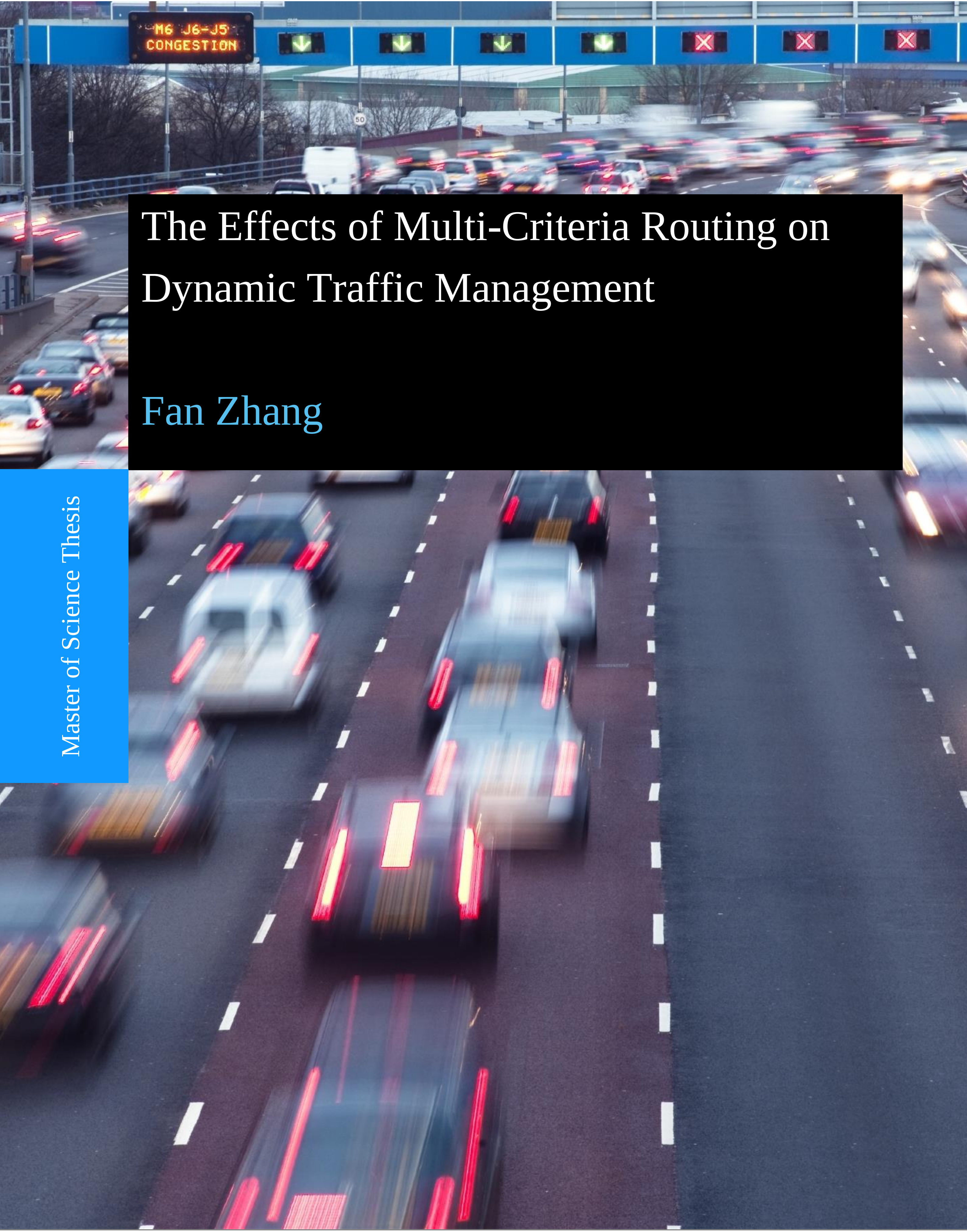

The Effects of Multi-Criteria Routing on Dynamic Traffic Management

Fan Zhang

Master of Science Thesis

TU Delft Delft University of Technology

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The Effects of Multi-Criteria Routing on Dynamic Traffic Management

MASTER OF SCIENCE THESIS

For the degree of Master of Science in Transport & Planning
at Delft University of Technology

Fan Zhang

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Faculty of Civil Engineering and Geosciences (CEG) ·Delft University of Technology

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Summary

Introduction

With the rapid increase in vehicle numbers, big cities are suffering from vehicle gas exhaust pollution and serious traffic congestion. According to a European Commission database (2007), road transport is responsible for about 20% of all CO2 emissions within the European Union, with passenger cars contributing about 12%.

