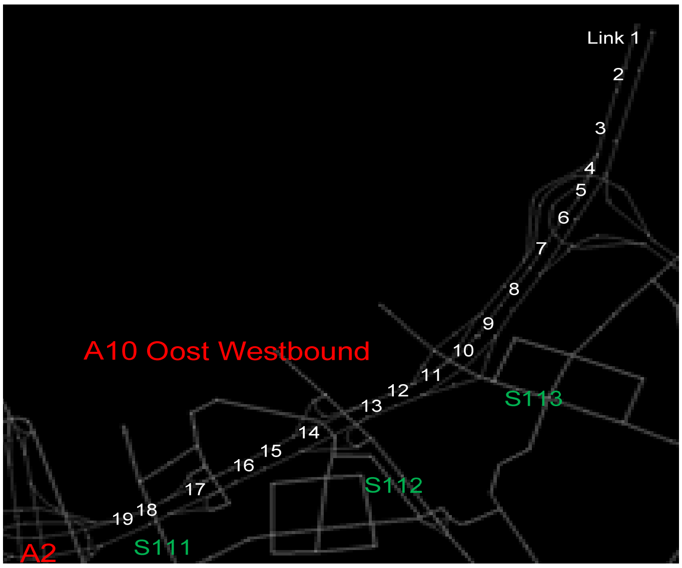


Figure 5-8 Implementation area of control designs for non-recurrent scenario

D_0: base design, without incident

This is the base design without incident or ITS controls. It is the same as the base design used in the recurrent scenario. The only difference is that in non-recurrent scenario, the application area is A10 East westbound.

ID_0: incident, do nothing

Once the incident happens (from 60th minute to 180th minute), the capacity of the incident link drops and the

densities on the links upstream to the incident link increase significantly according to time, as shown in Figure 5-9, row ID_0. A queue is propagating upstream due to the incident.

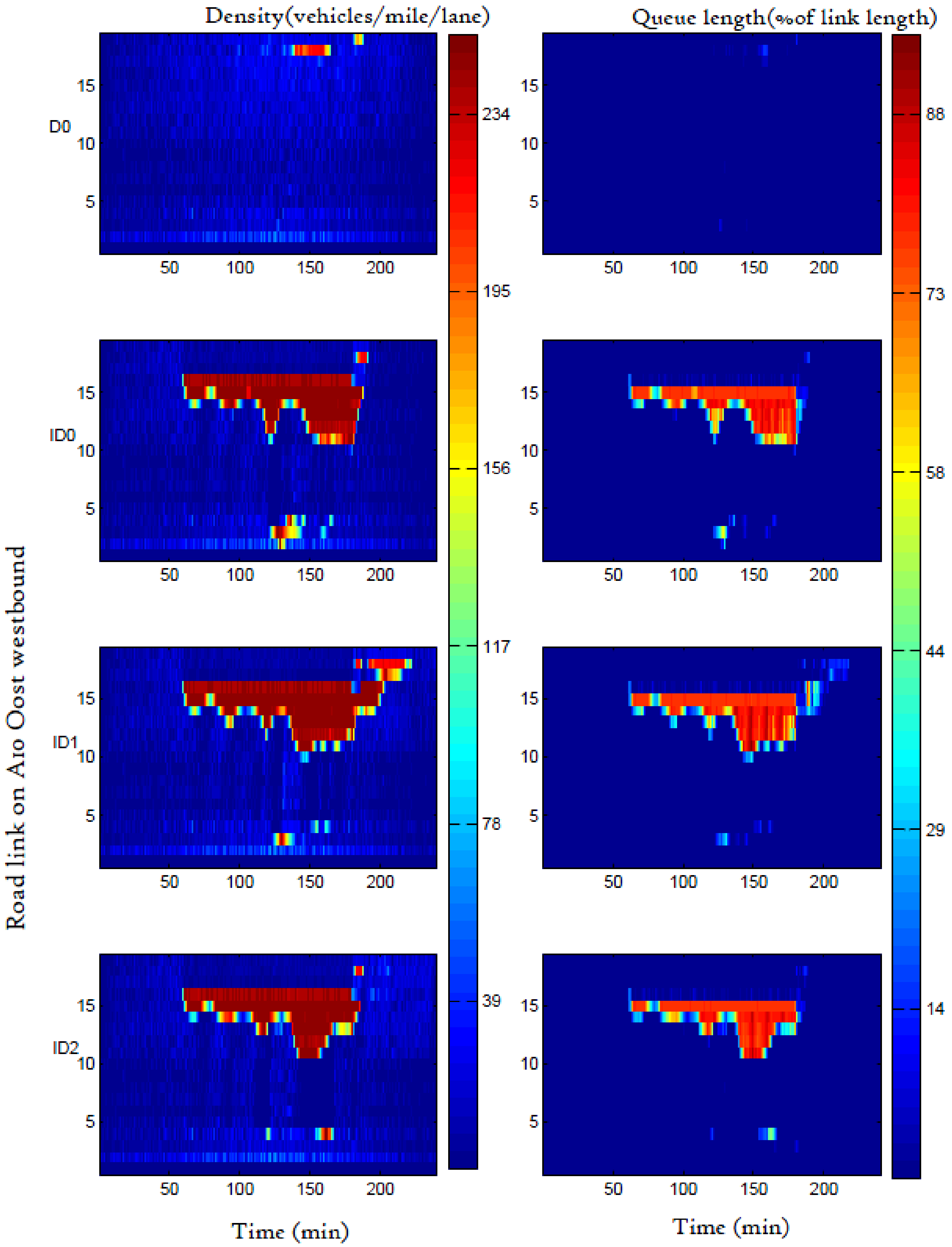


Figure 5-9 Density and queue length (in percentage of link length) on A10 East westbound of four control designs in incident scenario

$ID_{1:}$ local ramp metering

A local ramp metering is deployed at Duivendrecht, connecting S112 to A10 East westbound. With local ramp metering, the densities on freeway A10 East westbound seems have no significant difference from ID_0, as shown in Figure 5-9, row ID_1. One of the reasons could be the capacity of the incident link is seriously limited, to only 20% of its original capacity. One local ramp metering has limited effect on the congestions and queue propagation.

$ID_{2:}$ coordinated (ramp metering + multiple route advice)

Due to the limitation of local ramp metering, multiple route advice VMS are coordinated with the ramp metering. The local level performance of this coordinated control design is shown in Figure 5-9, row ID_2. Compared to ID_1, both the densities and queue lengths (in percentage of link length) are significantly improved in ID_2. This is because the route advice VMS control measures divert part of the vehicles, which wish to travel on A10 East westbound, to other alternatives once the incident happens. Diversion of traffic reduces the traffic inflow to the incident link, compared to ID_1. Therefore, the densities are lower and the queue lengths (in percentage of link length) are shorter.

5.3 Conclusion

In this chapter, simulations of the case study designs are performed. Results are presented and compared. Different types of control measures, ramp metering, variable speed limits, route information, and route advice VMS, as well as their combinations are implemented in different control designs for two scenarios of the case study, using results output from DSP to present and compare their individual and coordination effects on solving recurrent/non-recurrent traffic congestion.

For both recurrent and non-recurrent scenarios, results are presented on the network level and on the local level. On the network level, two MOEs, namely, average travel time and average stop time are used to indicate the performance of each control design. Quantitatively speaking, results on the network level are more informative, considering all vehicles during the simulation period are included and the basic set-ups (as introduced in section 4.1) of these control designs are the same. On the local level, results presentation and comparison are focused on the A10 freeway stretch (implementation area of CNM control designs). Limited by the modelling tool, two MOEs, densities and queue lengths (in percentage of link length) are selected to show the evolvement of these traffic characteristics and evolvement from design to design on the local level. Ramp queue length is supposed to be an appropriate MOE to evaluate local ramp metering and coordinated ramp metering. The ramp queue lengths (in percentage of ramp length) are compared in the local level analysis and some perspectives are shown in

section 6.2 with the implications from the modelling tool.

From the work of this chapter, the effectiveness of each control design are presumptuously summarized and concluded on the network level and on the local level in this section. Simply put, if control designs are effectively planned out according to the assessment methodology, the effectiveness of each control design increases with the level of coordination, excluding some unexpected ordinary performance of some control measures due to the defects of the inapplicable modelling tool.

Recurrent scenario

Network level evaluation

Network level evaluation is performed by comparing MOEs of the overall network. Figure 5-1 and Figure 5-2 show the statistic results of recurrent scenario in the case study. The total travel times are the total hours of travel time, which are measured from the instances vehicles are physically loaded onto the network. Divided by the number of vehicles (318511 vehicles in the case study), come the average travel times. The total travel times and the average travel times are equally effective MOEs considering the consistency of each control design. Due to the size of the network, total travel times are not sensitively perceivable through histograms for results presentation. Therefore, the average travel times of each control design are compared thereafter. Average stop times are the average queuing time for vehicles and indicate vehicle delay.

These aforementioned MOEs can also specify for three categories, equipped, non-equipped and overall. As discussed, the overall performance MOEs is used in this chapter. However, MOEs considering equipped and non-equipped vehicles can imply the different behaviours of vehicles under each control design. Related discussions of the case study can refer to Appendix I.

Based on the analysis of section 5.1.1, several preliminary conclusions can be drawn as follows:

1. Local ramp metering is an effective control measure to relieve recurrent traffic congestion on network level. Both average travel time and average stop time are reduced compared to the base scenario.

2. Coordinated ramp metering overcomes some limitations of local ramp metering and relieves the traffic congestion further, which can be shown from the less average travel time and average stop time compared to those figures with local ramp metering control design.

3. Coordinating variable speed limits shows no improvement at all on the network level. The reasons for mere improvement on average travel time and average stop time could be the defect of the macroscopic modelling tool. Relevant evaluation can refer to Appendix I and section 6.2.

4. Coordinating route information VMS also shows very disappointing results on the network level. It even has worse results than coordinated ramp metering without route information. This could be the implication from the function of congestion warning VMS in DSP, which will be further evaluated in section 6.2.

5. Coordinating route advice VMS shows some promising results finally. With single optional detour VMS, the simulation results of the network level are significantly improved, compared to all the other control designs. This is due to the diversion function of traffic flow by optional detour VMS in DSP. However, when multiple optional detour VMS are coordinated on the network level, the results have hardly improved compared with single optional detour VMS. This unexpected result shows the increasing complexity of coordination between traffic control measures from local level to network level.

Local level evaluation

The densities and queue length (in percentage of link length) on each A10 South eastbound freeway link are used to illustrate the local level improvement by each control design. After analysing Figure 5-4, Figure 5-5 and, several premature conclusions can be drawn on the effectiveness of different control designs on solving recurrent traffic congestion as follows:

1. Local ramp metering control keeps the traffic flow on A10 South eastbound from interruption by limiting the outflow of on-ramp. The densities of most links on A10 South eastbound are lower than that in base design, which relieves the congestion on freeway stretch partially.

2. Coordinated ramp metering control shows more improvement than local ramp metering control on local level. The densities and queue lengths (in percentage of link length) on freeway are further improved. Moreover, the ramp queue length (in percentage of ramp length) on the downstream ramp is improved compared to local ramp metering control.

3. Similar to the network performance, coordinated ramp metering and variable speed limit hardly shows any extra improvement on local the level compared with coordinated ramp metering design. The reason could be the coordination is not optimized or flaw exists in the modelling of variable speed limit in Dynasmart-P.

4. Opposite to the network performance, route information VMS shows much better results on the local level. It seems that route information VMS can divert a certain amount of traffic from freeway to arterials, which locally improves traffic flows of A10 South eastbound.

5. Single route advice VMS shows improvement on the local level as well as on the network level. With multiple route advice VMS, the local network performances are better than that with single route advice VMS on some links whereas worse on the other links. Thus, it is difficult to tell whether coordination of

multiple optional detour VMS has superior performance on local the level.

Non-recurrent scenario

Network level evaluation

Network level evaluation is performed by comparing MOEs of the overall network in like manner to recurrent scenario. Figure 5-6 and Figure 5-7 show the statistic results of incident scenario in the case study. Two MOEs, the average travel times and the average stop times can be specified for three categories, equipped, non-equipped and overall. As discussed, the overall category is used in this chapter. Related discussions considering equipped and non-equipped vehicles of the case study can refer to Appendix I.

Based on the analysis of section 5.2.1, several preliminary conclusions can be drawn as follows:

1. The incident makes the average travel time about 42% worse than the base design without incident. The average stop time is about twice higher than that of the base design without incident.

2. By introducing local ramp metering control, the average travel time is about 9% improved and the average stop time is about 32.6% improved, comparing to the incident design without control.

3. By introducing coordination between ramp metering and two route advice VMS, the average travel time is about 13.3% improved and the average stop time is about 42.4% improved, comparing to the design with incident but without control measures. Besides the ramp flow limitation by the ramp metering, this improvement is also due to the traffic diversion function of the route advice VMS.

Local level evaluation

The densities and queue lengths (in percentage of link length) on each A10 East westbound are used to illustrate the local level improvement by each control design. After analysing Figure 5-9, several premature conclusions can be drawn on the effectiveness of different control designs on solving non-recurrent traffic congestion as follows:

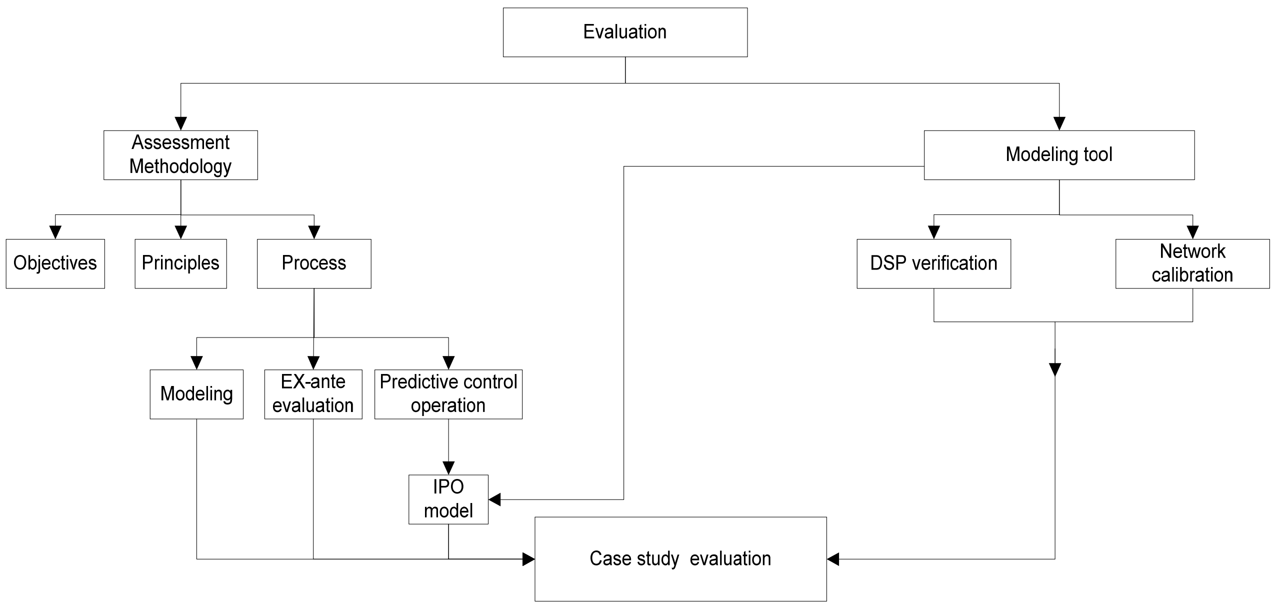
1. On the local level, the effectiveness of local ramp metering on densities and queue lengths (in percentage of link length) on A10 East westbound is not obvious.

2. Route advice VMS reduce densities and queue lengths (in percentage of link length) on A10 East westbound. It can divert vehicles to other freeways or urban roads so that these vehicles can avoid the incident link and traffic flow on the incident link can be reduced.

6 Evaluation

Chapter 5 mainly focused on performing simulation runs with control designs of the case study. Based on the simulation results, a preliminary ex-ante evaluation based on cross-comparisons of each control design was given to describe the directly perceived findings of the CNM effect. The direct perceived findings show the increasing effect of DTM/CNM control designs from local level to network level. But before any conclusive evaluation of the case study, a thorough evaluation work of the assessment methodology framework and the application example (the case study itself) needs to be accomplished.

The purpose of this chapter is to evaluate the proposed assessment methodology for modelling and ex-ante evaluation of CNM with the simulation results of the case study (using the assessment methodology) in order to find out and learn from the implications. To this end, this chapter is organized as shown in Flow Chart 6-1.



Flow Chart 6-1 Organization of evaluation work

Simulation results are obtained by applying the proposed assessment methodology to the case study. Therefore, section 6.1 and section 6.2 respectively evaluate the assessment methodology and modelling tool/case study network. Section 6.1 gives an evaluation of the proposed assessment methodology. Section 6.2 provides an evaluation of the modelling tool and case study network, including verification of modelling tool and a calibration of the case study network. Section 6.3 provides the case study evaluation, focusing on the validity of the simulation results.

6.1 Assessment methodology evaluation

As the first step of this thesis project, the rollout of assessment methodology was presented in section 3.1 and the objectives of this assessment methodology were determined. This section evaluates the principles and process of the assessment methodology, in order to find out the effectiveness and feasibility of this proposed assessment methodology for modelling and ex-ante evaluation of CNM. This section tries to answer the question that to what extent, the assessment methodology is functional to achieve the specific objectives of a given project, in this case, the case study of Amsterdam region.

The purpose of the assessment methodology is to provide an all-around process of modelling and ex-ante evaluation of CNM. To this end, the proposed assessment methodology includes three parts, namely, modelling, ex-ante evaluation and predictive control operation. The interrelations of these three parts are realized through modelling-based, principle-based and predictive operation-based approaches.

Strengths

The three fundamental principles of the assessment methodology are expanding control deployments if necessary, enhancing control degrees if needed and requisite degradation according to priorities. These principles are generated from a distributed hierarchical operational approach and they provide the basic principles for the principle-based assessment methodology. From a narrow sense, these principles also provide three upper level rules for control design and ex-ante evaluation of CNM. Thus, these principles provide solution directions during predictive control operation. The strength of principles instead of specific rules is the flexibility to adapt any specific project by providing solution directions.

The modelling and ex-ante evaluation sound tactically “hand in hand” and strategically optimal to serve the objectives. But they cannot clearly indicate the process of CNM without the linkage of predictive control operation. Therefore, the process of the assessment methodology includes a predictive control operation to provide supervision and control designs which link modelling and ex-ante evaluation together, as shown in Figure 3-1. Thus, the predictive operation-based approach has the strength of connecting various aspects of CNM.

The predictive operation-based approach is operable and practical because it renders CNM practice scalable and systematic to large networks. In addition, it is a relatively simple system to test the principles and realize the objectives. To illustrate, the case study was provided with a good start point during operation by the predictive control operation in order to execute and follow through the control objectives. The different effects between local/isolated DTM and CNM are shown in the simulation results of chapter 5.

Weaknesses

To demonstrate, the assessment methodology was applied to the case study. The predictive control operation (lower part of the assessment methodology in Figure 3-1) is examined here with evaluation of the three "triangles".

The current state monitoring module of predictive control operation identifies and diagnoses current traffic situations after modelling and ex-ante evaluation. This module only provides manual practice in the assessment methodology. For future improvement of the assessment methodology, it could be practiced with automatic systems in field operation. The current state monitoring can introduce external impacts which could lead to noticeable defect since the bottlenecks on a large network are being examined by the analyst based on prevailing prediction results of modelling tool, DSP, in the context of the case study. The modelling tool and the skills of the author both affect the case study inevitably. This is an obvious weakness of the assessment methodology. While the assessment methodology is modelling-based, it didn't include procedure of model choosing. Due to the complexity of CNM on a large-scale network, suitable model is hard to find. Therefore, ex-ante evaluation is difficult to make plausible with modelling-based approach.

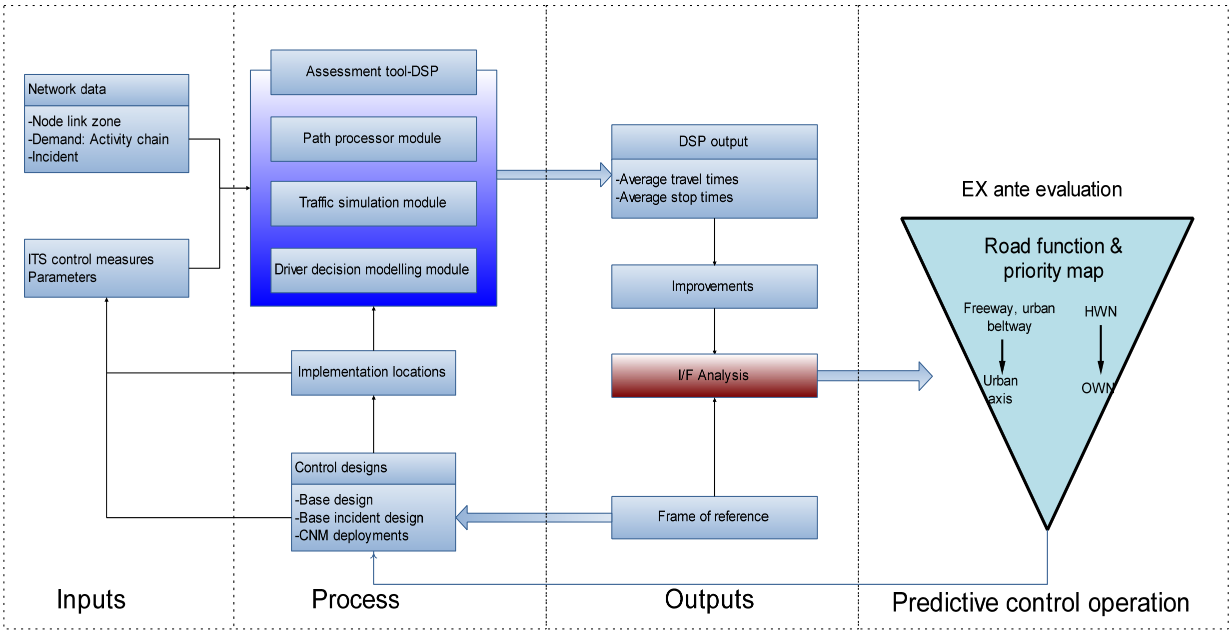
The CNM control design module of predictive control operation proposes control designs to solve the bottlenecks. By means of hierarchal controller, the CNM control design module provides control designs of different levels. To function properly, hierarchical controller needs to be aided with control algorithms. But modelling tool with coordination functions and fit algorithms is scarce if not at all. By this token, the hierarchical controller is largely case-based with the prevailing modelling tool. Case-based approach is complex and leads to many control scenarios, especially for coordinated traffic management on a large size network. Hence, the CNM control design module is not user-friendly and it requires analyst to make complex decisions or perform multiple trials to find a control design. This module is also inefficient and only simple cases are designed without control algorithms embedded in the modelling tool.

The ex-ante evaluation of predictive control operation ranks the control designs by comparing their simulation results to the frame of reference. This process is affected by the simulation results of modelling tool. The ranking is largely knowledge-based and affected by the author's limited knowledge and rules of thumb.

The evaluation above shows that predictive control operation of the assessment methodology could give sub-optimal control designs during control operation, which in turn, affects the modelling and ex-ante evaluation of CNM.

The modelling and ex-ante evaluation are examined here with an IPO model in Flow chart 6-2, focusing on the implications from the modelling tool from an enlarged angle. Predictive control operation connects the

modelling and ex-ante evaluation in the assessment methodology. To illustrate with an application (the case study), the detailed working mechanism is formed into the input-process-output model as shown in Flow Chart 6-2. The purpose of this IPO model is to conceptually show how the modelling tool is involved in the modelling and ex-ante evaluation of CNM. From inputs and process of control designs to outputs of control designs results, the modelling tool played an instrumental role. As shown in Flow Chart 6-2, each step of modelling, ex-ante evaluation and predictive control operation is more or less interconnected to the modelling tool. If a chosen tool turns out to be unfit during practice, it is likely leading to possible “error + error” effect. Here, a point of reflection for choosing modelling tool, besides making a carefully verified choice, is that combing and integrating verified modelling tools (e.g. macroscopic tool on the network level, microscopic tool on the local level and helps from tools with specialized coordination function), in order to make the best out of the modelling tools and avoid using one tool in every step.



Flow Chart 6-2 IPO model of the modelling and ex-ante evaluation in the assessment methodology

The idea of a desired field operation of CNM is to execute an automatic, consistent and responsive control operation on a network with proper modelling and ex-ante evaluation of CNM using the assessment methodology. Many predictive optimal CNM control designs are pre-studied using the assessment methodology (The case study could be one example). During field operation, the current state monitoring module of a network monitors and detects bottlenecks automatically. Then the corresponding CNM control design is selected and operated by corresponding controller of its level. Automation of this process is realized by leading the controller with principles (Road priority and function could be one norm to consider) and controlling their behaviours with pre-specified control algorithm (Heuristic, case-based, anticipatory etc.). Then the CNM control design is

activated and deployment is realized with the proposed assessment methodology. The response of the traffic is continually monitored through current monitoring module and the aforementioned process repeats automatically. Besides short term effect, short “long term” effect and long term effect of CNM are also captured using this assessment methodology. Adjustments to concerned elements can be made to the process of using the assessment methodology in order to provide for optimal CNM practice.

6.2 Modelling tool and network evaluation

This section gives an evaluation of the case study preparation, the modelling tool and the network preparation. The evaluation is carried out in two parts. In section 6.2.1, the modelling tool used in the case study- DSP is evaluated in order to show the capabilities and implications it brought to the case study. In section 6.2.2, the case study network in DSP is evaluated to show its implications to network building and calibration.

6.2.1 Verification of modelling tool

As mentioned in section 3.2, DSP is generally regarded as a mesoscopic simulation tool. The unit of its model is the individual vehicle. In other words, traffic flow in DSP is considered as non-compressible macroparticles. From a microscopic approach, Dynasmart-P assigns vehicle types and driver behaviour, as well as their relationships with the roadway characteristics, which triggered the discussion of mesoscropic traffic flow operation in section 3.2.2. From a macroscopic approach, vehicles moves according to the prevailing average speed of the link, that is governed by basic macroscopic model.

Three aspects of DSP will be assessed in this section. Vehicle loading/simulation mode examines whether activity chain and one shot simulation fit the case study. Traffic flow model examine and verify the modelling of traffic characteristics in DSP. Queue propagation explains how traffic flow is modelled without a capacity constraint on the traffic flow model and the implications it brings to the calibration of the network and the study of CNM effect.

Vehicle loading/simulation mode

In DSP, there are two methods for vehicle loading. The first method is to specify and load time-dependent OD matrix of origin-destination zones at different time intervals. The second method is activity chain, which loads vehicles through pre-specified vehicle files and path files [30].

The most significant difference between these two methods is the individual consistency between simulations. Time-dependent O-D demand loading scheme cannot grantee generating its vehicles identically for each simulation run. Comparability of different traffic management control designs, which closely relates to path

selection and driver behaviours, requires the consistency of vehicle departure pattern, initial path etc. Activity chain loading scheme can generate vehicles according to vehicle files and path files. This is used in the case study because the tasks include evaluation of different control designs in the case study. CNM control designs are based on previous DTM control designs and consistency of network input is crucial.

But, a predicament of activity chain loading scheme is that it need vehicle files (path.dat) to load vehicles. These files need to be prepared beforehand with dynamic traffic assignment using calibrated OD-demand. Extra steps have to be carried out before using activity chain loading scheme with vehicle profiles. This also implies that manipulating the demand using activity chain loading scheme is time-consuming.

Two types of simulation mode can be used in DSP, namely one-shot simulation and iterative consistent simulation. One-shot simulation is used in the case study. Verification of this simulation mode is given below.

One-shot

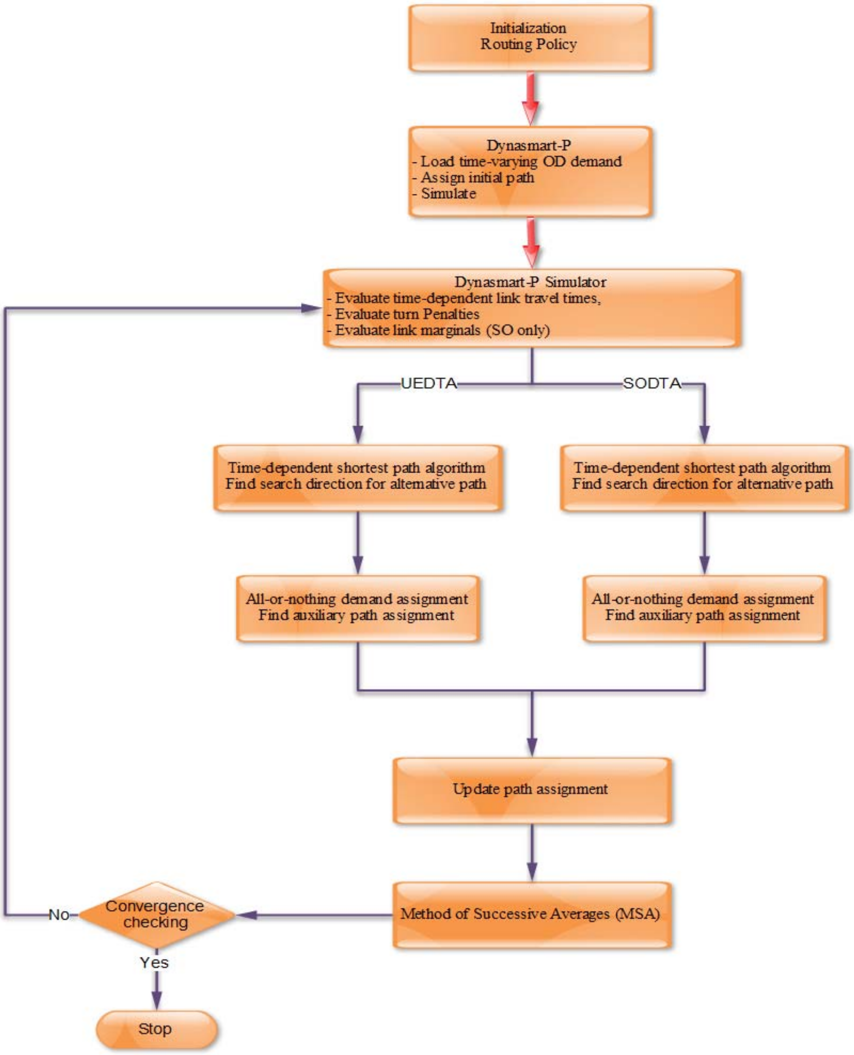
One shot-simulation using activity chain loading scheme is used in all the case study simulation runs. When one-shot simulation mode is chosen in DSP, simulations proceeds with a fixed time interval. Vehicles are assigned to current-best-paths, random paths or any pre-determined paths (historical paths). It is normally used to model traffic patterns and evaluate overall network performance, possibly under real-time information systems, for a given network configuration (including traffic control system) and given time-dependent demand pattern [30]. Since the main goal of the case study is to investigate the effectiveness of various CNM control designs on recurrent and non-recurrent scenarios, the function of one-shot simulation fits this purpose. Therefore, one-shot is used in the case study. The modelling approach of one-shot simulation procedure is shown in section 3.2.2, which integrates a traffic simulation module, a path processor module, a driver decision modelling module which takes information supply into consideration. One-shot simulation can load vehicles with both loading schemes discussed above. Activity chain is used as the loading scheme to ensure the consistence of basic network input. But the drawbacks of this is only short term effect of CNM can be observed. Short "long term" effect and long term effect of CNM are not taking into consideration, which implicates the ex-ante evaluation and thus implicates CNM field operation without giving consideration to these matters.

Iterative

Iterative solution mode in Dynasmart-P is a heuristic iterative procedure in which a special purpose traffic simulation model is used to model activity-based travel, represent traffic interactions in the network, and evaluate system performance under a given assignment [30]. The objective is to determine the minimum travel time (or least generalized travel cost in case of link pricing consideration) for each individual traveller of an assignment with class 2 and class 3 vehicles. Vehicles are allowed to exit the network at intermediate

destinations along their travel path to carry out individual activities so that they have no effect on the network traffic during their midway activities. Upon completion of an activity, the trip maker resumes its trip again from this destination to complete the trip according to its pre-specified travel pattern. Once the vehicle reaches its final destination, it exits the network. The procedure of iterative solution is described in Flow Chart 6-3 [30]. After initialization, Dynasmart-P loads OD matrix and assigns initial paths to vehicles. Then the simulator calculates travel times, penalties and link marginal under the set of departure time and path assignment. Then for two types of DTA, either user equilibrium or system optimal, time-dependent shortest path algorithm will be used to determine the shortest path and to search directions for alternative path. Depends on the calculations results, all or nothing instruction will be executed to assign all travel demands or to generate an auxiliary number of vehicles on current path. The new paths should be included into the path set to update the path assignment. Then the method of successive average is used to perform convergence checking. If the convergence criterion is met then the simulation is stopped. Otherwise, the simulation goes back and starts the next iteration with calculation of travel times, penalties and link marginal with updated path assignments. If the convergence criterion is met within a pre-specified number of iterative run of the assignment, the simulation stops; otherwise, the simulation stops after the pre-specified number of iterative run.

In iterative solution mode, O-D demand matrix must be used as vehicle loading method and some vehicles have to be defined as user equilibrium or system optimal user classes. During an iterative run, class 1, 4 and 5 will be assigned with their shortest paths based on prevailing conditions obtained from the last assignment iteration. If no vehicles were coded as UE or SO classes, then the iterative assignment procedure is replaced by a one-shot simulation assignment. Although CNM effect under dynamic traffic assignment is desired from a short “long term” view, allowing vehicles of SO or UE classes to respond to VMS information in DSP will result in inconsistent, unstable, and non-convergent path assignments. Because the VMS will provide paths that are based on the prevailing conditions which do not account for the future evolution of traffic and as such are not guaranteed to be optimal. Therefore, iterative solution mode is not suitable for the experiments of the case study. Nonetheless, DTA with iterative run is important from traffic engineering aspect and some recommendation is give in chapter 8.



Flow Chart 6-3 Solution algorithm of iterative UE and SO Procedure in DSP

Traffic flow model

In section 3.2.1, it was introduced that the speed to density function on freeway is characterized by Type 1 dual-regime modified Greenshield model in DSP. A minimum speed at jam density has to be specified to ensure that the simulation does not "shut down" due to zero speeds [37]. However, in reality or in a more realistic model, vehicle speeds should be zero when the density of the link increases to jam density. The non-zero minimal speed suggests the flow rate increases with density to possibly infinite, if the following equation is applied:

$$q = k \times v \tag{6.1}$$

As introduced in section 3.2.1, DSP calculates the flow rate based on the actual number of vehicles transferred to the downstream link during each simulation interval and uses equation (3.10) to constrain the actual flow rate from upstream link to downstream link. This flow rate calculation method will be validated by comparing

simulation results to conventional theoretical results in the following example.

One-shot simulation is performed in base scenario and the simulation results on link 784 (DSP term, in reality, this link is on A10 Oost eastbound, knooppunt Amstel) are kept. Link 784 is selected as the research object because during the simulation, the density on this link varies from 0 to the jam density. This provides enough (density, flow rate) data points to validate the flow rate to density relationship over the whole density range. Another reason is that saturation flow rate of this 5-lane freeway link on A10 East eastbound (default value is 2200vhphpl for freeway, 2000vhphpl for ramp and highway, 1800vhphpl for arterials) is surprisingly low. The geographic description of link 784 in DSP is given as follows:

358	834	0	0	1129	5	24	0	62	1254	1140	1	0

upstream node of link 784	358
downstream node of link 784	834
number of left-turn bays	0
number of right-turn bays	0
length of link 784	1129
number of lanes	5
traffic flow model type	24
posted speed limit adjustment margin (mph)	0
posted speed limit (mph)	62
maximum service flow rate (pc/hour/lane)	1254
saturation flow rate (vehicles/hour/lane)	1140
type of link (1=freeway)	1
grade (%)	0

From the 7th and 12th items, the traffic flow model of link 784 is type 24 and the link type is freeway (assigned with “1”). Corresponding to the file ‘TrafficFlowModel.dat’, the parameters of type 24 traffic flow model are

shown as follows:

24	1			
17	95	6	200	5.370000

1st item: 17vehicles/mile/lane, break point density

2nd item: 95miles/hour, speed intercept

3rd item: 6miles/hour, minimum speed

4th item: 200 vehicles/mile/lane, jam density

5th item: 5.37, parameter α

Now a one-shot simulation of the case study is performed with DSP to check if the simulation results of DSP are valid. During the four hour simulation period, starting from 15:00, the traffic conditions of link 784 varies and its densities and corresponding flow rates are kept in record, outputted per minute and plotted as the green dots in Figure 6-1. Meanwhile, the q-k relationship of conventional macroscopic model using modified Greenshield model (with the same parameters used during this on-shot simulation, the 1st to 5th item of type 24 traffic flow model) and equation (6.1), are calculated and plotted in Matlab, as the blue dot curve shown in Figure 6-1.

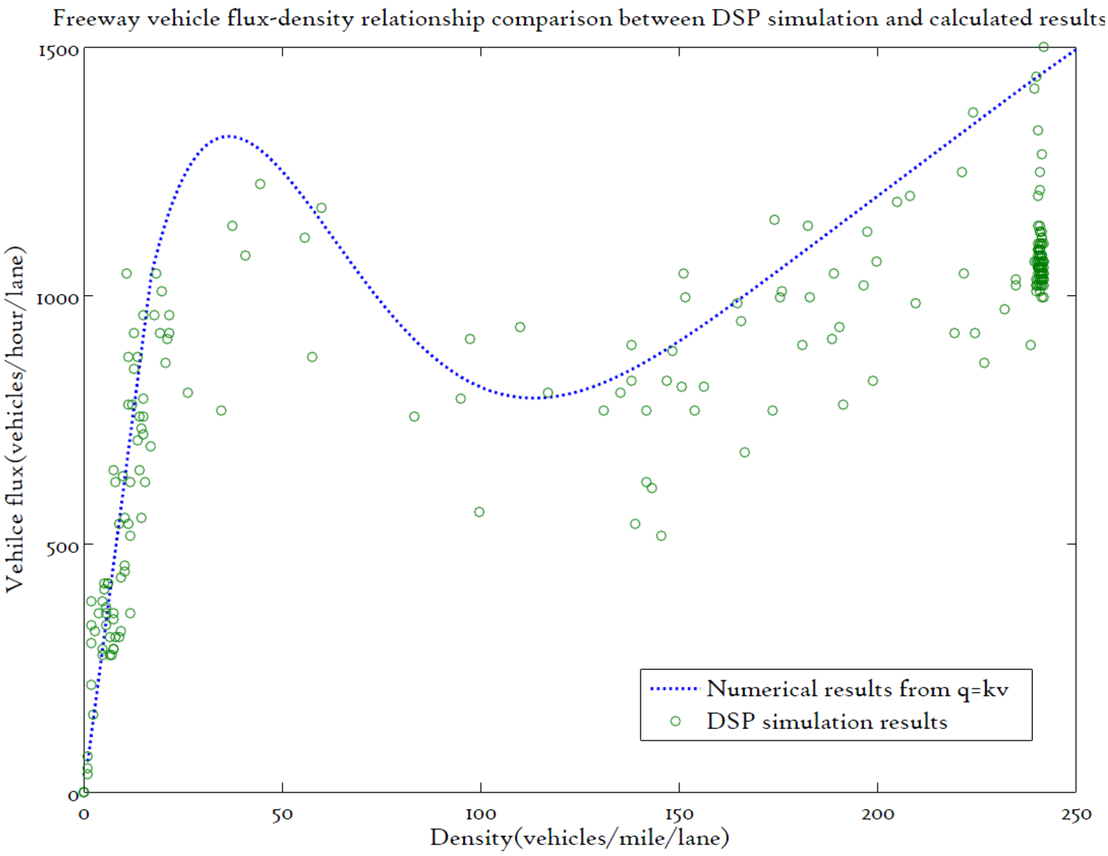


Figure 6-1 Flux-density relationship: q=kv and DSP simulation result

From Figure 6-1, several findings are put forward on link flux-density relationship and the effect of minimum speed in DSP.

1. The unconditional existing of minimum speed is not realistic. As discussed before, a more realistic solution is to set minimum speed at zero at jam density. However, a non-zero minimum speed is necessary to avoid DSP simulation from shutting down for operational purpose. This effect can be seen in the calculation of distance that vehicles can move from a node to its following link, as shown in equation (6.2).

$$R'_{i+1,m,t+1} = [\Delta t - \left(R_{i,m,t} / v_{i,t+1}\right)] \times v_{i+1,t+1} \tag{6.2}$$

   Where,

   Δt: Simulation time interval.

   $v_{i,t+1}$: Mean speed in link i, during the $(t+1)^{th}$ time step.

   $R_{i,m,t}$: Distance from vehicle m's current position to the downstream node of current link i at the t^{th} time steps.

   $R'_{i+1,m,t+1}$: Distance from vehicle m's current position to the downstream node of the following link (i+1) at the $(t+1)^{th}$ time steps.

   It can be seen that an expression $\left(R_{i,m,t} / v_{i,t+1}\right)$ is used to calculate the moving distance of a vehicle on the current link i. If the minimum speed is set to zero when the density on link i equals to jam density, then this expression leads to infinity mathematically, which has no physical meaning.

2. The q-k relationship of DSP using conventional macroscopic identity q=kv the v-k relationship in DSP looks highly questionable at high density regime (higher than 100vehicles/mile/lane) but seems reasonable at low density regime. Due to the minimum speed, it seems plausible that the theoretical flow rate increases with density at high density regime, which is not realistic. Although DSP doesn't use this method to calculate flow rate, the simulation data of flow rate still show increasing trend after density reaches over jam density.

3. In the low density regime (mainly before break point density), DSP simulation results are in accordance with the q-k relationship of conventional macroscopic model.

4. In the high density regime, DSP simulation results show deviations from conventional theoretical results (blue curve). This is because DSP has constraints at node to suppress the number of vehicles passing from link to link, as shown in equation (3.10). And the actual flow rate is determined by the transfer flow (flux from link to link), also known as the number of vehicles that can be transferred to downstream link. At high

density regime, the actual flow rates of DSP simulation fluctuate because the lack of appropriate constraints in equation (3.10), such as link capacity, which will be discussed below in queue propagation.

Queue propagation

DSP considers all vehicles in two states, moving or queuing. In fact, since queuing process using link-node pass is essential for the mesoscopic operations in traffic simulation module of DSP, queue propagation algorithms was mentioned in section 3.2.2.

As discussed above in traffic flow model evaluation, DSP doesn't retain a capacity constraint for traffic flow. However, DSP constrains the number of vehicles transferred to downstream link, as shown in equation (3.10). The simulated traffic flow of link and its relations to the other two basic macroscopic traffic characteristics: density and velocity are shown with an example in Figure 6-1. The tentative findings on flux-density relationship already reveal that such a simulated traffic flow can influence the performance of local control measure. However, the implications it brings to the case study network calibration and consequently, to the simulation results, are profound and inexplicable. As one of the most pressing limitations of the modelling tool, the queue propagation issues together with the simulated transfer flow are further discussed here as a coherent process with examples from the case study.

Issue one: Non-existing/Ineffective flow rate capacity constraints

This issue of link capacity is put forward here because the underlying flow rate is closely related to link-end queuing. Two parameters, seemingly related to capacity, saturation flow rate (SA) and maximum service flow rate (SF), were mentioned in the DSP system design manual. The saturation flow rate applies to downstream vehicles discharging from a queue (vehicles per hour per lane). The maximum service flow rate specifies the maximum capacity of moving vehicles along a given lane and provides an upper bound on the flow rate through a section under any condition. For freeways, flow rates need to be expressed as passenger cars per hour per lane (pcphpl). For all other link types, the unit of flow rates is vehicles per hour per lane (vphpl) [31]. The purpose of using different units could be due to the computation process of DSP. When updating link density with number of vehicles on the link (vehicle trajectories kept in record), the lengths of vehicles and vehicle types (car or truck) are in fact taking into account. So, passenger car equivalent (pce)-values are used as for weighting different types of vehicles in order to remedy the inaccuracy of using number of vehicles for link to link transfer flow, spare space on the downstream link and link density update thus link speed (Trucks have higher pce-values and thus contribute relatively more than cars to the total density).

However, despite these efforts in DSP to adjust the physical capacity of links and SF on freeways [31], it seems that these two parameters are not link capacity constraints but ambiguously affect the transfer flows from link to

link. Similar findings have been found in some parallel studies [40, 48]. Although the findings are inconsistent and some of the conclusions, as far as the author considered, are fallible, the basic ideas and research initiatives are in line. The theoretical evidence can be explained with a simple example. Figure 6-2 shows a simple stretch of three freeway link i-1, link i and link i+1. Link i between node 2 and 3 is a freeway bottleneck and the length of this bottleneck is quite long. If there is no capacity drop between node 3 and 4, one could expect that a queue begins to form at node 2, as shown in the realistic queue propagation at the bottom of Figure 6-2. But in DSP simulation, if the length of this bottleneck is not split properly, the second term $[k_j \times l_{i+1} \times nol_{i+1} - (NV_{i+1,t} - VO_{i+1,t})]$ in equation(3.10), $q_{i,t+1} = Min\{VQ_{i,t}, [k_j \times l_{i+1} \times nol_{i+1} - (NV_{i+1,t} - VO_{i+1,t})], k_j \times l_{i+1} \times nol_{i+1}\}$, becomes ineffective as a constraint. Thus, the supply constraint of link i (bottleneck link) is no longer effective and a queue could start at node 3 (as shown in the top of Figure 6-2), instead of node 2 (as shown in the bottom of Figure 6-2). In this case, link i between node 2 and 3 will be fully occupied before queue starts at link i-1.

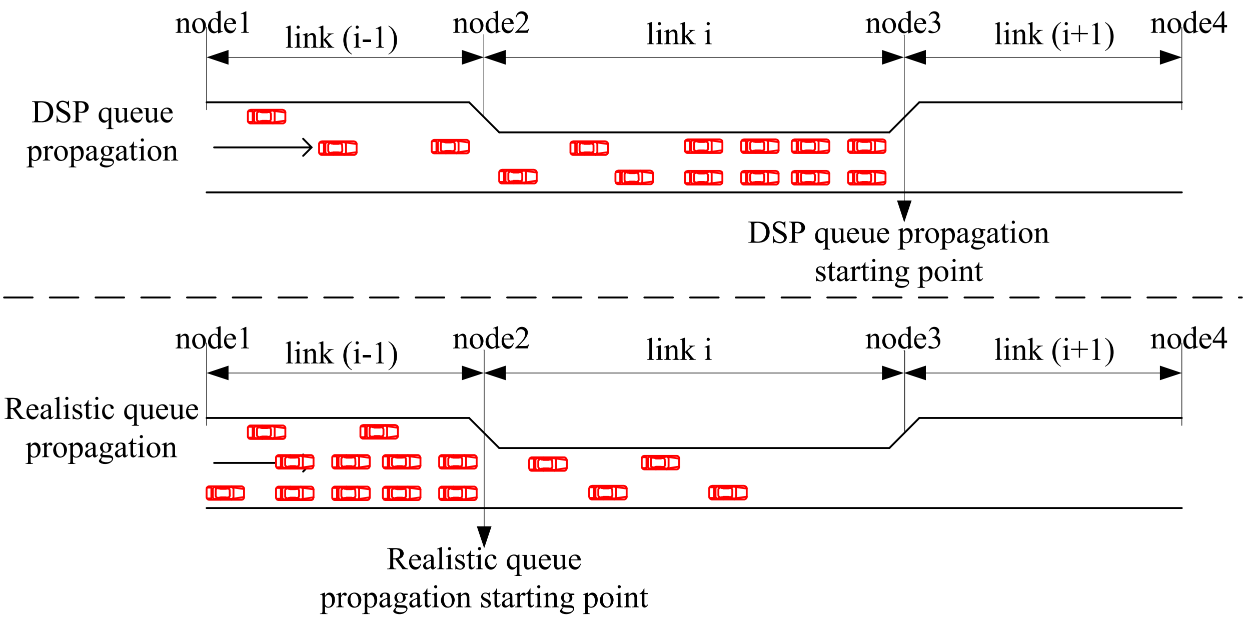


Figure 6-2 Freeway bottleneck queue propagation comparison between DSP and realistic model

Regarding flow rate constraints, some findings and possible explanations can be conjectured from the case study in this thesis project:

1. The flow rate capacities of links (in the approach of conventional macroscopic traffic model, providing with the first order flow theory) indeed exist in DSP, but it seems to be a fix set of values only specify link types in a general term. The default value is 2200vhphpl for freeway, 2000vhphpl for ramp and highway, 1800vhphpl for arterials. Manipulating SA may result in changes of link inflow capacity for the signalized

intersections (under the premises that the link is set to be arterial link and connecting to a signalized intersection). But manipulating the SA and SF cannot result in changes of the flow rate capacities of freeway links. The main reason could be the link-node pass transfer in traffic simulation module (see section 3.2.2) treats the nodes between freeway links as if they have continuous green. In addition, the node saturation flow rate of freeway link is fixed at a much higher value (2200vhphpl), in other words, without nodal constraints to properly respond to traffic dynamics such as network degradation or capacity drop.

2. The effect of changing SA is mainly shown in calculation of travel times. As shown in section 3.2.2, after traffic simulation module, one of the important link properties, the link travel times are calculated at the end of every time step and sent to path processor module for finding current path trip times. The travel time consists of the moving time and the queuing time (time for moving in queue). And the queuing time is calculated by dividing the queue length by a moving average of the discharge rate (SA) over several time steps [37]. Thus, the travel time, the vehicle positions and link densities can be slowly affected by manipulating SA and SF [48](the experiments ideas and raw simulation results in the appendix of this parallel study are informative).

3. For DSP, the flow rate of link is the link to link flux. As shown in equation (3.10), the three terms on the right side of the equation are the constraints to flow rate. This equation can be generally considered as an application of the Godunov scheme [49]. Godunov scheme is the most commonly used and well-established method to determine the fluxes by comparing the "demand" of cell i and the available "supply" in cell i+1 [7].

   In DSP, the mischief begins when the first term (demand of link i), the second term (supply of link i+1) and the third term (constraint of demand from link i) are not effectively simulating the constraints of link-node transfer. The lack of constraints leads to in unrealistic queue propagation and over-capacity volume around the freeway bottlenecks. The studies of traffic management, thus the case study are also affected since the one of the main objectives of dynamic traffic management are to resolve potential bottlenecks. The difficulties it brought to the case study calibration will be discussed in section 6.2.2.

4. A possible amending solution (besides introducing enhancement of constraints to DSP) would be to manipulate the link length and number of lanes carefully in order to achieve a moderate solution. For example, DSP simulates incident by reducing the capacity with effective lane miles ($l_i \times nol_i$). Another example would be to increase the number of lanes of the centroid connectors of generation/destination links in order to reduce vehicle entry time (included in average trip time) or exit time. But without flow rate constrains, manipulating road characteristics is a complicated process, which could bring external effects to dynamic CNM control designs. And it also leads to unreliability for control strategies such as static

infrastructure adjustments.

Issue two: The density of any queue is the pre-specified jam density, moving with the pre-specified, non-zero minimum speed (jam speed).

This assumption of DSP is stirring up many opinions against the queue propagation model in DSP because this queue density assumption is inconsistent with both theoretical and empirical evidence [40]. An empirical impression of queue on a road network is that the queue density should be in direct proportion to the severity of congestion on a freeway bottleneck. The density of queue, however, could be at jam density when vehicles are temporarily stopped and waiting for green at a signalized intersection.

Issue three: DSP simulations could “capture” the propagation of queue from link to link, but the propagation of queue is inaccurate and the vehicle position, thus the vehicle trajectory is deviated from reality when the vehicle is close to a node.

From the queue propagation algorithms in section 3.2.2, during step 5, updating vehicle location and queue list, if a vehicle is not able to transfer to the next link at the end of this simulation time step, the position of this vehicle will be assumed to be at the link-end node. Therefore, the position around node, of course, some records of the vehicle trajectory is not accurate.

If we take a second look at the simulation steps in section 3.2.2, the vehicles in a queue list are assumed to be taking up no space of a link and vertically stacking at link-end node while waiting to pass the node. Since the vertical queue model never predicts a queue spill-back situation in which a queue propagates across the link entrance and thereby blocks the intersection, one may speculate that there is no queue spill-back in DSP.

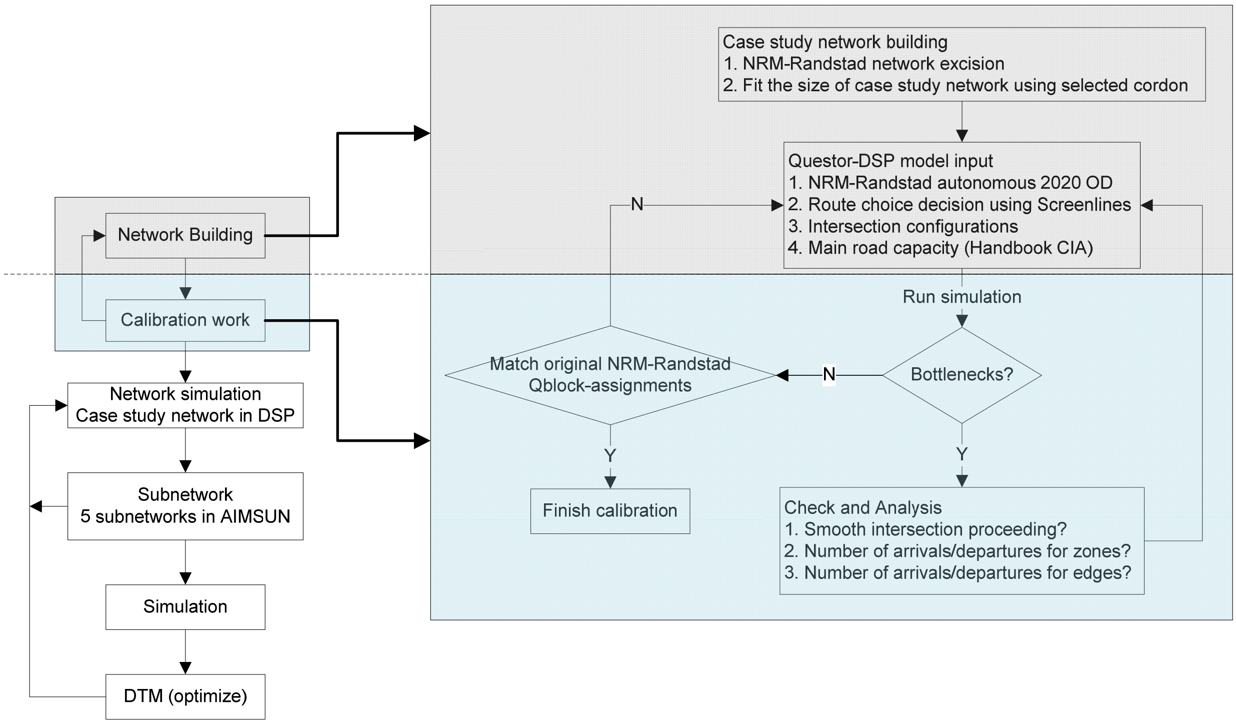
To clear the appearance of wrong vehicle position leads to wrong link density, thus wrong velocity, it is important to know that the number of vehicles on a link and the vehicles lengths are in fact considered during computation. This is the main reason of queue length expressed in term of percentage of the link length in DSP. Without the holistic underlying computation process of DSP, accuracy of link flow, link density and velocity are undeterminable. This renders many MOEs of no use for results evaluation. Anyhow, the poorly graphical representation of queue on a link in DSP interface could be given the benefit of the doubt of a macroscopic presentation. In addition, the FIFO (first in first out) rule is kept in DSP with the vehicle order in the queue list.

6.2.2 Calibration of case study network

As mentioned in section 4.1, the case study adopted a pre-calibrated network from DHV and Rijkswaterstaat, which was used for planning the Schipol-Amsterdam-Almere project (the SAA project, undergoing since 2011).

Considering this model takes into account the future traffic demand and the undergoing infrastructure adjustments, it was seemingly suitable to be the network for the case study. However, accurate evaluations of CNM effects depend on the baseline traffic conditions of each scenario, which depends on the selection of model parameters and the calibration methodology of the case study network. This section tries to provide an explanation and evaluation of the calibration work of the case study network [46].

Flow Chart 6-4 shows two processes. On the left, the process of the SAA project is described. Building the network and calibration work of the network are the first two stages and they are related to this section. On the right, details of network building and calibration work are presented in order to show the formation of the case study network.



Flow Chart 6-4 the case study network calibration

The case study network building has two steps. The first step is to obtain the static NRM-Randstad model, including data of traffic distribution of the base year 2010 and future year 2020, and to make a road network excision (bigger than the case study network) from NRM-Randstad model. The NRM-Randstad model concept is consistent with the state-of-the-art forecast such as the National Model forecasting system (LMS). Based on the base year 2010 and assumptions regarding socio-economic developments, the autonomous traffic demand of 2020 was generated by NRM model. Unfortunately, the static NRM-Randstad model (built with Qblock assignments) cannot change into dynamic model using selected-cordon. Therefore, the second step is to re-build the network in Questor-DSP with the excision network of NRM model and to cut the Questor-DSP network into

the case study network with selected-cordon. This is the initiative for the calibration work.

Calibration means determining the values of the model parameters in such a way that an agreement (usually matching as much as possible) is obtained between the calculated values of the model and the observations [50]. For the case study, equilibrium assignments and associated calibration program of DHV were used to check the transfer and make sure the Qblock-assignments model and Questor model fit as much as possible. So the calibration begins with determine the road sections on the edge and main road sections of the case study network by comparing the differences of Qblock model and Questor model. Screenlines are used for determine major route choices (such as A9 or A10). Since original intersection configurations from Qblock model causes gridlocks in the dynamic Questor model, intersection control configurations, based on current traffic regulations, are constructed for the case study so that traffic can proceed. The main road capacities are determined with Handbook CIA (Capaciteitswaarden Infrastructuur Autosnelwegen) and specific capacities at four sites are increased according to the consultations from Rijkswaterstaat.

After the network building and the calibration "war" [46], the case study network in Questor-DSP contains the inputs needed and simulation runs are performed in order to check bottlenecks of the networks. If bottlenecks are detected, then intersections are checked to see if it is proceeding properly. The arrivals/departures for zones are checked to ensure they must comply with the original NRM model and the arrivals/departures for edges are checked generally. If no bottlenecks are detected and simulation results match the original NRM-Randstad Qblock-assignments, the calibration ends.

Calibration is further carried out for five sub-networks of the case study. After network calibration, microscopic software, AIMSUN is used to further validate/verify the model parameters on A10 South, A10East, A2, A9 West and A9 East.

DSP, as discussed in section 3.2.3, has quite a realistic assessment of the route choices and therefore the distributions of traffic are calculated in Questor-DSP. This determines the amounts of vehicles on the approaches and the amounts and directions of vehicles out. These amounts are then converted from DSP to AIMSUN.

AIMSUN is a micro-simulation package where all vehicles have their own behaviours and hence individual rates are calculated. Due to the stochastic process with many variation and heavy computational processes, AIMSUN can only be applied to the five sub-networks. With detailed analysis of network design issues using AIMSUN, numbers of lanes and lengths of links at the approaches of intersections or freeways with a series of connections can be determined. This is highly important since effective lane-miles of links in DSP affect the link capacities and thus, simulation results of future traffic management designs.

Due to the limitation of knowledge, the specific validation/verification process from AIMSUN to Questor-DSP

cannot be specified here. Therefore, how trustworthy are all the traffic flow models used in the case study cannot be determined from a microscopic point of view. Nonetheless, one can speculate that adjusting the model parameters usually starts by using default parameters (in our case, the parameters from the network calibration). These parameters are changed in accordance with a theoretically sound calibration methodology until various observations from simulations, such as flows or travel times, match observed values (data from NRM-Randstad). These verified parameters for sub-networks are sent back to Questor-DSP in order to form the case study network with calibrated and validated parameters.

Despite many software models and techniques developed for traffic engineering, the state-of-the-art calibration systematic methodologies have not been agreed upon. Integrating microscopic model and macroscopic model for calibration, in our case, AIMSUN and DSP (and other associated calibration programmes of DHV), sounds like a possible way to calibrate a large network. This kind of method is certainly not new. The handling of such combinations has always caused controversy. Without detailed calibration process, the author is also not sure that to what extent, the case study network has been calibrated. So the control designs are limited to deploy on the calibrated and verified sub-networks (which basically cover most motorways) in order to avoid influence of insufficient calibration as much as possible.

Although calibrated, some of the problems arise in the case study network and their implications to the case study evaluation are discussed in the next section.

6.3 Case study evaluation

Validation of the case study simulation results is performed in this section. The purpose is to show the implications to CNM results evaluation in order to learn and reflect for future enhancements of CNM practice.

Ranking of CNM control designs

As explained before, the control designs of DTM and CNM are set up on the same base with the same vehicles, traffic distributions, departure times and vehicle trajectory (ensured with activity chain loading). Simulation results are retrieved from one shot simulation run for each design. In fact, k-alternatives were tried out for each design and the alternative with the best results are kept to be each control design that showed in chapter 5. Despite the disturbances and inaccuracy of “Trial and error” during scoping of best alternative for each control design, some interesting results and phenomena about CNM are clearly shown.

According to the simulation results evaluation, each control design is being ranked on their performances on the network level and local level. The potential benefits of these controls are also deduced and listed in Table 6-1. But, since the related performance indicators for evaluating potential benefits, such as flow rate, speed, and

queue propagation are not informative due to the implications of the modelling tool, these evaluations are not shown in chapter 5. But the simulation details and possible conclusions can be found in Appendix I.

Table 6-1 shows an overview of the CNM control designs performances under recurrent and non-recurrent scenarios.

Scenarios	Control designs	Network level	Local level	Potential benefits				
				Increase throughput	Travel Speed	Delay onset of freeway breakdown	More informed driver behavior	Increase number of finished trips
Recurrent	LRM	+	+	+	+	+	-	-
	CRM	++	+	+	+	+	-	-
	VS+ CRM	++	+	+	-	+	+	-
	RI+CRM	+	++	++	++	+	-	-
	RA+CRM	+++	+++	+++	++	++	++	+
	2RA+CRM	+++	+++	+++	++	++	+++	+
Non-recurrent	LRM	++	+	+	+	+	-	+
	RA + LRM	+++	++	++	++	++	++	++

Table 6-1 CNM control designs performance summary under recurrent and non-recurrent scenarios

The legends of scoring and control design coding are shown below.

Legend of performance score:

--slight deterioration

-, no improvement

+, good performance

Legend of control designs:

LRM: local ramp metering

CRM: coordinated ramp metering

VS: variable speed limits VMS

++, better performance RA: route advice VMS

+++, best performance RI: route information VMS

According to Table 6-1, the following phenomena can be concluded. Under recurrent scenario, local ramp metering can improve the traffic conditions on both network and local level. Coordination of ramp metering brings obvious further improvements on network level but not on local level. Coordination of route advice VMS brings quite noticeable further improvements on both network level and local level while it is hard to tell whether coordination of multiple route advice VMS brings even further improvements. In contrast, coordination of variable speed limit has no further improvement at all. Coordination of route information VMS brings backwards improvement on the network level but show further improvement on the local level.

Under non-recurrent scenario, ramp metering control can improve the incident congestion on both network and local level. Coordination of route advice VMS control can improve the incident congestion even further on both network and local level.

Another interesting phenomenon is that control measures, such as ramp metering, route advice VMS and their coordination show more obvious improvement under non-recurrent scenario than recurrent scenario.

Validity of the case study evaluation with DSP

The validity of the case study evaluation has raised many questions. One main question is pointed to the simulation results of DSP.

DSP is a global tool to show the effect of various control measures but as discussed in this chapter, it is not suitable for optimizing dynamic traffic management such as signal control, ramp metering and VMS control since several flaws have compromised the simulation results and performance indicators of DSP. In addition, DSP is by large a macroscopic tool, it cannot show effects of traffic control measures with which requires microscopic features and evaluations, such as weaving, traffic separation, car following, platoon dispersion etc. By the same token, it cannot show most of the infrastructure adjustments such as weaving marking, dynamic lane control, rush lane, junction lane control etc. One reason is that link lengths and number of lanes are highly sensitive to link capacity in DSP. So making infrastructure adjustments could easily result in inconsistency of performance. The other reason is that DSP only provides macroscopic features of road network. Different lanes on a link cannot be simulated.

Perhaps the most pressing problem for CNM practice in DSP is that DSP doesn't provide automatic coordination between control measures. To remedy the problem, several extreme artefacts were used during CNM practice, for example:

1. Coordination of control measures has to carry out in a clear order, based on previous control design results and consistency between them. The CNM practices on a medium size network are over-elaborate because coordination of any control measures needs to be applied, simulated and evaluated in order to provide a base for any more changes, preferably, according to the progressing of planning horizon. This artefact is to ensure that coordination of control measures can be clearly evaluated and problems can be detected so that counteractive effects of coordination can be avoided as much as possible and CNM practice on DSP doesn't become extensively unrealistic. But even so, there is no absolute guarantee that the new control design has a superior performance since this artefact only considers the action of newly implemented traffic control measures but the reaction of the network and existing control measures is not easy to predicted. Instead of proactive controls, this coordination artefact has a reactive nature.

2. Dynamic lane change control is tried out with freeway HOV lane control and intersection signal coordination is tried out with results from external signal optimizer. Despite these efforts, DSP gives questionable simulation results. These unsuccessful artefacts in the attempt to emulate more control measures manifest that DSP cannot deal with circumstances such as lane change, car following, overtaking manoeuvres and platoon dispersions that require microscopic analysis of traffic characteristics, even though many such functions are provided in DSP, such as variable speed limit and intersection control.

All in all, Dynasmart-P needs many enhancement works before it can optimize dynamic traffic management. It urgently needs proper coordination solution before becoming a desired tool for CNM evaluation. Using DSP as the modelling tool has certainly led to unreliable validity of CNM practice.

Implication to traffic demand

The demand of both recurrent and non-recurrent scenario of the case study is originated from NRM-Randstad model prediction for future year 2020 based on base year 2010. Although the demand is a bit high comparing to the current traffic situation of Amsterdam area, the undergoing road adjustments are included in the basic network and capacity increase of these adjustments are taking into account. Therefore, the input of the case study network is more in accordance with a recurrent congestion of evening peak when static traffic control measures are insufficient for the road situation. The non-recurrent scenario is created with an incident set-up on A10 East westbound, downstream of Duivendrecht. A10 East was selected for the non-recurrent scenario because this freeway stretch is not oversaturated during most of the simulation period. It is more obvious to show the effects of CNM practice on relieving non-recurrent congestion.

But there are three problems for using this demand. First, this demand is higher than the traffic situation now since it is a predictive demand of future year 2020. But, the trade-off is the on-going infrastructure adjustments

are fully included in the network. Without field data, to what extent, is the simulated traffic congestion different from the current real traffic situation is unknown. Second, the accuracy of this predictive demand is not sure since the author didn't provide an ex-post evaluation of the NRM-Randstad model. But related studies are conducted testing the accuracy of this prediction methodology with field data up till now [51]. Third, how accurate is the trips distribution in the NRM model transform into O-D matrix in DSP model is unknown. However, according to the project report, different organizations (DHV, Rijkswaterstaat NH) had agreed on the calibration [46].

Implications to CNM practice

Deployment areas

Based on the case study network [50], infrastructure adjustments applied to the motorways are determined and agree upon by involved parties. But, the connections and the underlying road network are built on current road network design since infrastructure changes are not established. With a higher demand predicted for 2020 and no capacities improvement on the urban roads, the underlying road network incurred gridlocks and unable to proceed. Therefore, the intersection controls have new configurations based on the current regulations after consulting with Rijkswaterstaat. The objective is to change as little as possible so that the traffic can proceed and gridlocks of the whole network can be avoided.

These artefacts of case study network can be seen from the calibration of the network in Flow Chart 6-4. Due to these complications, the CNM practice in the case study is mainly focused on motorways and their connectors. Coordination of intersection controls are tried out without success. Under this network, interesting coordination such as ramp metering and adjacent intersection signals was unable to practice on the urban road network although such coordination is desirable.

Limitations to control measure implementation

Control measures that can be applied for the CNM practice in the case study are also limited.

First, the signal controls on urban network are unfit for coordination. As discussed, the intersection signals have been manipulated to fit the SAA project. The signal controls are further implicated by the incapability of signal control optimization in DSP.

Second, many dynamic control measures are supposed to be capable in DSP but practice proves to be otherwise. Traffic control measures that are related to dynamic microscopic traffic characteristics such as weaving, dynamic lane changing, car following and platoon dispersion cannot be implemented. Traffic control measures that are related to static microscopic traffic characteristics, such as weaving marking, rush lane and junction lane control

could be emulated but the results are highly questionable since capacities are directly related to link length and number of lanes. In the case study, the basic network introduced from the SAA project does contain some current infrastructure adjustments. They are simulated and evaluated in AIMSUN. Results are then transferred back to the whole network in DSP.

Third, the calibrated case study network showed clearly manipulation in effective lane miles, particularly in link lengths. Adjacent links are set to have evenly effective lane miles by dividing links into desired lengths. This could be for fear of introducing bottlenecks or producing odd queue propagation phenomena on the motorways, which is quite often the case if not calibrated well with the help of some calibration programmes. Sadly, ramp metering, route information VMS and route advice VMS are still affected by the network and the modelling tool.

Validation to the CNM results

The generally improving performance of CNM control designs required countless alternatives and scoping the best one since DSP is unfit for traffic management optimizing. But some innate problems from the network are presented here to show the possible implication to ramp metering control and VMS controls.

Ramp metering: sub-optimal control designs and possible under/overestimated of ramp metering control.

Parameters of ramp metering control could be sub-optimal due to the queue propagation around ramp metering and calibration work of these areas, which could lead to under- or over-estimation of ramp metering control.

Queue propagation around on-ramp to freeway shows odd phenomena. When congestion set in, queuing of these areas often starts at the entrance node from on-ramp link (usually one lane, around 300 meters) to freeway. Its upstream on-ramp link (usually two lanes, around 150 meters) starts queuing the same time. Later, the downstream freeway link to the on-ramp becomes congested. Figure 6-5 shows the queuing situation of S109 connecting to A10 South eastbound. The two on-ramp links start queuing at 16:56 while downstream freeway links don't show any congestion. About ten minutes later, the speed of downstream freeway link drops and queuing starts at 17:05.

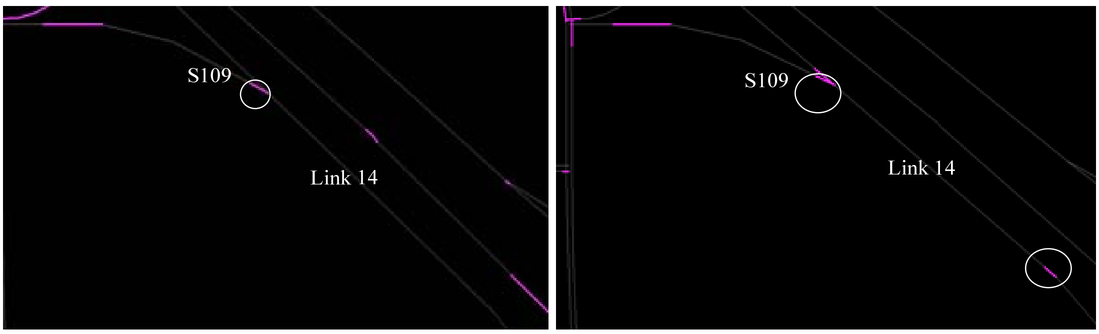


Figure 6-3 S109 to link 14 at 16:56 (left) and 17:05 (right)

In reality, the density of downstream freeway link first increases to its critical density and traffic breakdown happens on this freeway link first. Then the on-ramp starts queuing because of capacity drop of downstream freeway link. To avoid odd queuing process above, the on-ramp to freeway area has been calibrated by manipulating link lengths, as show in Figure 6-4. Usually, the on-ramp is divided into two links with even effective lane miles. The downstream freeway link is much longer comparing to downstream freeway link and either of the on-ramp links. From Figure 6-4 and equation (3.10), the extra length of link 10 on A10 South eastbound is to make sure that the second term of this equation could be a relatively large value so that traffic demand from upper links can transfer into link 10 and thus, congestion is likely to happen here.

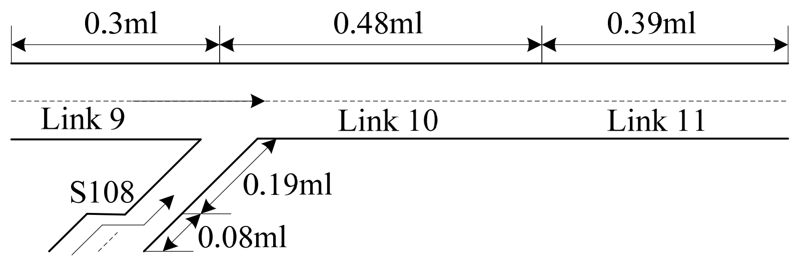


Figure 6-4 S108 on-ramp to A10South eastbound

Without judging right or wrong, this effort of calibration is not completely carried out on the case study network. The area of S109 connecting to A10 South eastbound showed in Figure 6-3 is one example that directly affect ramp metering control measure during CNM practice. The odd queuing seems like the on-ramp has an innate ability to control outflow to the freeway. During CNM practice, the parameters of ramp metering are set to be really critical (long time, low desired occupancy, see Appendix I) in order to observe the effect of ramp metering. The implications of these parameters are, first, the effectiveness of ramp metering is hard to tell quantitatively. Second, spill-backs to adjacent intersection could happen since the metering time is really long and desired freeway occupancy is low (exact situation cannot be determined since the upstream intersection controls are not optimized, also defects of queue propagation exists in DSP.). This could mean sub-optimal control design is practiced for ramp metering control.

As an important MOE, ramp queue length is usually used to evaluate the effectiveness of local ramp metering and coordinated ramp metering. Due to the modelling tool, DSP, ramp queue length as well as any queue length has to be expressed by its occupancy on corresponding link.

The ramp queue lengths on the ramp connecting S109 to link 14 of A10 South eastbound, which is the most downstream ramp in the case study, are examined in three control designs (D_0: do nothing, D_1: local ramp metering and D_2: coordinated ramp metering). As shown in Figure 6-5, in D_0, the queue length is quite high from the 120th minute to the 145th minute and from the 160th minute to the 200th minute (invisible part of blue lines

covered by red). Ramp queue length in D_1 doesn't show much difference to D_0. Although queue increases in D_1 around 170th minute, local ramp metering in D_1 seems to be even less effective than the false "innate control" of on-ramp in D_0 (from the 180th minute to the 210th minute, queue is shorter in D_1). In D_2, the queue length on this downstream ramp S109 is lower before the 150th minute, which could be due to the coordination with S108 ramp metering (using spare space of S108 on-ramp). But, ramp queue length on S109 becomes higher for unknown reason after the 150th minute (possibly due to the problems mentioned in Figure 6-3). Therefore, ramp queue length (in percentage of ramp length) is not informative to optimize ramp metering or coordinated ramp metering. The case study can only use network level MOE, such as average travel time to make sure control designs are deteriorating the traffic conditions.

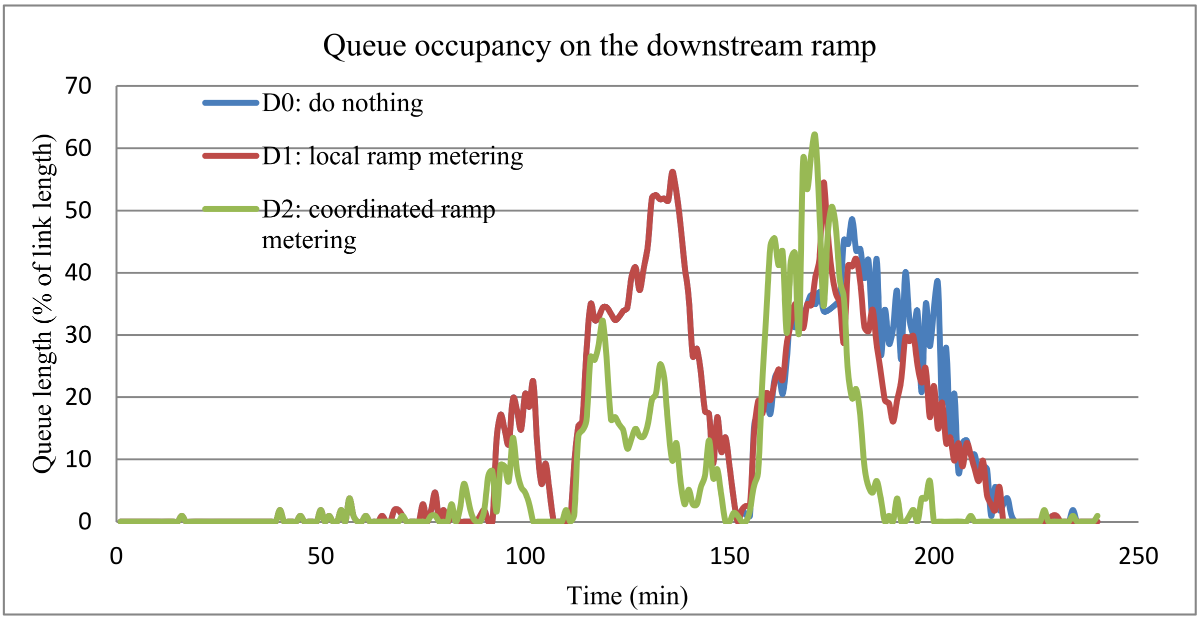


Figure 6-5 Comparison of queue length (in percentage of ramp length) on the ramp connecting S109 to link 14 of A10 South eastbound

Variable speed limit VMS: limit function from modelling tool

When variable speed limit VMS is coordinated to D_2, coordinated ramp meterings, this new control design D_3 has no further improvement. One reason is that vehicles travel on one link use the link average speed of each time step, the possible reductions (by VS) of speed differences among vehicles and of mean speed differences among lanes are not shown in DSP. The other reason could be the unclear critical densities of DSP (also related to unclear link capacity). Thus, the effect of variable speed limit to keep the mean speed under critical densities is also unsuccessful.

Route information VMS: limited function from modelling tool.

Coordination of route information VMS shows "backwards" improvement on the network level. This cannot conclude that route information VMS is not an effective control measure because the route information VMS has very limited function in DSP. Route information VMS (congestion warning VMS in DSP) needs to be deployed upstream to a diversion point to provide the drivers with congestion information downstream so that they can divert to less congested routes. But this function in DSP doesn't provide any specific information. When it is deployed upstream to a diversion point, the vehicles respond to the VMS have to consider all downstream routes are congested. Therefore, the capacities on these "congested" links are underutilized if vehicles respond and sort an alternative route from their path tree table. These routes could detour the vehicles and increase travel time while the downstream of original routes are not congested or only congested for a certain time. This could be the reason for deteriorate performance of route information VMS on the network level but noticeable improvement on the local level (downstream freeway stretch).

Route advice VMS: possible underestimation for recurrent scenario and possible overestimation for non-recurrent scenario.

For recurrent scenario, coordination of route advice VMS shows further improvement but when more route advice VMS control are deployed on network level, further improvement can hardly show. One explanation is that coordination on the network level is more complicated and the results could deviate from prediction. The other explanation is that the underlying roads of A4 and A10South are not calibrated well. Urban roads show recurrent congestion too and they are no good choices for alternative routes. The effect of route advice VMS under recurrent scenario could be underestimated.

For non-recurrent scenario, route advice VMS shows more obvious improvement than recurrent scenario. This could due to the effective alternative route advice since the underlying road network in this area is not that congested. The infrastructure adjustments on A10 East (the first phase of the SAA project) are included in the case study network. The alternative routes provided by multiple route advice VMS in the case study utilize the increased capacity of Watergraafsmeer – Diemen area (2×4 to 2×5 lanes) from static infrastructure adjustments. Since these infrastructure adjustments have not been fully realized (possibly realization around 2014). The effect of route advice VMS under non-recurrent scenario could be overestimated.

6.4 Conclusion

In an ideal plan of this thesis project, the research of CNM should start from proposing assessment methodology framework for modelling and ex-ante-evaluation of CNM Then a careful selection with verified modelling tool(s)

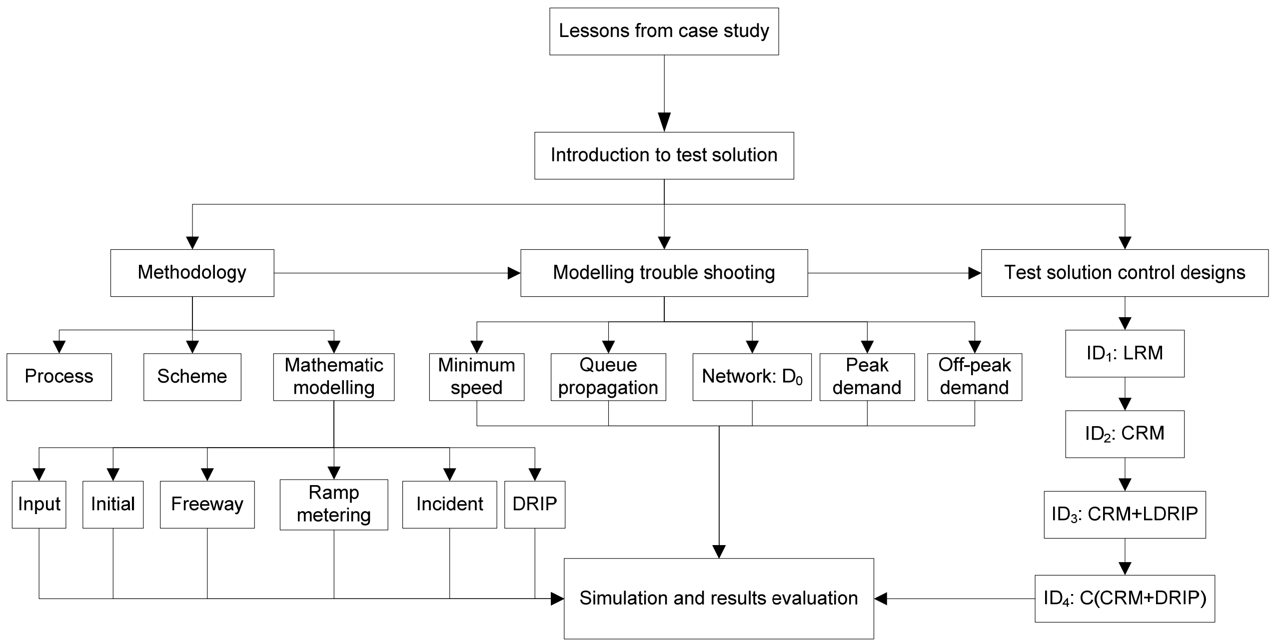
is made and the case study network can be built from scratch. After calibration of the case study network, control designs developed according to the proposed assessment methodology can be simulated and evaluated via simulation results. Reflections and implications of the case study become the initiatives to carry out enhancement study of CNM. Proposed test solution is verified before applying the assessment methodology to the empirical case. At last, conclusions are drawn from the simulate results. The problem for this ideal plan is that half of the time-consuming work is a bit off focus from the research objectives of this thesis project. Hence, the case study network is prepared and calibrated beforehand by previous projects using DSP. The case study simulations were performed in chapter 5 to test the proposed assessment methodology. Unfortunately, some issues of the modelling tool and the case study network are observed during evaluation.

This chapter is conducted here in order to learn from the mistakes and limitations of the case study by addressing the encountered issues during modelling and ex-ante evaluation of CNM. This limitations and flaws become the initiatives for part three.

Part III: Enhancement application with test solution for CNM

7 Test solution

Although simulation results in chapter 5 become improbable based on the evaluation in chapter 6, coordinated network management using the proposed assessment methodology still presents observable effects on solving both recurrent and non-recurrent congestions. Based on the lessons learnt from the case study, this chapter aims at developing a test solution for an empirical case in order to apply the proposed assessment methodology for modelling and ex-ante evaluation of CNM. This test solution is realized on an empirical case with several coordination control designs using Matlab as the modelling tool. The simulation results and ensuing ex-ante evaluations intend to provide informative evaluation of the proposed assessment methodology. And it also intends to give believable conclusions about the effect of coordinated network management.



Flow Chart 7-1 Organization of test solution

The initiatives of this chapter come in two-fold, to amend the mistakes of the assessment methodology framework (unfit tool and network), and to move towards advanced implementation of CNM.

This chapter is organized as shown in Flow Chart 7-1. In section 7.1, lessons learned from the case study are summarized. In section 7.2, the test solution is introduced descriptively. In section 7.3, applying the proposed assessment methodology to the empirical case is demonstrated in three parts, namely, process, coordination scheme and mathematic modelling. In section 7.4, several enhancement tests are performed, such as minimum speed and queue propagation tests. In section 7.5, several control designs are developed according to the

proposed assessment methodology, which are in accordance to the control designs in chapter 4. In section 7.6, these control designs are simulated and results are presented. In section 7.7, evaluations of the CNM control design effects and the assessment methodology for CNM are concluded.

7.1 Lessons from case study

In the previous chapters, an assessment methodology has been applied to the case study in order to systematically design, model and evaluate coordinated network management. According to the evaluation in chapter 6, the lessons and implications from the case study are summarized here. In order to solve the problems and provide proper coordination for network management, an exploratory event-triggered coordination scheme incorporating solutions to the lessons is put on the table later.

Summary of findings and lessons

1. Assessment methodology

   The assessment methodology proposed in chapter 3 provides an all-around methodology framework to model and evaluate CNM on a given project. According to the case study simulation results in chapter 5, with increases of the control degree or coordination levels, the overall performance of the network is improved.

2. DTM and CNM results

   As discussed in chapter 4 and chapter 5, using the assessment methodology proposed in chapter 3, various DTM and CNM are implemented in the case study, to evaluate their effectiveness. According to simulation results, coordinated ramp metering shows more effect at regulating traffic flows and improving the traffic conditions as a whole. After coordinating various VMS control measures to the coordinated ramp metering control design, route advice VMS shows more obvious results. The case study simulation result shows that CNM has significant potential in solving recurrent and non-recurrent congestions provided a reasonable coordination assessment methodology.

3. Limitations

   At this moment, the most significant limitations to CNM practice are the accuracy and realness of the modelling tool, DSP. The major imperfections of DSP can affect the accuracy of the case study simulation results, are listed as follows.

   a. Minimum speed

      As discussed in chapter 3 and chapter 6, the existing of jam speed in DSP is one of the major concerns

which could fundamentally affect modelling and ex-ante evaluation of CNM on the case study.

b. Un-realistic queue density

The density of queue in DSP is another concern because DSP considers any queue on a link as having jam density. However, in reality queues in a freeway bottleneck can have a range of densities, depending on the severity of the congestion.

c. Un-realistic queue propagation at bottleneck

As the evaluation in chapter 6, the queue propagation in DSP is not very realistic at bottleneck and performs particularly poorly with long links. Due to the lacking of the flow rate capacity constrains from upstream link to bottleneck link, queue starts to propagate from the end of the bottleneck link instead of the beginning of bottleneck link in DSP.

d. No coordination scheme

There is no coordination algorithm in the current version of DSP. All the coordination needs to be achieved by users with other means. This means the effect of CNM control design is limited by the user's knowledge and experience, to a great extent.

These limitations affect the effect of CNM and the performance of assessment methodology. The test solution intends to minimize the influence of these limitations and provide valid results. To this end, the answer to question d. is introduced in section 7.2 and section 7.3.2. The answers to question a. and c. are introduced in section 7.4 with enhancement tests.

Another limitation to CNM is related to the calibration of the case study network. Since a complete calibration of a large network is unrealistic in this part of the thesis project. The assessment methodology is applied to an empirical network with the test solution which is introduced descriptively in section 7.2 and in mathematical term in section 7.3.3.

7.2 Introduction

This section introduces the idea of the test solution. The test solution aims at providing a solution to properly model and evaluate CNM using the proposed assessment methodology on an empirical network with a severe incident. The schematic diagram of this test solution is shown in Figure 7-1.

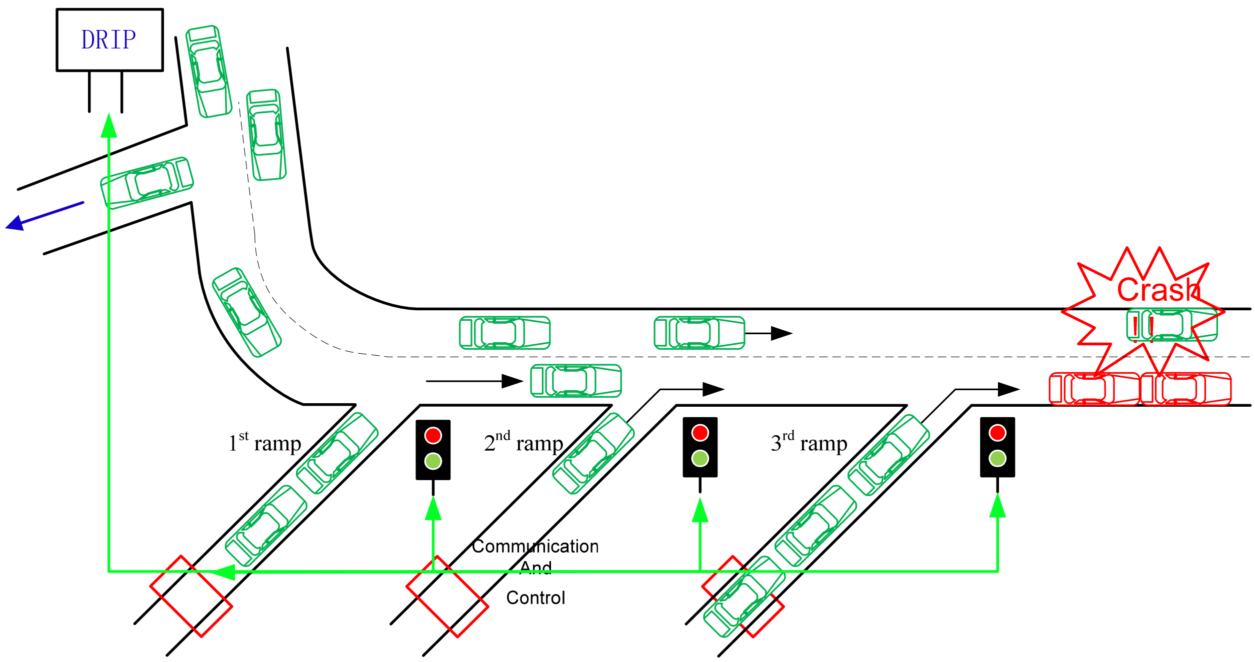


Figure 7-1 Idea of the test solution for CNM practice

An incident happens on a freeway stretch and the maximum service flow drops to an extremely low level instantly. Owning to the current state monitoring module, the incident can be detected and information of the incident is sent to the ex-ante evaluation and CNM control design modules. When ex-ante evaluation determines that this incident cannot be solved with local traffic management, the network controller of the CNM control design module is responsible to send out two instructions. One instruction is to engage the local ramp metering control directly upstream to the incident point to limit the number of vehicles joining in freeway to the incident location. The other instruction is to engage the VMS or DRIP (with route advice) located on the first possible diversion point upstream to the incident location. The purpose of this DRIP is to divert some vehicles to supporting roads so that traffic can be more evenly distributed on the network. In this way, diverted vehicles can avoid the incident bottleneck section. Meanwhile, the traffic demand to the incident road section is lightened.

The local ramp metering is engaged on the 3rd ramp (directly upstream to the incident road section), which means a queue is possibly formed on this ramp. The queue length is detected (with certain on-land electronic sensors such as detector loop) and monitored. When the queue length on this ramp is longer than a threshold, the closest ramp metering located upstream to the 3rd ramp is triggered. In this sense, the queue length becoming longer than a threshold value is the trigger event for the coordination between on-ramp metering.

Coordination of ramp metering can avoid situations under which the downstream ramp is congested with a long queue because its ramp metering is engaged but vehicles on the upstream ramp still drive onto the incident freeway without traffic management. This is due to the lacking of coordination between local ramp metering and congestion/queuing delay from downstream to upstream since congestion needs time to propagate upstream.

During this time, the upstream ramp metering control is not engaged until the spill-back congestion is close enough to be detected. The purpose of coordinated ramp metering is to increase the metering duration and utilized spare spaces on the network.

7.3 Methodology

7.3.1 Process

The proposed assessment methodology for modelling and ex-ante evaluation of CNM in chapter 3 cannot be fully evaluated in the case study due to complications discussed before. The main issue is the modelling tool. In this chapter, it is replaced by Matlab. In order to apply the assessment methodology to the empirical case, the assessment methodology for modelling and ex-ante evaluation of CNM is adapted to test solution. The adapted assessment methodology is shown in Figure 7-2.

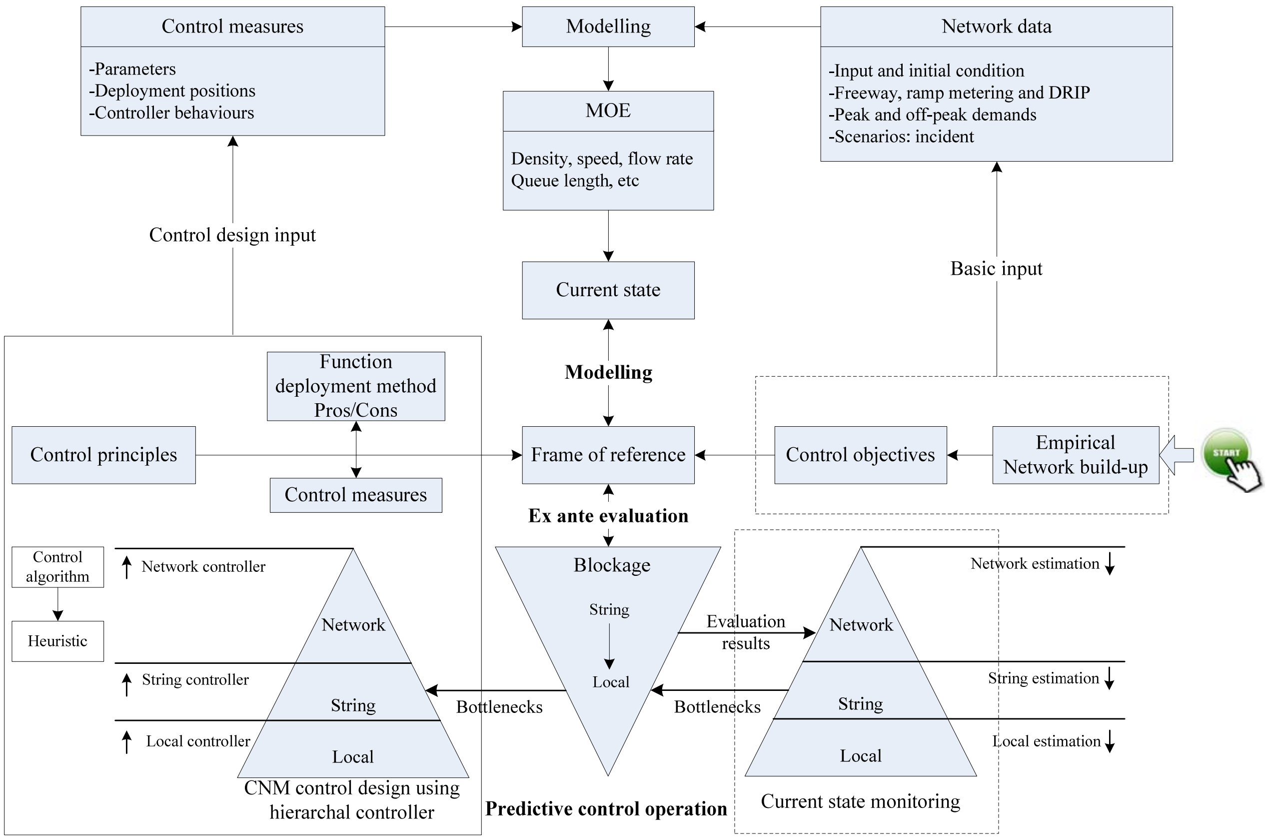


Figure 7-2 Assessment methodology for CNM modelling and ex-ante evaluation with the test solution

Each element in Figure 7-2 embodies the same idea as the assessment methodology in chapter 3. The levels of CNM showed here are specific to the empirical network, which can be expanded to larger scales in future study. In view of a severe incident-induced bottleneck, the ex-ante evaluation here is focused on blockage changes,

which is to effectively solve the spill-back congestion on the freeway. The desired situation of the blockage is the frame of reference. Therefore, queue lengths on the freeway and on-ramps are used to evaluate the performance of each control designs as the quantified MOE. Other MOEs, such as density, velocity and flow rate are used qualitatively to determine the network production, accessibility and quality (with contour graphs). The process of this adapted assessment methodology is the same as introduced in chapter 3. Guided by the same principles, the process of assessment methodology iterates from modelling, ex-ante evaluation to predictive control operation. The modelling is realized in matlab.