This fast-developing transport brings several extra challenges. First is serious congestion on urban roads and second is vehicle exhaust pollution, especially CO2 emissions. One way to combat rising traffic congestion and environmental problems is to use Dynamic Traffic Management (DTM). This is a way to make better use of the existing road network capacity and manage traffic flows. In DTM, traffic flows can be informed, regulated and facilitated on the basis of up-to-date information.

Traffic assignment modelling determines the traveller's route choice based on the routing strategies and rules. In recent years, urban road networks have grown larger, traffic control strategy has become more complicated and network-wide traffic management has become much more important. Traditional traffic assignment modelling considers traffic emission as an output, so it is challenged by the emerging need to take multi-criteria such as travel time or emissions into account. One promising solution to this challenge is to base route guidance on different criteria such as travel time and vehicle emissions on large urban-scale networks.

Research objective and research questions

This study aims to use the concept of multi-criteria routing (MCR) to improve the performance of the current urban traffic network and to address environmental concerns. MCR consistently considers traffic throughput, emissions, safety and other factors within a policy framework. In this thesis, we focus on introducing travellers' perceptions of environmental concerns into route choice. It introduces a new dimension in modelling traffic performance.

When the network is in free-flow conditions, travel time is independent of vehicles because the travel time on each link can be determined by the link's speed limit. However, vehicle emissions are dependent on the traffic state on the link, so they can only be computed after a journey is finished. The introduction of emission into the cost function requires a traffic model or simulation to take into account this delayed feedback and the necessary convergence. The city of Helmond was the case study area for this thesis. The composite travel cost function, which includes travel time cost and traffic emission cost, was used, and the network performance evaluation was carried out based on a consistent methodological framework. This thesis includes development of an MCR method, implementation of that method and its application to a real network simulation.

The main research question is: What is the impact of adding vehicular CO_2 emission cost into route choice on the network performance? Related to this main research question, a set of sub-questions has also been defined to help structure the research process. The idea is that the answers to these questions should lead to an answer to the main question. The sub-questions have been grouped in three clusters based on whether they relate to: 1) the definition of multi-criteria routing; 2) MCR methodology and experiments; or 3) evaluation of the simulation's results. These sub-questions are as follows:

- Definition:
  SQ1: What is multi-criteria routing and what is the state of previous research about it?
  SQ2: What are the objectives of MCR implementation?
- Methodology:

SQ3: Which traffic emission calculation model is more accurate for this study?
SQ4: What is the suitable traffic simulation model for MCR on an urban scale network?
SQ5: How can the traffic CO_2 emission cost be incorporated with travel time cost into a consistent dynamic traffic simulation framework?
SQ6: How can the conceptual method be applied with different levels of integration?
SQ7: Which method is most adequate to combine with dynamic traffic simulation tools?
SQ8: Which indicators are preferred to represent the network performance?

- Result:
SQ9: What changes to network performance occur when traffic CO2 emission cost is added into travellers' routing?
SQ10: What are the impacts for network performance when the cost components' weight changes?

Methodology

In order to make a clear overview and obtain sufficient knowledge related to the research topic, a literature review and theoretical framework are provided. In general, in DTM, vehicles are assigned to the network based on travel time, travel distance or their combination with other terms. Some previous studies have tried to use an analytical approach and mathematical formulation to explain MCR, but a lot of computation time is needed even for the simple network. The simulation-based approach emerged as the best option because it is impossible to use the analytical approaches to realise such a simultaneous optimisation and to implement them in a real, large network.

Travel time is independent of the traffic state on the link at the beginning of a simulation, because link travel time can be determined by speed limit on the free-flow part. Since traffic emissions are the product of vehicle movement and are dependent on the traffic state on the link, they can only be computed after a journey is finished. The introduction of emissions into cost function needs a simulation to take into account this output feedback and the necessary convergence. Based on the main goals of this thesis, travel time cost and traffic emission cost were considered in the composite cost function. These two different units of costs were obtained from travel time and emission by multiplying the value of time (VoT) and value of green (VoG), which were obtained from stated preference surveys and literature. These two coefficients also can be considered as the weight factors for time cost and emission cost.

A conceptual method was proposed to deal with the composite cost within a consistent framework. Three methods were extended from the conceptual method based on simultaneous composite cost update, one intermediate iteration lagging update and one iteration lagging update. The feasibility analysis for these three methods was performed in Matlab and assessed based on technique, quality, operational and policy criteria.

The simulation-based approach is preferable for investigating whether consistent MCR could be implemented in a dynamic traffic simulation and whether it could improve network performance. A mesoscopic traffic simulation model, Dynasmart-P, was used because it can work with a large-scale network, be incorporated with various Intelligent Transport System (ITS) components, simulate a traveller's route choice under different conditions, move vehicles individually and give individual vehicle trajectories. Dynasmart-P gives a richer representation of traveller behaviour decisions and network elements than some macroscopic tools and higher computation efficiency than some microscopic models.

Four network performance indicators were used to evaluate the impact of MCR on the case study network. The impacts of the cost components' weight on network performance was investigated by a sensitivity analysis of the scaling factor between VoT and VoG.

Multi-criteria routing method

A conceptual method was designed to devise a consistent simulation framework, which includes the same input and output emissions and the same travel cost between the input cost and end-experienced cost. The method's structure is shown in Figure 0-1. The simulation approach was selected in this research. Because vehicular emissions are dependent on the traffic states on the link, a bi-level structure was designed to devise a consistent simulation framework.