7.3.2 Coordination scheme

In this section, a description of the coordination scheme in the test solution is introduced. This coordination scheme tries to offer the desired situation of a coordinated network management in practice. The control measures are coordinated and formed into control designs using the hierarchal controller which is controlled by control algorithm with a heuristic approach. Aiming to solve incident-induced bottleneck, this coordination scheme is shown in Flow chart 7-2.

A freeway is divided into N pieces of small road sections and the traffic characteristics on each piece are calculated. The details of this mathematic modelling are introduced in section 7.3.3. During the initialization of the program, the initial condition module assigns an initial state to each road section. Meanwhile, a stream of input traffic is loaded at the beginning of the freeway. After the initialization, the program calculates the traffic situation on each road section. A "detector" is used to detect if there is traffic congestion on the road. Based on the detected information, two different modules are called respectively.

When no traffic congestion is detected, the normal flow traffic control module is invoked. This module first judges if the road section being calculated is a ramp section or a normal road section.

If the current road section is a ramp section, the flow traffic control module will do the following things:

1. ALINEA control block is used. The maximum allowed outflow rate of the ramp $r(t+\Delta T)$, at simulation step $(t+\Delta T)$, is calculated with $r(t)$, the maximum allowed outflow rate of the ramp from the previous time step.
2. If $r(t+\Delta T)$ is smaller than $r_{min,}$ the minimum value of the maximum allowed outflow rate, which is designed by user, then r_{min} is used. Otherwise, $r(t+\Delta T)$ is used.
3. If $r(t+\Delta T)$ is larger than r_{in}, the inflow rate of the ramp, then r_{in} is used as the outflow rate of the ramp.
4. If $r(t+\Delta T)$ is smaller than r_{in}, then a queue is formed on the ramp.
5. The density, velocity and flow rate of simulation step $(t+\Delta T)$ at the 1st road section downstream to the ramp,

$k_1(t+\Delta T)$, $v_1(t+\Delta T)$ and $q_1(t+\Delta T)$ are calculated using the finite difference form (discrete time steps and discretized road segments) of the differential equation (3.1).

If the current road section is a normal road section, the density, velocity and flow rate of the current road section at the next simulation time step $(t+\Delta T)$ are calculated with the finite difference form of the differential equation in the flow traffic control module. Afterwards, the next road section is calculated until all the road sections get their densities, velocities and flow rates for the simulation time step $(t+\Delta T)$. Combining $k_i(t+\Delta T)$, $v_i(t+\Delta T)$ and $q_i(t+\Delta T)$ with $r(t+\Delta T)$ from the ramp calculation, the normal flow traffic control module outputs the results and starts the next cycle of simulation time step.

When traffic congestion is detected on the freeway road section downstream to a ramp (three ramps are used in the test solution, incident is detected at downstream to the 3rd ramp), the congestion control module is invoked. This module first enables the VMS (DRIP) control block, which limits the input traffic by diverting them with alternative route advice. Meanwhile, it judges if the road section being calculated is a ramp section or a normal road section.

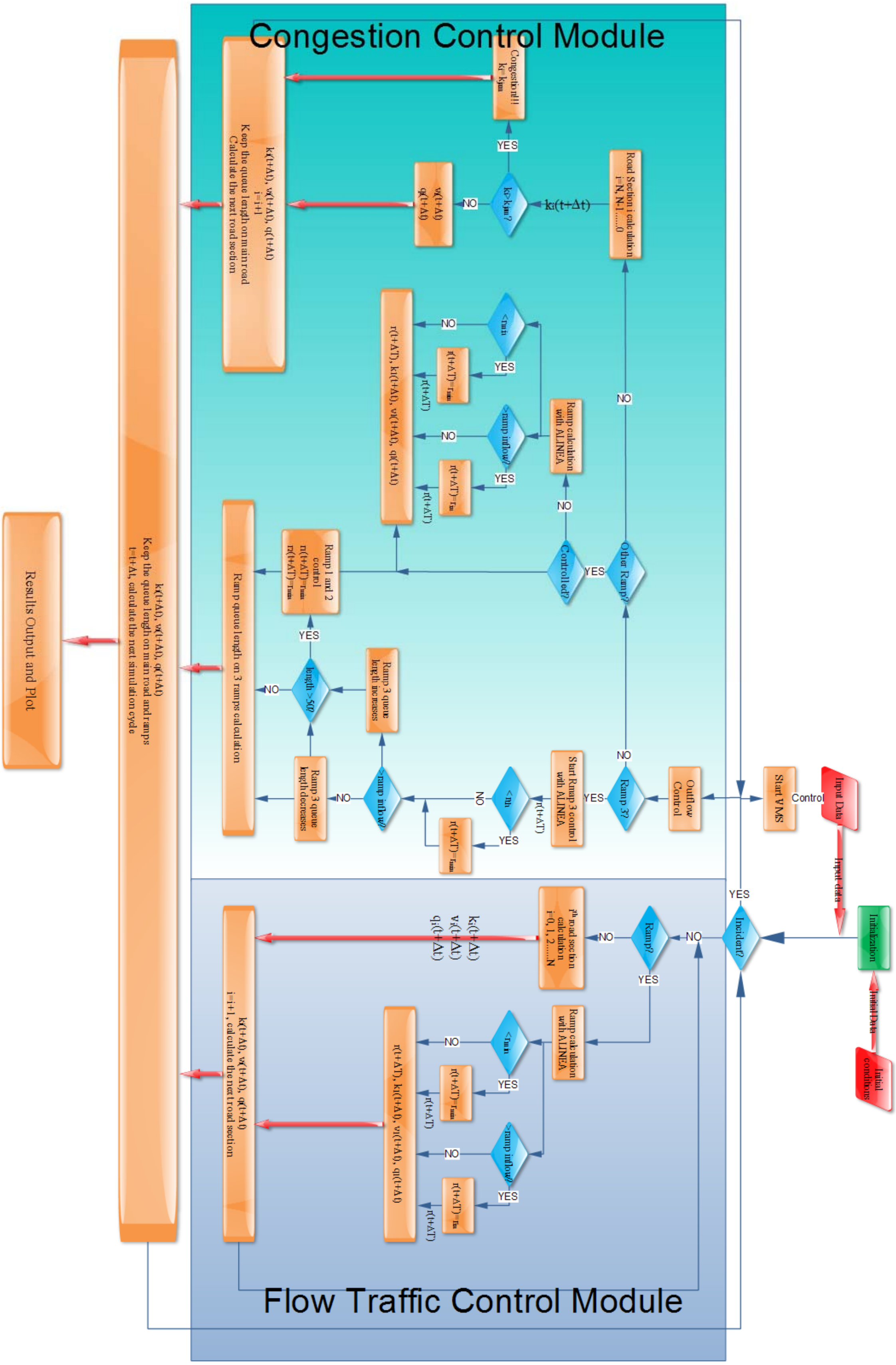
If the current road section is a ramp section, the congestion control module precedes the following things:

1. The congestion control module first judges if the ramp is the 3rd (final) ramp. If so, then the module takes the following steps:
    a. Maximum allowed outflow rate of the 3rd ramp is calculated by ALINEA control block.
    b. If the maximum allowed outflow rate by ALINEA is lower than the minimum outflow rate r_{min}, then the outflow rate of this ramp is set as r_{min}.
    c. If the ramp outflow rate calculated by ALINEA is lower than r_{in}, then r_{ALINEA} is used as the outflow rate of the ramp. In this case, the queue length increases. If the queue length is longer than a certain value, say 20 vehicles, a message is sent to the 1st and 2nd ramp. Now these two ramps limit their outflow rate to the main road to a pre-set value.
    d. If the ramp outflow rate calculated by ALINEA is higher than r_{in}, then r_{in} is used as the outflow rate of the ramp. In this case, the queue length decreases.
    e. The results, for example queue lengths, are kept.
2. If the current ramp is not the 3rd (final) ramp then the module takes the same steps as the steps described in the case without traffic congestion. The difference is that if they already received traffic congestion signal from the 3rd ramp, then the 1st or 2nd ramp are using the minimum outflow rate. And similar judgment and

control steps are taken to the 1st and 2nd ramp as described above.

If the current road section is a normal road section, a new density at simulation step (t+ΔT) is calculated. The new density is compared with the jam density. If the new density is higher than the jam density, then jam density should be used as the new density for simulation step (t+ΔT). With this density, the velocity and flow rate at the simulation step (t+ΔT) are re-calculated based on the jam density. Combining these results with the results from ramps calculation, the congestion control module outputs the results and then starts the next simulation time cycle.

The mathematical modelling details are introduced in the ensuing section.



Flow chart 7-2 Coordination scheme of the test solution

7.3.3 Mathematic modelling

In this section, the mathematical models (based on basic traffic flow theories) used in the test solution are introduced one by one. Related codes to each model are stored in Appendix II. The macroscopic traffic flow model used in mathematic modelling is tested during enhancement tests in section 7.4.

Input traffic

The input traffic is random signal defined by the input traffic density. The inflow densities are series of values subjected to Poisson distribution. With the input traffic density, the inflow traffic velocity and flow rate can be derived with modified dual-regime Greenshield model. Figure 7-3 shows the variation of flow rate of the input traffic according to time.

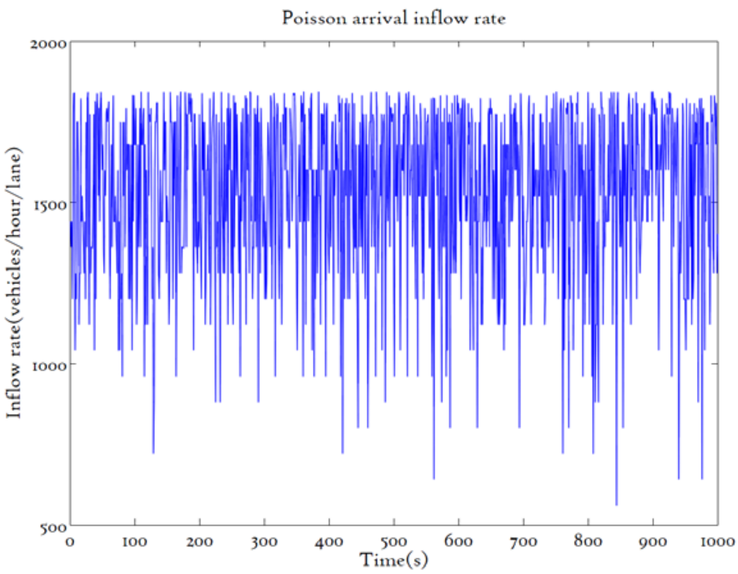


Figure 7-3 flow rate of input traffic as a function of time

Initial conditions

The initial conditions define the initial densities of each road section. The initial densities are series of values following Normal distribution. With initial traffic densities, the traffic velocities and flow rates at each road section at the beginning of the simulation period can be derived with dual-regime Greenshield relationship. In Matlab, they can be implemented with the following instruction. Figure 7-4 shows the initial flow rates at every road section according to space.

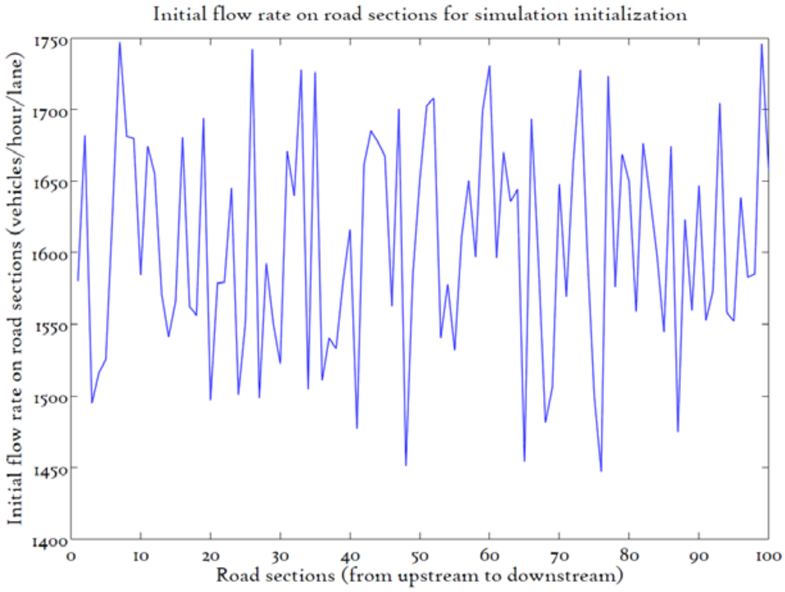


Figure 7-4 Initial flow rate at each road section as a function of space

Freeway Model

The freeway model is discussed here. The calculations and simulations of traffic flow are based on macroscopic traffic flow theory. As shown in Figure 7-5, a 5 km-long freeway stretch between two on-ramps can be divided into M pieces. The flow rate, speed and density of each road section are calculated according to macroscopic traffic flow model.

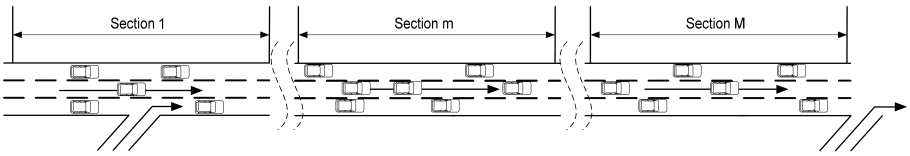


Figure 7-5 section 1…m…M of the freeway between two ramps

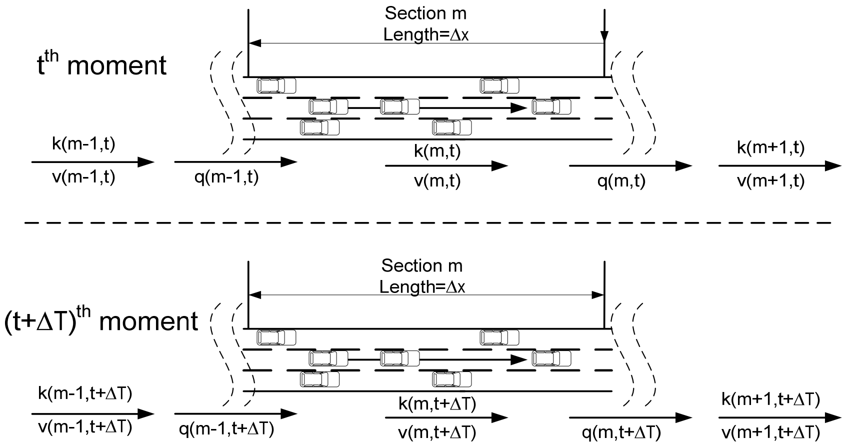


Figure 7-6 Mathematical derivation of freeway road section

Figure 7-6 shows the mathematical expressions of a segmentalized piece of freeway road section and the traffic characteristics of the road section according to discretized time steps. In Figure 7-6, ΔT is the time interval between calculations and Δx is the length of the road section m.

List of symbols:

k(m-1,t), k(m,t) and k(m+1,t): the densities on road section (m-1), m and (m+1) at the t^{th} moment;

k(m-1,t+ΔT), k(m,t+ΔT) and k(m+1,t+ΔT): the densities on road section (m-1), m and (m+1) at the $(t+\Delta T)^{th}$ moment;

v(m-1,t), v(m,t) and v(m+1,t): the speeds on road section (m-1), m and (m+1) at the t^{th} moment;

v(m-1,t+ΔT), v(m,t+ΔT) and v(m+1,t+ΔT): the speeds on road section (m-1), m and (m+1) at the $(t+\Delta T)^{th}$ moment;

q(m-1,t) and q(m,t): the flow rates from road section (m-1) to m, from road section m to (m+1), at the t^{th} moment;

q(m-1,t+ΔT) and q(m,t+ΔT): the flow rates from road section (m-1) to m, from road section m to (m+1), at the $(t+\Delta T)^{th}$ moment.

According to the traffic conservation law, the number of input vehicles should be equal to the number of output vehicles because there are no feeders or exits on road section m. Therefore, for road section m, the following formulation holds.

$$k\left(m,t+\Delta T\right)\times\Delta x = k\left(m,t\right)\times\Delta x + q\left(m-1,t\right)\times\Delta T - q\left(m,t\right)\times\Delta T \tag{7.1}$$

In the simulation, assuming that the parameters k(m,t), q(m-1,t), q(m,t), ΔT and Δx are known, the new density k on road section m and time (t+ΔT) can be expressed as follows:

$$k\left(m,t+\Delta T\right) = k\left(m,t\right) + \frac{q\left(m-1,t\right) - q\left(m,t\right)}{\Delta x}\times\Delta T \tag{7.2}$$

With k(m, t+ΔT), the speed and flow rate on the same road section and time can be calculated with the following equations.

$$V_m^{t+\Delta T} = \begin{cases} v_f & , \quad 0 \le k_i^t \le k_b \\ (v_{intercept} - v_{\min})\times(1 - k_m^{t+\Delta T}/k_{jam})^{\alpha} + v_{\min} & , \quad k_b \le k_i^t \end{cases} \tag{7.3}$$

$$q(k_m^{t+\Delta T}) = \begin{cases} v_f k_m^{t+\Delta T} & , \quad 0 \le k_i^t \le k_b \\ \left[(v_{intercept} - v_{\min}) \times (1 - k_m^{t+\Delta T} / k_{jam})^{\alpha} + v_{\min} \right] \times k_m^{t+\Delta T} & , \quad k_b \le k_i^t \end{cases} \tag{7.4}$$

All the parameters in equation (7.3) and (7.4) have the same definitions as in section 3.2.1.

Ramp model with ALINEA control

The arrival rate of on-ramp is modelled with series of values subjected to Poisson distribution, as shown in Appendix II. In section 3.2.4, a ramp metering control strategy, ALINEA, was introduced. A single stage of ALINEA is based on first order negative feedback. The gain factor K_R is critical for the settling speed and stability of the system. An empirical value of 70, which can generate a good experimental result, is used in section 3.2.4. However, this value may not be the best value for the Matlab simulation. Therefore, a simple way to generate the gain factor in real-time will be introduced by discussing the conditions for fast settling and stability of the system. And in the simulations of traffic control with coordination later, the same method will be used to calculate the gain factors for individual ramp under coordination. Assuming the input flow rate is a constant, the function of ALINEA can be expressed as the following equation in time domain.

$$r(k) = r(k-1) + K_R \left[\hat{o} - \frac{\left[r(k-1) + q_{in} \right] \times L}{v} \right] \tag{7.5}$$

Now z-transform can be applied to equation (7.5) to examine the ALINEA in frequency domain, which is useful for checking the settling speed and stability.

$$z^{-1} R\left(z^{-1}\right) = R\left(z^{-1}\right) + K_R \left(\hat{o} - \frac{\left[R\left(z^{-1}\right) + Q_{in} \right] \times L}{v} \right) \tag{7.6}$$

The equation (7.6) can be simplified further and the ramp flow rate in z-domain, $R(z^{-1})$, can be expressed as follows:

$$R\left(z^{-1}\right) = \frac{K_R \left(\hat{o} - L \times Q_{in} / v \right)}{z^{-1} - 1 + L \times K_R / v} \tag{7.7}$$

As shown in equation (7.7), first order ALINEA has single pole in z-domain. Based on first order control theory, to make this system stable, the pole should be located inside the unit circle, which means:

$$|z| > \left| \left(1 - L \times K_R / v\right)^{-1} \right| \tag{7.8}$$

And because $r(k)$ should be always positive, thus

$$\left(1 - L \times K_R / v\right)^{-1} > 0 \tag{7.9}$$

From equation (7.9), a restriction on the gain factor of first order ALINEA for stability can be concluded as:

$$K_R < \frac{v}{L} \tag{7.10}$$

From equation (7.10), it is very obvious the stability depends on K_R. But the dependency of the settling speed on K_R is not as obvious. However, the settling speed can be checked easily in time domain. Now the equation (7.7) is applied with inverse z-transform and then the equation can be expressed in time domain as follows:

$$r(k) = K_R\left(\hat{o} - L \times q_{in}/v\right) \times \left(1 - L \times K_R/v\right)^{-(k+1)} \times U(k) + r_c \tag{7.11}$$

Where,

$$U(k) = \begin{cases} 1 & , \quad k \geq 0 \\ 0 & , \quad k < 0 \end{cases} \tag{7.12}$$

r_c: a constant, which is the steady value of $r(k)$ given enough time

From equation (7.11), the settling speed of first order ALINEA system depends on the closeness of expression $(1 - L \times K_R/v)$ to zero. If this expression is approaching zero, then the settling is becoming fast and vice versa. Assuming this expression locates between a minor factor ε and zero, then another limitation on K_R can be derived as follows:

$$K_R > \frac{(1-\varepsilon) \times v}{L} \tag{7.13}$$

Combining equation (7.10) and equation (7.13), the gain factor of first order ALINEA should be designed with the following restriction:

$$\frac{(1-\varepsilon) \times v}{L} < K_R < \frac{v}{L} \tag{7.14}$$

If the gain factor K_R is designed to meet the above inequality, first order ALINEA should be stable and it should settle fast. In the Matlab simulation, a simple way was used to assign values to the gain factor. In this method, the system is forced to settle down within a given number of cycles, for example, 10 cycles. The occupancy rate is measured every cycle. According to the difference between the measured occupancy rate $o(k)$ and the desired occupancy rate $\hat{o}$, the gain factor will be recalculated and checked if it meets the inequality. In this sense, the gain factor is updated according to real time and proportional to the residual error between measured occupancy rate and desired occupancy rate.

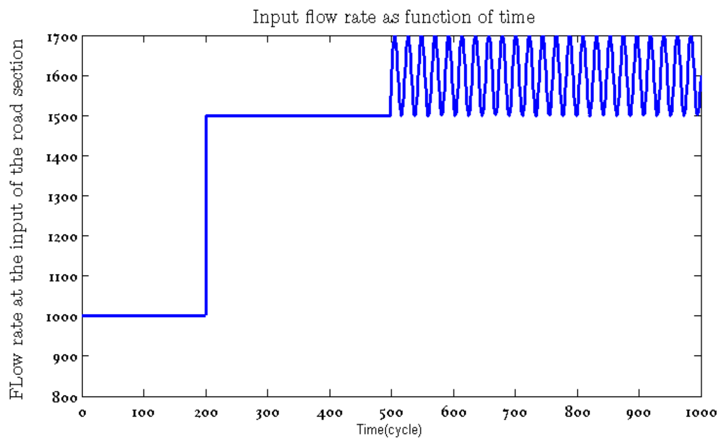


Figure 7-7 Input flow rate at the beginning of the road section in simulation

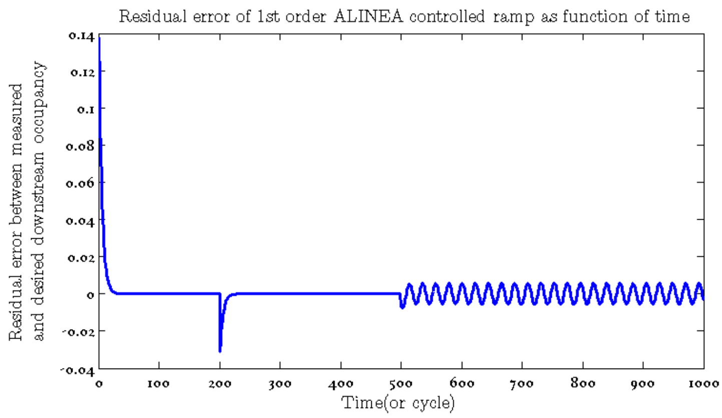


Figure 7-8 Residual error between measured and desired downstream occupancy rates

Figure 7-7 shows the input flow rate according to the input flow rate function at the beginning of the road section used in the simulation. In the input flow rate function, two kinds of mathematical functions are used to simulate the change of input flow rate on freeway. The first one is a step input which is used to simulate the sudden change of the traffic flow rate on freeway and check the step response of the ALINEA system. The second one is a sine wave which is used to simulate the response of the ALINEA system to the input traffic flow rate with small change such as a certain frequency. Figure 7-8 shows the residual error between the measured and desired downstream occupancy rates, given the input flow rate function in Figure 7-7. The conclusion is that the new method for calculating the gain factor for ALINEA can generate gain factors in real time and with these gain factors, the ALINEA system is stable and able to settle down with a satisfying speed.

The ramp model is similar to the freeway model. The only difference is the input flows include the inflows of the main road and the ramp. Borrowing the equation (7.2), the density at the downstream of the ramp can be expressed as the following equation.

$$k(1,t+\Delta T)=k(1,t)+\frac{q_{in}(t)+r(t)-q(1,t)}{\Delta x}\times\Delta T \tag{7.15}$$

The density and flow rate of the 1st road section downstream to the ramp section are used in equation (7.15). $r(t)$ is the flow rate of the ramp at the t th time step. In the simulation, a series of random values with Poisson distribution will be assigned as the input flow rate of the ramp, say $r_{in}(t)$. The ramp flow rate derived with ALINEA algorithm is the maximum ramp flow rate from the ramp to the main road, say $r_{ALINEA}(t)$. The real ramp flow rate in equation (7.15) should be the minimum value of $r_{in}(t)$ and $r_{ALINEA}(t)$ can be expressed as follows:

$$r(t)=\min\left(r_{in}(t),r_{ALINEA}(t)\right) \tag{7.16}$$

Equation (7.16) is useful for the calculation of the queue length on the ramp. When $r_{in}(t)$ is smaller than $r_{ALINEA}(t)$, then the queue length on the ramp starts to decrease and if $r_{in}(t)$ is larger than $r_{ALINEA}(t)$, then the queue length on the ramp starts to increase.

Incident

An Accident can be modelled as a sudden increase of density at the downstream of the freeway. The algorithm is designed to response with the following steps.

1. After a sudden increase of density is detected, the system first limits the maximum output flow rate, qout(n)=qout_max;
2. Next, the system calculates the density of the most downstream road section between the 2nd and the 3rd ramp, say m th, with the following instruction, k2(m,n+1)=k2(m,n)+(q2(m-1,n)-q2(m,n))*(1/3600)/delta_L.

Then the system determines if this density is larger or smaller than the jam density. If the new density is larger than the jam density, then the new density should be equal to the jam density and the state of this road section is defined as ‘jam’. All the vehicles must drive with minimum speed (0.05km/hr). Meanwhile, the inflow rate of this road section is recalculated. In reality this new inflow rate at the beginning of this road section should be equal to the outflow rate at the end of this road section because in a jam case, the density of this road section cannot physically increase any more. This step can be done with the following instructions.

```
if k2(m,n+1)>kjam

k2(m,n+1)=kjam;

q2(m-1,n)=q2(m,n)+delta_L*(k2(m,n+1)-k2(m,n))*3600;

end
```

3. Next, the system calculates the (m-1)th, (m-2)th,…1st road section with the same instructions given in step 2. Then, dynamic traffic management controls are incorporated. Depending on the existence of coordination, two categories DTM used in the process of calculation are discussed here.

   a. Without coordination

      In this category, no coordination exists between local ramps, nor does coordination exist between ramp control and VMS control. A VMS or ramp only activates locally, when the occupancy of the nearest downstream road section is detected to be exceeding the desired occupancy.

   b. With coordination

      In this category, coordination between local ramps and coordination between ramp control and VMS control make sure that traffic control measures starts working with event-triggers. Instead of detecting occupancy of the nearest downstream road section exceeds maximum value, a ramp or a VMS control is triggered with a certain threshold event, either the occupancy or queue length of the downstream ramp or a significant capacity drop of the freeway.

4. If the congestion cannot be dissolved, the traffic congestion gradually spills back to the beginning of the freeway and interacts with the inflow traffic. The inflow rate of the input traffic is limited by the maximum capacity of the freeway. So, a queue is generated at the input road section. Together with the ramp queue lengths, these queue lengths are the MOEs for evaluating CNM control designs. The above steps of calculation for each road section stop at the end of simulation period.

Route advice

During simulations, the VMS module is engaged when there is a significant capacity drop or the occupancy of the nearest downstream road section exceeding maximum value. The diversion function can be implemented by reducing the inflow rate at the beginning of the entire road. An indifference factor is used to indicate the percentage of the inflow traffic neglecting the VMS. The change of inflow rate is dependent to the indifference factor. The indifference factor is set as 0.8 during test solution modelling, which means 20% of vehicles are diverted. Codes of the VMS module are given in Appendix II.

During simulations, the route advice VMS works as follows:

With the indifference factor, the inflow rate after diversion is calculated. The maximum allowed inflow rate should be calculated by subtracting the ramp flows from the maximum allowed outflow at the downstream accident point. Comparing these two flow rate, the real flow rate at the input road section should be the minimum value of these two values.

7.4 Enhancement tests

In this section, the enhancement solutions for two limitations introduced in section 7.1 are tested first. They are the minimum speed problem and queue propagation problem. The third case is a basic function test.

Minimum speed in freeway model

In the test solution, modified dual-regime Greenshield model is used as the traffic flow model. The traffic flow model is modified to match realistic traffic characteristics. The test solution traffic flow model has the parameters showed in Table 7-1. The parameters used to model freeways are given in the following table.

v_f	$v_{intercept}$	v_{min}	k_{jam}	α
80km/h	150km/h	0.05km/h	150pc/km	4

Table 7-1 Freeway modelling parameters used in the test solution

With the parameters given in Table 7-1, the new modified Greenshield q-k and v-k relationships, which are used to model the freeway links in the test coordination scheme, is shown in Figure 7-9. It shows that as the density increases to the jam density, the speed of the link approaches to zero. But v_f cannot be zero due to speed appears as a denominator in ALINEA algorithm in the test solution, as shown in equation (7.11). The minimum speed under jam density is set to 0.05 km/hour, which is close enough to zero but necessary for keeping simulation running. The flow rate (top graph) in Figure 7-9 is the constraints of link flow rate.

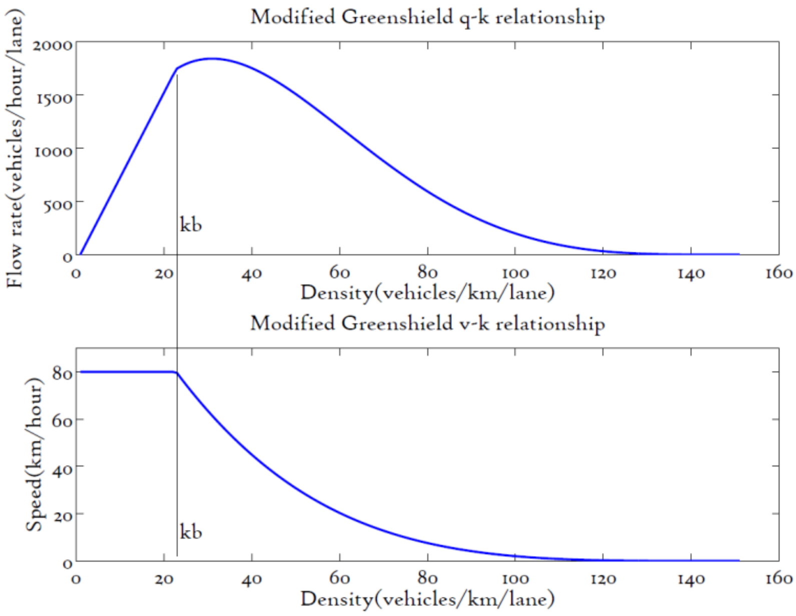


Figure 7-9 q-k and v-k relationships in the test solution

A five kilometre freeway divided into 100 sections with time interval of 1 second is simulated. The code for this enhancement test is given in Appendix II, freeway modelling part. The simulation results are shown in Figure 7-10, Figure 7-11 and Figure 7-12.

Figure 7-10 shows the density variation as the function of time and space. Both the inflow density at the beginning of the freeway and the initial densities of each road section at time 0 are designed to be random signals. However, the initial densities have a mean value larger than that of the inflow density. Therefore, a shock wave can be observed. Figure 7-11 shows the velocities as the function of time and space. Figure 7-12 shows the flow rates as the function of time and space. The shock wave also exists in these two figures.

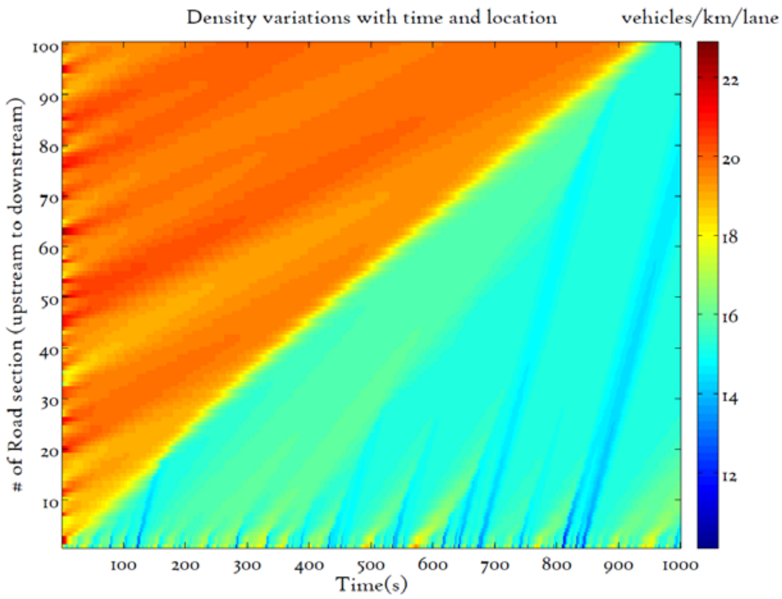


Figure 7-10 Densities on each road section as a function of time

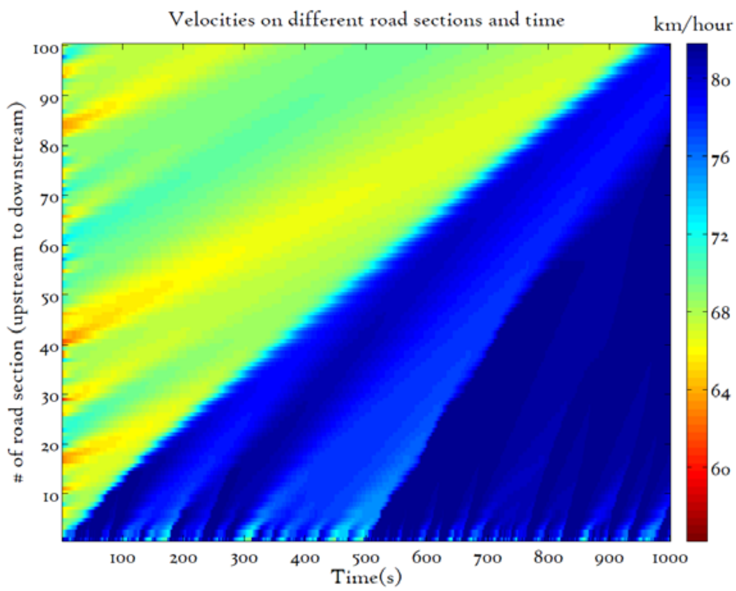


Figure 7-11 Velocities on each road section as a function of time

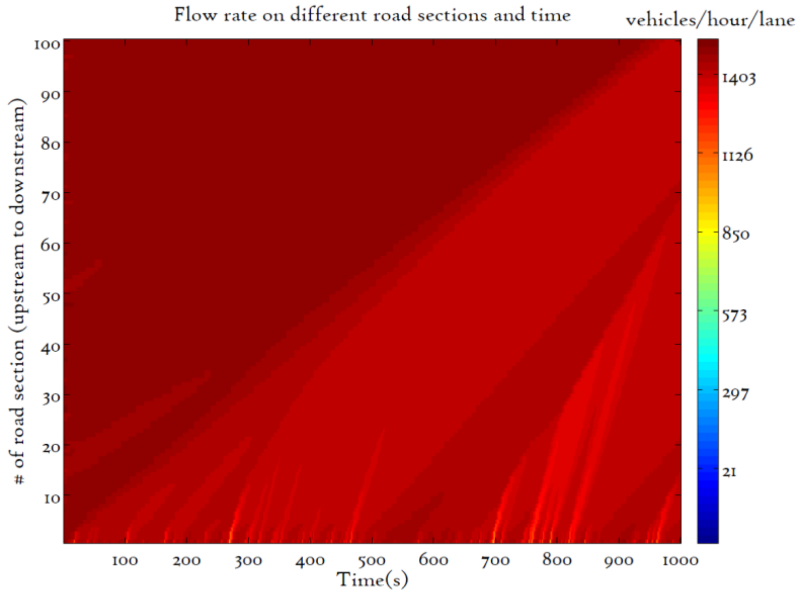


Figure 7-12 Flow rates on each road section as a function of time

The simulation results also show that the densities, velocities and flow rates from upstream to downstream need some time to propagate and achieve the equilibrium states. At the first few road sections there are some glitches of densities, velocities and flow rates because the input is at the 1st small piece of road section and it is defined as a series of random data objective to Poisson distribution. The following road sections show smoother characteristics on densities, velocities and flow rates. The aforementioned observations conclude that the freeway model corresponds with the theoretical foundations such as the fundamental diagram, shock wave theory and probability distribution. The freeway model is verified to be used in the later simulations.

Queue propagation

Several previous attempts have been made to solve the un-realistic queue propagation problem in DSP. For example, Jayaskrisnan suggested a method of dividing a link into smaller segments [37]; Hyejung Hu proposed a method for modelling more realistic queue propagation and dissipation based on the Kinematic Wave theory [40]. For simplicity, the method of fine-segmentation of link proposed by Jayaskrisnan is used in this test solution.

In this section, an example is given to show how this method can improve the queue propagation modelling. Since queue is strongly dependent on density, the queue propagation is presented with densities variation as the function of time and space.

Example: Queue propagation modelling

In this example, two 5km-long freeway stretches are used as the test road, as shown in Figure 7-13. Upstream freeway has 3 lanes and downstream freeway has 2 lanes. Lane of freeway has the same characteristics as

described in the '*Freeway Model*'. Therefore, a freeway bottleneck is set up here.

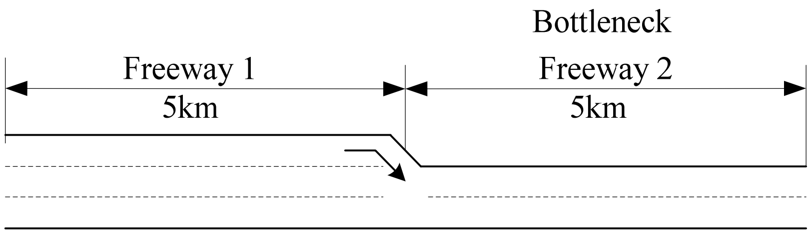


Figure 7-13 Freeways of queue propagation test

As described in the '*Freeway Model*', each freeway needs to be divided into segments and the characteristics of each segment is updated in every simulation time step by equation (7.2), (7.3) and (7.4). This example aims at proving the level of segmentation (rough to refine) has significant effect on the accuracy of queue propagation in this test solution. Two levels of segmentation are used: 500m/segment and 50m/segment, corresponding to 10 road sections and 100 road sections for each 5km-long freeway stretch.

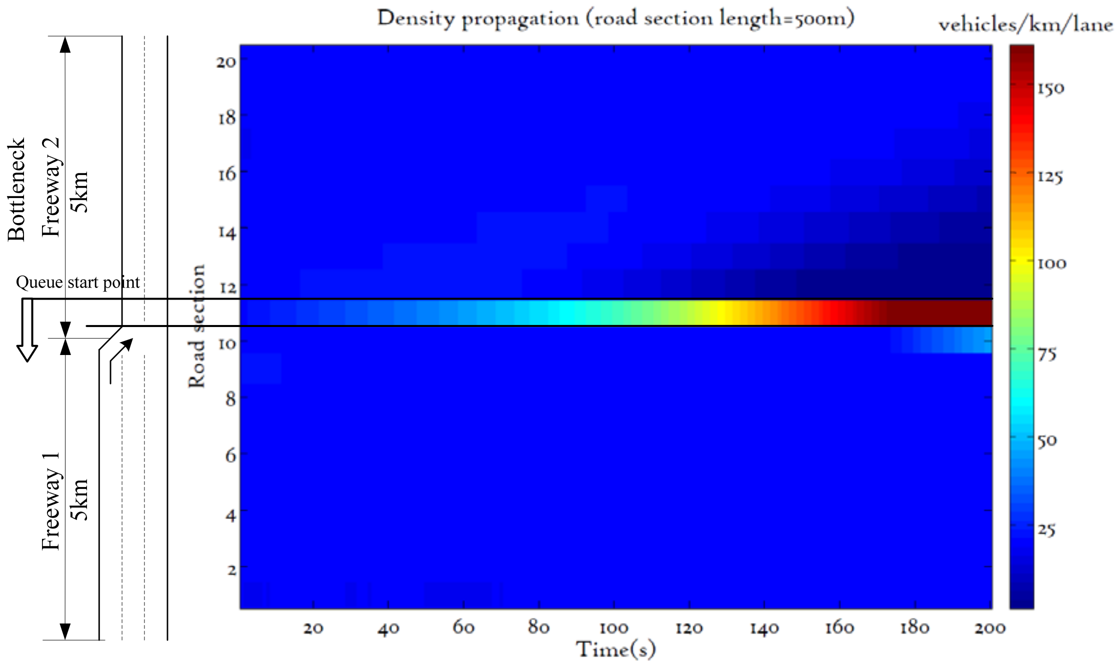


Figure 7-14 Queue propagation with segment length=500m

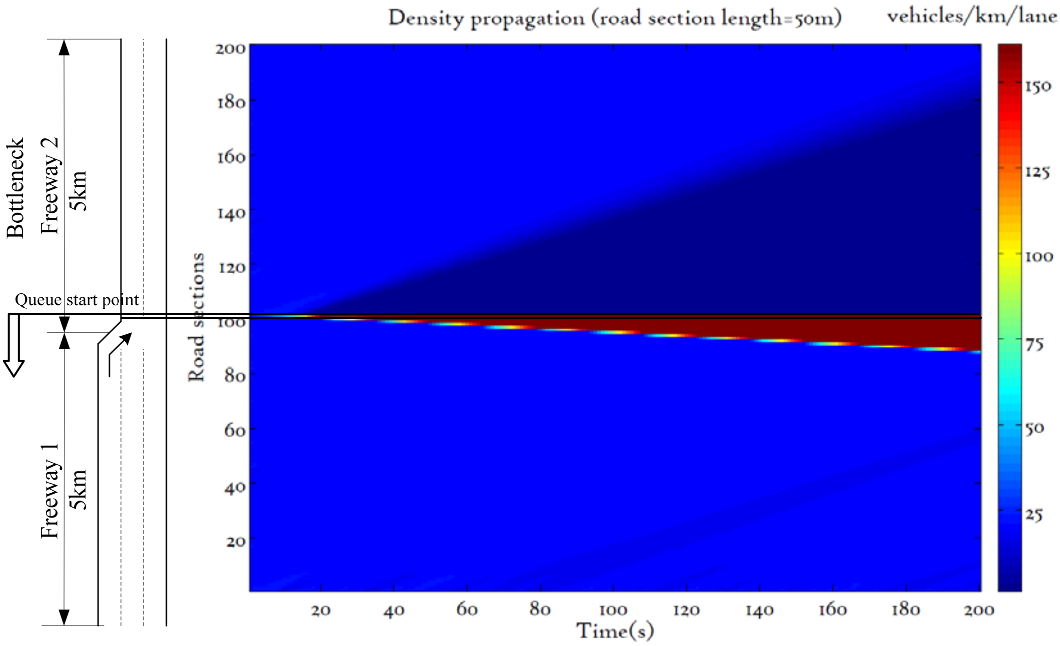


Figure 7-15 Queue propagation with segment length =50m

Figure 7-14 and Figure 7-15 show the density (queue) propagation in two cases with different segment lengths, namely, 500m/segment and 50m/segment. Both figures show that the jam starts from the end of the 1st road section of the freeway bottleneck, propagating back to upstream. The realistic start point of the jam should be at the beginning of the 1st road section of the freeway bottleneck. Therefore, for both cases, the mismatch between the realistic and simulation jam start points is the length of the 1st road section. Since road section in the second case is 50m, which is one tenth of the 1st case. Therefore, even though fine-segmentation method cannot radically eradicate the unreality of the queue propagation modelling, however, this method can help to improve the accuracy and reduce the unreality to a negligible level.

Base design (D_0)

In this simulation, four stretches of 5km-long freeway with three on-ramps in-between are used. The input traffic flow is given at the beginning of the first 5km-long freeway and it follows Poisson distribution. The initial condition on each freeway road section again follows Normal distribution at time 0. The no incident case is simulated with reasonable inflow and ramp flow.

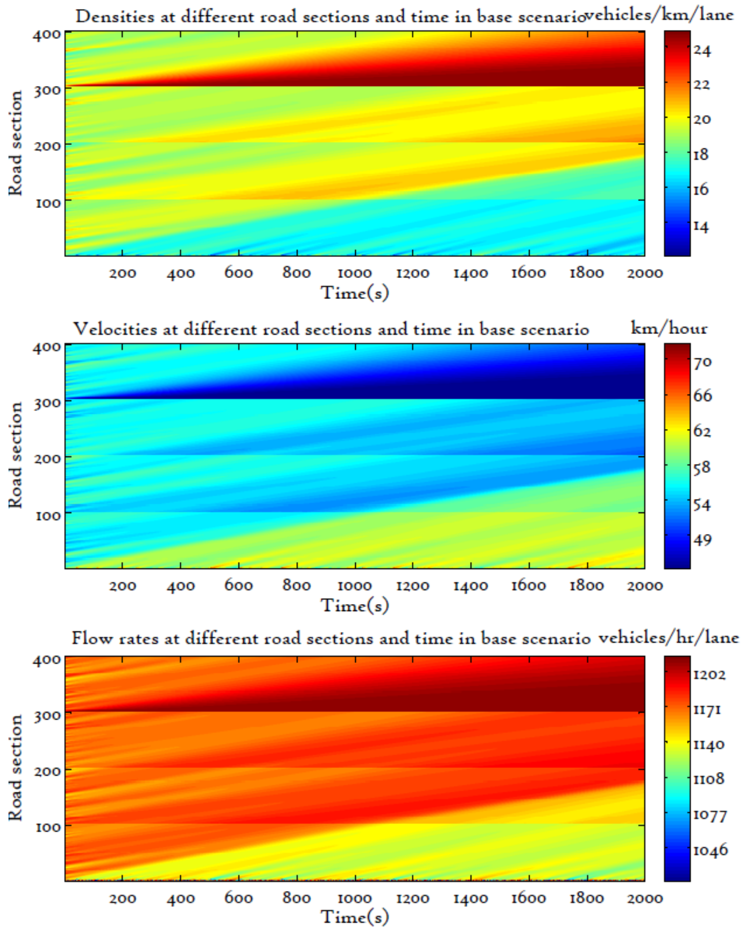


Figure 7-16 Densities, velocities and flow rates in base design

The densities, velocities and flow rates as the function of time and space are shown in Figure 7-16. In this figure, three sudden changes of densities can be seen. This is due to the inflows from the on-ramps, which increase the density of downstream freeway road section. The sudden change of densities leads sudden change of velocities. Because the density here is higher than the break density, any increase on density will reduce the speed. This is the reason of the three sudden changes of velocities at the three ramps. Due to the sudden changes of densities and velocities at the downstream links to the ramps, the sudden changes of flow rates at the same locations are reasonable.

The simulation result shows that the performance freeway model with on-ramps in base design is in accordance with basic traffic flow theories. Therefore, this model can be further used for the simulations of test solution.