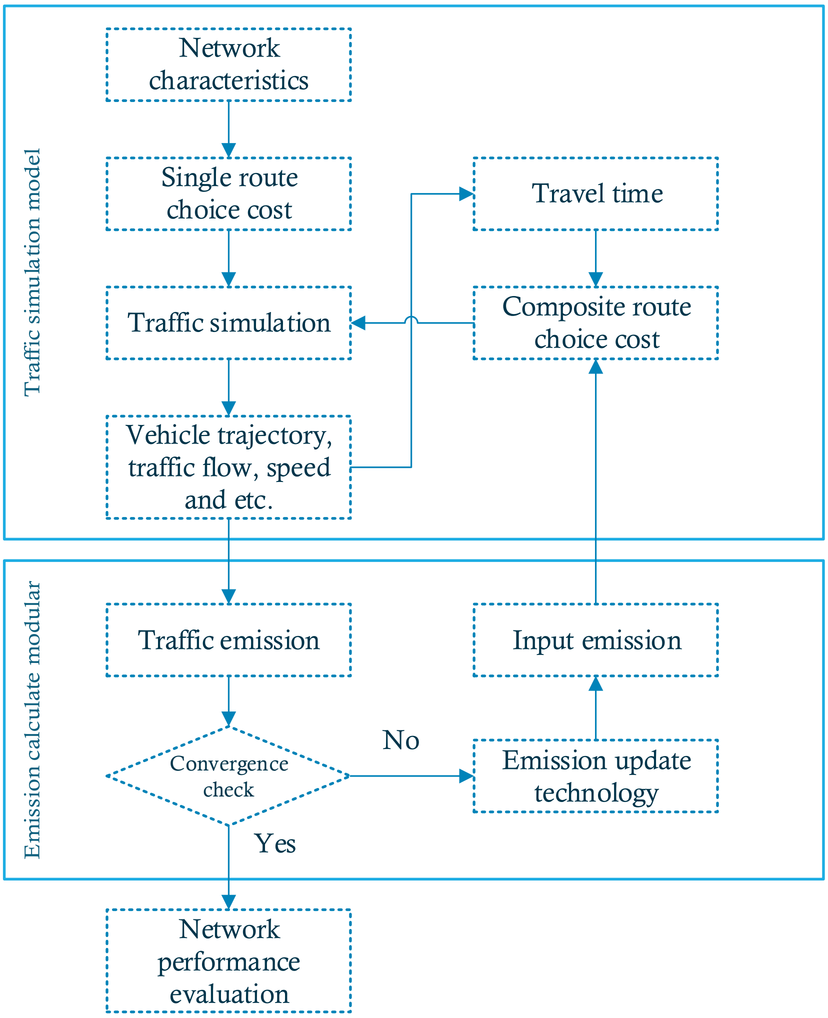

Figure 0-1 Conceptual structure of the method

Through the characteristics of the traffic simulation, this conceptual method was extended to three different methods based on different ways to update the emission cost in order to update the composite cost. Method 1 computes and updates the emission cost for each simulation interval, which is a kind of simultaneous update. Method 2 calculates and updates the emission cost after each intermediate iteration during the iterative equilibrium process, which is one intermediate iteration lagging update. Method 3 computes and updates the emissions after finishing the user equilibrium assignment in the simulation, which is one iteration lagging update.

A simple dynamic traffic simulation was created in Matlab to test the convergence and feasibility of each method. Four kinds of assessment criteria were proposed to show the feasibility of each method and to help select the most suitable method for a Dynasmart-P simulation with a real, large traffic network. Method 3 with the individual travel cost was selected because it has almost the same quality as Method 1 and it can be implemented with Dynasmart-P without making modifications to the simulation software.

Helmond multi-criteria routing case study

The Helmond road network was recreated in Dynasmart-P with real input data and was used as the case study. To quantify network performance under the traffic management measurements, four key network performance indicators were defined: average travel time, average trip distance, average vehicle emissions and trip completion rate. Ten different random seeds were generated and were used in both single-criterion routing (reference) experiments and MCR experiments. The reference case used single-criterion routing (SCR), a traditional traffic routing method that only considers travel time in the route choice cost function. The MCR case takes both travel time and traffic CO_2 emissions into account. In this case study, the value of time was 15 euro/h and value of green is 0.4 euro/kg in the case study. The maximum multi-criteria iteration was. Comparisons of network performance between SCR experiments and MCR experiments are shown in Figure 0-2.