Peak-demand

In this enhancement test, a step input (sudden increase of traffic flow or density) is added at the input of the whole road section. The purpose of this test is to simulate the system response to sudden demand increase. The inflow traffic is defined with the instructions in Appendix II, *peak-demand enhancement test*. The simulation

period can be divided into two phases at the critical time boundary of inflow jump. In the first simulation phase, the inflow traffic densities are random values following Poisson distribution with a mean value of 20vehicles/km. In the second simulation phase (from the 1000th second), the inflow traffic densities are still random values following Poisson distribution but the mean value suddenly increases to 30vehicles/km.

The densities, velocities and flow rates on each road section according to time are shown in Figure 7-17. After 1000 seconds, the inflow traffic density suddenly increases to 30vehicles/km. But after the second road section, the density drops below 20vechicles/km because the blocked vehicles are dissolved quickly. The velocity at the first road section suddenly drops due to the sudden increase of inflow density. However, passing the first road section boundary, the velocities increase to about 60km/hour. Due to the increase of density, the flow rates at each road section also increases after 1000 seconds. The simulation results of velocities show the characteristic of fan.

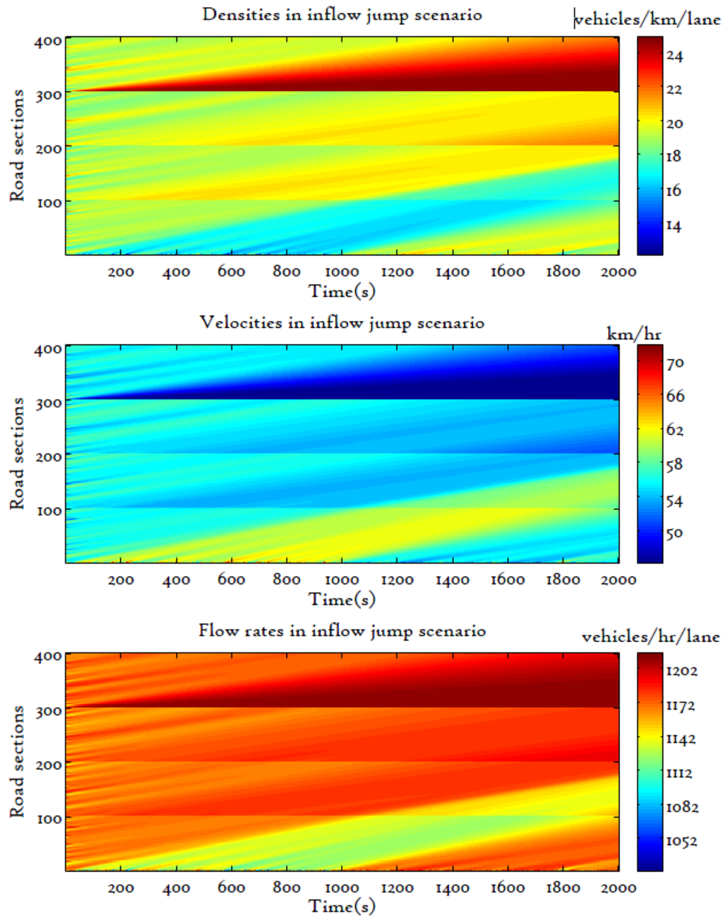


Figure 7-17 Densities, velocities and flow rates in peak-demand enhancement tests

Off-peak demand

In this section, a step input (sudden decrease of traffic flow or density) is added at the input of the whole road

section. The purpose of this test is to simulate the system response to sudden demand decrease in order to study the possible improvement by VMS. The inflow traffic is defined with the instructions in Appendix II, *Off-peak demand enhancement tests*. The simulation period can be divided into two phases at the critical time boundary of inflow drop. In the first simulation phase, the inflow traffic densities are random values following Poisson distribution with a mean value of 20vehicles/km. In the second simulation phase (from the 1000th second), the inflow traffic densities are still random values following Poisson distribution but the mean value suddenly decreases to 10vehicles/km.

The densities, velocities and flow rates as the function of time and space are shown in Figure 7-18. After 1000 seconds, the inflow traffic density decreases to 10vehicles/km. The densities drop gradually from the first road section to downstream. The shock wave can be observed clearly because the inflow density is smaller than the prevailing density on the main road. After 1000 seconds, the velocity at the first road section starts to increase, thus the other road sections downstream, due to the decrease of inflow traffic density. The simulation results of velocities also show the characteristic of a shock wave.

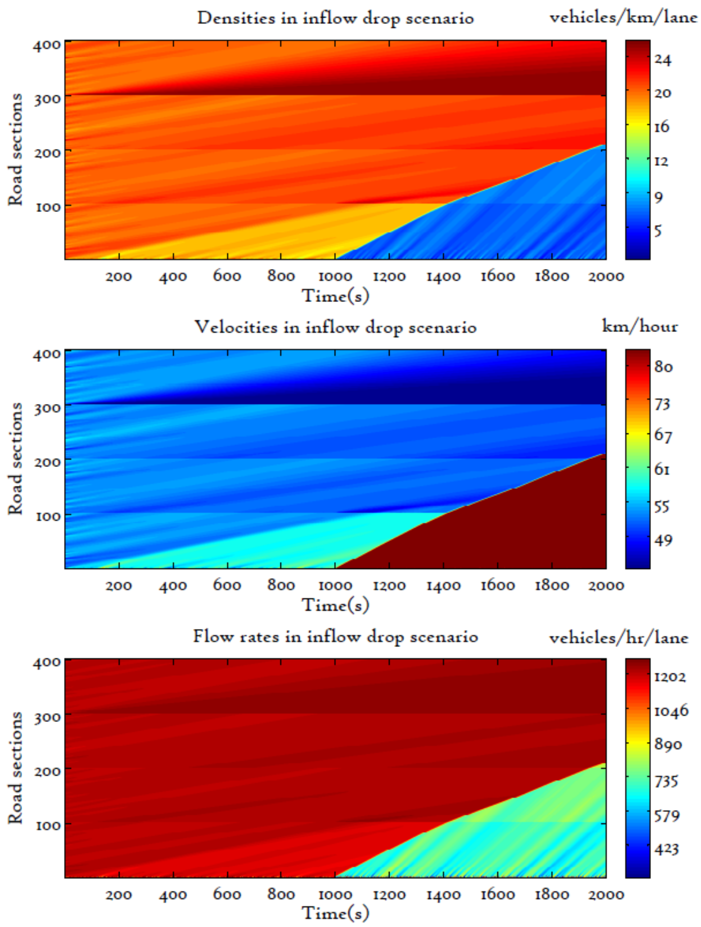


Figure 7-18 Densities, velocities and flow rates in off-peak-demand enhancement tests

7.5 Test solution control design

In section 7.5, the test solution control designs are introduced. Four control designs of the test solution are created: incident design with local ramp metering, incident design with coordinated ramp metering, incident design with coordinated ramp and un-coordinated VMS control and finally incident design with coordinated ramp and coordinated VMS control. Local ramp metering control design is set as the starting point and reference design. The effects of the other three control strategies are compared to the effect of local ramp metering design, under an incident scenario. The simulation results of these control designs will be compared and presented in section 7.6.

ID_1: Incident with local ramp metering (LRM)

In this control design, the traffic incident is placed at the downstream link to the 3rd ramp. The traffic model is the same as the one described in section 7.3.3. Ramp metering is deployed locally on each. This means the ramp metering is only engaged when traffic congestion can be detected. The modelling of ramp metering is referred to section 7.3.3.

In this simulation, the variations of density, velocity and flow rate on the freeway and the queue lengths on the ramps and freeway are of interest.

ID_2: Incident with coordinated ramp metering (CRM)

The purpose of this simulation is to check the effect of coordination between local ramp metering. Again, a traffic incident is placed on the downstream road section to the 3rd ramp. The traffic model is the same as the one described in section 7.3.3. In this case, coordination between ramp metering controls is applied, as described in the coordination scheme introduced in section 7.3.2.

ID_3: Incident with coordinated ramp metering and local route advice (CRM+RA)

In this control design, the incident is the same. Besides coordinated ramp metering, a local route advice VMS is added into the simulation. This VMS works independently and has no coordination with ramp metering controls. Therefore, the VMS is engaged only after it detects the congestion on its nearest downstream section.

At the beginning, this control design is similar to ID_2. First, the 3rd ramp starts local ALINEA control and a queue is generated on the 3rd ramp. The 1st and 2nd ramps start coordinated control when the queue length on the 3rd ramp reaches the threshold value. If the congestion propagates back upstream and covers the whole freeway, the route advice VMS at the beginning of the freeway is engaged because the congestion is detected. A certain percentage of vehicles are assumed to be diverted by this VMS and the inflow rate is reduced.

ID_4: Incident with coordinated ramp metering and coordinated route advice [C(CRM+RA)]

In this control design, the incident is the same. Besides coordinated ramp metering, coordinated route advice VMS is added into the simulation. This VMS works co-ordinately and is activated along with the 3rd ramp metering control when incident is detected. Therefore, the VMS is engaged with the prediction of possible congestion spill-back.

At the beginning, the incident is detected and the 3rd ramp metering control is activated. Meanwhile, the VMS module is activated. The 1st and 2nd ramps start coordinated control when the queue length on the 3rd ramp reaches the threshold value. The inflow rate of the freeway is limited because the route advice VMS diverts some vehicles to alternative route. Therefore, the densities on the upstream road sections, where traffic congestion has not been spilled back yet, will decrease. Meanwhile, the queue length on the 3rd ramp is detected every time step and if the queue is longer than the threshold value, say 20 vehicles, the 3rd ramp sends a signal to the 1st and 2nd ramp and they begin to control their outflow rates to the main road, which will further limit the inflow to the freeway. Because the coordinated ALINEA control of all the ramp metering is responsive to real-time traffic condition, once the coordination between VMS and ramp metering relieves the congestion, the ramp metering control can be loosed up to achieve minimum ramp total queue length.

7.6 Simulation results and evaluation

The control designs described in section 7.5 are implemented and simulated in Matlab. The simulation results are presented and evaluated in this section. Comparing the simulation results of the four control designs, some conclusions about the effectiveness of the test solution, the CNM control designs and the assessment methodology can be drawn.

Densities

In four control designs, the densities of the freeway road sections through the simulation time period are presented in Figure 7-19.

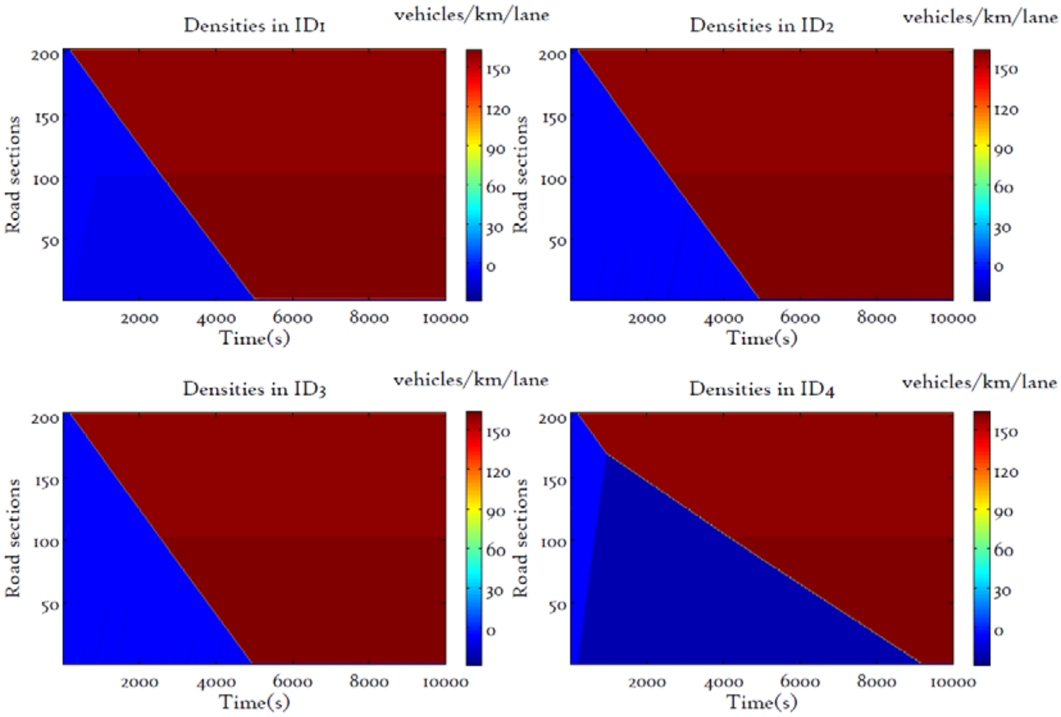


Figure 7-19 Densities on freeway in four control designs

The densities of freeway sections in ID_1 are shown on the top-left corner in Figure 7-19. In ID_1, the incident at the end of the freeway limits the maximum road capacity and a bottleneck is generated on the incident road section. The density increases significantly to the jam density on the incident road section. Besides, the vehicles from upstream are still driving with their prevailing speeds due to lacking coordination. And the total inflow is higher than the maximum road capacity of the bottleneck section. Therefore, jam density propagates to upstream of freeway and the queue spills back in the same way. The congestion moves from downstream to upstream. In fact, each road section needs some time to be fully congested. This can be observed as a small fragment between blue region and red region. Since the simulation planning horizon is respectively longer than the few merging simulation steps, this region are not quite visible.

The densities of freeway sections in ID_2 are shown on the top-right corner in Figure 7-19. Now coordination between ramps as described in section 7.3 is added into the simulation. The moment the incident happens at the end of the freeway, the density here increases immediately to the jam density, similar to ID_1. The effect of using coordinated ramp metering controls cannot be easily observed since the network scope is too large and the planning horizon is too long. However, there is improvement on reducing queue length on the freeway by using coordinated ramp metering controls. Figure 7-20 shows that the queue length on the freeway is shorter than ID_1 at each time step. And the freeway queue length in ID_2 covers the entire freeway 200 seconds later than ID_1. It seems that coordinated ramp metering helps to delay the propagation of traffic congestion.

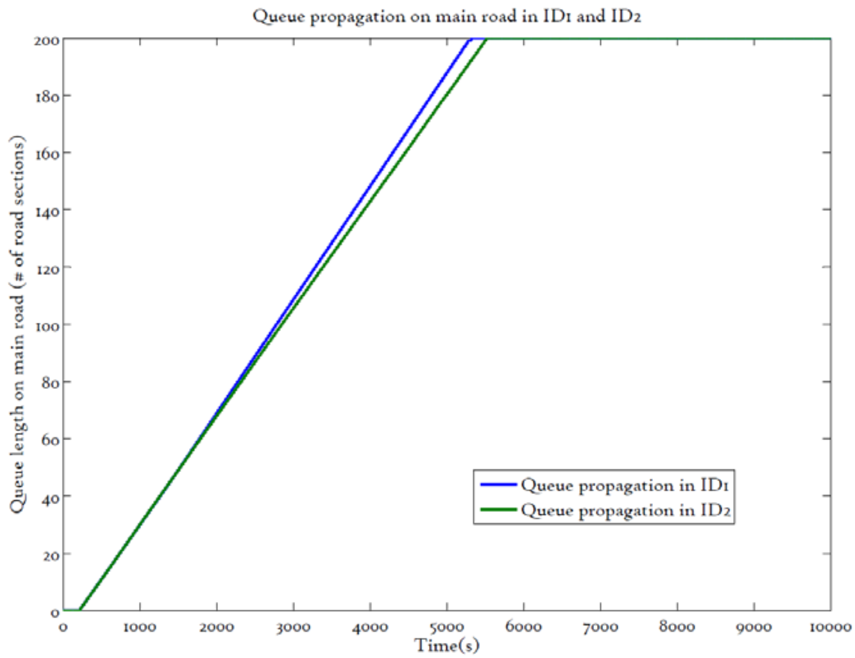


Figure 7-20 Queue lengths of freeway in ID_1 and ID_2

The densities of freeway sections in ID_3 are shown on the bottom-left corner in Figure 7-19. Before the 5500th second, the VMS is not engaged and the density variations in this case is, as expected, the same as the density performance ID_2. From the 5500th second, the VMS starts to work and the inflow rate of freeway is limited. The indifference level is 0.8, which means only 20% of the total vehicles are diverted. Because the first road section still has a higher inflow rate than outflow rate, the congestion on the first road section cannot be dissolved.

The densities of freeway sections in ID_4 are given on the bottom-right corner in Figure 7-19. According to the density, the whole road can be divided into three regimes. The 1st regime is the regular inflow regime, where the density is from the input density. The 2nd regime is inflow-reduced regime, where the density is the lowest due to VMS diversion function. The 3rd regime is the congestion regime, where the density is the highest. Due to the coordination, two shock waves can be seen clearly. Finally these two shock wave boundaries merge into a single shock wave boundary in the density figure. The moving direction of this shock wave determines if the congestion continues or dissolves, depending on the indifference level of drivers to the route advice system. In our test, the indifference level is set to 80%, which means only 20% of the total vehicles are diverted to other routes. This estimation is quite conservative. In this case, the congestion cannot be dissolved. However, the queue propagation is delayed. The fully-congested time of the whole road is approximately 1000 seconds later than the case ID_3. Different diversion rate are simulated and results can be seen in Appendix I, **test solution**.

Velocities

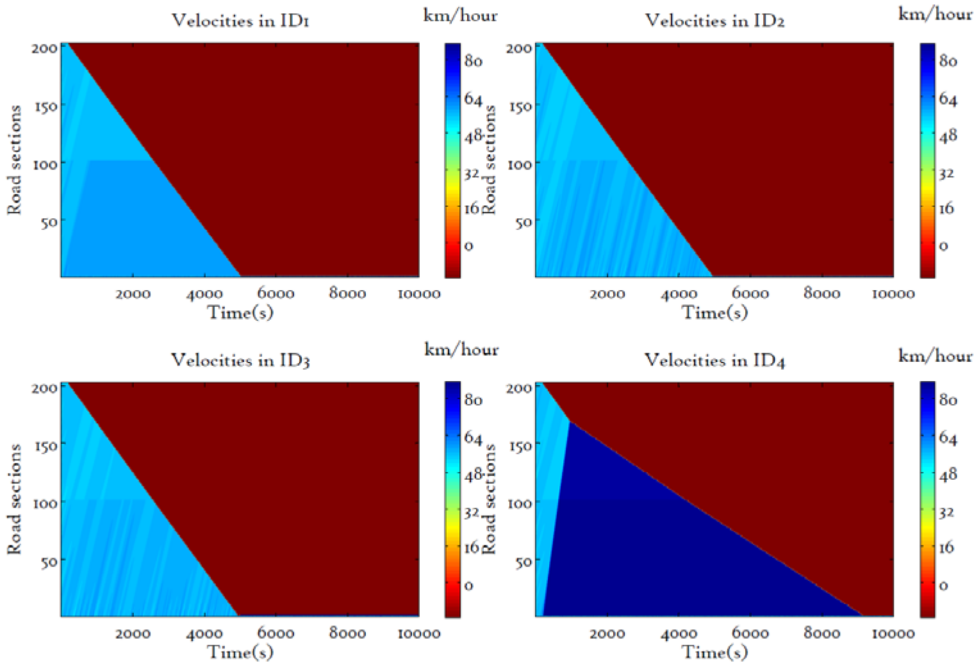


Figure 7-21 Velocities on freeway in four control designs

In four control designs, the velocities of the freeway road sections through the simulation time period are presented in Figure 7-21.

The velocities of freeway sections in ID_1 are presented on the top-left corner in Figure 7-21. Similar to the simulation results of density, the velocities of the vehicles drops from free flow speed to the minimum speed (0.05km/hour), from the last road section upstream to the first road section.

The velocities of freeway sections in ID_2 are shown on the top-right corner in Figure 7-21. Similar to the density figure, the difference from ID_2 to ID_1 is not obvious.

The velocities of freeway sections in ID_3 are given on the bottom-left corner in Figure 7-21. Similar to the density figure, after the 5500th second, even the route advice VMS starts to work, congestion cannot be dissolved due to the inflow rate higher than the outflow rate.

The velocities of freeway sections in ID_4 can be seen on the bottom-right corner in Figure 7-21. It can be seen that speed drops to minimum eventually with current indifference level (80% indifference, 20% diverted). However, this process was delayed for some of the road sections due to the reduced inflow rate by the route advice VMS.

Flow rates

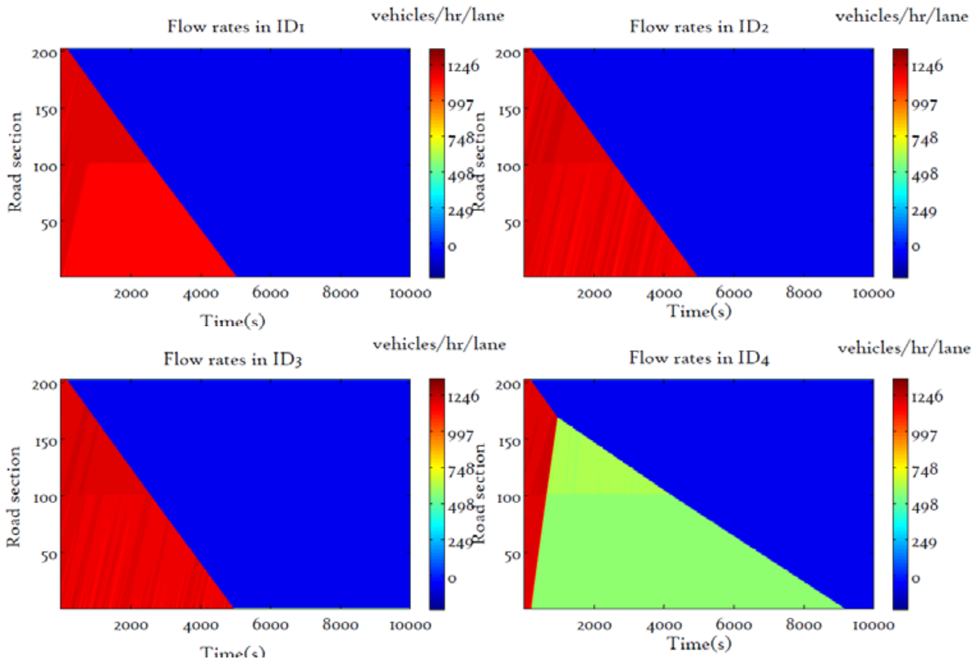


Figure 7-22 Flow rates distributions on freeway sections in four test scenarios

In four control designs, the flow rates of the freeway road sections through the simulation time period are presented in Figure 7-22.

The flow rates of freeway sections in ID_1 can be seen on the top-left corner in Figure 7-22. Although local ALINEA control starts to work, it is not effective enough to resolve the incident congestion. A queue is quickly propagating back to the input road section.

The flow rates of freeway sections in ID_2 are shown on the top-right corner in Figure 7-21. The effect of CRM is not obvious comparing to LRM. Eventually, a queue at the input road section is formed and the queue length can be outputted for evaluation later.

The flow rates of freeway sections in ID_3 are given on the bottom-left corner in Figure 7-21. When the diversion rate of VMS is set to be 20%, more vehicles enter the first road section than exit the first road section. Thus, no further improvement can be seen in this design case.

The flow rates of freeway sections in ID_4 are presented on the bottom-left corner in Figure 7-21. In accordance with the conclusion of density and velocity, the congestion cannot be dissolved but the congestion spill-back is delayed.

Ramp queue length

Until now, the effect of each control designs on the freeway traffic has been presented. Since ramp metering controls (either local or coordinated) are involved in these case designs, the ramp queue length is also an important MOE to check the effectiveness of various controls. Figure 7-23 shows the ramp queue length in four test solution control designs, including queue length on each ramp and the total ramp queue length.

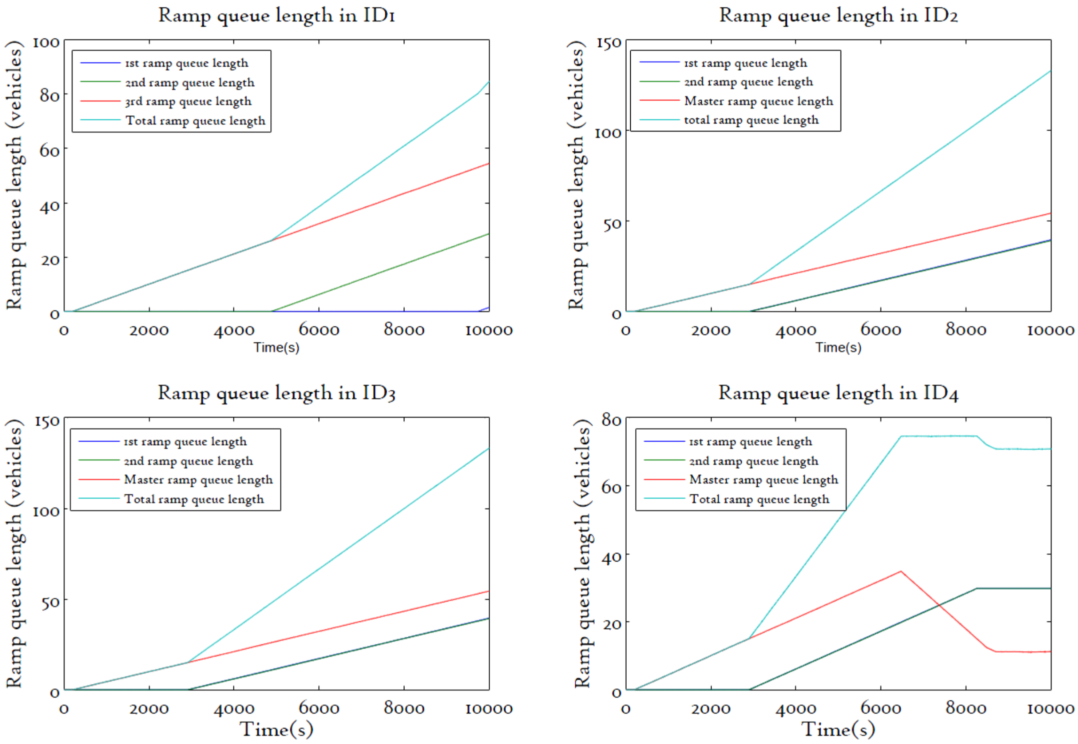


Figure 7-23 Ramp queue length in four control designs

The ramp queue length in ID_1 is shown on the top-left corner in Figure 7-23. At the beginning of the simulation, the traffic situation on the freeway is normal with no incident and ramp inflow is smaller than the maximum allowed ramp outflow rate according to ALINEA calculation. The queue lengths on all the ramps are zero. When the incident happens on the downstream road section to the 3rd ramp at the 200th second, ALINEA control of the 3rd ramp is activated and the outflow rate of the ramp is limited to a threshold value which is lower than the inflow rate. Thus a queue is generated on the 3rd ramp (The first section of red line, it is overlapped by the light blue line). However, since there is no coordination, the 1st and 2nd ramp outflow rates are not limited and there is no queue on these two ramps. Around the 4874th second, the traffic congestion arrives at the downstream of the 2nd ramp and the 2nd ramp outflow rate is limited to the threshold value according to local ALINEA. Now a queue is generated on the 2nd ramp, so is the situation for the 1st ramp later, around the 9730th second. From this figure, the queue length on each ramp and thus the total queue length keep increasing linearly after the accident. Even with the help of local ramp metering control, the total queue length can still be very high as time goes on

and the incident-reduced congestion cannot be relieved.

The ramp queue length in ID_2 is presented on the top-right corner in Figure 7-23. The 3rd ramp control is activated first around the 200th second the moment the incident happens on the downstream road section. The 1st and 2nd ramps start to coordinate and control outflow rates when the queue length on the 3rd ramp reaches 20 vehicles. Because of the severity of incident-induced congestion, these ramps start coordinated ALINEA control from the 2912th second till the end of simulation. The ramp outflow rate is controlled to the threshold value, which is lower than the ramp inflow rate. Therefore, queues are generated on the ramps and queue lengths increase linearly according to time. The total queue length in this case is a bit higher than that in incident case with local ramp metering control. The reason is that due to coordination between local ramp metering controls, the 1st and 2nd ramps start to generate queues earlier than the incident case with local ramp metering control. Since the ramp inflow rates and minimum outflow rates are the same for both cases, with and without ramp coordination, the total queue length in incident case with ramp coordination is longer than that in incident case without ramps coordination given the same simulation time. The trade-off is that the queue length on freeway is reduced.

The ramp queue length in ID_3 is given on the bottom-left corner in Figure 7-23. The ramp queue length in this design case is the same as the results in design case ID_2 because they have the same coordination scheme between ramp metering.

The ramp queue length in ID_3 is given on the bottom-right corner in Figure 7-23. A queue is generated on the 3rd ramp first. After the queue length is longer than 20 vehicles, the controls of the 1st and 2nd ramp are engaged. After a certain time step, the inflow rate on freeway road section upstream to the 3rd ramp is reduced because of VMS diversion function. Thus the control to the 3rd ramp is loosened up and the ramp queue length starts to decrease. The other two ramps work in a similar way. Therefore, the total queue length can be limited and it is much smaller than the values in the other three design cases. For simplicity, the 1st and 2nd ramps are designed with the same control parameters. And their coordination are engaged and released at the same time. Thus in the queue length curves for the 1st and 2nd ramps are the same.

7.7 Conclusion

The test solution simulation results show that with CRM, the incident-induced congestion cannot be dissolved. Also the ramp queue length will keep increasing linearly with time and even a bit higher than LRM. However, due to the coordination between ramp metering, the queue length on the freeway is slightly. But it is not enough to dissolve the congestion on freeway. The congestion is spilled back (about 200 seconds later comparing to LRM) and covers the whole freeway.

With CRM+RA, the network performance is similar to CRM before the VMS is engaged. After the VMS is engaged, whether the congestion starts to dissolve or not depends on the driver indifference level. In the design case, the indifference level is set as 80%, which is quite conservative. In this case, this coordinated VMS has almost no effect on relieving congestions.

Finally, with C(CRM+RA), the non-recurrent traffic congestion can be improved in the following aspects:

1. The diversion function of coordinated VMS control can slow down the congestion spilling back speed (bending the slope). The effect of "slowing down" congestion spill-back is proportional to the diversion rate of VMS. Another example with a higher diversion rate, approximately 80% (The percentage of the captive vehicles that cannot be diverted equals to [q_{out}-$q_{ramp\ 1}$- $q_{ramp\ 2}$- $q_{ramp\ 3}$]) is given in Appendix I, which show that under high diversion rate, C(CRM+RA) can clear the incident congestion during simulation period.

2. The queue length on each ramp and the total queue length of three ramps in C(CRM+RA) are shorter than the other control designs.

In conclusion, although the test solution modelling and evaluation cannot include all the characteristics of traffic flow accurately, the simulation results heuristically show that the test solution can model and simulate the effect of CNM practice in order to solve freeway bottlenecks.

8 Synthesis

This master thesis project is divided into three parts. They link together with connections between the preceding part and following part. Objective of each part can reveal theses connections. One main objective of part one is to develop a possible assessment methodology for modelling and ex-ante evaluation of CNM. The objective of part two is to propose an assessment methodology and apply it to the case study. Then, learn and reflect from the results and complications. The objective of part three is to design a coordination test solution, amending the lessons from part two as much as possible in order to apply and improve the proposed assessment methodology on the empirical case as well as show some perspectives about CNM practice. The three objectives are attained with three parts of this thesis work organized as shown in Figure 8-1.

This chapter tries to answer the proposed research questions as much as possible. To this end, this final chapter synthesizes the thesis with conclusions of main findings, recommendations to CNM practice and future directions of CNM research and operation.

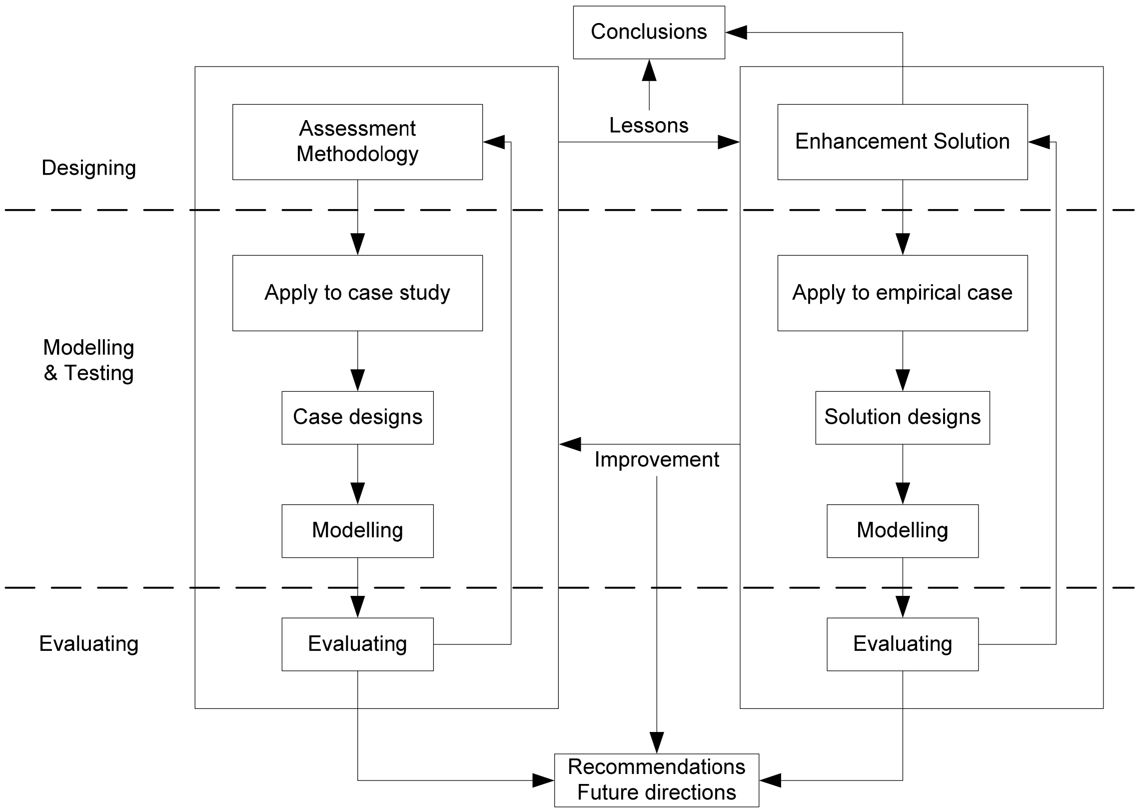


Figure 8-1 Thesis work vision and operation

8.1 Conclusions

This section concludes the main findings of the thesis project and tries to answer related research questions.

Why is the CNM practice important? What is the state-of-the-art CNM?

Traffic management embodying ITS control measures, with the nature of monitoring and controlling traffic based on existing infrastructure through intelligent technology system, is generally accepted as a promising solution to slow down growth of traffic congestion. Practice of traffic management has evolved from isolated dynamic traffic management to coordinated traffic management, and heading towards coordinated network management. The need of traffic management and the trend towards coordination, signify the importance of CNM.

The importance of CNM can be explained with the characteristics of traffic individual, traffic flow and traffic network. From the conventional fundamental diagram (traffic flow on link base) and the network macroscopic fundamental diagram (traffic network production), the task of traffic management is to control the density or accumulation under critical point. To what extent the shape of FD may be changed and for how long the maximum production can be kept, are determined by the practice of CNM. From the policy perspective, the importance of CNM is shown from minimizing conflict and maximizing synergetic functions between various local controls, meanwhile keeping different levels of objectives within frame.

CNM practice is complicated, both from the scientific level and the practical level. As far as described, the PPA project is one of the most comprehensive CNM practice. With the emerging of CNM projects around the world (mentioned in chapter 2), the state-of the art CNM is in the making.

What could be the proper assessment methodology and modelling tool for CNM?

Limited cases are found for demonstrating the state-of the art CNM. Most of the state-of-the-art CNM cases don't provide an assessment methodology framework for modelling and ex-ante evaluation of CNM. One objective of this thesis project is to develop a feasible assessment methodology which includes the stepwise process for modelling and ex-ante evaluation of CNM.

An assessment methodology is proposed in chapter 3 with an assessment methodology and a modelling tool. The methodology is principle-based, modelling-based and predictive operation-based. The tool was chosen to be Dynasmart-P. This assessment methodology is applied to the case study. Although it seems to be feasible and operable for modelling and ex-ante evaluation of CNM, the performance of this assessment methodology (so is the effect of CNM) is implicated by several reasons, such as the modelling tool choice and the case study network.

The test solution in chapter 7 is developed to realize an enhancement application of the assessment methodology. Some adjustments are made to the assessment methodology when it is applied to the empirical case for

modelling and ex-ante evaluation of CNM. The modelling tool is changed to Matlab and the network is an empirical network with incident congestion. Again, the assessment methodology for modelling and ex-ante evaluation of CNM shows feasibility when applied to the empirical case with the test solution. And the effects of CNM are clearly shown.

How should the experiments of case study be carried out under recurrent and non-recurrent conditions to test the effects of CNM and the proposed assessment methodology?

The experiments of the case study are set-up in chapter 4. The steps of designing are shown in Figure 8-2. The purpose of the case study is to model and evaluate CNM using the proposed assessment methodology. To this end, control designs of the case study are created using the assessment methodology in section 3.1. The case study network is built in the modelling tool-DSP. Simulations and results are also obtained from DSP. The simulation results are evaluated later in order to find out the effect of CNM and the performance of the proposed assessment methodology.

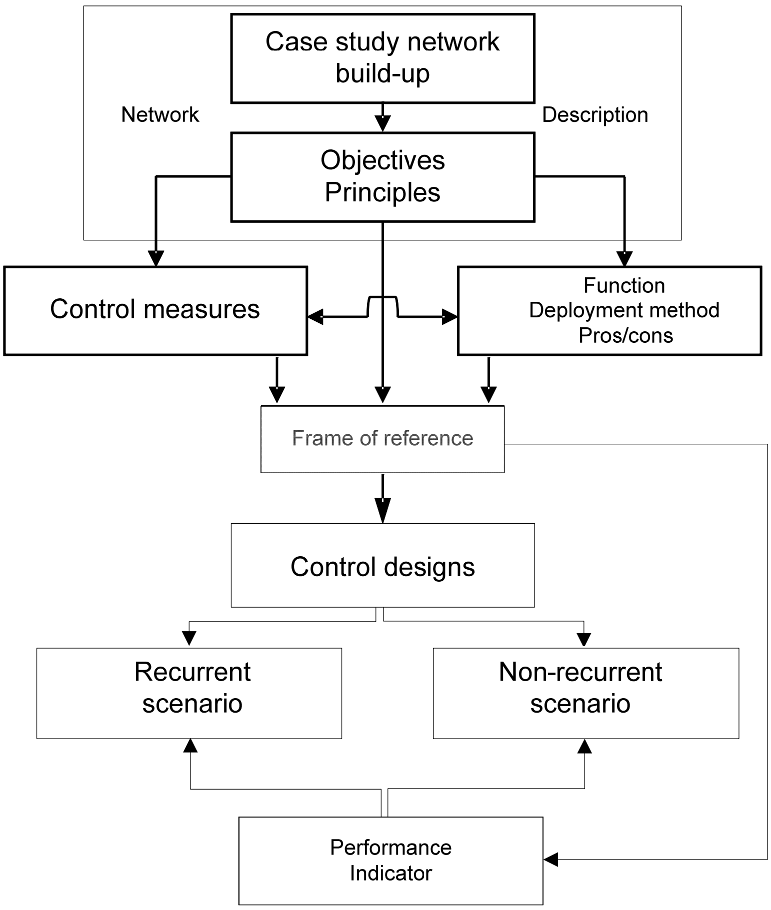


Figure 8-2 Case study experimental steps

According to the simulation results of the experiments in the case study, what are the effects of DTM and CNM and how could the simulation results be interpreted? *What are the findings in the enhancement application, considering the same subject?*

As mentioned above, the case study with CNM control designs were simulated with the modelling tool, Dynasmart-P. According to the simulation results, the effects of each DTM/CNM control design are interpreted directly.

For recurrent scenario, seven control designs are simulated and their performances are summarized and compared on the network level and the local level.

Comparing the values of chosen MOEs, the performances show that local ramp metering has some positive effect while coordinated ramp metering has better performance on the network level but not better on the local level. Coordinating variable speed limit with coordinated ramp metering shows no further improvement on either level. Coordinating route information VMS with coordinated ramp metering also shows no further improvement on the network level but shows some positive effect on the local level (freeway stretch). Coordinating route advice VMS with coordinated ramp metering shows effective performance on both levels. With single route advice VMS, the network performance is significantly improved. However, multiple route advice VMS hardly shows any further improvement.

For non-recurrent congestion, four designs are simulated and their performances are summarized and compared on both network and local levels. Local ramp metering control can improve network and local performance under incident congestion. Coordinating ramp metering with route advice VMS shows further improvements on both network level and local level.

Therefore, local ramp metering, coordinated ramp metering and route advice VMS show positive performance for both recurrent and non-recurrent scenarios.

Besides limited knowledge of the author, many defects in the modelling tool and the possible underlying problems in the case study network lead to unreliable simulation results and evaluation.

But based on the direct results output, an arbitrary finding is that coordinated network management shows promising effects on solving both freeway bottlenecks and improving network performance. This prediction is tested in part three of this project.

The enhancement application of the proposed assessment methodology is realized with a test solution, which includes amending the implications as much as possible and providing a desired coordination scheme. Then basically the same assessment methodology is applied to the empirical case for modelling and ex-ante evaluation

of CNM. Control designs are simulated on Matlab. The simulation results show the following findings:

1. Coordinated ramp metering has some effects on utilizing spare spaces on ramps and postponing blockage. But it is not effective to solve the incident congestion in the test solution case.
2. Route advice VMS has enhancing effect when coordinated with CRM. The diversion rate strongly affects the incident congestion. From low to high diversion rate, effects of route advice VMS can range from reducing the congestion spill-back rate to solving the incident congestion.
3. The framework for modelling and ex-ante evaluation is feasible on CNM. At the very least, it provides auxiliary help to CNM practice.

8.2 Recommendations

In this section, recommendations to the proposed assessment methodology and also to CNM practice are presented. These recommendations are introduced while answering the original research questions and the recommendation questions (Italic).

> How did the proposed assessment methodology and modelling tool perform when it is applied to the case study? What impacts and implications have been put to CNM practice on the case study? What can be learned from the case study? *In order to evaluate the assessment methodology, how can an enhancement application with test solution for CNM be designed?*

The proposed assessment methodology is applied both onto the case study and the enhancement application (with some adjustments). In the case study, the assessment methodology is operable and practical because it renders the modelling and ex-ante evaluation of CNM scalable and systematic in a large network. To say the very least, it is a relatively simple system to test the principles and realize the objectives. However, the modelling tool of the assessment methodology framework performed poorly, which implicates the simulation results and thus evaluation. These impacts to CNM practice on the case study are listed below.

1. Innate problems of DSP

   Several problems have been discussed and some of them are amended as much as possible in part III of this thesis project. These problems include non-zero minimum speed, lack of capacity constraint (sensitivity to effective lane miles), queue propagation, unfit for optimization of traffic management, flawed traffic control measures and unfit for network calibration (at least on the link level). All the above problems have caused inaccuracy in simulation results in the case study, which makes either the evaluation of the assessment methodology or the evaluation of CNM effects invalid. The most pressing

three problems, non-zero jam speed, no capacity constraint and bottleneck queue propagations are amended in the test solution as much as possible for the enhancement application.

2. Accurate/valid control measures are very limited and coordination of control measures doesn't exit. To model and evaluate CNM, the modelling tool should have valid control measures. While DSP does provide a wide range of ITS controls and corresponding driver responses and route choice, some of them are unfit for optimization of traffic management, such as intersection signal controls and some of them are flawed, such as mandatory detour VMS.

3. The innate problems of modelling in DSP also implicate the accuracy of these control measures. Static traffic management, such as most kinds of the infrastructure adjustments are not operable because of link capacity constraints and queue propagation. Ramp metering is easily affected by queue propagation problem.

4. No coordination between control measures

   To model and evaluate coordinated network management, the tool should have coordination between those control measures. In the current version of DSP, there is no coordination scheme or algorithm exists, to the author's knowledge. In the case study, artefacts to simulate coordination are used and they could cause sub-optimal designs for CNM practice.

The above implications are learnt from the case study. A test solution featuring the advanced deployment of CNM scheme is initiated from these lessons. Amending the learned lessons as much as possible, the test solution is based on conventional macroscopic flow theories and mathematical model. Control designs are made according to the assessment methodology and simulations are performed and evaluated in Matlab.

How did the assessment methodology performed in the enhanced coordination test solution?

In the test solution, the proposed assessment methodology is also applied. Some adjustments were made, such as changing the modelling tool to Matlab and revising the frame of reference for the empirical network. The assessment methodology for modelling and ex-ante evaluation CNM works well together with the test solution. Simulation results are presented and some findings are listed in section 8.1.

What can be recommended for CNM practice and operation? What can be recommended for DSP usage?

The thesis project is focus on developing and applying an assessment methodology for modelling and ex-ante evaluation CNM. Abundant tests were performed applying the assessment methodology to projects, either on a field network or an empirical network. Some recommendations for CNM practice and operation are listed below.

1. An assessment methodology for CNM practice is needed. The CNM practice is aiming at coordination of heterogeneous control measures on a large-scale network. Such an assessment methodology framework should be made beforehand to guide the modelling, ex-ante evaluation and control operation of CNM.
2. A verified traffic simulation tool is helpful for modelling and ex-ante evaluation the effects of CNM. The case study was performed on DSP, which turned out to be unsuitable for CNM practice. The results and evaluation are implicated. So, before extensive CNM works are put into practice, the choice of modelling tool should be carefully considered and verified.
3. Ex-ante evaluation of CNM must be performed on a calibrated network. A network must represent the current traffic situation before any traffic management is evaluated. Otherwise, the results are likely to be flawed.

Recommendations for DSP usage

1. The current version of DSP is not designed for optimization of traffic management but offers a great deal of ITS control measures. However, some of them are not performing logically or resembling the traffic characteristics. Before more profound studies and improvements are carried out on DSP, it is not a suitable tool for short-term prediction and evaluation of CNM effect. Nonetheless, DSP is widely used for studying the evolvement of traffic on a network. The dynamic traffic assignment function is considered to be informative.
2. Some innate problems have been found in DSP. They can affect the simulation and evaluation of DTM. To solve these problems, a pressing task for DSP is to revise and include related enhancement to amend these problems.
3. A network built on DSP needs to be calibrated well, preferable with the help of calibration tools or other microscopic tool
4. DSP doesn't include coordination between control measures. So it is not recommended for CNM practice. If it is chosen for CNM practice, coordination of control measures needs to carry out in auxiliary modelling tools before returning the results to DSP.

How did the enhanced coordination test solution performed? What are the recommendations for the test solution?

The test solution tries to amend some of the lessons learned previously with enhancements. The simulations results obtained from Matlab show promising effects of CNM in incident scenario. Matlab is a powerful tool for

mathematic modelling and calculating. However, it is not professional traffic engineering software to simulate traffic flow with proper infrastructures and layouts built up on an existing network. Therefore, the test solution realized in Matlab is suitable for theoretical modelling and ex-ante evaluation but it cannot simulate or solve traffic congestion of real large-scale network. This test solution also abstracts from reality because of some assumptions and shortcomings. The recommendations to the test solution are:

1. Several assumptions were made in the test solution for simplicity. In the future, these assumptions need to be examined in order further validate the test solution. These assumptions include discretized time steps, segmentalized road sections, consistent traffic demand and system performance within each time interval and the density of queue is a fixed value of jam density. Due to the limited time, these assumptions are unsolved in the test solution. They are recommended for the future enhancing.

2. Some input assumptions are made for the consistency of control measures and cross-comparison between different control designs so that the effect of CNM can be observed clearly under a homogeneous traffic flow. The traffic inflows to the three ramps are designed to be random; their mean values are designed to be the same for simplicity. But in real cases, these assumptions may not stand.

3. The VMS control is modelled based on its expected diversion effect. In the real case, it can be very complicated. For example, the vehicles are assumed to be diverted to other routes with a certain percentage. However, in real case, the human-related behaviour is very difficult to estimate. Therefore, this is recommended for the test solution to tackle more complicate situations.

4. Microscopic characteristics of traffic flow are not considered. Many elements of traffic flow can affect the CNM control strategy microscopically. Therefore, microscopic characteristics need to be considered in the test solution in the future.

5. The test solution should be developed to completion. First, the network used in this thesis project is simplified for the convenience of theoretical research. It should be extended to a more realistic network. For example, only the freeway is considered in the simulation for simplicity. The relationship between the freeways and arterials way was not modelled. These need to be modified in the test solution.