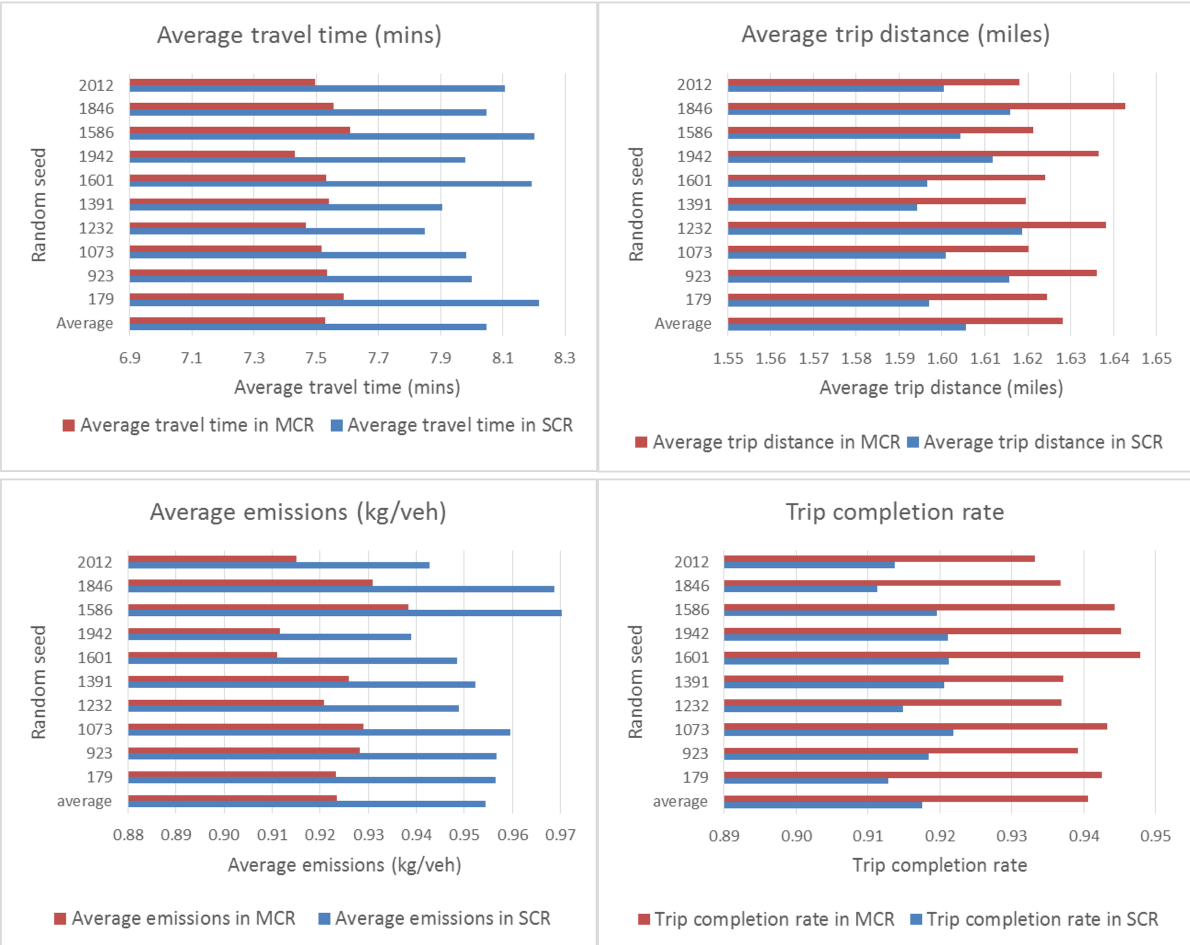

Figure 0-2 Network performance results

The mean value over these 10 random seed and the relative percentage changes are listed in Table 0-1.

Table 0-1 Average network performance over 10 random seeds

	Mean value over 10 random seeds (SCR)	Mean value over 10 random seeds (MCR)	Relative changes
Average travel time (mins)	8.048	7.528	-6.46%
Average trip distance (miles)	1.606	1.628	+1.41%
Average emission (kg/veh)	0.954	0.923	-3.25%
Trip completion rate	91.75%	94.06%	+2.51%

In MCR experiments, a rough convergence was achieved over 30 updates and iterations. In summary, compared with the SCR experiments, MCR can save around 6% average travel time and reduce around 3% of vehicle CO_2 emissions. The average trip distances increased by 1.4% and the trip completion rate increased by 2.5%.

The sensitivity analysis of the different weightings of time cost and emission cost in the composite route choice cost function have important impacts on MCR performance. In the current situation, travellers make their decisions based on the route cost towards their destination at that time, so there is no predictive cost in the route choice. Thus, in some extreme conditions, serious urban blocked congestion occurred.

The results show that when traffic emissions were effectively taken into account in the route choice cost function, the traffic spread more efficiently over the network and both average travel time and average emission decreased while average vehicle distances slightly increased. A careful MCR design can improve network performance.

Conclusions

The main conclusions with regard to the research questions are as follows:

1. A conceptual method for multi-criteria routing was designed and three methods based on this conceptual method were proposed to achieve a consistent MCR simulation framework. Methods 1 and 2 need to be highly integrated with the traffic simulation model and the emission model, while Method 3 applies an outer loop emission model that combines with the traffic model. The feasibility of each method was tested by a simple dynamic traffic simulation in Matlab. All three MCR methods can reach an approximately consistent framework. From the technique and quality assessment, there are no big differences among these three methods. The differences between the different combinations of cost type in one method are quite small. All three methods can be used to achieve consistent MCR. Based on the current technique limitations and the objectives of this thesis, Method 3 was implemented in the case study because it makes it easy to combine the emission update with other traffic simulation models.