6. More control measures should be included for coordination besides ramp metering control and VMS control. For example, individual module can be used for modelling each control measure.

8.3 Future directions

This master thesis project gives some possible explanations to some questions. But some other questions are raised and unfortunately, they cannot be solved due to the limitations of the author and due to the scope of this

project. They are given in this section for future directions of CNM research and practice.

What are the future directions for CNM research and practice?

Future directions for CNM research and practice

Judging on its complicated nature, a lot of work needs to be done for CNM research and practice.

1. CNM research and practice is in great need for a system (including software, algorithms and monitoring) guided by a CNM assessment methodology, so that the system can provide a more intelligent use of already existing dynamic traffic management.

2. CNM could have effect on traffic on a longer term than "one-shot". A short-term prediction model with only instantaneous reaction to the CNM control design will be insufficient for the research. It would be interesting to include CNM in DTA from a traffic engineering aspect.

3. For future deployment, the research and practice scope of CNM needs to be extended. Static, dynamic traffic management control measures need to be coordinated in a more proactive way. Scenarios such as extreme weather condition are also interesting to exploit. Judging from the state-of-the-art nature of CNM, it sounds like a promising solution to solve unforeseeable scenario. Simply put, the question that needs to be answer is, can CNM solve a traffic congestion of 831 km in a snow storm? (The traffic jam length of entire Netherlands, 03-02-2012)

4. CNM is not exclusive to roadside traffic management. To achieve an optimal network management, CNM should be more active in the area of coordination between information services, either in-car or road-side.

5. There are countless traffic simulation tools. But it is rare to find one that includes automatic coordination between various control measures. Choice for modelling tool of CNM is critical. If one effective tool is recognized, then careful examination and evaluation of the tool is needed before CNM research. Separate tools (e.g. SCOOT for intersection coordination, HERO for ramp metering coordination), may have to be applied and then integrated to study CNM on a network level.

6. If the PPA project provides a promising prototype of coordinated network management, caution is needed to ensure consistency between the predictions for different networks. And if in the future, these different networks becomes sub-networks and combine into one national network, the boundary conditions must match when adhering to a multi-agent architecture of dividing the network in smaller sub-networks [52]

Future directions for the thesis project

Future directions considering a sequel of this thesis project can be carried out in two directions, practical field

experiments or theoretical research and tests.

Practical

1. The network of a large-scale project could require integration of microscopic and macroscopic models. The case study network used Aimsun and Dynasmart. Other tool choice combination could be Paramics and Dynasmart, or Vissum and Dynasmart. However, such integration needs to operate carefully.

2. A test bed is needed for realizing coordination algorithms and methodologies with the CNM control designs. This requires a profound and comprehensive understanding of CNM, also an all-around sophisticated technique of DTM/CNM modelling tools. For example, the test bed must provide either or both a compatible background for integrations of results from different tools, a system for the embedding of coordination methodologies. The development and application of such a test bed require vast knowledge and cooperation of intelligences, agencies and stake holders.

Theoretical and practical

1. Realizing the test solution in a proper simulation model, with the simulation results of a realistic the network, the test solution can be better evaluated. Individual modules of each control measure can be synthesized with coordination algorithm and transformed into a traffic simulation tool embedded with CNM module.

2. In the future, this simulation model could provide temporal solution when the detected field situation has no match case in the decision support system. Therefore, fast temporal solution is needed. A desired simulation tool with pre-programmed algorithms and flexible modules of control measures will need to be developed with theoretical and practical research.

The research of CNM will continue. A final remark for this thesis project is:

Traffic ought to flow perpetually. The stationary condition means the beginning of the end. The future research of CNM will keep on solving traffic jam.

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Appendices

Appendix I

Appendix I provides additional information of the case study experiments. Due to the limit knowledge of the author and the doubtful MOEs in DSP, such as flow rates, queue lengths and even average speed and density, etc., this part is not reliable for evaluation conclusions. But it might still provide some process of the original experiments. Thus, flaws and lessons can be learnt for future enhancement.

Recurrent scenario

D_0: Base design, do nothing

Base design includes intersection control data. Among all the intersections, 837 intersections are of no control, 33 intersections are of yield signs, 20 intersections are of 4-way stop signs and 58 intersections are of actuated control. All the above intersections are modeled in DSP according to different signal control strategies of the case study area. Since the case study network is already calibrated from previous parallel study, the base design will be sited as a benchmark for this thesis project. Therefore, future control designs will be developed on this base scenario, so will the results analysis and evaluation.

From a one-shot simulation run of the base design, the traffic situation can be visually viewed by time steps of the planning horizon. The first impression is that ring A10 is quite congested, particular for the A10 South eastbound. This could be explained by the fact that the simulation period is the evening peak hours when traffic volume is the highest, which puts pressure to the inner ring road like A10, replying on its "roundabout" like function and traffic distribution function. The simulation results are shown in Figure 0-1. Densities of A10 South eastbound are presented according to links on A10 South eastbound, and according to planning horizon from 0 minute to 240 minute. This density figure points out four locations that have the high densities peak.

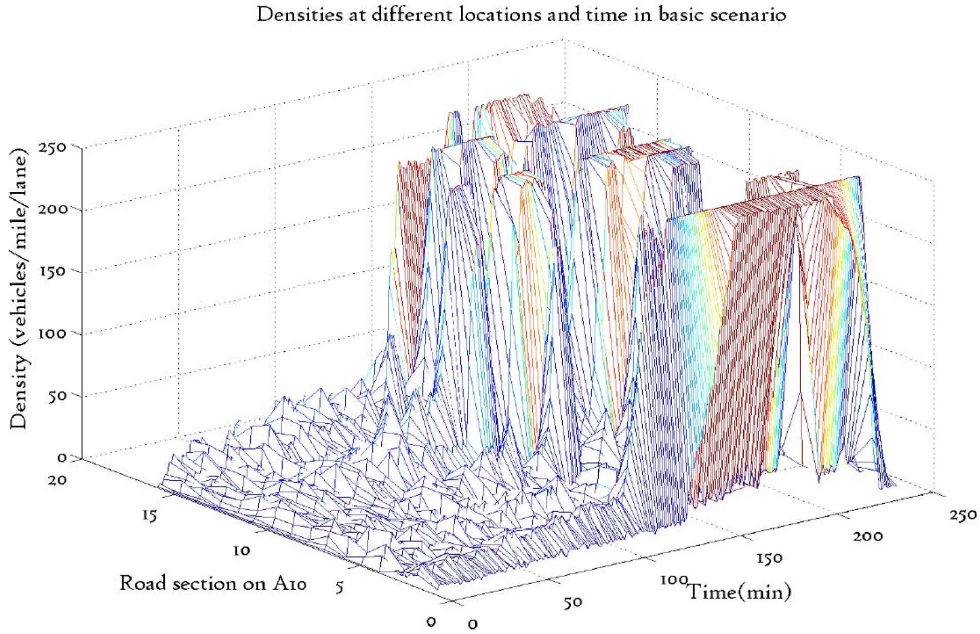


Figure 0-1 Densities of A10 west at each location and time, base scenario

The statistics results of the entire network in base design are given in Table 0-1.

Vehicle Types	Total Travel Times (HRS)	Average Travel Times (MINS)	Average Trip Times (MINS)	Average Stop Times (MINS)	Average Trip Distance (MLS)
Non-Equipped	55906	12.42	14.75	2.45	5.95
Equipped	9451	11.69	14.05	1.97	6.06
Overall	65357	12.31	14.64	2.38	5.97

Table 0-1 Statistics results on network level, D_0: base design

From Table 0-1, it can be seen that the major part of average trip time is average travel time. Average stop time, which means average queue time of vehicles, is only about 16% of average trip time. Therefore, the network in base scenario has a certain level of congestion but not too serious. Meanwhile, the average travel time, average trip time and average stop time of equipped vehicles are slightly lower than those figures of non-equipped vehicles, due to the different accessibilities of information for these two classes of vehicle. However, the average trip distance of equipped vehicles is not necessarily lower than non-equipped vehicles. This means that the equipped vehicles may have to take a longer route in order to avoid traffic congestions on the shortest-distance-path.

D_1: Local ramp metering

In this control design, a local ramp metering control is installed on an on-ramp (S109 to A10 South eastbound freeway). Visible congestions of this area are presented in Figure 0-1. So a ramp metering control is placed on this on-ramp to limit the traffic flow from ramp to freeway and reduce the interruption to the freeway through traffic. The parameters of the ramp metering are shown in Figure 0-2. The ramp metering control starts from the 130th and stops at the 210th minute because the downstream freeway link reaches jam density during this time. The occupancy-to-flow rate is set to 0.32, which is used to define the K_R in ALINEA algorithm described in section 3.2.4. The desired occupancy rate on freeway is set to 0.1. The saturation flow rate of the ramp is set as 0.5veh/sec/lane, which corresponds to 1800vehicles/hour/lane.

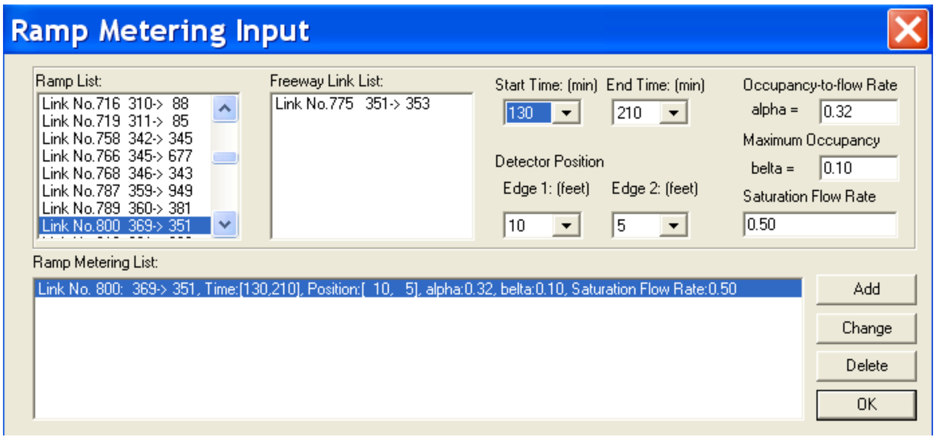


Figure 0-2 Parameters set-up of local ramp metering in recurrent scenario, D_1: local ramp metering

Vehicle Types	Total Travel Times (HRS)	Average Travel Times (MINS)	Average Trip Times (MINS)	Average Stop Times (MINS)	Average Trip Distance (MLS)
Non-Equipped	54822	12.18	14.76	2.34	5.95
Equipped	9357	11.57	14.19	1.92	6.04
Overall	64179	12.09	14.68	2.27	5.96

Table 0-2 Statistics results on network level, D_1: local ramp metering

D_2: coordinated ramp metering

A simple coordination between two ramps (with same traffic flow direction) is implemented on A10 South eastbound to examine the effects of coordinated ramp metering on local and network level. The second ramp

metering is based on the simulation results of D_1. The second ramp metering is located on an on-ramp (S108 to A10 South eastbound). The second ramp metering is engaged from the 70^{th} minute because the outflow of the second ramp starts to increase around the 70^{th} minute in D_1. The parameters of ramp metering are shown in Figure 0-3. The ramp metering control starts from the 70^{th} minute and stops at the 240^{th} minute. The occupancy-to-flow rate is set to 0.32, which is used to define the K_R in ALINEA algorithm described in section 3.2.4. The desired occupancy rate at the downstream freeway link connected to the on-ramp is set to 0.1. The saturation flow rate of the ramp is set as 0.5veh/sec/lane, which corresponds to 1800vehicles/hour/lane. Since there is no ramp coordination function in DSP, an automatic coordination of control time and a unilateral coordination based on layered hierarchy designs are practiced here. Statistic results are exported and listed in Table 0-3.

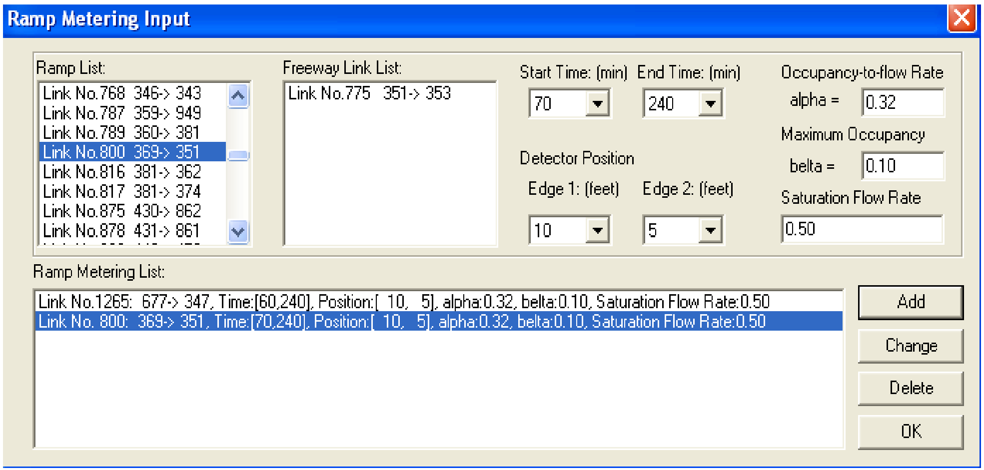


Figure 0-3 Parameters set-up of local ramp metering in recurrent scenario, D_2: coordinated ramp metering

Vehicle Types	Total Travel Times (HRS)	Average Travel Times (MINS)	Average Trip Times (MINS)	Average Stop Times (MINS)	Average Trip Distance (MLS)
Non-Equipped	52392	11.64	14.73	2.21	5.83
Equipped	8933	11.05	14.21	1.80	5.90
Overall	61326	11.55	14.65	2.14	5.84

Table 0-3 Statistics results on network level, D_2: coordinated ramp metering

Table 0-3 shows the overall average travel time in D_2 is 11.55 minutes, which is about 6.17% lower than the

overall average travel time in D_0. The overall average stop time is 2.14 minutes, which is about 10.08% less than the overall average stop time in D_0 (2.38 minutes). The reduction of overall average stop time means the average queuing time or average delay time is less on the network level. On one hand, this is because another ramp is applied so that the traffic flow to freeway is further limited. On the other hand, this type of coordination between two ramps in this control design can possibly help to reduce or even out the total queue length on two ramps.

D_3: coordinated (ramp metering + variable speed limits)

Variable speed limitation is one of the many measures for lane control. It is generally thought that variable speed limitation can help to bring about a homogenization state of the traffic flow. In Dynasmart-P, speed advisory VMS suggests a dynamic optimal speed ('speed threshold' in Dynasmart-P) of the link. Vehicles travelling on this link will increase or decrease their speeds by a pre-specified percentage of change when their speeds are below or above the speed threshold. Therefore, vehicles are gradually approaching the specified optimal speed so that a homogeneous traffic flow can be achieved in order to avoid congestion.

Simulation results of D_2 show that link 755 (in DSP term), which is upstream to the two coordinated ramp, bears high density from the 180th minute to the 210th minute. Link 755 retains jam density during this period and a long queue was formed on this link.

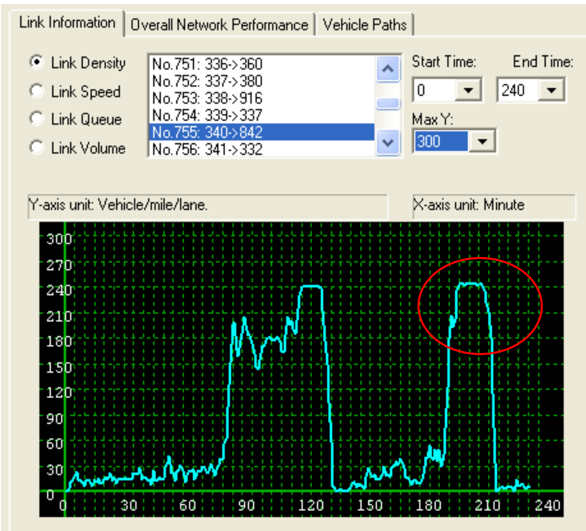


Figure 0-4 Densities of link 755 in D_2

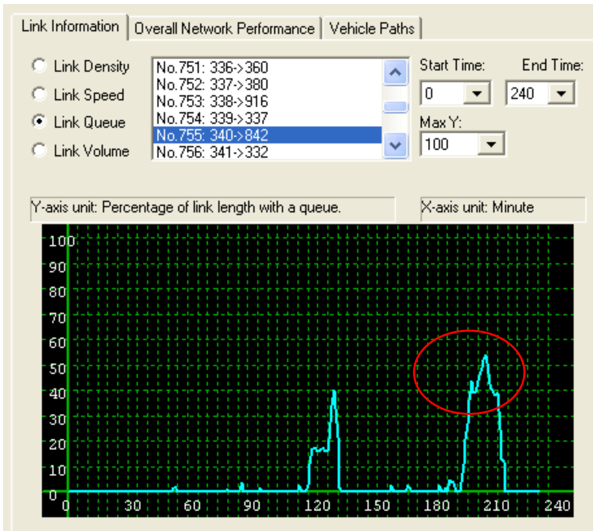


Figure 0-5 Queue of link 755 in D_2

It is clear that coordinated ramp metering control cannot relieve the congestion of link 755 during the 180th minute till the 210th minute. Link 755 is a five-lane freeway with a two-lane upstream link 731 from A10 and a three-lane upstream link 744 from A4. The maximum service flow rate of five-lane link 755 is 1440 vehicle/hour/lane while the SA of two-lane link 731 is 2236 vehicle/hour/lane and the SA of three-lane link 744 is 2288 vehicle/hour/lane. Although the number of lanes from upstream links to downstream link adds up, link

755 has a relatively lower SA comparing to regular five-lane freeway link, which usually bears a SA around 2100vehicle/hour/lane. The lower SA of link 755 indicates excessive turning movements, in this case, lane change movements when vehicles from upstream links (link 731 and link 744) merge in downstream link (link 755). These traffic flow characteristics of vicinity also imply that during peak hours (the 180^{th} minute till the 210^{th} minute), in-flows from two upstream links could be higher than out-flow of downstream link.

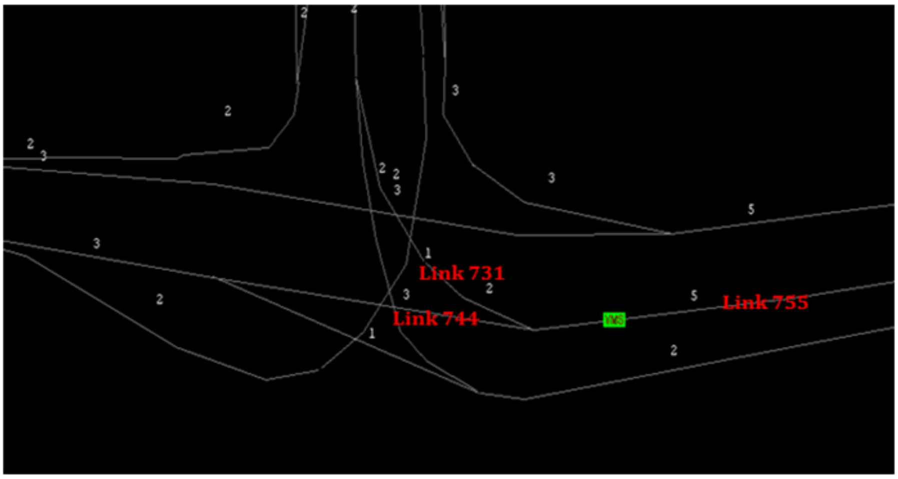


Figure 0-6 Conjunction of link 755, link 731 and link744

	Avg. Flow Rate (vehicle/hour/lane)	No. of lanes	Tot. Flow 180^{th} to 210^{th} (30minutes)	Avg. Speed (mile/hour)
Link 755	1146	5	2865	26
Link 731	838	2	838	52
Link 744	1422	3	2133	50

Table 0-4 Traffic flow characteristics of merging links, D_2

From a macroscopic view, if traffic flows on these links are assumed to be continuum flows under stationary conditions, vehicles on a roadway cannot be lost or created under conservation of vehicle law. Table 0-4 testified the speculation of in-flow exceeding out-flow with total flow. Within 30 minutes, total flows from link 731 and link 744 are 2971 vehicles while total flow on link 755 is 2865 vehicles. The difference of in-flow and out-flow on link755 is 106 vehicles during 30 minutes and they are inclined to form a queue on this link. From a microscopic view, both upstream links maintain around free flow speeds of 50mile/hour/lane while downstream link has an average speed of 26mile/hour/lane. Longitudinally speaking, vehicles undergo deceleration phase from free flow to congestion and may cause traffic breakdowns. Laterally speaking, vehicles could experience lane changing and overtaking movements from upstream merging in to downstream. All the above circumstances

contribute to the fact that vehicles on these links can easily leave the stable state on link 731, 744 and run into a transient state, even congestion on link 755.

Speed advisory VMS is coordinated with ramp metering control in order to solve the congestion here. Speed advisory VMS is placed on link 755 of A10 South, upstream to the coordinated ramp metering control. Simulation results of each time step in scenario with coordinated ramp metering control show that the two coordinated ramp metering controls did not solve the congestion on A10 South completely. Starting from the two on-ramp merging road sections of A10 South, freeway mainline began to form congestion from the 168th minute and congestion gradually spilled back to upstream link 755, which caused traffic disturbance on link 755. From Figure0-5, a queue started to aggregate during the 180th minute till the 210th minute. It started to disperse slowly after the 210th minute from upstream to downstream. With the last scattering queue around on-ramp merging road sections, freeway mainline are finally cleared up by the 226th minute. Therefore, the speed advisory VMS on link 755 are enabled from the 180th minute till the 210th minute. The parameters set-up of this speed advisory VMS in Dynasmart-P are shown in Figure 0-7. The speed threshold is set to be 30 mile/hour (≈48km/hour) while the designed free-flow speed is originally 62 mile/hour (≈100km/hour), as shown in Table 4-2. The percentage of change is set as 70%, which may seems high but it is specifically set high enough to conduct fast adjustment for this control design.

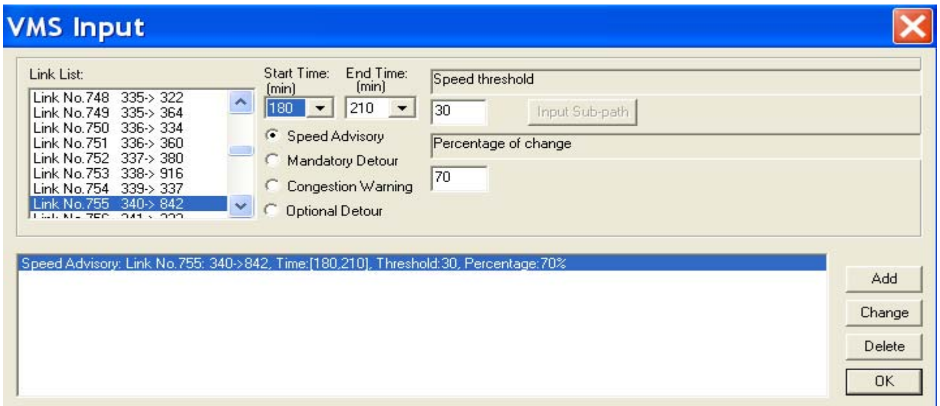


Figure 0-7 Parameters set-up of speed advisory VMS in D_3

After simulation, the statistic results are listed in Table 0-5. Table 0-5 shows the overall average travel time of D_3 is 11.54 minutes, which is about 6.26% lower than the overall average travel time in D_0 and 0.09% lower than the overall average travel time in D_2. The overall average stop time is 2.14 minutes, which is about 10.08% less than the overall average stop time in D_0 (2.38 minutes) and no change to D_2. The recurrent traffic congestion is hardly further relieved on network level in this scenario.

Vehicle Types	Total Travel	Average Travel	Average Trip	Average Stop	Average Trip

	Times (HRS)	Times (MINS)	Times (MINS)	Times (MINS)	Distance (MLS)
Non-Equipped	52340	11.63	14.72	2.20	5.83
Equipped	8926	11.04	14.20	1.80	5.90
Overall	61267	11.54	14.64	2.14	5.84

Table 0-5 Statistics results on network level, D_3

The density, flow rate, speed and queue length on each link of A10 South eastbound are averaged over time and plotted in Figure 0-8, Figure 0-9, Figure 0-10 and Figure 0-11. In Figure 0-8, average densities on each link of D_3 are almost the same as D_2, except for 1^{st}, 2^{nd} link and 14^{th}, 15^{th} link. These links have a slightly lower densities and a slightly higher speed, as shown in Figure 0-9. The queue lengths of these sections slightly reduced as shown in Figure 0-11. In Figure 0-9, for the 7^{th} link where the speed advisory is implemented, average speed is slightly lower which shows direct effect of speed advisory VMS. But it brings out a longer queue for the 7^{th} link, as shown in Figure 0-11. In Figure 0-10, flow rates of each section are almost identical before and after the application of speed advisory VMS. And Table 0-5 confirms that there is negligible improvement with coordination of speed advisory VMS. An assertion of null effect can be made for coordination of speed advisory VMS and ramp metering controls.

It is expected that with the help of speed advisory VMS, a homogeneous flow can be formed in order to traffic breakdowns on the A10 South freeway, which is not completely resolved by coordinated ramp metering control. Even though there is effective speed control with deployment of speed advisory, and certain links of the freeway are slightly improved, the controlled link is not promised to perform better than before.

Speed advisory can only adjust the speeds of vehicles but the analysis of flow rates in Table 0-4 and above are completely flawed since DSP doesn't have a flow rate constraint, thus no effective SA. Also, variable speed limit in DSP cannot show its effectiveness since lane change and overtaking maneuvers are not possible in DSP (macroscopic software, no lane separation for any link). In DSP, the effect of speed control is rendered and vehicles are likely to enter instability with chaotic behaviors that are impossible to know or to be sure with the current knowledge of the speed advisory VMS function in DSP.

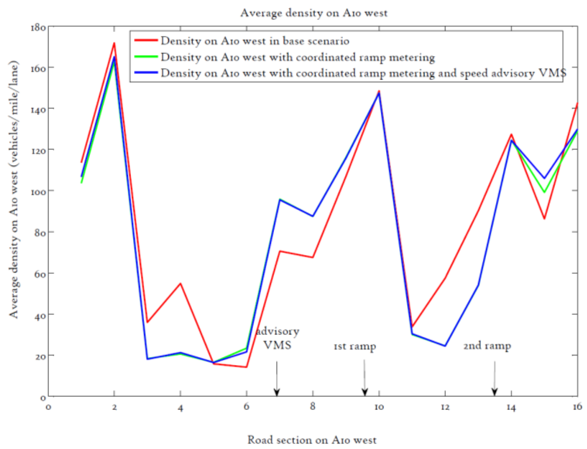


Figure 0-8 Average density on A10 South, D_0, D_1, and D_2

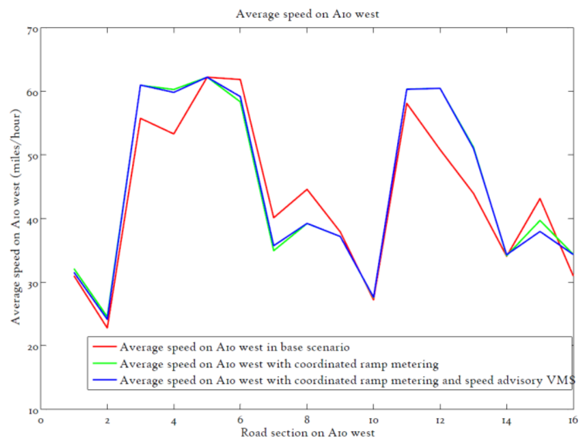


Figure 0-9 Average speed on A10 South, D_0, D_1 and D_2

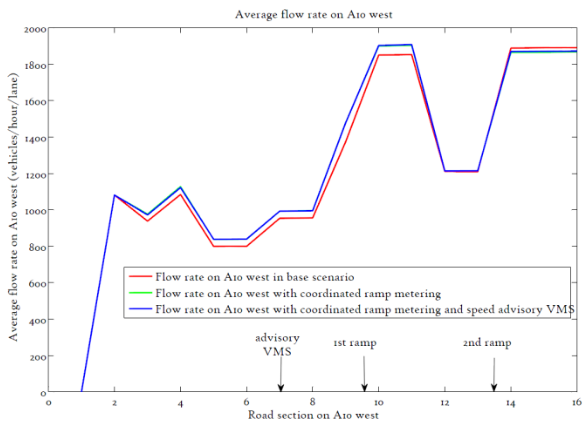


Figure 0-10 Average flow rate on A10 South, D_0, D_1 and D_2

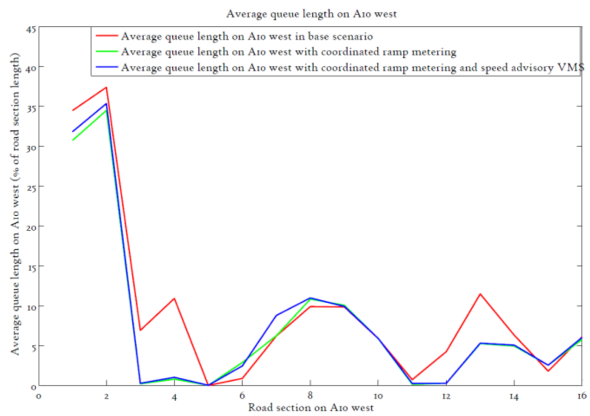


Figure 0-11 Average queue length on A10 South, D_0,$D_1$and D_2

D_4: coordinated (ramp metering +route information VMS)

The simulation results of D_3 have limited improvement to the case study. Here, another type of VMS, congestion warning VMS, will be implemented in Dynasmart-P. With simulation runs, the effectiveness of coordination between congestion warning VMS and coordinated ramp metering under recurrent traffic congestion will be evaluated.

In Dynasmart-P, the function of congestion warning VMS is to allow the users to specify a percentage of VMS-responsive vehicles (user class 5) to evaluate the VMS information and divert if a better path exists. Therefore, congestion warning VMS needs to be placed on a link upstream to a divert point. The specific location and operation mode of the congestion warning VMS in the Dynasmart-P experiment are shown in Figure 0-12. It is on a diversion point of A10 South eastbound where A10 is bifurcated into branches. One branch is the continuation of A10 eastbound. The other branch is an off-ramp and leads to arterial road. During the simulation period, A10 South is congested. A congestion warning VMS is deployed here to warn the vehicles about the congestion on A10 South. After seeing this warning VMS, some vehicles will re-calculate and divert to

the less congested arterial roads. The parameters of the congestion warning VMS are shown in Figure 0-13. According to the simulation results in D_2, the congestion on A10 South starts around the freeway links (around coordinated ramp meterings, S108) and spills back to Link 755 as shown in Figure 0-5 around the 117^{th} minute (right before the first peak). From the 117^{th} minute, different road sections on A10 South are congested at different time but the queue length on A10 South always keeps high until the 220^{th} minute. After the 220^{th} minute, congestion of A10 South dissolves completely. While speed advisory VMS dealt with the second peak in Figure 0-5, it is assume that congestion warning VMS with only alert of congestion and no compulsory, will not promise effectiveness. Therefore, the congestion warning is activated from the 117^{th} minute to the 220^{th} minute. And during this period, 90% of en-route info vehicles (user class 4) and VMS-responsive vehicles (user class 5) will re-calculate and divert if a better path is available.

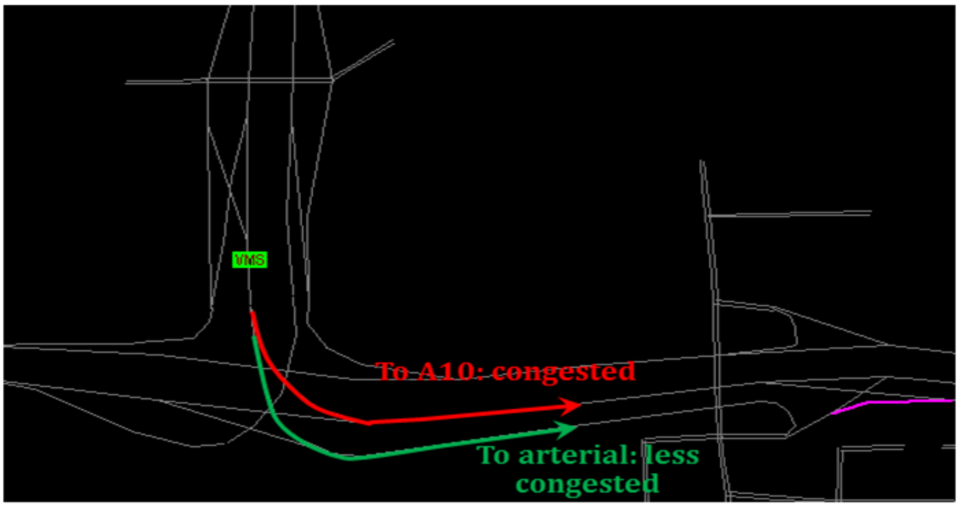


Figure 0-12 Specific location of the congestion warning VMS in D_4

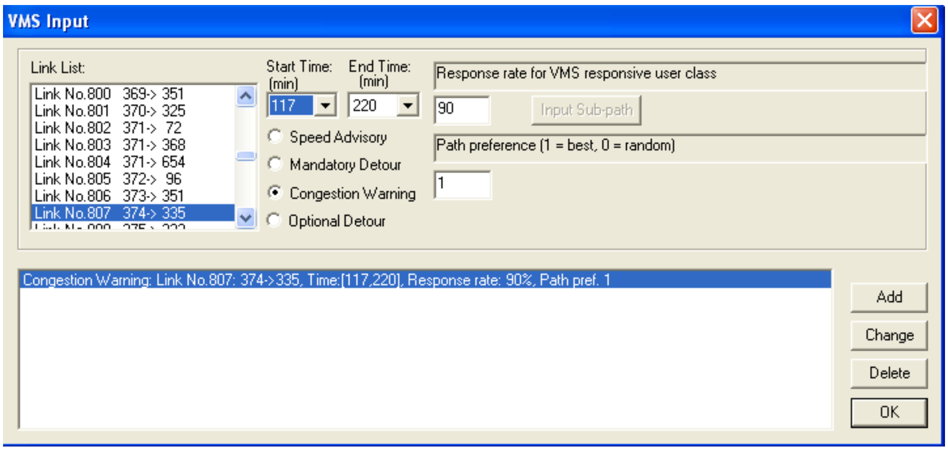


Figure 0-13 Parameters set-up of congestion warning VMS, D_4

Vehicle Types	Total Travel Times (HRS)	Average Travel Times (MINS)	Average Trip Times (MINS)	Average Stop Times (MINS)	Average Trip Distance (MLS)
Non-Equipped	52603	11.69	14.79	2.26	5.82
Equipped	8986	11.11	14.27	1.78	5.90
Overall	61589	11.60	14.71	2.19	5.83

Table 0-6 Statistics results on network level, D_4

Table 0-6 shows the overall average travel time in D_4 is 11.60 minutes, which is about 5.7% lower than the overall average travel time in D_0 and 0.5% higher than the overall average travel time inD_2. The overall average stop time is 2.19 minutes, which is about 8% less than the overall average stop time in D_0 (2.38minutes) and 2.3% higher than D_2 (2.14minutes). The recurrent traffic congestion is not further relieved on network level in this scenario and even slightly worsened than D_2.

The density, flow rate, speed and queue length on each road section are averaged over time and plotted in Figure 0-14, Figure 0-15, Figure 0-16 and Figure 0-17, with comparisons between D_0, D_2 and D_4. The comparison of densities, as shown in Figure 0-14, show that on almost all the A10 links, D_4 has the lowest densities in all three control designs. This might be because the congestion warning diverts quite a few vehicles (class 4 and class 5, about 84%) to alternative routes so that the congestion on A10 South is locally relieved. The comparison of flow rate, as shown in Figure 0-15, shows that the flow rates in D_4 are the highest in all three scenarios from the 2nd link to the 8th link and the lowest from the 10th link to the 16th link. And from the 4th link on which the congestion warning VMS is deployed, until the 8th link, the flow rate in D_4 becomes significantly higher than the other two scenarios. The comparison of density and flow rate between three control designs suggest that due to the diversion of traffic at the 4th link, a relatively free flow can be achieved in D_4. Therefore, D_4 has the best average speed performance in all three control designs, as shown in Figure 0-16. Due to the low density, high flow rate and relatively free flow speed on A10 South, the queue length on A10 South in D_4 is, as expected, the lowest in all three control designs. In a nutshell, the local network performance is improved by the coordination effect from congestion warning VMS and congestion is further relieved on A10 South locally. However, this positive local network performance doesn't bring reciprocal improvement on the network level, as shown in Table 0-3. A twofold explanation of the contradiction results is provided here. First, congestion warning VMS in Dynasmart-P lacks accurate and flexible functionality. The VMS must be placed on an upper joint link with divert point. It can only warn vehicles of congestion ahead but fail to provide any real-time traffic information.

So, characteristics of the congestion such as severity, on which link and during what time are still not available to the majority of vehicles. For instance, A10 South is congested on different time, different links. The congestion warning applied during simulation cannot specify any details and vehicles are diverted to arterials with the only warning of 'freeway congestion ahead', which is why only the links close to congestion warning VMS are improved (the 4th to 8th links). Second, congestion warning VMS cannot provide re-routing information under real-time traffic congestion. As mentioned in section 4.1, 85% of the vehicles in this case study are non-equipped (non-responsive and VMS responsive). Congestion warning VMS may have diverted vehicles to avoid the congested freeway, but it doesn't give any further instructions. From there on, majority percentage of the diverted vehicles can only refer to the K-best path trees assigned to them at the beginning of the simulation, which cannot update according to current traffic condition. In D_4, the arterials parallel to A10 South eventually become very congested from all the diverted vehicles. Most of these vehicles cannot recalculate optimal paths according to real-time traffic conditions. Traffic situations on some A10 South freeway links are relieved with compromise of the arterials. Traffic congestion of the arterials hinders the off-ramp traffic near the 12th link on A10 South eastbound. The off-ramp congestion spills back to A10 mainline, which is why worse results are observed from the 10th to the 16th links. Thus, congestion warning VMS could improve the adjacent freeway congestion locally, but it may also bring little improvement or even setbacks to the downstream coordinated ramp control area and to the overall network performance.

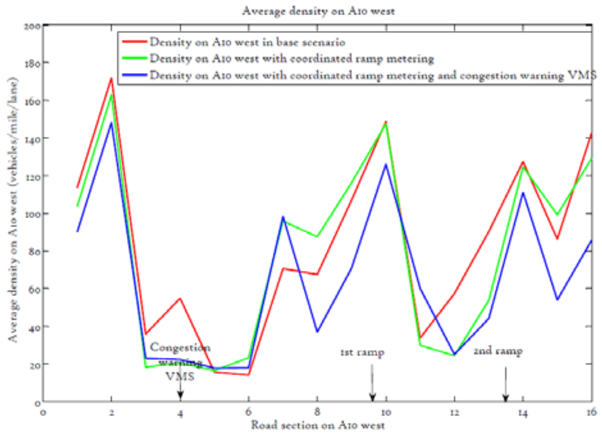


Figure 0-14 Average density on A10 South, D_0, D_2 and D_4

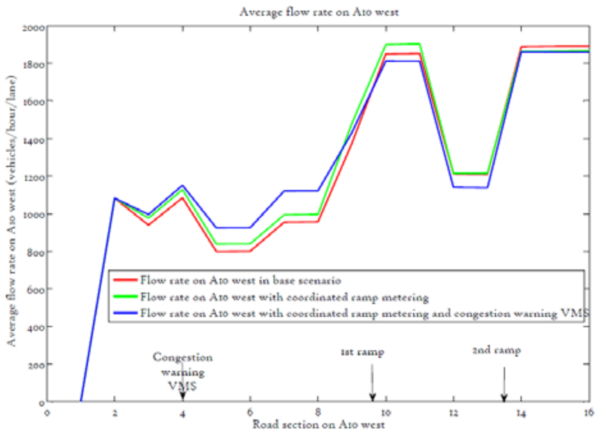
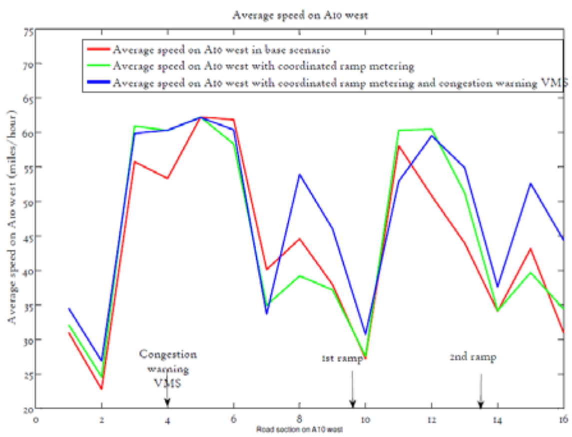


Figure 0-15 Average flow rate on A10 South, D_0, D_2 and D_4



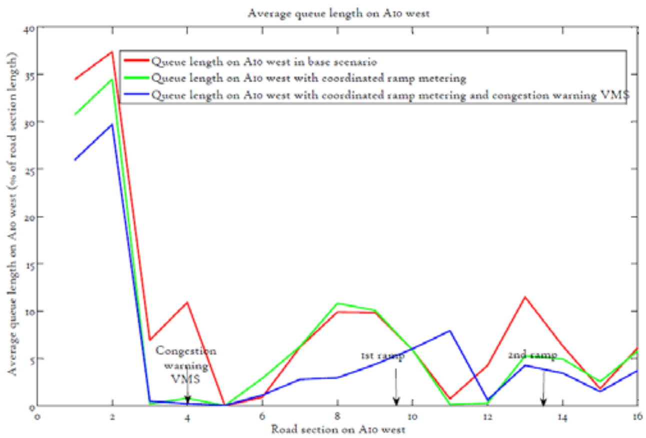


Figure 0-16 Average speed on A10 South, D_0, D_2 and D_4

Figure 0-17 Average queue length on A10 South, D_0, D_2 and D_4

D_5: coordinated (ramp metering + route advice VMS)

Optional detour VMS works similar to congestion warning VMS but the difference is that optional detour provides alternative detour route. By simulation run, the effectiveness of D_5 under recurrent traffic congestion will be evaluated.

The function of optional detour VMS is to advise drivers with optional detour route to avoid traffic congestions. Users can define a detour route with any number of sub-paths so that the sub-paths can be systematically optimal to all encounter vehicles. In addition, optional detour VMS gives drivers the option to follow the detour path or keep their original path. In VMS pre-emption mode, both class 4 (en-route info vehicles) and class 5 (VMS responsive vehicles) will respond to optional detour VMS. VMS responsive vehicles can decide whether to keep their current paths or to use the detour paths based on the bounded rationality rule, so are En-route vehicles (as they always do even without VMS control). Although both classes make switching decisions using bounded rationality rule, user behaviours of these two classes are different. As described in section 3.2.3, upon an optional detour VMS (with link end node k), a vehicle j of VMS responsive vehicles compares $TTC_j(k)$, trip time according to the K-best path tree table from node k till its destination with $TTB_j(k)$, trip time of the entire suggested route (including all sub-paths) plus trip time according to the K-best path tree table from the end of suggested route till its destination. If the gain outside the threshold suffices, vehicle k will switch to the first sub-path provided by the optional detour VMS. Once on the sub-path, it will follow through all the sub-paths, unless it encounters another VMS. On the other hand, en-route info vehicles only consider the first sub-path provided by the optional detour VMS when they recalculate and make decisions using bounded rationality rule. They can still switch their paths at any node along the suggested sub-paths, if their superior access of information and shortest path algorithm suggest so. Up to here, the user behaviour difference of en-route info and VMS responsive vehicles under optional detour VMS is a realistic simulation of real traffic situation with ITS route advice along the roads.

The specific location of the congestion warning VMS in the Dynasmart-P experiment is shown in Figure 0-18.

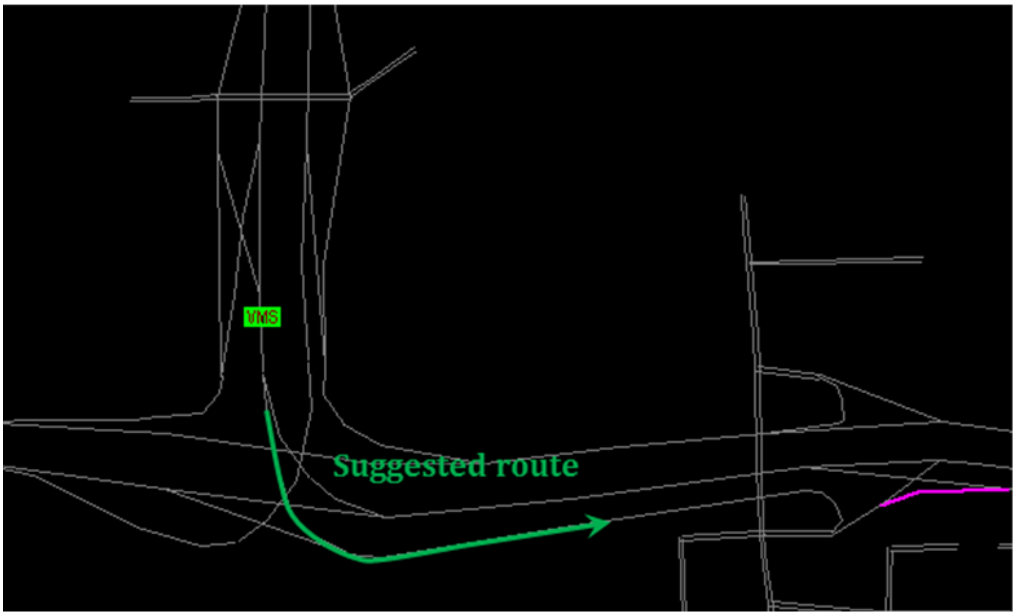


Figure 0-18 Specific location of optional detour VMS in D_5

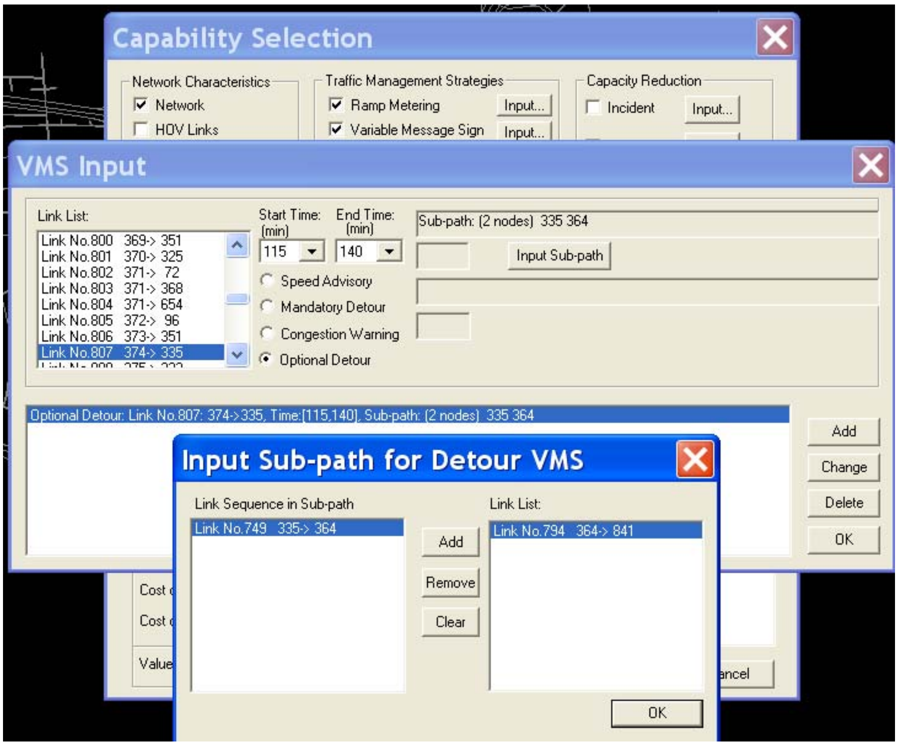


Figure 0-19 Parameters set-up of optional detour VMS in D_5

Figure 0-19 shows the parameters setting of the applied optional detour VMS. The optional detour is engaged from the 115th minute to the 140th minute. This is because a peak of queue is generated on the downstream link (link 755, shown in Figure 0-6) in D_2, as shown in Figure 0-5. Another peak of queue is generated from the 190th

minute to the 210th minute. However, optional detour VMS is not activated in order to avoid misleading the vehicles with degradation route during this period because the suggested route is also congested during this period.