2. Network performance indices were applied to quantify the effects of multi-criteria routing on traffic management. An OD demand matrix was fixed during the simulation period and the total vehicles on the network were almost the same in different scenarios, so the average values of indicators can more precisely represent network performance. Altogether, four indices were introduced: average travel time, average trip distance, average CO2 emissions and the trip completion rate during the statistical period.

3. An urban-scale simulation model was set up to simulate multi-criteria routing in Helmond. The simulation model was calibrated with bottlenecks, queues and flow fluctuations from the real network data observed by field detectors. Calibration of the model showed that the final network model can better mimic the real network traffic conditions on critical links and it was successfully prepared for the case study. Ten different random seeds were implemented in both reference experiments and MCR experiments to eliminate the random seed effect of the simulation software.

The results from the MCR scenario showed that consistent simulation can be achieved under the multi-criteria routing method we used in the case study. The results show that MCR can save about 6.46% average travel time and reduce 3.25% of vehicle CO_2 emissions. The average trip distances increased by and the trip completion rate increased by 2.51%.

The results from the case study showed that when the traffic emission is effectively taken into account in the route choice cost function, the traffic spreads more efficiently over the network. Average travel time and average emission decreased while average vehicle distances slightly increased. Emissions can be used as feedback in an assignment and routing loop and can help improve network routing efficiency. The effective composition of cost influences travel behaviour and, thus, route choice.

4. The sensitivity analysis of the scaling factors between VoT and VoG demonstrated that the cost components should be combined with reasonable VoT and VoG. The rational scaling factors were based on the emission values calculated by the emissions model. In this study, using the TNO macro emission model, the rational scaling factors ranged from 2 to 100. Network routing efficiency can be improved by a carefully designed MCR system.

In summary, this thesis illustrates that, through concerning the emission delayed feedback in a bi-level structure, well-designed MCR can improve network routing efficiency and simultaneously reduce traffic CO_2 emissions. This method can also be used for other traffic management simulations and emission calculation models. Road authorities can consider this study as a solution for addressing traffic routing efficiency and traffic-related environmental problems.

Recommendations for further research

The conclusions of this investigation into MCR led to the following recommendations for future research on this topic.

1. Investigate the theoretical mechanism of multi-criteria routing on DTM.

Through the simulation approach, we found that MCR has positive effects on network performance, but the theoretical mechanism of MCR was not examined in this thesis. More theoretical and analytical research can be done to reveal the depth mechanism of MCR.

2. Examine more comprehensive multi-criteria routing with more criteria.

This thesis only took travel time and emissions into account. More criteria, such as reliability, safety or comfort, can be examined in the future.

3. Improve traffic simulation tools.

In future studies, the emission calculation and update could perhaps be highly integrated in the new traffic simulation, which is an efficient way to deal with emissions as delayed feedback into travel cost.

4. Make routing decisions with a predictive network state.

The current routing algorithm calculates route cost based on the instant link cost at the calculation and updating simulation interval. In the sensitivity analysis, some odd results may have been caused by this routing algorithm. Using the predictive cost information may give better and more accurate route guidance than the current routing algorithm.

5. Improve the calculation of marginal cost and system and user optimum.

Computation of system optimum and user optimum is simplified in each of the available simulation packages, which impacts precise assessment of MCR. Improving and calculating the marginal cost of indicators (e.g. travel time, emissions) as well as the system optimum and user optimum would allow researchers to understand the exact influence of the methodology on MCR.

6. Determine how best to implement multi-criteria routing in a real traffic network.

A real-time MCR framework for the urban network in the traffic management centre should be built in the future and should contains three basic systems: a real-time network monitoring system, a driver decision support system and a real-time network operations system. Implementing MCR in a real traffic network requires various advanced ITS traffic systems and a fast and reliable decision support system.