Vehicle Types	Total Travel Times (HRS)	Average Travel Times (MINS)	Average Trip Times (MINS)	Average Stop Times (MINS)	Average Trip Distance (MLS)
Non-Equipped	50894	11.31	14.41	2.01	5.81
Equipped	8713	10.77	13.92	1.64	5.88
Overall	59607	11.23	14.34	1.96	5.82

Table 0-7 Statistics results on network level, D_5

Table 0-7 shows the overall average travel time in D_5 is 11.23 minutes, which is about 8.8% lower than the overall average travel time in D_0 and 2.8% lower than that in D_2. The overall average stop time is only 1.96 minutes, which is about 17.65% less than the overall average stop time in D_0 (2.38 minutes) and 8.57% less than that in D_2. The recurrent traffic congestion is more alleviated on network level in this control design than all the previous ones.

The density, flow rate, speed and queue length on each link of A10 South are averaged over time and plotted in Figure 0-20, Figure 0-21, Figure 0-22 and Figure 0-23, with comparisons between D_0, D_2 and D_5. The comparison of density, as shown in Figure 0-20, shows that on almost all the links, D_5 has the lowest densities in all three scenarios. This is because the optional detour VMS diverts quite a few vehicles (class 4 and class 5) to alternative routes so that congestion on A10 South is relieved. The comparison of flow rate, as shown in Figure 0-20, shows that the average flow rates in D_5 are comparable or slightly higher than that in the other two scenarios from the 2nd link to the 8th link and the lowest in all three control designs from the 10th link to the 16th link. The comparison of density and flow rate between three control designs suggest that due to the diversion of traffic, a relatively free flow can be achieved in D_5. Hence, D_5 has the best average speed performance, as shown in Figure 0-22. Due to the low density, high flow rate and relatively free flow speed, the queue length on A10 South in D_5 is, as expected, the lowest, as shown in Figure 0-23. Therefore, due to the non-mandatory diversion function of optional detour VMS, the local network performance is improved and congestion is relieved on A10 South, so are the network traffic performances.

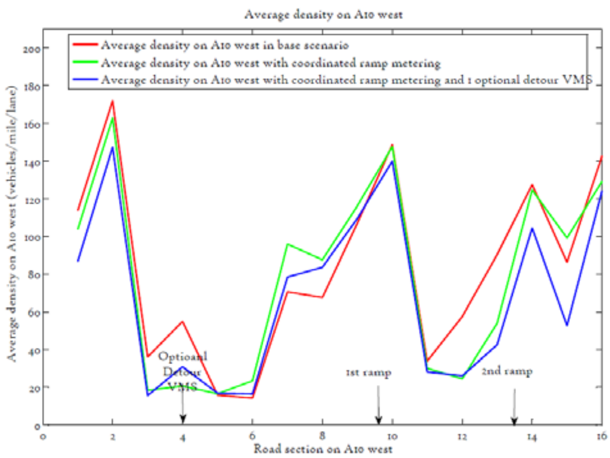


Figure 0-20 Average density on A10 South, D_0 D_2 D_5

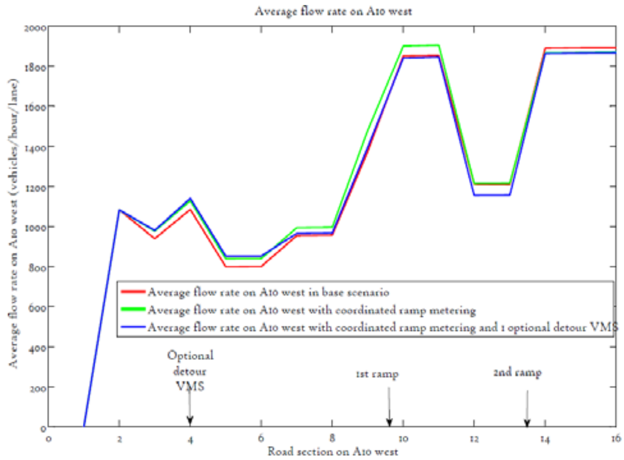


Figure 0-21 Average flow rate on A10 South, D_0 D_2 D_5

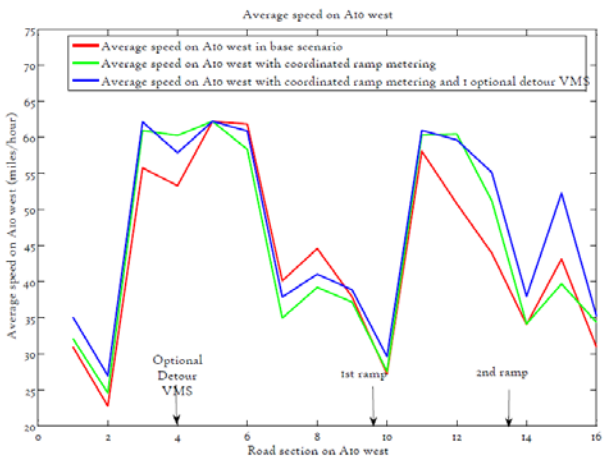


Figure 0-22 Average speed on A10 South, D_0 D_2 D_5

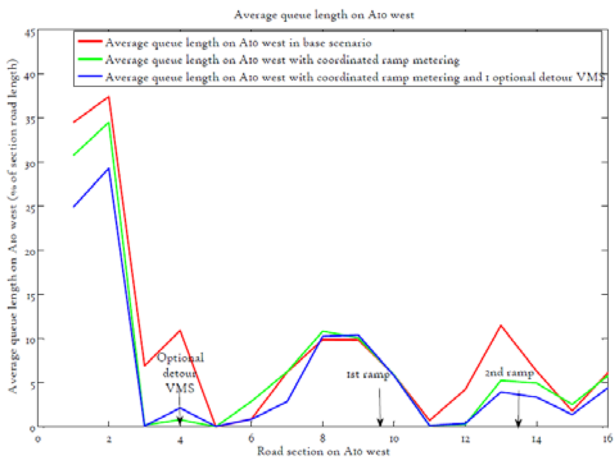


Figure 0-23 Average queue length on A10 South, D_0 D_2 D_5

D_6: coordinated (ramp metering + multiple route advice VMSs)

The simulation results show that D_5 has significantly improved the research network on both network level and local level. Here, the coordination potential of optional detour VMS will be further investigated.

To further explore the effectiveness of CNM with coordinated optional detour VMS, local network performance in A4-A10 crossover area in D_5 is checked. In order to depict the traffic situation here after coordinating one optional detour VMS, an enlarged A4-A10 crossover area is shown in Figure 0-24. From the 145th minute to the 160th minute, a queue, as shown in Figure 0-25, forms on link 794 because of a significant increase of diverted traffic flows from the first optional detour VMS and an increase flow from upstream link 745. Therefore, from the 145th minute to the 160th minute, another optional detour VMS is incorporated on link 741 with suggested route shown in Figure 0-24.

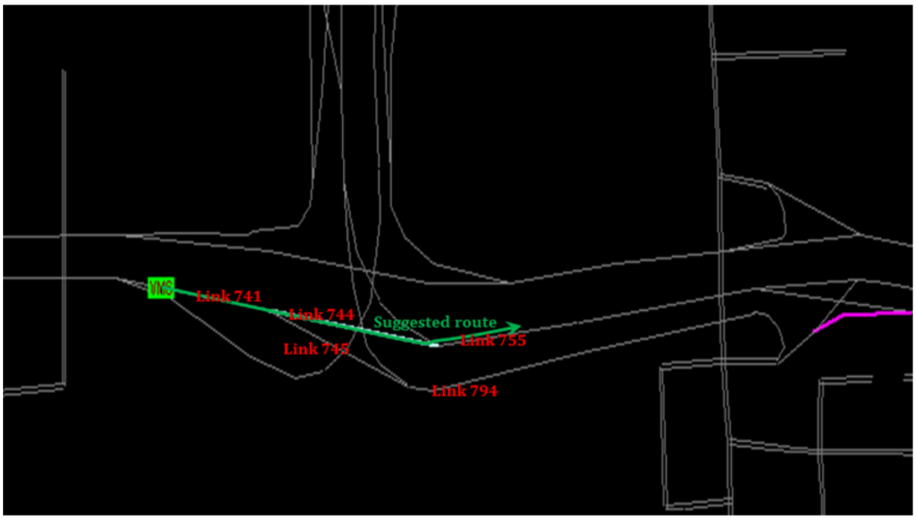


Figure 0-24 Links at the crossover between A4 and A10

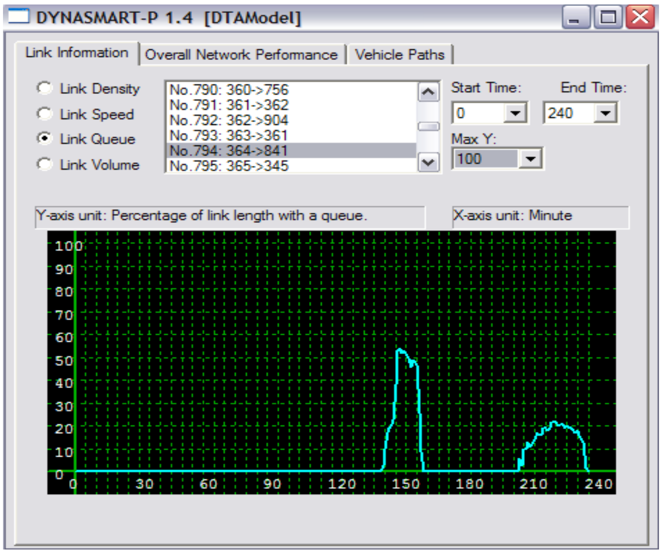


Figure 0-25 Queue on link 794 from the 145th minute to the 160th minute

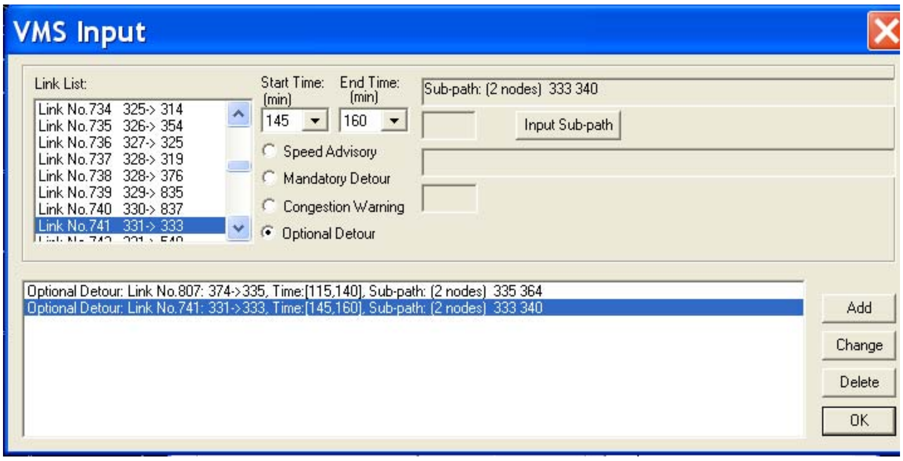


Figure 0-26 Parameters set-up of two coordinated optional detour

Figure 0-26 shows the parameters setting of two coordinated optional detour VMS.

Vehicle Types	Total Travel Times (HRS)	Average Travel Times (MINS)	Average Trip Times (MINS)	Average Stop Times (MINS)	Average Trip Distance (MLS)
Non-Equipped	50955	11.32	14.37	2.01	5.82
Equipped	8760	10.83	13.94	1.67	5.88
Overall	59715	11.25	14.31	1.96	5.83

Table 0-8 Statistics results on network level, D_6

Table 0-8 shows the overall average travel time in D_6 is 11.25 minutes, which is about 8.6% lower than the overall average travel time in D_0 and 0.18% higher than that in D_5. The overall average stop time is 1.96 minutes, which is about 17.65% less than the overall average stop time in D_0 (2.38 minutes) and is the same as that in D_5. The recurrent traffic congestion is relieved on network level in this control design compared to D_0 but has no improvement compared to D_5.

The average density, flow rate, speed and queue length on each road section are averaged over time and plotted in Figure 0-27, Figure 0-28, Figure 0-29 and Figure 0-30, with comparisons between D_0, D_2, D_5 and D_6. The comparison of density, as shown in Figure 0-27, shows that on the 1st to the 6th links, D_6 has similar densities as D_5, so are average flow rates, average speeds and average queue, as shown in Figure 0-28, Figure 0-29 and Figure 0-30. This is expectable as the second optional detour VMS in this new control design provides sub-path downstream to the 6th link. So traffic flow characteristics changes on the first six links can be invisible or non-existed. On the 7th to the 9th links, D_6 has lower densities and higher flow rates, as shown in Figure 0-27 and Figure 0-28, than that in D_5. This could mean that the second optional detour VMS is coordinated with the first optional detour VMS and these freeway links capacities are better utilized. This also could be speculated from Figure 0-29 and Figure 0-30, which show higher average speeds and lower queue lengths on the 7th to the 9th links. From the 10th to the 16th links, D_6 has higher densities and lower flow rates than that in D_5, as shown in Figure 0-27 and Figure 0-28. The reason could be that diversion effect of the second optional detour VMS aggravates the freeway links around the coordinated on-ramps, which could also be the reason of little improvement on the network level in this new control design. Due to higher densities and slightly lower flow rates on these links, the 10th to the 16th links have lower average speeds and longer queue lengths in D_6 than that in D_5, as shown in Figure 0-29 and Figure 0-30.

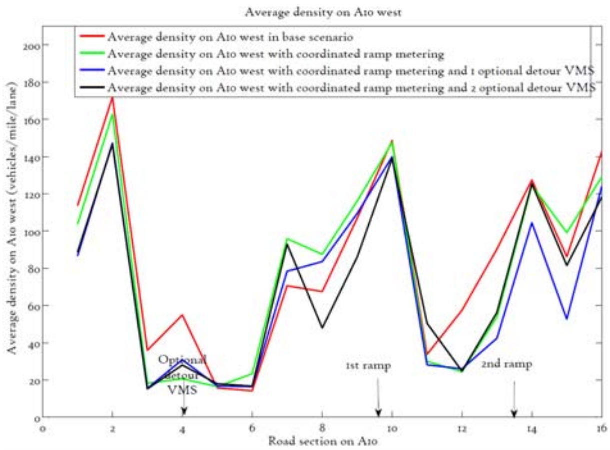


Figure 0-27 Average density on A10South: D_0, D_2, D_5 and D_6

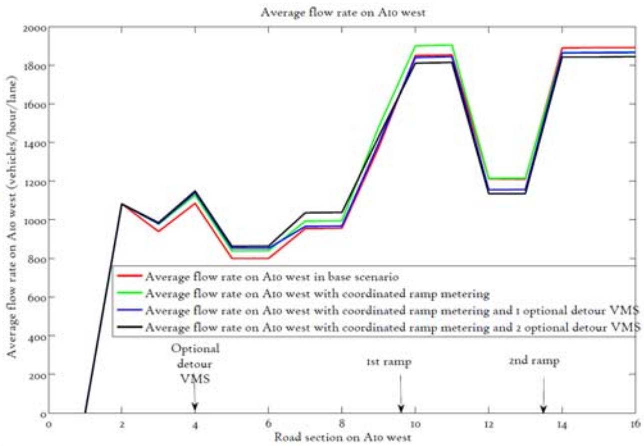


Figure 0-28 Average flow rate on A10 South: D_0, D_2, D_5 and D_6

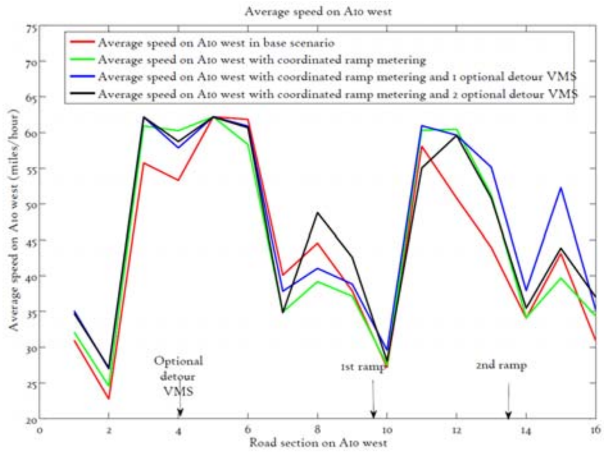


Figure 0-29 Average speed on A10South: D_0, D_2, $D_5$and D_6

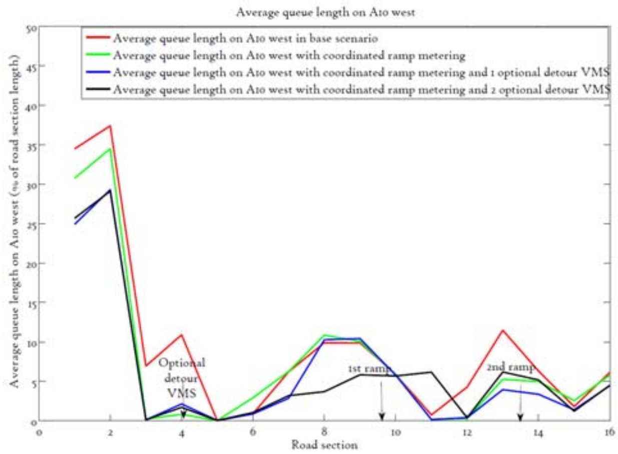


Figure 0-30 Average queue length on A10South: D_0, D_2, D_5 and D_6

Equipped vehicles are info vehicles that can receive and respond to real-time traffic info, namely class 4 en-route info vehicle. Non-equipped vehicles have no innate ability to access real-time traffic info, unless provided by VMS control measures. Average trip distance is a direct indicator of difference between equipped and non-equipped vehicles. Network level MOEs can also imply the different behaviours of vehicles under each control designs.

Figure 0-31 and Figure 0-32 clearly show that when coordination designs include VMS about real-time traffic information and advice, the improvement of non-equipped vehicles (decrease of avg. travel times and avg. stop times) is more obvious. These phenomena could also be observed from Figure 0-33 with the reduction of avg. trip distances.

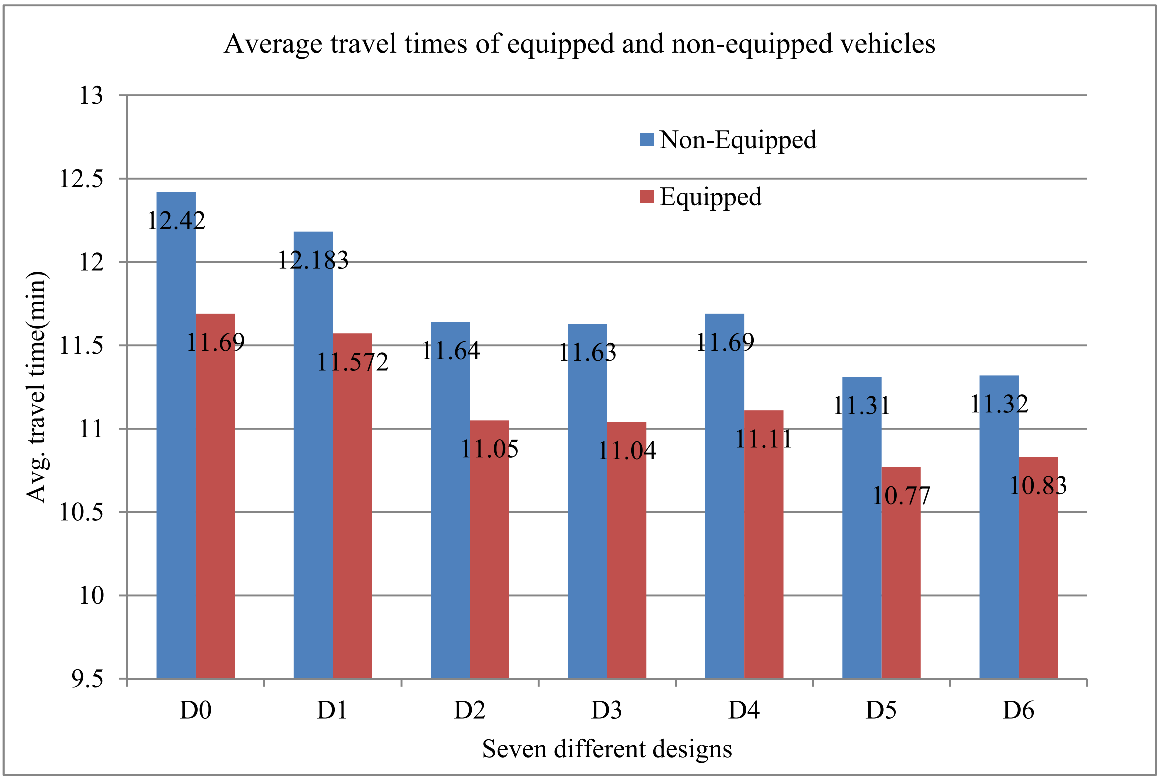


Figure 0-31 Avg. travel times change of equipped and non-equipped vehicles

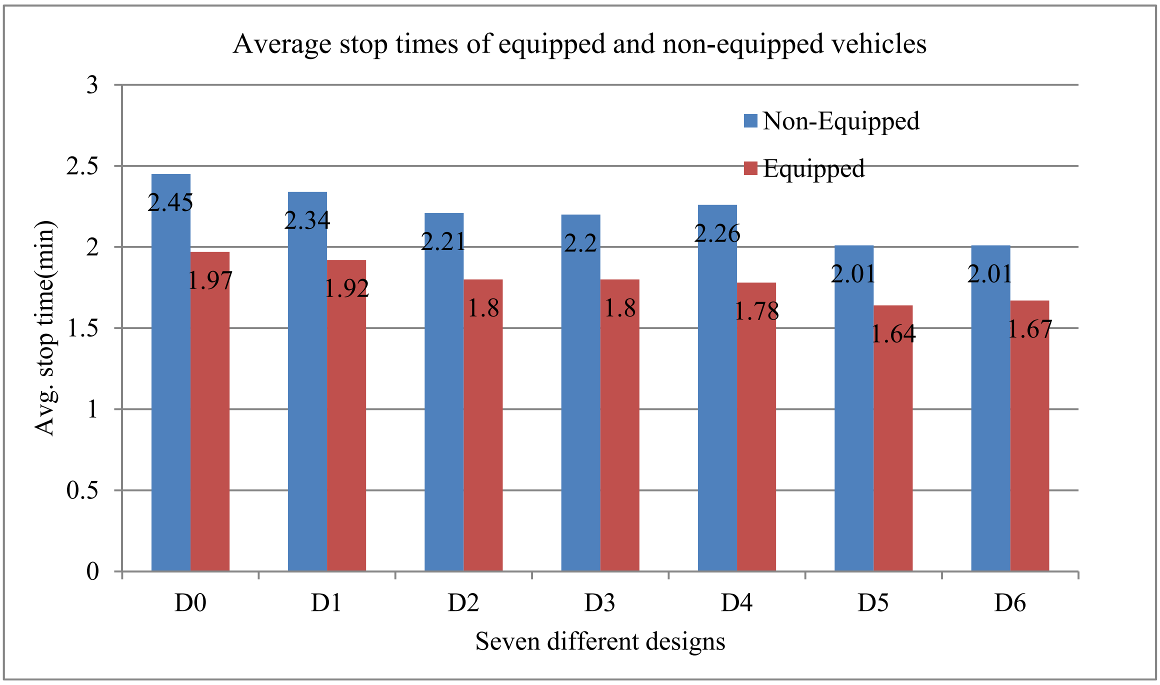


Figure 0-32 Avg. stop times change of equipped and non-equipped vehicles

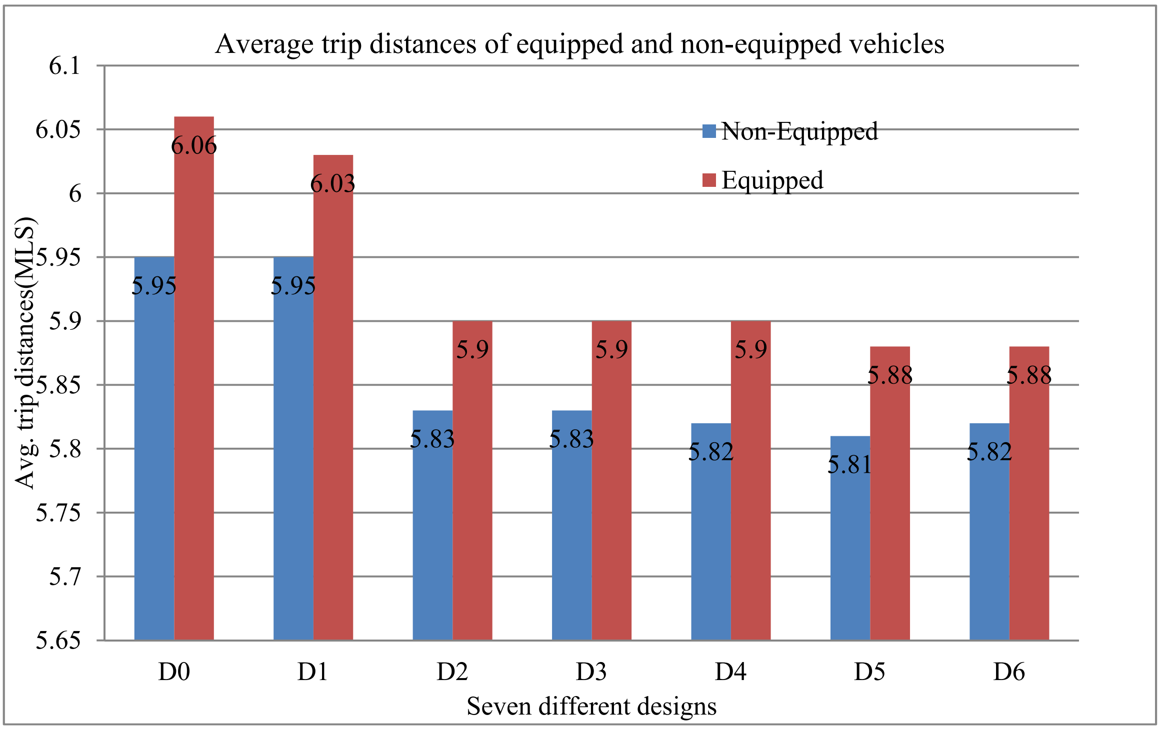


Figure 0-33 Avg. trip distances change of equipped and non-equipped vehicles

Non-recurrent scenario

First, from a one-shot run of D_0: base design do nothing, the vehicles from zone 85 to zone 80 will be checked. During the simulation, all the road users from zone 85 to zone 80 will choose the freeway A10 East and A2. This is because A10 to A2 is the shortest path for O-D pair 85 to 80, considering a 30% freeway bias factor. By using the vehicle path function in Dynasmart-P, the routes from zone 85 to zone 80 are given as red and yellow vehicle path in Figure 0-34.

Figure 0-34 D_0, paths for O-D pair 85 to 80

From Figure 0-34, given the complete planning horizon (240minutes), about 96% of the vehicles travelling from zone 85 to zone 80 followed the red path and the other 4% followed the yellow path. As shown, D_0 has a certain level of recurrent congestion.

Figure 0-35 shows the densities on A10Eeast at each link according to each simulation time step. The A10 east is divided into 19 links. From Figure 0-34, A10 East is where the vehicles from zone 85 to zone 80 need to drive through first. At the end of A10 East, the vehicles will transfer to A2 and go south from then on. Or, a small percentage (4%) will transfer to A2 north, make a U turn at the nearest roundabout and then go south on A2.

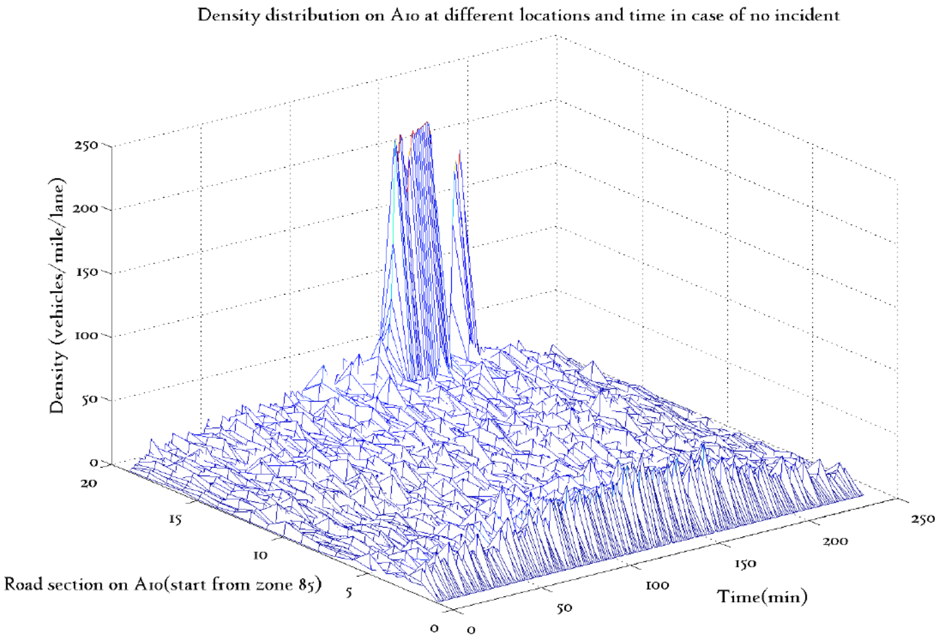


Figure 0-35 Density on A10East, D_0

From Figure 0-35, it can be seen that A10 East links have reasonable densities except for the sections close to the end, where the A10 East part is split into three branches. In Figure 0-36, the link 19 of A10 East (link flagged in red) to A2 north, A2south and A10 west reduces from five lanes to two lanes and finally to one lane. Here, the five-lane link bifurcates into a three-lane link which goes on to the A10 South, and a two-lane link which will soon bifurcates again into a one-lane link to A2 north and a two-lane link to A2 south. The drastic changes of road configuration cause bottleneck and multiple bifurcations here also indicate excessive lane change movements.

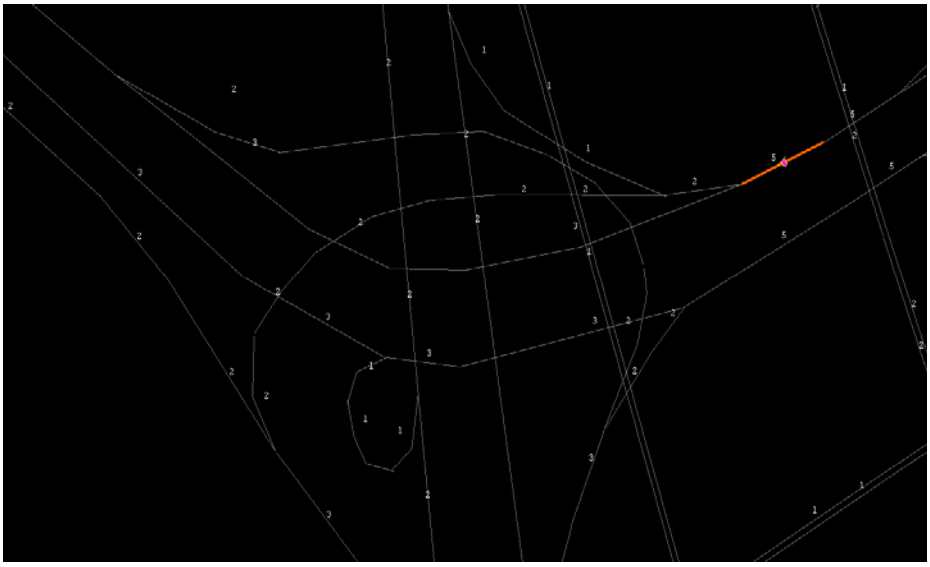


Figure 0-36 Conjunctions of A10East, A2 north, A2 south, and A10 South

From the discussion of D_0 in recurrent scenario, it is known that traffic flows of the last few links on A10 South are quite heavy from 120 minute till the end of simulation. The heavy traffic from A10 South to A2 south causes spill-back to A10 East. All the above phenomena could cause enormous increase of density on link 19 of A10 East.

ID_0: Base design with incident

In this design, an accident happens on A10 East. The accident happened on link 16 of A10 East at the 60th minute, corresponding to 5:00 PM in reality. The end of the accident is the 180th minute, which means the accident lasts for two hour. The severity of the accident equals to 0.8, which means the maximum service flow rate (link length in DSP simulation algorithm) of this link drops to 20% of its origin value (1920vehicle/hour/lane) during the two hour accident. The parameters set-up in DSP is shown in Figure 0-37.

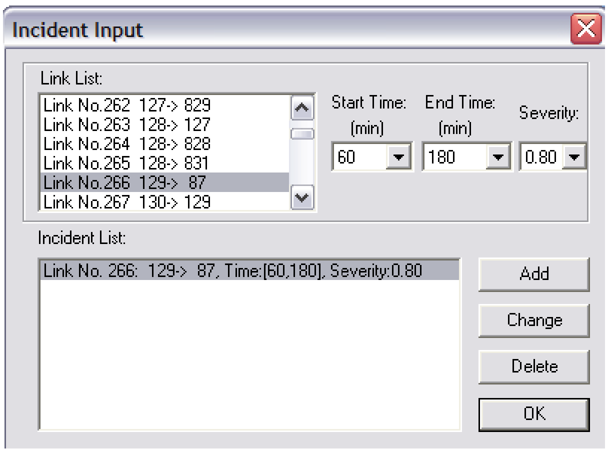


Figure 0-37 Incident set-up in Dynasmart-P

With incident, the route distribution of OD pair 85 to 80 is given in different colours in Figure 0-38 and Figure 0-39. About 65% of the vehicles take the red path shown in Figure 0-38 and another 13.7% choose the yellow path shown in Figure 0-39, which is to A1 first, then to A9 East and finally join back to A2 south to the zone 80. The paths change comparing to D0 is due to the behaviours of type 4 en-route info vehicles. They are innately equipped so that real-time congestion information can be considered when re-calculating and updating K-best path. Therefore, they are able to change to the yellow path in Figure 0-39 in order to avoid the traffic congestion introduced by the accident.

Figure 0-38 Route taken the most

Figure 0-39 Route taken the 2^{nd} most

After a one-shot simulation run of ID_0, the summary statistics of the network simulation results are outputted and given in Table 0-9.

Vehicle Types	Total Travel Times(HRS)	Avg. Travel Times(MINS)	Average Trip Times(MINS)	Average Stop Times(MINS)	Average Trip Distance(MLS)
Non-Equipped	79840	17.74	22.18	7.63	5.22
Equipped	12924	15.98	20.56	5.70	5.55
Overall	92764	17.47	21.94	7.34	5.27

Table 0-9 Statistics results on network level, ID_0

Table 0-9 shows the overall average travel time in ID_0 is 17.47 minutes, which is about 42% higher than the overall average travel time in D_0. This significant increase of the overall average travel time is due to the traffic congestion introduced by the accident. Another interesting phenomenon is that the percentage increases on average travel time, average trip time and average stop time from no incident to incident scenario for non-equipped vehicles are higher than those MOEs increases for equipped vehicles. This suggests that equipped

vehicles are superior to non-equipped vehicles on searching for an alternative route with shorter travel time during incident-induced congestion.

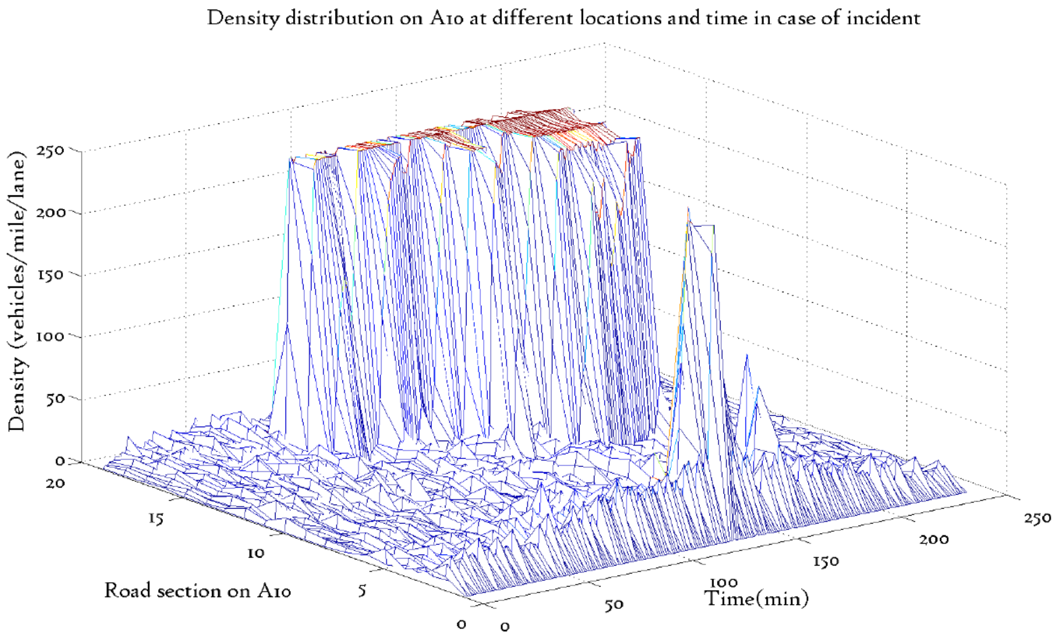


Figure 0-40 Densities on A10 East, ID_0

Figure 0-40 show the densities distribution at different links and simulation time steps on A10 East in ID_0. The incident starts at the 60th minute; traffic congestion is formed on the 16th road section and gradually spilled back to the 9th road section. Thus there are eight links involved in the congestion. During the incident, the densities on these incident-impacted links increase to the jam density and a queue is formed. At the end of the incident (the 180th minute), the queue on these eight links starts to dissolve and it costs about 11 minutes to clear the queue caused by the incident. The density, flow rate and queue on the first ramp upstream to the incident link (S112 to A10 East) are relevant for the research later. They are averaged over incident time (two hour) and shown in Table 0-10.

Avg. density (vehicles/mile/lane)	Avg. flow rate (vehicles/hour/lane)	Avg. queue length (% of road section length)
85.2	253.6	28.6

Table 0-10 Average density, flow rate and queue length on the ramp, S112 to A10 East

ID_1: Local ramp metering

In ID_1, a ramp metering is applied at the on-ramp upstream to the incident link. Ideally, the traffic flow from on-ramp to freeway should be controlled so that less traffic flow is allowed to the incident freeway link.

In Dynasmart-P, the locations of the incident and ramp metering are shown in Figure 0-41. The parameters of the ramp metering are shown in Figure 0-42. The ramp metering control starts once the incident happens and stops once the incident ends. The occupancy-to-flow rate is set to 0.32, which is used to define the K_R in ALINEA algorithm. The desired occupancy rate at the downstream freeway link connected to the on-ramp is set to 0.2. The saturation flow rate on ramp is set to 0.5veh/sec/lane, which corresponds to 1800 vehicles/hour/lane.

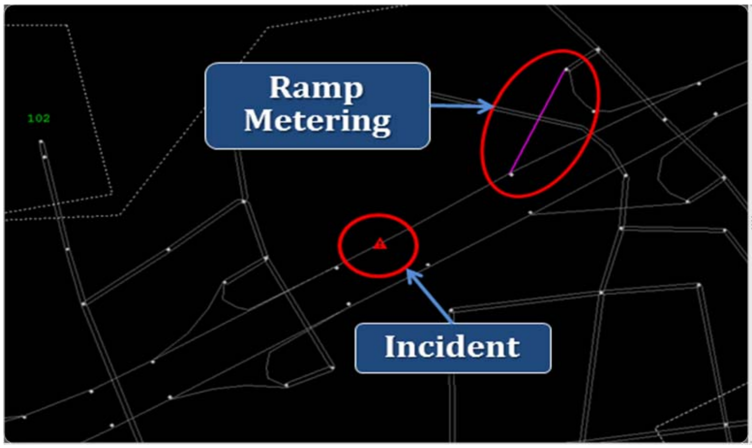


Figure 0-41 locations of incident and ramp metering control in ID_1

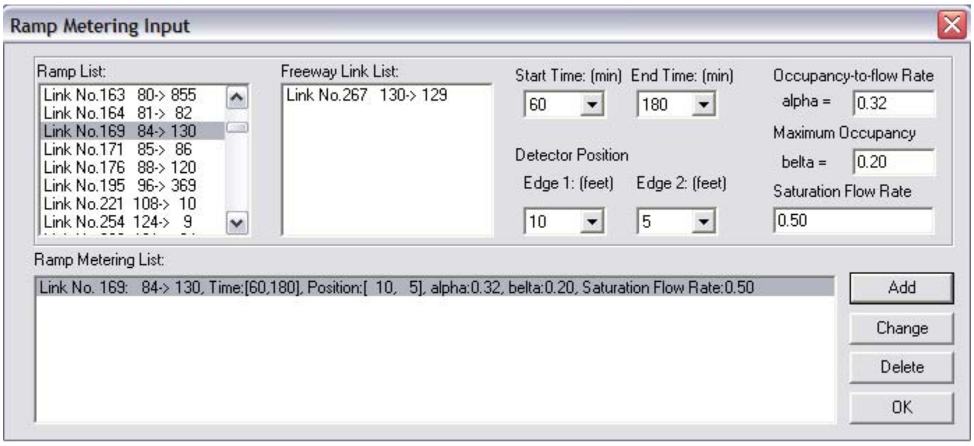


Figure 0-42 Parameters set-up of the ramp control, ID_1

Figure 0-43 and Figure 0-44 show the routes of vehicles travelling from zone 85 to zone 80 in ID1. About 62% of the vehicles take the red path shown in Figure 0-43. About 15% of the vehicles choose the yellow path shown in Figure 0-44. The percentage of vehicles that take the second best route is slightly higher than that in ID_0, which is 13.7%. The slight change could be caused by dynamic ramp control, which can be explained by the slight increase of overall average trip distance from Table 0-9 to Table 0-11.

Figure 0-43 Route taken the most Figure 0-44 Route taken the 2^{nd} most

Vehicle Types	Total Travel Times (HRS)	Average Travel Times (MINS)	Average Trip Times (MINS)	Average Stop Times (MINS)	Average Trip Distance (MLS)
Non-Equipped	72820	16.18	20.00	5.20	5.70
Equipped	11626	14.38	18.25	3.56	5.97
Overall	84447	15.91	19.74	4.95	5.74

Table 0-11 Statistics results on network level, ID_1

Table 0-11 shows the overall average travel time of ID_1 is 15.91 minutes, which is about 9% lower than that of ID_0. This is because the inflow from on-ramp to the freeway is limited so that the traffic load on the freeway is lower. Another phenomenon is that the overall average stop time of ID_1 is 4.95 minutes, which is about 32% lower than that in ID_0, which is 7.34 minutes. The reduction of overall average stop time means average delay of vehicle is reduced on the network level. Therefore, the incident-induced traffic congestion is alleviated by the ramp control.

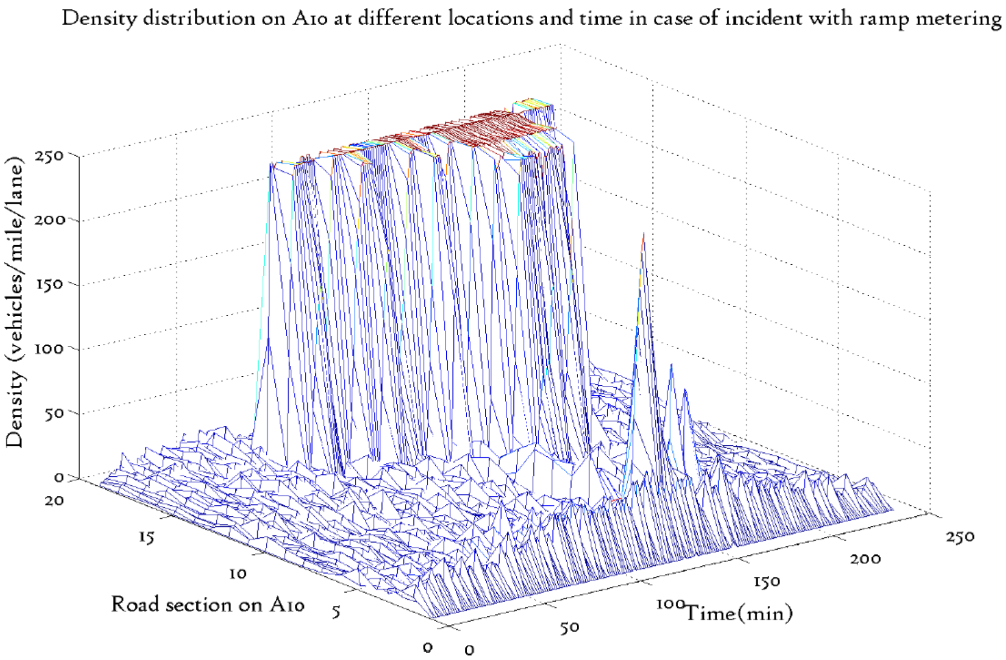


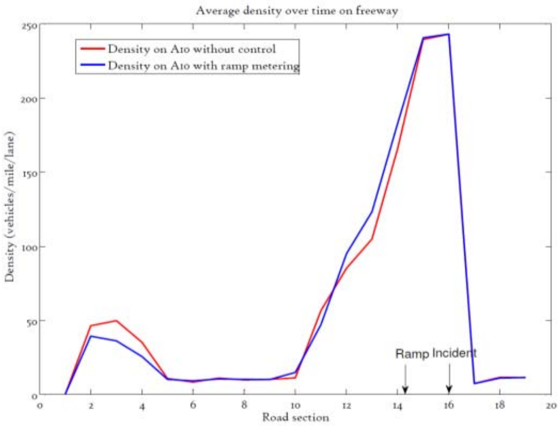
Figure 0-45 Densities on A10 east at each link according to time step, ID_1

Figure 0-45 shows the densities distribution on A10 East in ID_1. Comparing to Figure 0-40, it can be visually speculated that there is slight improvement on density on freeway links by introducing the ramp metering control. To confirm the speculation, the density, flow rate and queue length on each link are averaged over the incident period and plotted in Figure 0-46, Figure 0-47 and Figure 0-48. In Figure 0-46, it can be seen that the densities on the incident link and its downstream links (16^{th}, 17^{th}, 18^{th} and 19^{th} links) remain unchanged for ID_0 and ID_1 because jam densities are remained. On-ramp link is located in parallel with the 14^{th} link and merged with the 14^{th} link into the 15^{th} link on A10 East. For the densities on the links upstream of the incident link (12^{th}, 13^{th}, 14^{th} and 15^{th} links), the figures in ID_1 are higher than that in ID_0. This could be due to the control of outflow rate of the on-ramp and increase of outflow rate on the 14^{th} link. The flow rates in this area bear the following relationships in incident scenario with ramp metering control.

1. The outflow from the on-ramp to the freeway is limited by the ramp metering control;

2. The total flow rate, including the outflow rate from the on-ramp and the outflow rate from the 14^{th} road section, should be equal to the inflow rate to the 15^{th} road section, which is the max. link capacity under incident.

Due to these relationships, the flow rates on freeway links increase as shown in Figure 0-47. So the densities on the 14th link and the upstream links are higher than that in ID_0. And due to the higher densities, the queues are also longer than that in ID_0, as shown in Figure 0-48.