Table of Contents

List of Figures

List of Tables

Acknowledgements

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Fan Zhang

Delft, University of Technology

The Netherlands

November, 2013

List of Acronyms and Terms

DTA: Dynamic Traffic Assignment

DTM: Dynamic Traffic Management

ITS: Intelligent Transport System

MCR: Multi-Criteria Routing

MUC: Multi-User Class

OD: Origin-Destination

SCR: Single-Criterion Routing

SO: System Optimum

STA: Static Traffic Assignment

UE: User Equilibrium

VMS: Variable Message Signs

VoT: Value of Time

VoG: Value of Green

1. Introduction

With the rapid increase in vehicle numbers, big cities all over the world are suffering from vehicular exhaust gas pollution and serious traffic congestion. Currently, emissions of nitrogen oxides (NO_X), non-methane hydrocarbons (HCs), carbon monoxide (CO), carbon dioxide (CO_2) and particulate matter (PM) are regulated for most vehicle types, including cars, lorries, trains and tractors. According to the European Commission's database, road transport is responsible for about 20% of all CO_2 emissions within the European Union, with passenger cars contributing about 12% (European Commission's database 2007). Vehicular exhaust may cause severe smog pollution, as seen in cities such as Los Angeles, London and Mexico City. Traffic congestion in urban areas also aggravates traffic emission pollution because vehicles emit more pollutants when they travel at low velocities and frequently change speeds.

Traffic jams waste a lot of time and make travellers feel anxious. Some traffic behaviour experiments have shown the power of social influence on travellers' decisions. More and more people are concerned about the negative emission impacts of traffic. What would be the network performance if the road authority provided CO_2 emission information and gave this social power to travellers? What would happen if travellers took CO_2 emissions into account when making their route choice decisions?

This thesis analyses the effect of implementing multi-criteria routing (MCR) on dynamic traffic management (DTM). The focus is on how to incorporate the traffic emission cost and travel time cost into the route choice and network performance with MCR in a consistent framework. A consistent framework means that the input cost should be the same as the end-experienced cost in order to achieve convergence and stability.

1.1 Background

As is well known, greenhouse gas contributes to the greenhouse effect, for example, carbon dioxide (CO_2), sulphur dioxide (SO_2), nitrogen oxides (NO_X), hydrocarbons (HCs), and particulate matter (PM). In these greenhouse gases, carbon dioxide (CO_2) is proportionally the largest contributor. Nowadays, manufacturing, industry and transport create most of the world's CO_2 emissions. The 2006 and 2010 IEA CO_2 emission statistics reports (shown in Figure 1-1), show that transport is the second largest sector, contributing about 22% of CO_2 emissions among the different kinds of sectors.

With globalisation and economic development come more and more transportation activities. This means that the CO_2 emissions from the transport sector will also increase quickly and there will be more CO_2 emissions from transport in the future. Currently, many measures are employed to reduce CO_2 emissions, such as efficient traffic management and alternative fuel vehicles. Some previous studies have investigated detailed vehicle emission models to prove that congestion has a great impact on traffic emissions (Barth & Boriboonsomsin, 2008). Thus, appropriate congestion mitigation, route guidance, speed advice and joint control traffic management can decrease traffic CO_2 emissions. Traffic researchers and modellers pay much more attention to improving traffic operations than to the mechanical and fuel revolutions.