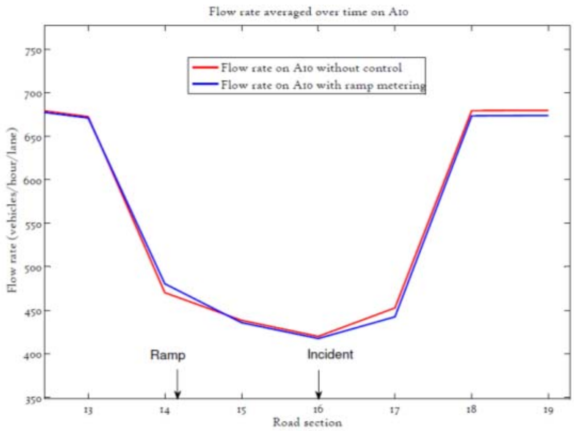


Figure 0-46 Density averaged over incident period on A10 East, ID0 and ID1 Figure 0-47 Flow rate averaged over incident period on A10 East, ID0 and ID1

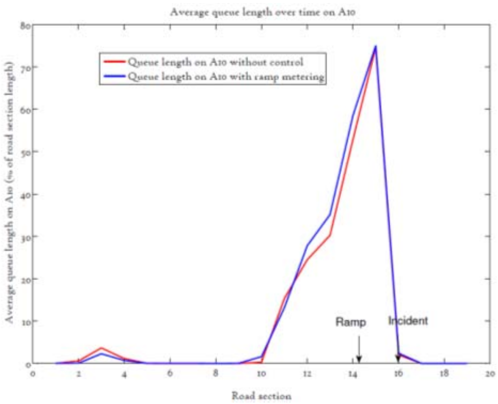


Figure 0-48 Queue length averaged over incident period on A10 East, ID_0 and ID_1

Control design	Average density (vehicles/mile/lane)	Average flow rate (vehicles/hour/lane)	Average queue length
ID_0	85.2	253.6	28.6
ID_1	108.6	230.8	36.6

Table 0-12 Average density, flow rate and queue length of on-ramp

Moreover, in ID_1, more time (about 30 minutes) is needed to clear the queue after the incident period. This could be caused by the sudden increase of traffic flow from the on-ramp after ramp metering control. Due to ramp metering control during the incident period, a queue is also formed on the on-ramp. After ramp control is released, these vehicles enter the highway immediately, which retains the high density on the freeway. Therefore, the queue clearing time on the freeway is longer. However, this depicts the impact to the local traffic. Under non-recurrent congestion, the effect of ramp metering control is positive on the network level with sacrifice of the traffic situation on the local level. This phenomenon is different from the effect of ramp control under recurrent congestion, which relieves the traffic congestion on both network level and local level.

The density, flow rate and queue length of the on-ramp are re-examined and compared with those figures in ID_0. The results are shown in Table 0-12. The average density of on-ramp is higher in ID_1 than that of ID_0. Because ramp metering control limits the outflow from on-ramp to freeway, more vehicles are stopped on on-ramp by ramp control, which explains why the queue length of on-ramp with ramp metering control is higher than ID_0.

ID_2: coordinated (ramp metering + multiple route advice)

Two optional detour VMS will be applied to evaluate the effect of CNM on the incident-induced traffic congestion. VMS can compensate ramp control in the aspect of diverting inflows to the incident link. In Dynasmart-P, type 2 mandatory detour VMS, type 3 congestion warning VMS and type 4 optional detour VMS have such function. But due to the reluctant effect of type 3 congestion warning VMS, it will not be used here. Type 4 optional detour VMS is used instead of type 2mandatory detour VMS because of the complexity of mandatory VMS setting. Mandatory detour VMS compels all the vehicles to follow the detour route to avoid incident. However, because of the difficulty to find the best mandatory detour routes for all the vehicles, these mandatory routes defined by user can worsen the traffic by misleading some vehicles to non-optimal routes. This type of VMS is more suitable for work zone or closure. An optional detour VMS is more flexible. Type5 VMS responsive and type4 en-route info vehicles can respond to the optional detour VMS to avoid incident. After taking the alternative route, en-route info vehicles can re-calculate the k-best path while non-equipped vehicles can go on according to their k-best path tree table.

The parameters set-ups of two optional detour VMS applied here are shown in Figure 0-49.

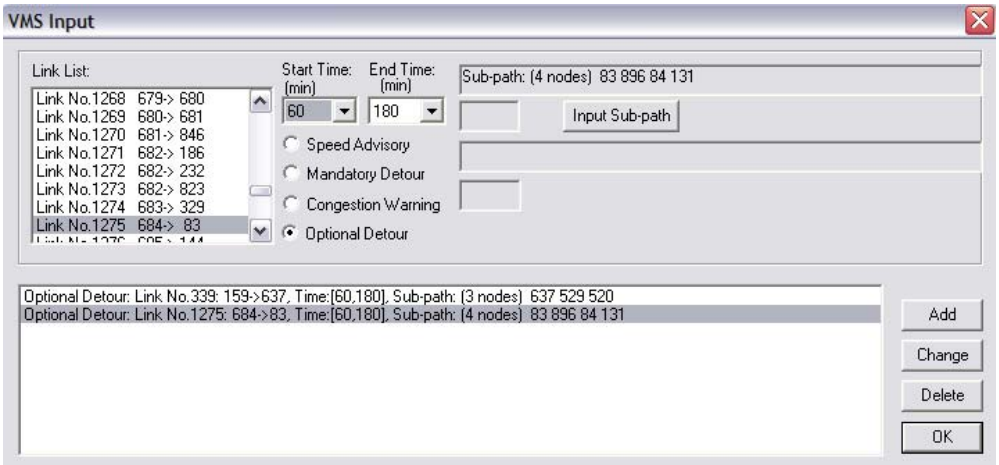


Figure 0-49 Parameters set-up of optional detour VMS, ID_2

Two optional detour VMS are implemented on the positions as shown in Figure 0-50. The 1st VMS is placed on link 339 (DSP term), which bifurcates to A10 East and A1. The traffic heading to A10 East increases traffic flow to incident link. Therefore, the 1st VMS is aimed at diverting traffic from A10 to A1, where the freeway capacity is similar to A10 east but without incident. The 2nd VMS is placed on link 1275 (DSP term), which is upstream to an off-ramp that is upstream to the incident link. The 2nd VMS aims at diverting some vehicles, for example the vehicles heading for destination zone 102, to the arterials so that they can avoid the traffic congestion on freeway. The traffic flow to the incident link can also be relieved. The ramp metering control and VMSs are immediately engaged when the incident occurs and released when the incident ends. Therefore, ramp metering control and optional detour VMSs are automatically coordinated.

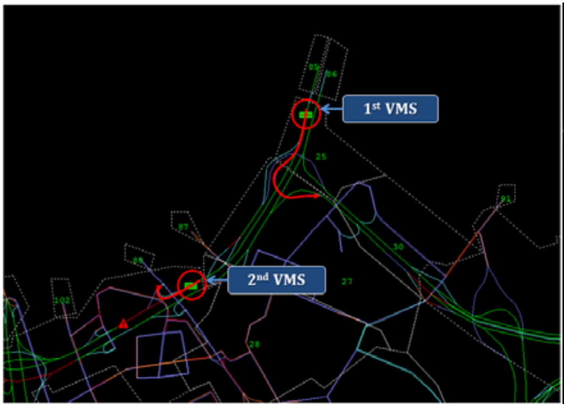


Figure 0-50 VMS position, ID2 Figure 0-51Route taken the most

The routes used the most, the 2nd most and the 3rd most are shown in Figure 0-51, Figure 0-52 and Figure 0-53 respectively. The percentage of vehicles that take the route of 'A10-A2', as flagged red in Figure 0-51, now drops to 55.6%. The percentage of vehicles that take the route of 'A10-A1-A9', as flagged yellow in Figure 0-52, is about 20.7%, which is close to the number in ID_1. The percentage of vehicles that take the route of 'A10-arteiral-A9', as flagged green in Figure 0-53, is about 7%, which is a significant increase comparing to ID_1. This means the 2nd VMS does divert some vehicles from A10 upstream of the incident link to arterials so that the traffic flow on A10 East can be lighter.

Figure 0-52 Route taken the 2nd most Figure 0-53 Route taken the 3rd most

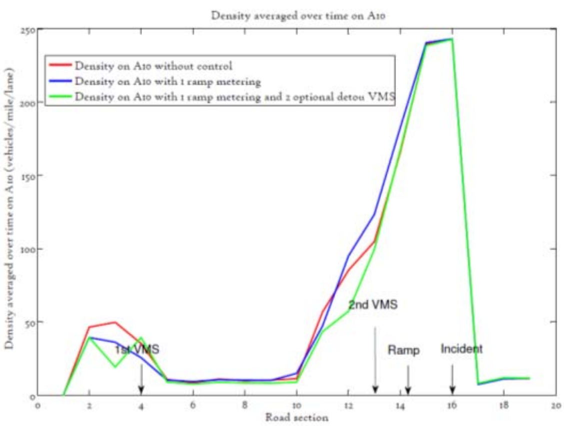
Vehicle Types	Total Travel Times (HRS)	Average Travel Times (MINS)	Average Trip Times (MINS)	Average Stop Times (MINS)	Average Trip Distance (MLS)
Non-Equipped	69052	15.34	18.25	4.40	5.81
Equipped	11348	14.03	16.99	3.28	6.04
Overall	80399	15.14	18.06	4.23	5.85

Table 0-13 Statistics results on network level, ID_2

Table 0-13 shows the overall average travel time is 15.14 minutes in ID_2, which is about 13.3% lower than the overall average travel time in ID_0 and 4.8% lower than that in ID_1. The overall average stop time is 4.23 minutes, which is about 42.4% lower than that of ID_0 and about 14.5% lower than that of ID_1. This is due to the diversions of traffic flows from the incident freeway to other alternatives by optional detour VMSs, which significantly reduce traffic flows on A10 East comparing to other designs without optional detour VMS. Therefore, A10 East freeway can be avoided so that it can clear up the congestion induced by the incident. The average travel time, average trip time and average stop time are all further reduced on network level.

Moreover, comparing Table 0-11 and Table 0-13, the decrease of average trip time for non-equipped vehicle is 8.6% and 6.9% for equipped vehicles. This could suggest that optional detour VMS has obvious effect on reducing average trip time for both equipped and non-equipped vehicles. Coordination of ramp metering control and VMS control can reinforce the positive effect of individual traffic control under non-recurrent congestion, on the premise of reasonable coordination solution.

The density, flow rate, queue length and average speed are averaged over incident period and plotted in Figure 0-54, Figure 0-55, Figure 0-56 and Figure 0-57 respectively. As shown in Figure 0-54, ID_2 has the lowest densities on the 11^{th}, 12^{th} and 13^{th} links, which are upstream to the incident link. And the flow rates of these links are the highest in all three designs. The 11^{th}, 12^{th} and 13^{th} links have highest average velocities in ID_2 as shown in Figure 0-57. From density, flow rate and average speed figures, the optional detour VMS can indeed divert some vehicles so that the traffic flow on the incident freeway is relieved. From Figure 0-56, the queue length is the shortest in ID_2. Furthermore, the queue clearing time for ID_2 is only 4 minutes, which is also shorter than that of ID_0 (11 minutes) and ID_1 (30 minutes). The best performance from this CNM control design could be due to the diversion of traffic flows by the optional detour VMSs and the controlled outflow from on-ramp to freeway.



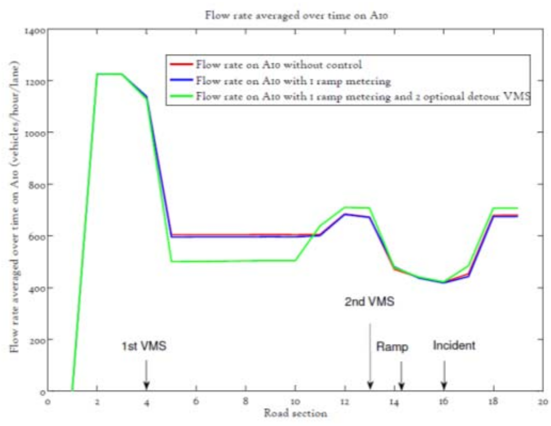
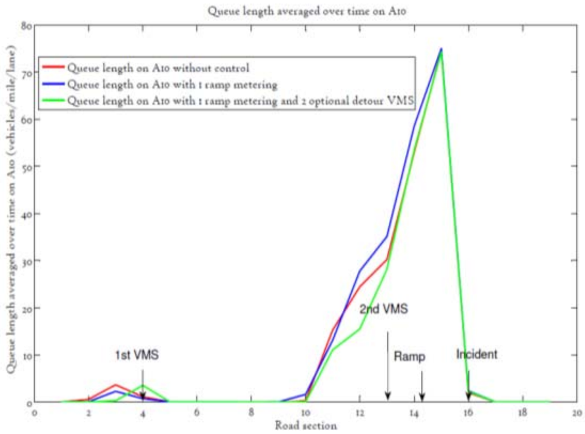


Figure 0-54 Density over incident period on A10 East, ID0 ID1 ID2 Figure 0-55 Flow rate over incident period on A10 East, ID0 ID1 ID2



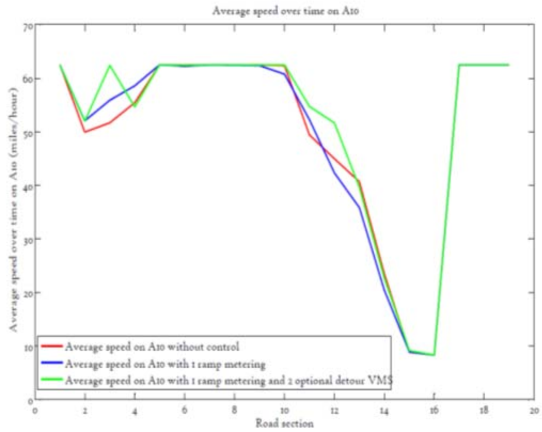


Figure 0-56 Queue length over incident period on A10 East, ID0 ID1 ID2   Figure 0-57 Average speed over incident period on A10 East, ID0 ID1 ID2

Table 0-14 shows that the average density on on-ramp of ID_2 is higher than that of ID_1. This is because some vehicles are diverted from A10 freeway to arterials by the 2^{nd} VMS as shown in Figure 0-50. However, at the end of the off-ramp, vehicles re-calculate or re-examine their k-best path tree table and decide to go back to the freeway. This means these vehicles will turn to the on-ramp instead of using arterials, which increases the average density on the controlled on-ramp. On the other hand, the average flow rates on the controlled on-ramp for both designs are almost the same, which means the average speed on the on-ramp of ID_2 is lower than that of ID_1. So, the queue length on the on-ramp of ID_2 is 44.7% of the ramp length and it is longer than that of ID_1. From Table 0-14, it seems plausible that ID_2 may bring counteractive effect to the incident-induced congestion. But the reinforced network results of ID_2 show that VMS control not only diverts incoming flow from using incident link but also further exploits usage of ramp metering control by leading more vehicles onto the controlled ramp.

Control design	Average density (vehicles/mile/lane)	Average flow rate (vehicles/hour/lane)	Average queue length (% of road section length)
ID0	85.2	253.6	28.6
ID1	108.6	230.8	36.6
ID2	130.8	232.6	44.7

Table 0-14 Comparison of average density, flow rate and queue length on the on-ramp

Figure 0-58 clearly shows that when the level of coordination increases, the number of vehicles out of the network during the same simulation period is increasing, thus the number of vehicle still in the network (trip not finished) is decreasing. If the control designs are proper, the network production increases with the level of

coordination under incident scenario.

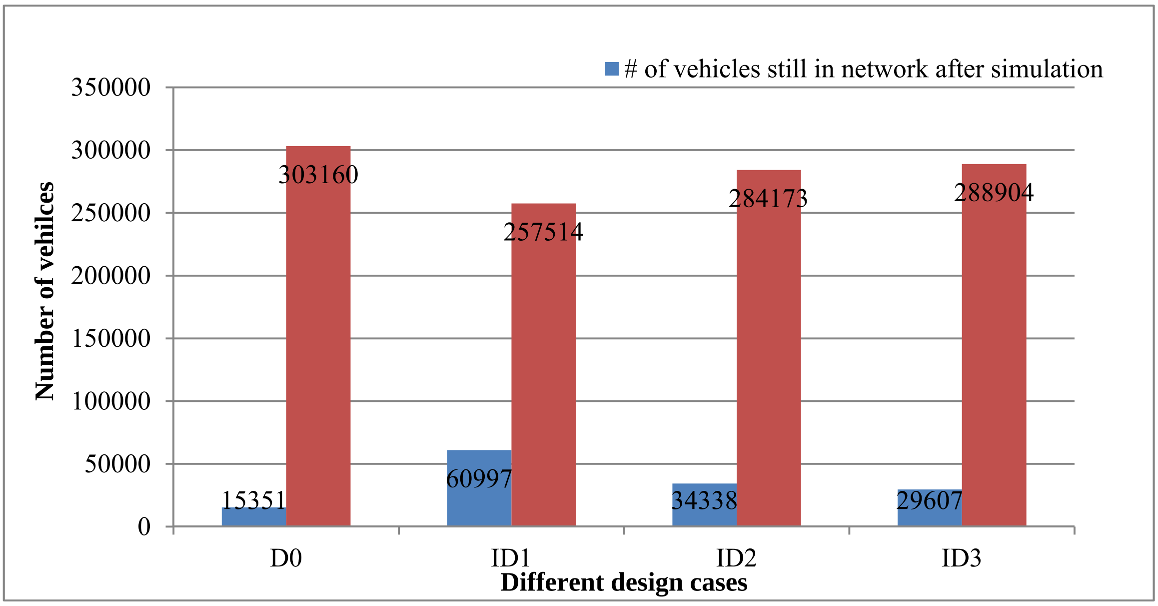


Figure 0-58 Number of vehicle out of the network (production) in incident scenario

Chapter 7 Test solution

In section 7.6, ID_4 of the test solution uses an indifference rate of 80%, which means 20% vehicles are diverted. If the diversion rate of route advice VMS increases, the "bending slope" changes from negative to positive. The shock wave boundary of new equilibrium state changes moving directions from going upstream (spilling back) to going downstream (queue dispersing).

Figure 0-59 and Figure 0-60 show the density and velocity variation as the function of time and space in ID_4, with a high diversion rate (80%) of route advice VMS. The new equilibrium reaches the incident road section around 13500 second and the incident congestion is cleared with the coordination of route advice VMS and coordinated ramp metering.

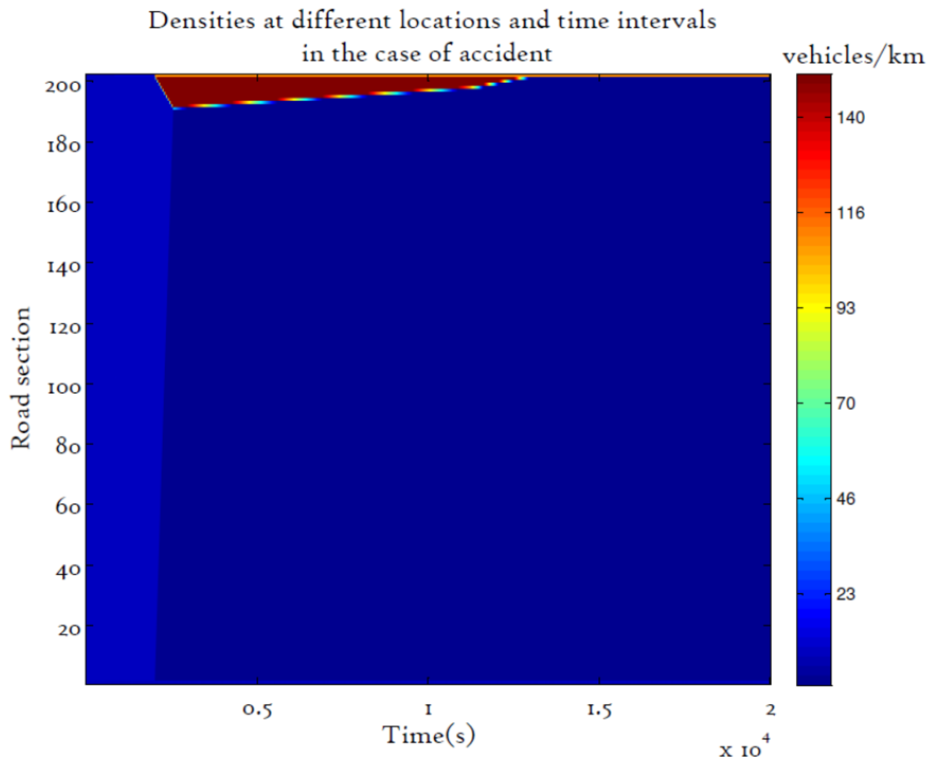


Figure 0-59 Density as the function of time and space in ID_4, diversion rate 80%

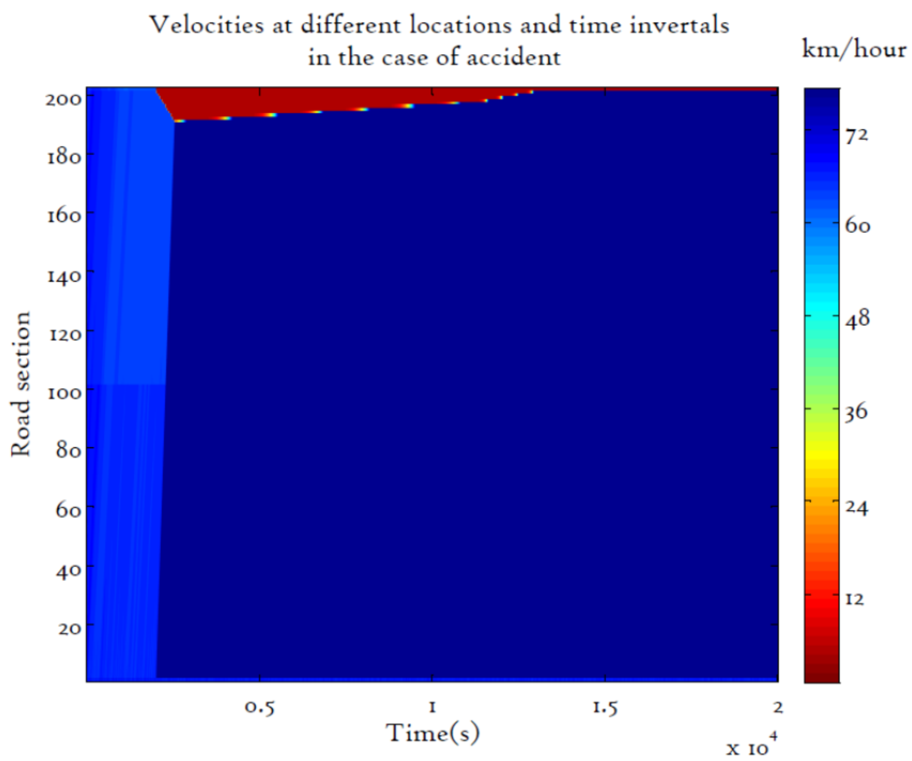


Figure 0-60 Velocity as the function of time and space in ID_4, diversion rate 80%

Appendix II

Matlab codes for mathematic models and enhancement tests

Input traffic

```
ink=poissrnd(20,1,(T+1));
for n=1:(T)
    if ink(n)<=kbreak
        v(1,n)=Uf;
    else
        v(1,n)=(Vf-V0)*(1-(ink(n)/k0))^alpha+V0;
    end
    q(1,n)=v(1,n)*ink(n);
end
```

Initial condition

```
for m=1:N
    k(m,1)=inik(m);
    if k(m,1)<=kbreak
        v(m,1)=Uf;
    else
        v(m,1)=(Vf-V0)*(1-(ink(n)/k0))^alpha+V0;
    end
    q(m,1)=k(m,1)*v(m,1);
    if q(m,1)>qmax
        qmax=q(m,1);
    end
    if q(m,1)<qmin
        qmin=q(m,1);
    end
end
```

Freeway modelling

```
function main_road
%clear all;
L=5; %length of a single vehicle
N=100;%number of road section
```

```
T=1000;%number of simulation time cycle
delta_L=5/N;%length of a single road section
ink=poissrnd(20,1,(T+1));%input arrival of vehicle density---Poisson Arrival
inik=NORMRND(20,1,1,N);%initial conditions at different road sections
Uf=80;
Vf=150;
V0=0.05;
alpha=4;
kjam=150;
kbreak=kjam*(1-((Uf-V0)/(Vf-V0))^(1/alpha))%break density
kmax=0;
kmin=1000;
qmin=0;
qmax=64;
%input traffic flow definition
for n=1:(T)
    if ink(n)<=kbreak
        inv(n)=Uf;
    else
        inv(n)=(Vf-V0)*(1-(ink(n)/kjam))^alpha+V0;
    end
    inq(n)=inv(n)*ink(n);
if n<=0.1*T
    qcap(n)=3000;
else
    qcap(n)=3000;
end
end
%initial condition definition
for m=1:N
    k(m,1)=inik(m);
    if k(m,1)<=kbreak
        v(m,1)=Uf;
    else
        v(m,1)=(Vf-V0)*(1-(k(m,1)/kjam))^alpha+V0;
    end
    q(m,1)=k(m,1)*v(m,1);
    if k(m,1)>kmax
```

```
        kmax=k(m,1);
    end
    if k(m,1)<kmin
        kmin=k(m,1);
    end
end
%main road operation
for n=1:T
    if q(N,n)<=qcap(n)
    for m=1:(N-1)
        t=N-m+1;
        k(t,n+1)=k(t,n)+((q(t-1,n)-q(t,n)))*(1/3600)/delta_L;
        if k(t,n+1)>kjam
            k(t,n+1)=kjam;
            q(t-1,n)=q(t,n)+delta_L*(k(t,n+1)-k(t,n))*3600;
        end
        if k(t,n+1)<=kbreak
            v(t,n+1)=Uf;
        else
            v(t,n+1)=(Vf-V0)*(1-(k(t,n+1)/kjam))^alpha+V0;
        end
        q(t,n+1)=k(t,n+1)*v(t,n+1);
        if kmax<k(t,n+1)
            kmax=k(t,n+1);
        end
        if k(t,n+1)<kmin
        kmin=k(t,n+1);
        end
    end
    k(1,n+1)=k(1,n)+((inq(n)-q(1,n)))*(1/3600)/delta_L;
        if k(1,n+1)>kjam
            k(1,n+1)=kjam;
            inq(n)=q(1,n)+delta_L*(k(1,n+1)-k(1,n))*3600;
        end
        if k(1,n+1)<=kbreak
            v(1,n+1)=Uf;
        else
            v(1,n+1)=(Vf-V0)*(1-(k(1,n+1)/kjam))^alpha+V0;
```

```
        end
        q(1,n+1)=k(1,n+1)*v(1,n+1);
        if kmax<k(1,n+1)
            kmax=k(1,n+1);
        end
        if k(1,n+1)<kmin
        kmin=k(1,n+1);
        end
    else
       q(N,n)=qcap(n);
        k(N,n+1)=k(N,n)+((q(N-1,n)-q(N,n)))*(1/3600)/delta_L;
        if k(N,n+1)>kjam
            k(N,n+1)=kjam;
            q(N-1,n)=q(N,n)+delta_L*(k(N,n+1)-k(N,n))*3600;
        end
        if k(N,n+1)<=kbreak
            v(N,n+1)=Uf;
        else
            v(N,n+1)=(Vf-V0)*(1-(k(N,n+1)/kjam))^alpha+V0;
        end
        q(N,n+1)=k(N,n+1)*v(N,n+1);
        if kmax<k(N,n+1)
            kmax=k(N,n+1);
        end
        if k(N,n+1)<kmin
        kmin=k(N,n+1);
        end
    for m=2:(N-1)
        t=N-m+1;
        k(t,n+1)=k(t,n)+((q(t-1,n)-q(t,n)))*(1/3600)/delta_L;
        if k(t,n+1)>kjam
            k(t,n+1)=kjam;
            q(t-1,n)=q(t,n)+delta_L*(k(t,n+1)-k(t,n))*3600;
        end
        if k(t,n+1)<=kbreak
            v(t,n+1)=Uf;
        else
            v(t,n+1)=(Vf-V0)*(1-(k(t,n+1)/kjam))^alpha+V0;
```

```
        end
        q(t,n+1)=k(t,n+1)*v(t,n+1);
        if kmax<k(t,n+1)
            kmax=k(t,n+1);
        end
        if k(t,n+1)<kmin
        kmin=k(t,n+1);
        end
    end
    k(1,n+1)=k(1,n)+((inq(n)-q(1,n)))*(1/3600)/delta_L;
        if k(1,n+1)>kjam
            k(1,n+1)=kjam;
            inq(n)=q(1,n)+delta_L*(k(1,n+1)-k(1,n))*3600;
        end
        if k(1,n+1)<=kbreak
            v(1,n+1)=Uf;
        else
            v(1,n+1)=(Vf-V0)*(1-(k(1,n+1)/kjam))^alpha+V0;
        end
        q(1,n+1)=k(1,n+1)*v(1,n+1);
        if kmax<k(1,n+1)
            kmax=k(1,n+1);
        end
        if k(1,n+1)<kmin
        kmin=k(1,n+1);
        end
    end
end
for n=1:T
for m=1:N
        if kmax<k(1,n+1)
            kmax=k(1,n+1);
        end
        if k(1,n+1)<kmin
        kmin=k(1,n+1);
        end
        if vmax<v(1,n+1)
            vmax=v(1,n+1);
```

```
        end
        if v(1,n+1)<vmin
        vmin=v(1,n+1);
        end
        if qmax<q(1,n+1)
            qmax=q(1,n+1);
        end
        if q(1,n+1)<qmin
        qmin=k(1,n+1);
        end
        k(m,n)=floor(64*((k(m,n)-kmin)/(kmax-kmin)));
        q(m,n)=floor(64*((q(m,n)-qmin)/(qmax-qmin)));
        v(m,n)=floor(64*((v(m,n)-60)/(vmax-60)));
    end
end
%subplot(3,1,1),
image(k);
colormap(jet);
%colormap(flipud(colormap));
h=colorbar;
set(h,'YTickLabel',(num2str(floor((kmin))),num2str(floor((0.2*kmax+0.8*kmin))),
num2str(floor((0.4*kmax+0.6*kmin))), num2str(floor((0.6*kmax+0.4*kmin))),
num2str(floor((0.8*kmax+0.2*kmin))),num2str(floor(kmax)))) ;
```

Ramp model with ALINEA control

```
%This function is designed to test the gain factor calculation method
%discussed above. A variable input traffic flow rate will be used to check the response
of the system
function ALINEA_s_rt_3 (N,M,o_cap,L,v,e)
%define a change of the flow rate on main road
for m=1:(N+1)
    if m<=200
        qin(m)=1000;
    elseif m<500
        qin(m)=1500;
    else
        qin(m)=1600+200*sin(2*pi*0.23*m/5);
    end
```

```
end
%Initialization
e=10^(-5);
al=0.001*L/v;
r=zeros(1,(N+1)); %flow rate: with physical meaning
g=zeros(1,(N)); %physical gain, defined in:
r(k+1)=r(k)+g(k)[o_cap-al*(qin(k)+r(k))]
x=zeros(1,(N+1)); %x(k)=o_cap-al*(qin(k)+r(k))
%Main Body of Simulation
for n=1:N
   x(n)=o_cap-al*(qin(n)+r(n));
   if abs(x(n))>e
      g(n)=2*(al^(-1)*o_cap-qin(n)-r(n))/((M+1)*x(n));
   else
      g(n)=0;
   end
   r(n+1)=r(n)+g(n)*x(n);
end
plot(x(1:N));
```

Route advice VMS

```
q_vms=qin(n)*(1-indiff);
   if q_vms<(qout_max-rin1(n)-rin2(n)-rin3(n))
     qin(n)=q_vms;
   else
     qin(n)=qout_max-rin1(n)-rin2(n)-rin3(n);
   end
for k=kin(n):kmax
   if k<=kbreak
     vin(n)=Uf;
   else
     vin(n)=(Vf-V0)*(1-(k/k0))^alpha+V0; %calculate the speed limitation
   end
   qin_break=vin(n)*k;
   if qin(n)>qin_break
     kin(n)=k;
     break;
   end
```

```
end
qin(n)=qin_break;
```

D_0=Base design (no incident)

```
function global_ramp_noacc_3road
clear all;
T=2000;
L=5;
N=100;
M=10;
delta_L=5/N;
Uf=80;
Vf=120;
V0=0.05;
rth=10;
alpha=4;
k0=150;
kbreak=k0*(1-((Uf-V0)/(Vf-V0))^(1/alpha));
kin1=poissrnd(20,1,T+1);
kin2=poissrnd(10,1,T+1);
inik1=normrnd(20,1,1,N);
inik2=normrnd(20,1,1,N);
inik3=normrnd(20,1,1,N);
inikz=normrnd(20,1,1,N);
o_cap1=0.08;
o_cap2=0.1;
o_cap3=0.12;
e=10^(-5);%good thing to write:make the selection of gain numbers easy
r1=zeros(1,(T+1));
rin1=NORMRND(40,1,1,(T+1));
rql1=zeros(1,(T+1));
r2=zeros(1,(T+1));%flow rate: physical meaning
rin2=NORMRND(40,1,1,(T+1));
rql2=zeros(1,(T+1));
r3=zeros(1,(T+1));
rin3=NORMRND(40,1,1,(T+1));
rql3=zeros(1,(T+1));
g1=zeros(1,T); %physical gain, defined in:
```

```
r(k+1)=r(k)+g(k)[o_cap-al*(qin(k)+r(k))]
g2=zeros(1,T);
g3=zeros(1,T);
x1=zeros(1,(T+1)); %x(k)=o_cap-al*(qin(k)+r(k))
x2=zeros(1,(T+1));
qmin=10000;
qmax=0;
%define input
for n=1:(T+1)
    if n<=T/2
        kin(n)=kin1(n);
    end
    if n>T/2
        kin(n)=kin1(n);
    end
    if kin(n)<=kbreak
        vin(n)=Uf;
    else
        vin(n)=(Vf-V0)*(1-(kin(n)/k0))^alpha+V0;
    end
    qin(n)=vin(n)*kin(n);
end
%define initial condition
for m=1:N
    k1(m,1)=inik1(m);
    k2(m,1)=inik2(m);
    k3(m,1)=inik3(m);
    kz(m,1)=inikz(m);
    if kz(m,1)<=kbreak
        vz(m,1)=Uf;
    else
        vz(m,1)=(Vf-V0)*(1-(kz(m,1)/k0))^alpha+V0;
    end
    if k1(m,1)<=kbreak
        v1(m,1)=Uf;
    else
        v1(m,1)=(Vf-V0)*(1-(k1(m,1)/k0))^alpha+V0;
    end
```

```
    if k2(m,1)<=kbreak
        v2(m,1)=Uf;
    else
        v2(m,1)=(Vf-V0)*(1-(k2(m,1)/k0))^alpha+V0;
    end
    if k3(m,1)<=kbreak
        v3(m,1)=Uf;
    else
        v3(m,1)=(Vf-V0)*(1-(k3(m,1)/k0))^alpha+V0;
    end
    qz(m,1)=kz(m,1)*vz(m,1);
    q1(m,1)=k1(m,1)*v1(m,1);
    q2(m,1)=k2(m,1)*v2(m,1);
    q3(m,1)=k3(m,1)*v3(m,1);
end
%road simulation
for n=1:T
    for m=1:N
        if m==1
            al1=0.001*L/v1(m,n);
            al2=0.001*L/v2(m,n);
            al3=0.001*L/v3(m,n);
            kz(m,n+1)=kz(m,n)+((qin(n)-qz(m,n)))*(1/3600)/delta_L;
            k1(m,n+1)=k1(m,n)+((qz(N,n)+r1(n)-q1(m,n)))*(1/3600)/delta_L;
            k2(m,n+1)=k2(m,n)+((q1(N,n)+r2(n)-q2(m,n)))*(1/3600)/delta_L;
            k3(m,n+1)=k3(m,n)+((q2(N,n)+r3(n)-q3(m,n)))*(1/3600)/delta_L;
            x1(n)=o_cap1-al1*((qin(n)+r1(n)));
            x2(n)=o_cap2-al2*((q1(N,n)+r2(n)));
            x3(n)=o_cap3-al3*((q2(N,n)+r3(n)));
            if kz(m,n+1)<=kbreak
               vz(m,n+1)=Uf;
            else
               vz(m,n+1)=(Vf-V0)*(1-(kz(m,n+1)/k0))^alpha+V0;
            end
            qz(m,n+1)=vz(m,n+1)*kz(m,n+1);
            if abs(x1(n))>e
               g1(n)=2*al1^(-1)*(o_cap1-al1*qin(n)-al1*r1(n))/((M+1)*x1(n));
            else
```

```
        g1(n)=0;
     end
     r1(n+1)=r1(n)+g1(n)*x1(n);
     if r1(n+1)<rth
        r1(n+1)=rth;
     end
     if r1(n+1)>rin1(n+1)
         r1(n+1)=rin1(n+1);
     end
     if k1(m,n+1)<=kbreak
        v1(m,n+1)=Uf;
     else
        v1(m,n+1)=(Vf-V0)*(1-(k1(m,n+1)/k0))^alpha+V0;
     end
     q1(m,n+1)=v1(m,n+1)*k1(m,n+1);
     rql1(n+1)=rql1(n)+(rin1(n)-r1(n))*(1/3600);
     if rql1(n+1)<=0
        rql1(n+1)=0;
     end
     if abs(x2(n))>e
        g2(n)=2*al2^(-1)*(o_cap2-al2*q1(N,n)-al2*r2(n))/((M+1)*x2(n));
     else
        g2(n)=0;
     end
     r2(n+1)=r2(n)+g2(n)*x2(n);
     if r2(n+1)<rth
        r2(n+1)=rth;
     end
     if r2(n+1)>rin2(n+1)
         r2(n+1)=rin2(n+1);
     end
     if k2(m,n+1)<=kbreak
        v2(m,n+1)=Uf;
     else
        v2(m,n+1)=(Vf-V0)*(1-(k2(m,n+1)/k0))^alpha+V0;
     end
     q2(m,n+1)=v2(m,n+1)*k2(m,n+1);
     rql2(n+1)=rql2(n)+(rin2(n)-r2(n))*(1/3600);
```

```
        if rql2(n+1)<=0
           rql2(n+1)=0;
        end
        if abs(x3(n))>e
           g3(n)=2*al3^(-1)*(o_cap3-al3*q2(N,n)-al3*r3(n))/((M+1)*x3(n));
        else
           g3(n)=0;
        end
        r3(n+1)=r3(n)+g3(n)*x3(n);
        if r3(n+1)<rth
           r3(n+1)=rth;
        end
        if r3(n+1)>rin3(n+1)
            r3(n+1)=rin3(n+1);
        end
        if (k3(m,n+1))<=kbreak
           v3(m,n+1)=Uf;
        else
           v3(m,n+1)=(Vf-V0)*(1-(k3(m,n+1)/k0))^alpha+V0;
        end
        q3(m,n+1)=v3(m,n+1)*k3(m,n+1);
        rql3(n+1)=rql3(n)+(rin3(n)-r3(n))*(1/3600);
        if rql3(n+1)<=0
           rql3(n+1)=0;
        end
    else
        kz(m,n+1)=kz(m,n)+((qz(m-1,n)-qz(m,n)))*(1/3600)/delta_L;
        k1(m,n+1)=k1(m,n)+((q1(m-1,n)-q1(m,n)))*(1/3600)/delta_L;
        k2(m,n+1)=k2(m,n)+((q2(m-1,n)-q2(m,n)))*(1/3600)/delta_L;
        k3(m,n+1)=k3(m,n)+((q3(m-1,n)-q3(m,n)))*(1/3600)/delta_L;
        if kz(m,n+1)<=kbreak
           vz(m,n+1)=Uf;
        else
           vz(m,n+1)=(Vf-V0)*(1-(kz(m,n+1)/k0))^alpha+V0;
        end
        if k1(m,n+1)<=kbreak
           v1(m,n+1)=Uf;
        else
```

```
            v1(m,n+1)=(Vf-V0)*(1-(k1(m,n+1)/k0))^alpha+V0;
          end
          if k2(m,n+1)<=kbreak
            v2(m,n+1)=Uf;
          else
            v2(m,n+1)=(Vf-V0)*(1-(k2(m,n+1)/k0))^alpha+V0;
          end
          if k3(m,n+1)<=kbreak
            v3(m,n+1)=Uf;
          else
            v3(m,n+1)=(Vf-V0)*(1-(k3(m,n+1)/k0))^alpha+V0;
          end
          qz(m,n+1)=kz(m,n+1)*vz(m,n+1);
          q2(m,n+1)=k2(m,n+1)*v2(m,n+1);
          q1(m,n+1)=k1(m,n+1)*v1(m,n+1);
          q3(m,n+1)=k3(m,n+1)*v3(m,n+1);
      end
  end
end
%for output plot
kmax=0;
kmin=10000;
vmax=0;
vmin=1000;
for n=1:T
    ker(1,n)=kin(n);
    ver(1,n)=vin(n);
    qer(1,n)=qin(n);
    for m=2:(N+1)
        ker(m,n)=kz(m-1,n);
        ker(m+N,n)=k1(m-1,n);
        ker(m+2*N,n)=k2(m-1,n);
        ker(m+3*N,n)=k3(m-1,n);
        ver(m,n)=vz(m-1,n);
        ver(m+N,n)=v1(m-1,n);
        ver(m+2*N,n)=v2(m-1,n);
        ver(m+3*N,n)=v3(m-1,n);
        qer(m,n)=qz(m-1,n);
```

```
        qer(m+N,n)=q1(m-1,n);
        qer(m+2*N,n)=q2(m-1,n);
        qer(m+3*N,n)=q3(m-1,n);
        if qmax<qer(m,n)
           qmax=qer(m,n);
        end
        if qmax<qer(m+N,n)
           qmax=qer(m+N,n);
        end
        if qmax<qer(m+2*N,n)
           qmax=qer(m+2*N,n);
        end
        if qmax<qer(m+3*N,n)
           qmax=qer(m+3*N,n);
        end
        if qer(m,n)<qmin
           qmin=qer(m,n);
        end
        if qer(m+N,n)<qmin
           qmin=qer(m+N,n);
        end
        if qer(m+2*N,n)<qmin
           qmin=qer(m+2*N,n);
        end
        if qer(m+3*N,n)<qmin
           qmin=qer(m+3*N,n);
        end

        if kmax<ker(m,n)
           kmax=ker(m,n);
        end
        if kmax<ker(m+N,n)
           kmax=ker(m+N,n);
        end
        if kmax<ker(m+2*N,n)
           kmax=ker(m+2*N,n);
        end
        if kmax<ker(m+3*N,n)
```

```
        kmax=ker(m+3*N,n);
      end
      if ker(m,n)<kmin
        kmin=ker(m,n);
      end
      if ker(m+N,n)<kmin
        kmin=ker(m+N,n);
      end
      if ker(m+2*N,n)<kmin
        kmin=ker(m+2*N,n);
      end
      if ker(m+3*N,n)<kmin
        kmin=ker(m+3*N,n);
      end

      if vmax<ver(m,n)
        vmax=ver(m,n);
      end
      if vmax<ver(m+N,n)
        vmax=ver(m+N,n);
      end
      if vmax<ver(m+2*N,n)
        vmax=ver(m+2*N,n);
      end
      if vmax<ver(m+3*N,n)
        vmax=ver(m+3*N,n);
      end
      if ver(m,n)<vmin
        vmin=ver(m,n);
      end
      if ver(m+N,n)<vmin
        vmin=ver(m+N,n);
      end
      if ver(m+2*N,n)<vmin
        vmin=ver(m+2*N,n);
      end
      if ver(m+3*N,n)<vmin
        vmin=ver(m+3*N,n);
```

```
        end


    end
end
for n=1:T
    ker(1,n)=floor(64*(ker(1,n)-kmin)/(kmax-kmin));
    ver(1,n)=floor(64*(ver(1,n)-vmin)/(vmax-vmin));
    qer(1,n)=floor(64*(qer(1,n)-qmin)/(qmax-qmin));
    for m=2:(N+1)
        ker(m,n)=floor(64*(ker(m,n)-kmin)/(kmax-kmin));
        ker(m+N,n)=floor(64*(ker(m+N,n)-kmin)/(kmax-kmin));
        ker(m+2*N,n)=floor(64*(ker(m+2*N,n)-kmin)/(kmax-kmin));
        ker(m+3*N,n)=floor(64*(ker(m+3*N,n)-kmin)/(kmax-kmin));
        qer(m,n)=floor(64*((qer(m,n)-qmin))/(qmax-qmin));
        qer(m+N,n)=floor(64*((qer(m+N,n)-qmin))/(qmax-qmin));
        qer(m+2*N,n)=floor(64*((qer(m+2*N,n)-qmin))/(qmax-qmin));
        qer(m+3*N,n)=floor(64*((qer(m+3*N,n)-qmin))/(qmax-qmin));
        ver(m,n)=floor(64*((ver(m,n)-vmin))/(vmax-vmin));
        ver(m+N,n)=floor(64*((ver(m+N,n)-vmin))/(vmax-vmin));
        ver(m+2*N,n)=floor(64*((ver(m+2*N,n)-vmin))/(vmax-vmin));
        ver(m+3*N,n)=floor(64*((ver(m+3*N,n)-vmin))/(vmax-vmin));
    end
end
%pmin=0;
%pmax=32;
%image(ker);
%colormap(jet);
%colormap(flipud(colormap));
%h=colorbar;
%set(h,'YTickLabel',{num2str(floor((kmax-pmin)/6)),num2str(floor((pmax-pmin)*2/
6)), num2str(floor((pmax-pmin)*3/6)), num2str(floor((pmax-pmin)*4/6)),
num2str(floor((pmax-pmin)*5/6)),num2str(floor(pmax))}) ;
subplot(3,1,1),image(ker);
colormap(jet);
%colormap(flipud(colormap));
h=colorbar;
set(h,'YTickLabel',{num2str(floor((kmin))),num2str(floor((0.2*kmax+0.8*kmin))),
num2str(floor((0.4*kmax+0.6*kmin))), num2str(floor((0.6*kmax+0.4*kmin))),
```

```
num2str(floor((0.8*kmax+0.2*kmin))),num2str(floor(kmax))});
%plot(inq)
%xlswrite('D:\matlab\main_road_datak.xls',k(98,:));
%xlswrite('D:\matlab\main_road_dataq.xls',q(98,:));

subplot(3,1,2),image(ver);
colormap(jet);
%colormap(flipud(jet));
h=colorbar;
set(h,'YTickLabel',{num2str(floor((vmin))),num2str(floor((0.2*vmax+0.8*vmin))),
num2str(floor((0.4*vmax+0.6*vmin))), num2str(floor((0.6*vmax+0.4*vmin))),
num2str(floor((0.8*vmax+0.2*vmin))),num2str(floor(vmax))}) ;

subplot(3,1,3),image(qer);
colormap(jet);
%colormap(flipud(colormap));
h=colorbar;set(h,'YTickLabel',{num2str(floor((qmin))),num2str(floor((0.2*qmax+0
.8*qmin))), num2str(floor((0.4*qmax+0.6*qmin))),
num2str(floor((0.6*qmax+0.4*qmin))),
num2str(floor((0.8*qmax+0.2*qmin))),num2str(floor(qmax))}) ;
```

Peak demand enhancement tests

```
kin1=poissrnd(20,1,T+1);
kin2=poissrnd(30,1,T+1);
for n=1:(T+1)
    if n<=T/2
        kin(n)=kin1(n);
    end
    if n>T/2
        kin(n)=kin2(n);
    end
    if kin(n)<=kbreak
        vin(n)=Uf;
    else
        vin(n)=(Vf-V0)*(1-(kin(n)/k0))^alpha+V0;
    end
    qin(n)=vin(n)*kin(n);
end
```

Off-peak demand enhancement tests

```
kin1=poissrnd(20,1,T+1);
kin2=poissrnd(10,1,T+1);
for n=1:(T+1)
    if n<=T/2
        kin(n)=kin1(n);
    end
    if n>T/2
        kin(n)=kin2(n);
    end
    if kin(n)<=kbreak
        vin(n)=Uf;
    else
        vin(n)=(Vf-V0)*(1-(kin(n)/k0))^alpha+V0;
    end
    qin(n)=vin(n)*kin(n);
end
```

ID_1=LRM

```
function incident_wo_control
clear all;
T=10000;
L=5;
N=100;
M=10;
delta_L=5/N;
Uf=80;
Vf=100;
V0=0.05;
rth=20;
alpha=4;
k0=150;
kbreak=k0*(1-((Uf-V0)/(Vf-V0))^(1/alpha));
kin=NORMRND(10,1,1,T+1);
inik1=NORMRND(10,1,1,N);
inik2=NORMRND(10,1,1,N);
o_cap1=0.08;
```

```
o_cap2=0.1;
o_cap3=0.12;
e=10^(-5);%good thing to write:make the selection of gain numbers easy
r1=zeros(1,(T+1));
rin1=NORMRND(30,5,1,(T+1));
rql1=zeros(1,(T+1));
r2=zeros(1,(T+1));%flow rate: physical meaning
rin2=NORMRND(30,5,1,(T+1));
rql2=zeros(1,(T+1));
r3=zeros(1,(T+1));
rin3=NORMRND(30,5,1,(T+1));
rql3=zeros(1,(T+1));
g1=zeros(1,T); %physical gain, defined in:
r(k+1)=r(k)+g(k)[o_cap-al*(qin(k)+r(k))]
g2=zeros(1,T);
g3=zeros(1,T);
x1=zeros(1,(T+1)); %x(k)=o_cap-al*(qin(k)+r(k))
x2=zeros(1,(T+1));
qout_max=300;
kmax=150;
kout(1)=0;
vout(1)=Uf;
qout(1)=kout(1)*vout(1);
qmin=10000;
qmax=0;
%define input
for n=1:(T+1)
    if kin(n)<=kbreak
        vin(n)=Uf;
    else
        vin(n)=(Vf-V0)*(1-(kin(n)/k0))^alpha+V0;
    end
    qin(n)=vin(n)*kin(n);
end
%define accident at output
for n=1:(T+1)
    if n<=(0.1*T)
      delta_kout(n)=0;
```

```
    else
      delta_kout(n)=100;
    end
end
%define initial condition
for m=1:N
    k1(m,1)=inik1(m);
    k2(m,1)=inik2(m);
    if k1(m,1)<=kbreak
       v1(m,1)=Uf;
    else
       v1(m,1)=(Vf-V0)*(1-(k1(m,1)/k0))^alpha+V0;
    end
    if k2(m,1)<=kbreak
       v2(m,1)=Uf;
    else
       v2(m,1)=(Vf-V0)*(1-(k2(m,1)/k0))^alpha+V0;
    end
    q1(m,1)=k1(m,1)*v1(m,1);
    q2(m,1)=k2(m,1)*v2(m,1);
end
%road simulation
for n=1:T
    if delta_kout(n)==0 %no accident
    for m=1:N
       ml(n)=0;
       if m==1
          al1=0.001*L/v1(m,n);
          al2=0.001*L/v2(m,n);
          al3=0.001*L/vout(n);
          k1(m,n+1)=k1(m,n)+((qin(n)+r1(n)-q1(m,n)))*(1/3600)/delta_L;
          k2(m,n+1)=k2(m,n)+((q1(N,n)+r2(n)-q2(m,n)))*(1/3600)/delta_L;
          kout(n+1)=kout(n)+((q2(N,n)+r3(n)-qout(n)))*(1/3600)/delta_L;
          x1(n)=o_cap1-al1*((qin(n)+r1(n)));
          x2(n)=o_cap2-al2*((q1(N,n)+r2(n)));
          x3(n)=o_cap3-al3*((q2(N,n)+r3(n)));
          if abs(x1(n))>e
            g1(n)=2*al1^(-1)*(o_cap1-al1*qin(n)-al1*r1(n))/((M+1)*x1(n));
```

```
else
   g1(n)=0;
end
r1(n+1)=r1(n)+g1(n)*x1(n);
if r1(n+1)<rth
   r1(n+1)=rth;
end
if r1(n+1)>rin1(n+1)
    r1(n+1)=rin1(n+1);
end
if k1(m,n+1)<=kbreak
   v1(m,n+1)=Uf;
else
   v1(m,n+1)=(Vf-V0)*(1-(k1(m,n+1)/k0))^alpha+V0;
end
q1(m,n+1)=v1(m,n+1)*k1(m,n+1);
rql1(n+1)=rql1(n)+(rin1(n)-r1(n))*(1/3600);
if rql1(n+1)<=0
   rql1(n+1)=0;
end
if abs(x2(n))>e
   g2(n)=2*al2^(-1)*(o_cap2-al2*q1(N,n)-al2*r2(n))/((M+1)*x2(n));
else
   g2(n)=0;
end
r2(n+1)=r2(n)+g2(n)*x2(n);
if r2(n+1)<rth
   r2(n+1)=rth;
end
if r2(n+1)>rin2(n+1)
    r2(n+1)=rin2(n+1);
end
if k2(m,n+1)<=kbreak
   v2(m,n+1)=Uf;
else
   v2(m,n+1)=(Vf-V0)*(1-(k2(m,n+1)/k0))^alpha+V0;
end
q2(m,n+1)=v2(m,n+1)*k2(m,n+1);
```

```
        rql2(n+1)=rql2(n)+(rin2(n)-r2(n))*(1/3600);
        if rql2(n+1)<=0
          rql2(n+1)=0;
        end
        if abs(x3(n))>e
          g3(n)=2*al3^(-1)*(o_cap3-al3*q2(N,n)-al3*r3(n))/((M+1)*x3(n));
        else
          g3(n)=0;
        end
        r3(n+1)=r3(n)+g3(n)*x3(n);
        if r3(n+1)<rth
          r3(n+1)=rth;
        end
        if r3(n+1)>rin3(n+1)
           r3(n+1)=rin3(n+1);
        end
        if (kout(n+1))<=kbreak
          vout(n+1)=Uf;
        else
          vout(n+1)=(Vf-V0)*(1-(kout(n+1)/k0))^alpha+V0;
        end
        qout(n+1)=vout(n+1)*(kout(n+1)+delta_kout(n+1));
        kout(n+1)=kout(n+1)+delta_kout(n+1);
        rql3(n+1)=rql3(n)+(rin3(n)-r3(n))*(1/3600);
        if rql3(n+1)<=0
          rql3(n+1)=0;
        end
    else
        k1(m,n+1)=k1(m,n)+((q1(m-1,n)-q1(m,n)))*(1/3600)/delta_L;
        k2(m,n+1)=k2(m,n)+((q2(m-1,n)-q2(m,n)))*(1/3600)/delta_L;
        if k1(m,n+1)<=kbreak
          v1(m,n+1)=Uf;
        else
          v1(m,n+1)=(Vf-V0)*(1-(k1(m,n+1)/k0))^alpha+V0;
        end
        if k2(m,n+1)<=kbreak
          v2(m,n+1)=Uf;
        else
```

```
            v2(m,n+1)=(Vf-V0)*(1-(k2(m,n+1)/k0))^alpha+V0;
         end
         q2(m,n+1)=k2(m,n+1)*v2(m,n+1);
         q1(m,n+1)=k1(m,n+1)*v1(m,n+1);
     end
 end
else %accident
     qout(n)=qout_max;
     kout(n+1)=kout(n);
     if (kout(n+1))<=kbreak
         vout(n+1)=Uf;
     else
         vout(n+1)=(Vf-V0)*(1-(kout(n+1)/k0))^alpha+V0;
     end
     r3(n)=qout_max-q2(N,n);
     if r3(n)<rth
        r3(n)=rth;
     end
     if r3(n+1)>rin3(n+1)
        r3(n+1)=rin3(n+1);
     end
     q2(N,n)=qout_max-r3(n);
     rql3(n+1)=rql3(n)+(rin3(n)-r3(n))*(1/3600);
     if rql3(n+1)<=0
        rql3(n+1)=0;
     end
     for p=1:N
         m=N-p+1;
         if m==1
             al2=0.001*L/v2(m,n);
             k2(m,n+1)=k2(m,n)+((q1(N,n)+r2(n)-q2(m,n)))*(1/3600)/delta_L;
             if k2(m,n+1)>kmax
                k2(m,n+1)=kmax;
                ml(n)=N-m+1;
                q1(N,n)=q2(m,n)+delta_L*(k2(m,n+1)-k2(m,n))*3600-r2(n);
             end
             x2(n)=o_cap2-al2*((q1(N,n)+r2(n)));
             if abs(x2(n))>e
```

```
            g2(n)=2*al2^(-1)*(o_cap2-al2*q1(N,n)-al2*r2(n))/((M+1)*x2(n));
         else
            g2(n)=0;
         end
         r2(n+1)=r2(n)+g2(n)*x2(n);
         rql2(n+1)=rql2(n)+(rin2(n)-r2(n))*(1/3600);
         if rql2(n+1)<=0
            rql2(n+1)=0;
         end
         if r2(n+1)<rth
            r2(n+1)=rth;
         end
         if r2(n+1)>rin2(n+1)
         r2(n+1)=rin2(n+1);
         end
         if k2(m,n+1)<=kbreak
            v2(m,n+1)=Uf;
         else
            v2(m,n+1)=(Vf-V0)*(1-(k2(m,n+1)/k0))^alpha+V0;
         end
         q2(m,n+1)=k2(m,n+1)*v2(m,n+1);
      else
         k2(m,n+1)=k2(m,n)+(q2(m-1,n)-q2(m,n))*(1/3600)/delta_L;
         if k2(m,n+1)>kmax
            k2(m,n+1)=kmax;
            ml(n)=N-m+1;
            q2(m-1,n)=q2(m,n)+delta_L*(k2(m,n+1)-k2(m,n))*3600;
         end
         if k2(m,n+1)<=kbreak
            v2(m,n+1)=Uf;
         else
            v2(m,n+1)=(Vf-V0)*(1-(k2(m,n+1)/k0))^alpha+V0;
         end
         q2(m,n+1)=k2(m,n+1)*v2(m,n+1);
      end
   end
   for p=1:N
      m=N-p+1;
```

```
        if m==1
            al1=0.001*L/v1(m,n);
            k1(m,n+1)=k1(m,n)+((qin(n)+r1(n)-q1(m,n)))*(1/3600)/delta_L;
            if k1(m,n+1)>kmax
               k1(m,n+1)=kmax;
               ml(n)=2*N-m+1;
               qin(n)=q1(m,n)+delta_L*(k1(m,n+1)-k1(m,n))*3600-r1(n);
            end
            x1(n)=o_cap1-al1*((qin(n)+r1(n)));
            if abs(x1(n))>e
               g1(n)=2*al1^(-1)*(o_cap1-al1*qin(n)-al1*r1(n))/((M+1)*x1(n));
            else
               g1(n)=0;
            end
            r1(n+1)=r1(n)+g1(n)*x1(n);
            rql1(n+1)=rql1(n)+(rin1(n)-r1(n))*(1/3600);
            if rql1(n+1)<=0
               rql1(n+1)=0;
            end
            if r1(n+1)>rin1(n+1)
               r1(n+1)=rin1(n+1);
            end
            if r1(n+1)<rth
               r1(n+1)=rth;
            end
            if k1(m,n+1)<=kbreak
               v1(m,n+1)=Uf;
            else
               v1(m,n+1)=(Vf-V0)*(1-(k1(m,n+1)/k0))^alpha+V0;
            end
            q1(m,n+1)=k1(m,n+1)*v1(m,n+1);
            qin_l=qin(n+1)-(q1(m,n+1)-r1(n+1))*(1/3600);
            if qin_l>0
                qin(n+1)=q1(m,n+1)-r1(n+1);
            end
        else
            k1(m,n+1)=k1(m,n)+(q1(m-1,n)-q1(m,n))*(1/3600)/delta_L;
            if k1(m,n+1)>kmax
```

```
                k1(m,n+1)=kmax;
                ml(n)=2*N-m+1;
                q1(m-1,n)=q1(m,n)+delta_L*(k1(m,n+1)-k1(m,n))*3600;
             end
             if k1(m,n+1)<=kbreak
                v1(m,n+1)=Uf;
             else
                v1(m,n+1)=(Vf-V0)*(1-(k1(m,n+1)/k0))^alpha+V0;
             end
             q1(m,n+1)=k1(m,n+1)*v1(m,n+1);
         end
      end
   end
end
for n=1:T
   ker(1,n)=kin(n);
   ver(1,n)=vin(n);
   qer(1,n)=qin(n);
   ker((2*N+2),n)=kout(n);
   ver((2*N+2),n)=vout(n);
   qer((2*N+2),n)=qout(n);
   for m=2:(N+1)
      ker(m,n)=k1(m-1,n);
      ker(m+N,n)=k2(m-1,n);
      ver(m,n)=v1(m-1,n);
      ver(m+N,n)=v2(m-1,n);
      qer(m,n)=q1(m-1,n);
      qer(m+N,n)=q2(m-1,n);
      if qmax<qer(m,n)
         qmax=qer(m,n);
      end
      if qmax<qer(m+N,n)
         qmax=qer(m+N,n);
      end
      if qer(m,n)<qmin
         qmin=qer(m,n);
      end
      if qer(m+N,n)<qmin
```

```
        qmin=qer(m+N,n);
      end
   end
end
for n=1:T
   ker(1,n)=floor(64*ker(1,n)/150);
   ver(1,n)=floor(64*ver(1,n)/80);
   qer(1,n)=floor(64*((qer(1,n)))/(qmax));
   ker((2*N+2),n)=floor(64*ker((2*N+2),n)/150);
   ver((2*N+2),n)=floor(64*ver((2*N+2),n)/80);
   qer((2*N+2),n)=floor(64*((qer((2*N+2),n)))/(qmax));
   for m=2:(N+1)
      ker(m,n)=floor(64*ker(m,n)/150);
      ker(m+N,n)=floor(64*ker(m+N,n)/150);
      qer(m,n)=floor(64*((qer(m,n)))/(qmax));
      qer(m+N,n)=floor(64*((qer(m+N,n)))/(qmax));
      ver(m,n)=floor(64*ver(m,n)/80);
      ver(m+N,n)=floor(64*ver(m+N,n)/80);
   end
end
plot(ml);hold all;
plot(rql1);hold all;
plot(rql2);hold all;
plot(rql3);hold all;
plot(rql1+rql2+rql3);hold all;
pmin=0;
pmax=150;
image(ker);
colormap(jet);
colormap(flipud(colormap));
h=colorbar;
set(h,'YTickLabel',(num2str(floor((pmax-pmin)/6)),num2str(floor((pmax-pmin)*2/6
)), num2str(floor((pmax-pmin)*3/6)), num2str(floor((pmax-pmin)*4/6)),
num2str(floor((pmax-pmin)*5/6)),num2str(floor(pmax)))) ;
```

ID_2=CRM

```
function incident_w_ramp_coor
clear all;
```

```
T=10000;
L=5;
N=100;
M=10;
delta_L=5/N;
Uf=80;
Vf=100;
V0=0.05;
rth=20;
alpha=4;
k0=150;
kbreak=k0*(1-((Uf-V0)/(Vf-V0))^(1/alpha));
kin=NORMRND(10,1,1,T+1);
inik1=NORMRND(10,1,1,N);
inik2=NORMRND(10,1,1,N);
o_cap1=0.08;
o_cap2=0.1;
o_cap3=0.12;
e=10^(-5);%good thing to write:make the selection of gain numbers easy
r1=zeros(1,(T+1));
rin1=NORMRND(30,5,1,(T+1));
rql1=zeros(1,(T+1));
r2=zeros(1,(T+1));%flow rate: physical meaning
rin2=NORMRND(30,5,1,(T+1));
rql2=zeros(1,(T+1));
r3=zeros(1,(T+1));
rin3=NORMRND(30,5,1,(T+1));
rql3=zeros(1,(T+1));
g1=zeros(1,T); %physical gain, defined in:
r(k+1)=r(k)+g(k)[o_cap-al*(qin(k)+r(k))]
g2=zeros(1,T);
g3=zeros(1,T);
x1=zeros(1,(T+1)); %x(k)=o_cap-al*(qin(k)+r(k))
x2=zeros(1,(T+1));
qout_max=300;
kmax=150;
kout(1)=0;
vout(1)=Uf;
qout(1)=kout(1)*vout(1);
qmin=10000;
qmax=0;
%define input
for n=1:(T+1)
```

```
    if kin(n)<=kbreak
        vin(n)=Uf;
    else
        vin(n)=(Vf-V0)*(1-(kin(n)/k0))^alpha+V0;
    end
    qin(n)=vin(n)*kin(n);
end
%define accident at output
for n=1:(T+1)
    if n<=(0.1*T)
       delta_kout(n)=0;
    else
       delta_kout(n)=100;
    end
end
%define initial condition
for m=1:N
    k1(m,1)=inik1(m);
    k2(m,1)=inik2(m);
    if k1(m,1)<=kbreak
        v1(m,1)=Uf;
    else
        v1(m,1)=(Vf-V0)*(1-(k1(m,1)/k0))^alpha+V0;
    end
    if k2(m,1)<=kbreak
        v2(m,1)=Uf;
    else
        v2(m,1)=(Vf-V0)*(1-(k2(m,1)/k0))^alpha+V0;
    end
    q1(m,1)=k1(m,1)*v1(m,1);
    q2(m,1)=k2(m,1)*v2(m,1);
end
%road simulation
for n=1:T
    if delta_kout(n)==0 %no accident
        ml(n)=0;
       for m=1:N
        if m==1
            al1=0.001*L/v1(m,n);
            al2=0.001*L/v2(m,n);
            al3=0.001*L/vout(n);
            k1(m,n+1)=k1(m,n)+((qin(n)+r1(n)-q1(m,n)))*(1/3600)/delta_L;
            k2(m,n+1)=k2(m,n)+((q1(N,n)+r2(n)-q2(m,n)))*(1/3600)/delta_L;
```

```
kout(n+1)=kout(n)+((q2(N,n)+r3(n)-qout(n)))*(1/3600)/delta_L;
x1(n)=o_cap1-al1*((qin(n)+r1(n)));
x2(n)=o_cap2-al2*((q1(N,n)+r2(n)));
x3(n)=o_cap3-al3*((q2(N,n)+r3(n)));
if abs(x1(n))>e
  g1(n)=2*al1^(-1)*(o_cap1-al1*qin(n)-al1*r1(n))/((M+1)*x1(n));
else
  g1(n)=0;
end
r1(n+1)=r1(n)+g1(n)*x1(n);
if r1(n+1)<rth
  r1(n+1)=rth;
end
if r1(n+1)>rin1(n+1)
   r1(n+1)=rin1(n+1);
end
if k1(m,n+1)<=kbreak
  v1(m,n+1)=Uf;
else
  v1(m,n+1)=(Vf-V0)*(1-(k1(m,n+1)/k0))^alpha+V0;
end
q1(m,n+1)=v1(m,n+1)*k1(m,n+1);
rql1(n+1)=rql1(n)+(rin1(n)-r1(n))*(1/3600);
if rql1(n+1)<=0
  rql1(n+1)=0;
end
if abs(x2(n))>e
  g2(n)=2*al2^(-1)*(o_cap2-al2*q1(N,n)-al2*r2(n))/((M+1)*x2(n));
else
  g2(n)=0;
end
r2(n+1)=r2(n)+g2(n)*x2(n);
if r2(n+1)<rth
  r2(n+1)=rth;
end
if r2(n+1)>rin2(n+1)
   r2(n+1)=rin2(n+1);
end
if k2(m,n+1)<=kbreak
  v2(m,n+1)=Uf;
else
  v2(m,n+1)=(Vf-V0)*(1-(k2(m,n+1)/k0))^alpha+V0;
end
```

```
        q2(m,n+1)=v2(m,n+1)*k2(m,n+1);
        rql2(n+1)=rql2(n)+(rin2(n)-r2(n))*(1/3600);
        if rql2(n+1)<=0
          rql2(n+1)=0;
        end
        if abs(x3(n))>e
          g3(n)=2*al3^(-1)*(o_cap3-al3*q2(N,n)-al3*r3(n))/((M+1)*x3(n));
        else
          g3(n)=0;
        end
        r3(n+1)=r3(n)+g3(n)*x3(n);
        if r3(n+1)<rth
          r3(n+1)=rth;
        end
        if r3(n+1)>rin3(n+1)
           r3(n+1)=rin3(n+1);
        end
        if (kout(n+1))<=kbreak
          vout(n+1)=Uf;
        else
          vout(n+1)=(Vf-V0)*(1-(kout(n+1)/k0))^alpha+V0;
        end
        qout(n+1)=vout(n+1)*(kout(n+1)+delta_kout(n+1));
        kout(n+1)=kout(n+1)+delta_kout(n+1);
        rql3(n+1)=rql3(n)+(rin3(n)-r3(n))*(1/3600);
        if rql3(n+1)<=0
          rql3(n+1)=0;
        end
    else
        k1(m,n+1)=k1(m,n)+((q1(m-1,n)-q1(m,n)))*(1/3600)/delta_L;
        k2(m,n+1)=k2(m,n)+((q2(m-1,n)-q2(m,n)))*(1/3600)/delta_L;
        if k1(m,n+1)<=kbreak
          v1(m,n+1)=Uf;
        else
          v1(m,n+1)=(Vf-V0)*(1-(k1(m,n+1)/k0))^alpha+V0;
        end
        if k2(m,n+1)<=kbreak
          v2(m,n+1)=Uf;
        else
          v2(m,n+1)=(Vf-V0)*(1-(k2(m,n+1)/k0))^alpha+V0;
        end
        q2(m,n+1)=k2(m,n+1)*v2(m,n+1);
        q1(m,n+1)=k1(m,n+1)*v1(m,n+1);
```

```
        end
    end
    else %accident
        qout(n)=qout_max;
        kout(n+1)=kout(n);
        if (kout(n+1))<=kbreak
            vout(n+1)=Uf;
        else
            vout(n+1)=(Vf-V0)*(1-(kout(n+1)/k0))^alpha+V0;
        end
        r3(n)=qout_max-q2(N,n);
        if r3(n)<rth
           r3(n)=rth;
        end
        q2(N,n)=qout_max-r3(n);
        rql3(n+1)=rql3(n)+(rin3(n)-r3(n))*(1/3600);
        if rql3(n+1)<=0
           rql3(n+1)=0;
        end
        if rql3(n+1)>=20
            r2(n+1)=rth;
            r1(n+1)=rth;
           for p=1:N
            m=N-p+1;
            if m==1
                k2(m,n+1)=k2(m,n)+((q1(N,n)+r2(n)-q2(m,n)))*(1/3600)/delta_L;
                if k2(m,n+1)>kmax
                   k2(m,n+1)=kmax;
                   ml(n)=N-m+1;
                   q1(N,n)=q2(m,n)+delta_L*(k2(m,n+1)-k2(m,n))*3600-r2(n);
                end
                rql2(n+1)=rql2(n)+(rin2(n)-r2(n))*(1/3600);
                if rql2(n+1)<=0
                   rql2(n+1)=0;
                end
                if k2(m,n+1)<=kbreak
                   v2(m,n+1)=Uf;
                else
                   v2(m,n+1)=(Vf-V0)*(1-(k2(m,n+1)/k0))^alpha+V0;
                end
                q2(m,n+1)=k2(m,n+1)*v2(m,n+1);
            else
                k2(m,n+1)=k2(m,n)+(q2(m-1,n)-q2(m,n))*(1/3600)/delta_L;
```

```
        if k2(m,n+1)>kmax
           k2(m,n+1)=kmax;
           ml(n)=N-m+1;
           q2(m-1,n)=q2(m,n)+delta_L*(k2(m,n+1)-k2(m,n))*3600;
        end
        if k2(m,n+1)<=kbreak
           v2(m,n+1)=Uf;
        else
           v2(m,n+1)=(Vf-V0)*(1-(k2(m,n+1)/k0))^alpha+V0;
        end
        q2(m,n+1)=k2(m,n+1)*v2(m,n+1);
    end
   end
   for p=1:N
    m=N-p+1;
    if m==1
        k1(m,n+1)=k1(m,n)+((qin(n)+r1(n)-q1(m,n)))*(1/3600)/delta_L;
        if k1(m,n+1)>kmax
           k1(m,n+1)=kmax;
           ml(n)=2*N-m+1;
           qin(n)=q1(m,n)+delta_L*(k1(m,n+1)-k1(m,n))*3600-r1(n);
        end
        rql1(n+1)=rql1(n)+(rin1(n)-r1(n))*(1/3600);
        if rql1(n+1)<=0
           rql1(n+1)=0;
        end
        if k1(m,n+1)<=kbreak
           v1(m,n+1)=Uf;
        else
           v1(m,n+1)=(Vf-V0)*(1-(k1(m,n+1)/k0))^alpha+V0;
        end
        q1(m,n+1)=k1(m,n+1)*v1(m,n+1);
    else
        k1(m,n+1)=k1(m,n)+(q1(m-1,n)-q1(m,n))*(1/3600)/delta_L;
        if k1(m,n+1)>kmax
           k1(m,n+1)=kmax;
           ml(n)=2*N-m+1;
           q1(m-1,n)=q1(m,n)+delta_L*(k1(m,n+1)-k1(m,n))*3600;
        end
        if k1(m,n+1)<=kbreak
           v1(m,n+1)=Uf;
        else
           v1(m,n+1)=(Vf-V0)*(1-(k1(m,n+1)/k0))^alpha+V0;
```

```
            end
            q1(m,n+1)=k1(m,n+1)*v1(m,n+1);
         end
      end
      else
         for p=1:N
          m=N-p+1;
          if m==1
             al2=0.001*L/v2(m,n);
             k2(m,n+1)=k2(m,n)+((q1(N,n)+r2(n)-q2(m,n)))*(1/3600)/delta_L;
             if k2(m,n+1)>kmax
                k2(m,n+1)=kmax;
                ml(n)=N-m+1;
                q1(N,n)=q2(m,n)+delta_L*(k2(m,n+1)-k2(m,n))*3600-r2(n);
             end
             x2(n)=o_cap2-al2*((q1(N,n)+r2(n)));
             if abs(x2(n))>e
                g2(n)=2*al2^(-1)*(o_cap2-al2*q1(N,n)-al2*r2(n))/((M+1)*x2(n));
             else
                g2(n)=0;
             end
             r2(n+1)=r2(n)+g2(n)*x2(n);
             rql2(n+1)=rql2(n)+(rin2(n)-r2(n))*(1/3600);
             if rql2(n+1)<=0
                rql2(n+1)=0;
             end
             if r2(n+1)<rth
                r2(n+1)=rth;
             end
             if r2(n+1)>rin2(n+1)
                r2(n+1)=rin2(n+1);
             end
             if k2(m,n+1)<=kbreak
                v2(m,n+1)=Uf;
             else
                v2(m,n+1)=(Vf-V0)*(1-(k2(m,n+1)/k0))^alpha+V0;
             end
             q2(m,n+1)=k2(m,n+1)*v2(m,n+1);
          else
             k2(m,n+1)=k2(m,n)+(q2(m-1,n)-q2(m,n))*(1/3600)/delta_L;
             if k2(m,n+1)>kmax
                k2(m,n+1)=kmax;
                ml(n)=N-m+1;
                q2(m-1,n)=q2(m,n)+delta_L*(k2(m,n+1)-k2(m,n))*3600;
```

```
            end
            if k2(m,n+1)<=kbreak
               v2(m,n+1)=Uf;
            else
               v2(m,n+1)=(Vf-V0)*(1-(k2(m,n+1)/k0))^alpha+V0;
            end
            q2(m,n+1)=k2(m,n+1)*v2(m,n+1);
        end
       end
       for p=1:N
        m=N-p+1;
        if m==1
            al1=0.001*L/v1(m,n);
            k1(m,n+1)=k1(m,n)+((qin(n)+r1(n)-q1(m,n)))*(1/3600)/delta_L;
            if k1(m,n+1)>kmax
               k1(m,n+1)=kmax;
               ml(n)=2*N-m+1;
               qin(n)=q1(m,n)+delta_L*(k1(m,n+1)-k1(m,n))*3600-r1(n);
            end
            x1(n)=o_cap1-al1*((qin(n)+r1(n)));
            if abs(x1(n))>e
               g1(n)=2*al1^(-1)*(o_cap1-al1*qin(n)-al1*r1(n))/((M+1)*x1(n));
            else
               g1(n)=0;
            end
            r1(n+1)=r1(n)+g1(n)*x1(n);
            rql1(n+1)=rql1(n)+(rin1(n)-r1(n))*(1/3600);
            if rql1(n+1)<=0
               rql1(n+1)=0;
            end
            if r1(n+1)<rth
               r1(n+1)=rth;
            end
            if r1(n+1)>rin1(n+1)
               r1(n+1)=rin1(n+1);
            end
            if k1(m,n+1)<=kbreak
               v1(m,n+1)=Uf;
            else
               v1(m,n+1)=(Vf-V0)*(1-(k1(m,n+1)/k0))^alpha+V0;
            end
            q1(m,n+1)=k1(m,n+1)*v1(m,n+1);
        else
            k1(m,n+1)=k1(m,n)+(q1(m-1,n)-q1(m,n))*(1/3600)/delta_L;
```

```
            if k1(m,n+1)>kmax
               k1(m,n+1)=kmax;
               ml(n)=2*N-m+1;
               q1(m-1,n)=q1(m,n)+delta_L*(k1(m,n+1)-k1(m,n))*3600;
            end
            if k1(m,n+1)<=kbreak
               v1(m,n+1)=Uf;
            else
               v1(m,n+1)=(Vf-V0)*(1-(k1(m,n+1)/k0))^alpha+V0;
            end
            q1(m,n+1)=k1(m,n+1)*v1(m,n+1);
         end
      end
      end
   end
end
for n=1:T
   ker(1,n)=kin(n);
   ver(1,n)=vin(n);
   qer(1,n)=qin(n);
   ker((2*N+2),n)=kout(n);
   ver((2*N+2),n)=vout(n);
   qer((2*N+2),n)=qout(n);
   for m=2:(N+1)
      ker(m,n)=k1(m-1,n);
      ker(m+N,n)=k2(m-1,n);
      ver(m,n)=v1(m-1,n);
      ver(m+N,n)=v2(m-1,n);
      qer(m,n)=q1(m-1,n);
      qer(m+N,n)=q2(m-1,n);
      if qmax<qer(m,n)
         qmax=qer(m,n);
      end
      if qmax<qer(m+N,n)
         qmax=qer(m+N,n);
      end
      if qer(m,n)<qmin
         qmin=qer(m,n);
      end
      if qer(m+N,n)<qmin
         qmin=qer(m+N,n);
      end
   end
end
```

```
for n=1:T
   ker(1,n)=floor(64*ker(1,n)/150);
   ver(1,n)=floor(64*ver(1,n)/80);
   qer(1,n)=floor(64*((qer(1,n)))/(qmax));
   ker((2*N+2),n)=floor(64*ker((2*N+2),n)/150);
   ver((2*N+2),n)=floor(64*ver((2*N+2),n)/80);
   qer((2*N+2),n)=floor(64*((qer((2*N+2),n)))/(qmax));
   for m=2:(N+1)
      ker(m,n)=floor(64*ker(m,n)/150);
      ker(m+N,n)=floor(64*ker(m+N,n)/150);
      qer(m,n)=floor(64*((qer(m,n)))/(qmax));
      qer(m+N,n)=floor(64*((qer(m+N,n)))/(qmax));
      ver(m,n)=floor(64*ver(m,n)/80);
      ver(m+N,n)=floor(64*ver(m+N,n)/80);
   end
end
plot(ml);hold all;
plot(rql1);hold all;
plot(rql2);hold all;
plot(rql3);hold all;
plot(rql1+rql2+rql3);hold all;
pmin=0;
pmax=140;
image(ker);
colormap(jet);
colormap(flipud(colormap));
h=colorbar;
set(h,'YTickLabel',(num2str(floor((pmax-pmin)/6)),num2str(floor((pmax-pmin)*2/6
)), num2str(floor((pmax-pmin)*3/6)), num2str(floor((pmax-pmin)*4/6)),
num2str(floor((pmax-pmin)*5/6)),num2str(floor(pmax))}) ;
```

ID_4=[C(CRM+RA)]

```
function incident_w_CNM
clear all;
T=10000;
L=5;
N=100;
M=10;
delta_L=5/N;
Uf=80;
Vf=100;
V0=0.05;
rth=10;
```

```
alpha=4;
k0=150;
kbreak=k0*(1-((Uf-V0)/(Vf-V0))^(1/alpha));
kin=NORMRND(10,1,1,T+1);
inik1=NORMRND(10,1,1,N);
inik2=NORMRND(10,1,1,N);
o_cap1=0.08;
o_cap2=0.1;
o_cap3=0.12;
e=10^(-5);%good thing to write:make the selection of gain numbers easy
r1=zeros(1,(T+1));
rin1=NORMRND(30,5,1,(T+1));
rql1=zeros(1,(T+1));
r2=zeros(1,(T+1));%flow rate: physical meaning
rin2=NORMRND(30,5,1,(T+1));
rql2=zeros(1,(T+1));
r3=zeros(1,(T+1));
rin3=NORMRND(30,5,1,(T+1));
rql3=zeros(1,(T+1));
g1=zeros(1,T); %physical gain, defined in:
r(k+1)=r(k)+g(k)[o_cap-al*(qin(k)+r(k))]
g2=zeros(1,T);
g3=zeros(1,T);
x1=zeros(1,(T+1)); %x(k)=o_cap-al*(qin(k)+r(k))
x2=zeros(1,(T+1));
qout_max=300;
kmax=150;
kout(1)=0;
vout(1)=Uf;
qout(1)=kout(1)*vout(1);
qmin=10000;
qmax=0;
%define input
for n=1:(T+1)
    if kin(n)<=kbreak
        vin(n)=Uf;
    else
        vin(n)=(Vf-V0)*(1-(kin(n)/k0))^alpha+V0;
    end
    qin(n)=vin(n)*kin(n);
end
%define accident at output
for n=1:(T+1)
    if n<=(0.1*T)
```

```
      delta_kout(n)=0;
   else
      delta_kout(n)=100;
   end
end
%define initial condition
for m=1:N
   k1(m,1)=inik1(m);
   k2(m,1)=inik2(m);
   if k1(m,1)<=kbreak
      v1(m,1)=Uf;
   else
      v1(m,1)=(Vf-V0)*(1-(k1(m,1)/k0))^alpha+V0;
   end
   if k2(m,1)<=kbreak
      v2(m,1)=Uf;
   else
      v2(m,1)=(Vf-V0)*(1-(k2(m,1)/k0))^alpha+V0;
   end
   q1(m,1)=k1(m,1)*v1(m,1);
   q2(m,1)=k2(m,1)*v2(m,1);
end
%road simulation
for n=1:T
   if delta_kout(n)==0 %no accident
      for m=1:N
       if m==1
          al1=0.001*L/v1(m,n);
          al2=0.001*L/v2(m,n);
          al3=0.001*L/vout(n);
          k1(m,n+1)=k1(m,n)+((qin(n)+r1(n)-q1(m,n)))*(1/3600)/delta_L;
          k2(m,n+1)=k2(m,n)+((q1(N,n)+r2(n)-q2(m,n)))*(1/3600)/delta_L;
          kout(n+1)=kout(n)+((q2(N,n)+r3(n)-qout(n)))*(1/3600)/delta_L;
          x1(n)=o_cap1-al1*((qin(n)+r1(n)));
          x2(n)=o_cap2-al2*((q1(N,n)+r2(n)));
          x3(n)=o_cap3-al3*((q2(N,n)+r3(n)));
          if abs(x1(n))>e
             g1(n)=2*al1^(-1)*(o_cap1-al1*qin(n)-al1*r1(n))/((M+1)*x1(n));
          else
             g1(n)=0;
          end
          r1(n+1)=r1(n)+g1(n)*x1(n);
          if r1(n+1)<rth
             r1(n+1)=rth;
```

```
        end
        if r1(n+1)>rin1(n+1)
            r1(n+1)=rin1(n+1);
        end
        if k1(m,n+1)<=kbreak
          v1(m,n+1)=Uf;
        else
          v1(m,n+1)=(Vf-V0)*(1-(k1(m,n+1)/k0))^alpha+V0;
        end
        q1(m,n+1)=v1(m,n+1)*k1(m,n+1);
        rql1(n+1)=rql1(n)+(rin1(n)-r1(n))*(1/3600);
        if rql1(n+1)<=0
          rql1(n+1)=0;
        end
        if abs(x2(n))>e
          g2(n)=2*al2^(-1)*(o_cap2-al2*q1(N,n)-al2*r2(n))/((M+1)*x2(n));
        else
          g2(n)=0;
        end
        r2(n+1)=r2(n)+g2(n)*x2(n);
        if r2(n+1)<rth
          r2(n+1)=rth;
        end
        if r2(n+1)>rin2(n+1)
            r2(n+1)=rin2(n+1);
        end
        if k2(m,n+1)<=kbreak
          v2(m,n+1)=Uf;
        else
          v2(m,n+1)=(Vf-V0)*(1-(k2(m,n+1)/k0))^alpha+V0;
        end
        q2(m,n+1)=v2(m,n+1)*k2(m,n+1);
        rql2(n+1)=rql2(n)+(rin2(n)-r2(n))*(1/3600);
        if rql2(n+1)<=0
          rql2(n+1)=0;
        end
        if abs(x3(n))>e
          g3(n)=2*al3^(-1)*(o_cap3-al3*q2(N,n)-al3*r3(n))/((M+1)*x3(n));
        else
          g3(n)=0;
        end
        r3(n+1)=r3(n)+g3(n)*x3(n);
        if r3(n+1)<rth
          r3(n+1)=rth;
```

```
        end
        if r3(n+1)>rin3(n+1)
           r3(n+1)=rin3(n+1);
        end
        if (kout(n+1))<=kbreak
           vout(n+1)=Uf;
        else
           vout(n+1)=(Vf-V0)*(1-(kout(n+1)/k0))^alpha+V0;
        end
        qout(n+1)=vout(n+1)*(kout(n+1)+delta_kout(n+1));
        kout(n+1)=kout(n+1)+delta_kout(n+1);
        rql3(n+1)=rql3(n)+(rin3(n)-r3(n))*(1/3600);
        if rql3(n+1)<=0
           rql3(n+1)=0;
        end
    else
        k1(m,n+1)=k1(m,n)+((q1(m-1,n)-q1(m,n)))*(1/3600)/delta_L;
        k2(m,n+1)=k2(m,n)+((q2(m-1,n)-q2(m,n)))*(1/3600)/delta_L;
        if k1(m,n+1)<=kbreak
           v1(m,n+1)=Uf;
        else
           v1(m,n+1)=(Vf-V0)*(1-(k1(m,n+1)/k0))^alpha+V0;
        end
        if k2(m,n+1)<=kbreak
           v2(m,n+1)=Uf;
        else
           v2(m,n+1)=(Vf-V0)*(1-(k2(m,n+1)/k0))^alpha+V0;
        end
        q2(m,n+1)=k2(m,n+1)*v2(m,n+1);
        q1(m,n+1)=k1(m,n+1)*v1(m,n+1);
    end
end
else %accident
    qin(n)=qout_max-rin1(n)-rin2(n)-rin3(n);
    qout(n)=qout_max;
    kout(n+1)=kout(n);
    if (kout(n+1))<=kbreak
        vout(n+1)=Uf;
    else
        vout(n+1)=(Vf-V0)*(1-(kout(n+1)/k0))^alpha+V0;
    end
    r3(n)=qout_max-q2(N,n);
    if r3(n)<rth
       r3(n)=rth;
```

```
        end
        q2(N,n)=qout_max-r3(n);
        rql3(n+1)=rql3(n)+(rin3(n)-r3(n))*(1/3600);
        if rql3(n+1)<=0
           rql3(n+1)=0;
        end
        if rql3(n+1)>=50
            r2(n+1)=rth;
            r1(n+1)=rth;
           for p=1:N
            m=N-p+1;
            if m==1
                k2(m,n+1)=k2(m,n)+((q1(N,n)+r2(n)-q2(m,n)))*(1/3600)/delta_L;
                if k2(m,n+1)>kmax
                   k2(m,n+1)=kmax;
                   q1(N,n)=q2(m,n)+delta_L*(k2(m,n+1)-k2(m,n))*3600-r2(n);
                end
                rql2(n+1)=rql2(n)+(rin2(n)-r2(n))*(1/3600);
                if rql2(n+1)<=0
                   rql2(n+1)=0;
                end
                if k2(m,n+1)<=kbreak
                   v2(m,n+1)=Uf;
                else
                   v2(m,n+1)=(Vf-V0)*(1-(k2(m,n+1)/k0))^alpha+V0;
                end
                q2(m,n+1)=k2(m,n+1)*v2(m,n+1);
            else
                k2(m,n+1)=k2(m,n)+(q2(m-1,n)-q2(m,n))*(1/3600)/delta_L;
                if k2(m,n+1)>kmax
                   k2(m,n+1)=kmax;
                   q2(m-1,n)=q2(m,n)+delta_L*(k2(m,n+1)-k2(m,n))*3600;
                end
                if k2(m,n+1)<=kbreak
                   v2(m,n+1)=Uf;
                else
                   v2(m,n+1)=(Vf-V0)*(1-(k2(m,n+1)/k0))^alpha+V0;
                end
                q2(m,n+1)=k2(m,n+1)*v2(m,n+1);
            end
           end
           for p=1:N
            m=N-p+1;
            if m==1
```

```
            k1(m,n+1)=k1(m,n)+((qin(n)+r1(n)-q1(m,n)))*(1/3600)/delta_L;
            if k1(m,n+1)>kmax
               k1(m,n+1)=kmax;
               ml(n)=2*N-m+1;
               qin(n)=q1(m,n)+delta_L*(k1(m,n+1)-k1(m,n))*3600-r1(n);
            end
            rql1(n+1)=rql1(n)+(rin1(n)-r1(n))*(1/3600);
            if rql1(n+1)<=0
               rql1(n+1)=0;
            end
            if k1(m,n+1)<=kbreak
               v1(m,n+1)=Uf;
            else
               v1(m,n+1)=(Vf-V0)*(1-(k1(m,n+1)/k0))^alpha+V0;
            end
            q1(m,n+1)=k1(m,n+1)*v1(m,n+1);
        else
            k1(m,n+1)=k1(m,n)+(q1(m-1,n)-q1(m,n))*(1/3600)/delta_L;
            if k1(m,n+1)>kmax
               k1(m,n+1)=kmax;
               q1(m-1,n)=q1(m,n)+delta_L*(k1(m,n+1)-k1(m,n))*3600;
            end
            if k1(m,n+1)<=kbreak
               v1(m,n+1)=Uf;
            else
               v1(m,n+1)=(Vf-V0)*(1-(k1(m,n+1)/k0))^alpha+V0;
            end
            q1(m,n+1)=k1(m,n+1)*v1(m,n+1);
        end
    end
    else
       for p=1:N
        m=N-p+1;
        if m==1
            al2=0.001*L/v2(m,n);
            k2(m,n+1)=k2(m,n)+((q1(N,n)+r2(n)-q2(m,n)))*(1/3600)/delta_L;
            if k2(m,n+1)>kmax
               k2(m,n+1)=kmax;
               q1(N,n)=q2(m,n)+delta_L*(k2(m,n+1)-k2(m,n))*3600-r2(n);
            end
            x2(n)=o_cap2-al2*((q1(N,n)+r2(n)));
            if abs(x2(n))>e
               g2(n)=2*al2^(-1)*(o_cap2-al2*q1(N,n)-al2*r2(n))/((M+1)*x2(n));
            else
```

```
            g2(n)=0;
         end
         r2(n+1)=r2(n)+g2(n)*x2(n);
         rql2(n+1)=rql2(n)+(rin2(n)-r2(n))*(1/3600);
         if rql2(n+1)<=0
            rql2(n+1)=0;
         end
         if r2(n+1)<rth
            r2(n+1)=rth;
         end
         if r2(n+1)>rin2(n+1)
            r2(n+1)=rin2(n+1);
         end
         if k2(m,n+1)<=kbreak
            v2(m,n+1)=Uf;
         else
            v2(m,n+1)=(Vf-V0)*(1-(k2(m,n+1)/k0))^alpha+V0;
         end
         q2(m,n+1)=k2(m,n+1)*v2(m,n+1);
     else
         k2(m,n+1)=k2(m,n)+(q2(m-1,n)-q2(m,n))*(1/3600)/delta_L;
         if k2(m,n+1)>kmax
            k2(m,n+1)=kmax;
            q2(m-1,n)=q2(m,n)+delta_L*(k2(m,n+1)-k2(m,n))*3600;
         end
         if k2(m,n+1)<=kbreak
            v2(m,n+1)=Uf;
         else
            v2(m,n+1)=(Vf-V0)*(1-(k2(m,n+1)/k0))^alpha+V0;
         end
         q2(m,n+1)=k2(m,n+1)*v2(m,n+1);
     end
    end
    for p=1:N
     m=N-p+1;
     if m==1
         al1=0.001*L/v1(m,n);
         k1(m,n+1)=k1(m,n)+((qin(n)+r1(n)-q1(m,n)))*(1/3600)/delta_L;
         if k1(m,n+1)>kmax
            k1(m,n+1)=kmax;
            qin(n)=q1(m,n)+delta_L*(k1(m,n+1)-k1(m,n))*3600-r1(n);
         end
         x1(n)=o_cap1-al1*((qin(n)+r1(n)));
         if abs(x1(n))>e
```

```
               g1(n)=2*al1^(-1)*(o_cap1-al1*qin(n)-al1*r1(n))/((M+1)*x1(n));
            else
               g1(n)=0;
            end
            r1(n+1)=r1(n)+g1(n)*x1(n);
            rql1(n+1)=rql1(n)+(rin1(n)-r1(n))*(1/3600);
            if rql1(n+1)<=0
               rql1(n+1)=0;
            end
            if r1(n+1)<rth
               r1(n+1)=rth;
            end
            if r1(n+1)>rin1(n+1)
               r1(n+1)=rin1(n+1);
            end
            if k1(m,n+1)<=kbreak
               v1(m,n+1)=Uf;
            else
               v1(m,n+1)=(Vf-V0)*(1-(k1(m,n+1)/k0))^alpha+V0;
            end
            q1(m,n+1)=k1(m,n+1)*v1(m,n+1);
         else
            k1(m,n+1)=k1(m,n)+(q1(m-1,n)-q1(m,n))*(1/3600)/delta_L;
            if k1(m,n+1)>kmax
               k1(m,n+1)=kmax;
               q1(m-1,n)=q1(m,n)+delta_L*(k1(m,n+1)-k1(m,n))*3600;
            end
            if k1(m,n+1)<=kbreak
               v1(m,n+1)=Uf;
            else
               v1(m,n+1)=(Vf-V0)*(1-(k1(m,n+1)/k0))^alpha+V0;
            end
            q1(m,n+1)=k1(m,n+1)*v1(m,n+1);
         end
      end
      end
   end
end
for n=1:T
   ker(1,n)=kin(n);
   ver(1,n)=vin(n);
   qer(1,n)=qin(n);
   ker((2*N+2),n)=kout(n);
   ver((2*N+2),n)=vout(n);
```

```
    qer((2*N+2),n)=qout(n);
    for m=2:(N+1)
        ker(m,n)=k1(m-1,n);
        ker(m+N,n)=k2(m-1,n);
        ver(m,n)=v1(m-1,n);
        ver(m+N,n)=v2(m-1,n);
        qer(m,n)=q1(m-1,n);
        qer(m+N,n)=q2(m-1,n);
        if qmax<qer(m,n)
           qmax=qer(m,n);
        end
        if qmax<qer(m+N,n)
           qmax=qer(m+N,n);
        end
        if qer(m,n)<qmin
           qmin=qer(m,n);
        end
        if qer(m+N,n)<qmin
           qmin=qer(m+N,n);
        end
    end
end
for n=1:T
    ker(1,n)=floor(64*ker(1,n)/150);
    ver(1,n)=floor(64*ver(1,n)/80);
    qer(1,n)=floor(64*((qer(1,n)))/(qmax));
    ker((2*N+2),n)=floor(64*ker((2*N+2),n)/150);
    ver((2*N+2),n)=floor(64*ver((2*N+2),n)/80);
    qer((2*N+2),n)=floor(64*((qer((2*N+2),n)))/(qmax));
    for m=2:(N+1)
        ker(m,n)=floor(64*ker(m,n)/150);
        ker(m+N,n)=floor(64*ker(m+N,n)/150);
        qer(m,n)=floor(64*((qer(m,n)))/(qmax));
        qer(m+N,n)=floor(64*((qer(m+N,n)))/(qmax));
        ver(m,n)=floor(64*ver(m,n)/80);
        ver(m+N,n)=floor(64*ver(m+N,n)/80);
    end
end
plot(rql1);hold all;
plot(rql2);hold all;
plot(rql3);hold all;
plot(rql1+rql2+rql3);hold all;
pmin=0;
pmax=qmax;
```

```
image(qer);
colormap(jet);
colormap(flipud(colormap));
h=colorbar;
set(h,'YTickLabel',(num2str(floor((pmax-pmin)/6)),num2str(floor((pmax-pmin)*2/6
)), num2str(floor((pmax-pmin)*3/6)), num2str(floor((pmax-pmin)*4/6)),
num2str(floor((pmax-pmin)*5/6)),num2str(floor(pmax)))) ;
```