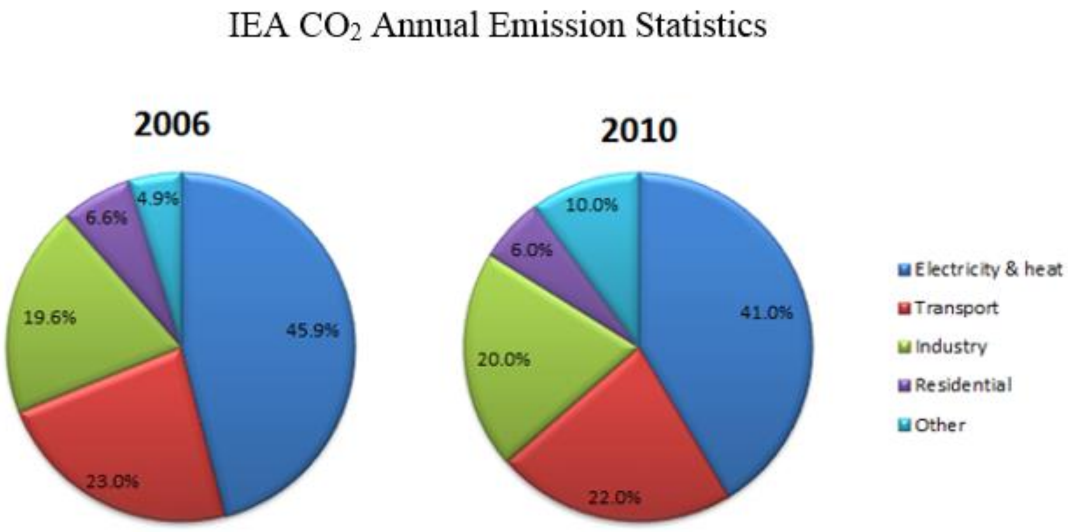


Figure 1-1 IEA CO_2 emission statistics for 2006 and 2010 (Hoeven, 2012)

Recently, network traffic management has becomes more and more important as urban road networks have become larger and traffic control strategy has become more complicated. There is an emerging need to take multi-criteria such as emission and safety into account together with throughput challenges to conventional modelling and daily operations. By installing new Intelligent Transport System (ITS) facilities, road authorities can manage traffic accordingly, on the whole network level. The possibility of route guidance based on different criteria such as MCR on large urban-scale networks has become more attractive.

Environmental issues, as mentioned above, have created a major challenge and a transportation problem. Problems such as vehicle exhaust pollution, harm from vehicle noise and the increasing cost of new construction are pushing traffic engineers to put more effort into determining how to use the existing road network more efficiently while simultaneously considering environmental impacts. Reducing vehicle emissions and mitigating traffic congestion are key topics in recent traffic research.

1.2 Problem definition

In the past, traffic engineers tried to meet increasing traffic demand mainly by planning and constructing new roads. However, this method is not suitable for an existing intensive road network. The continued growth in travel along congested urban freeway corridors is exceeding the ability of transportation agencies to provide sufficient roadway capacity in major metropolitan areas where there is limited public funding for roadway expansion and improvement projects (Mirshahi et al., 2007).

In recent years, the traffic network has become increasingly busy and traffic jams have become common on both freeways and urban roads. It is well known that vehicle CO_2 emissions increase with increasing traffic congestion. “Eco-driving” studies have shown that travelling at a steady-state speed will lead to fewer CO_2 emissions and less fuel consumption. Fuel consumption is related to both speed and acceleration rate. Research results from real driving tests conducted by Boriboonsomsin and Barth (2008) and Frey et al. (2008) concluded that, in real conditions, there is a rapid nonlinear growth in emissions and fuel consumption as travel speeds fall below 30 mph. Based on these findings, the more frequently speed changes, such as in stop-go-stop conditions, the more CO_2 will be emitted and the more fuel will be consumed.

One way to combat rising congestion and the related environmental problems is to use Dynamic Traffic Management (DTM). DTM makes better use of existing road network capacity and managing traffic flows. In real-time DTM, traffic flows are informed, regulated and facilitated on the basis of up-to-date information, which is dependent on the situation, such as route information panels, traffic merging filtering, traffic lights and rush-hour lanes. Among DTM measures, network-wide traffic management has recently become more important. As urban road networks become larger and traffic control strategies become more complicated, there is an emerging need to take multi-criteria such as emissions, safety and throughput into account. This challenges conventional modelling and daily operations. Route guidance based on different criteria such as traffic throughput and vehicle emission on large urban-scale networks has thus become an important research topic.

1.3 Research motivation

Previous studies that analysed the effects of MCR on dynamic traffic assignment have several limitations, which makes it difficult to apply the methods to a real large-scale network. First, some studies considered this issue to be an optimum network design problem, which means they tried to find a way to expand and improve the existing network, like (Nagurney, 2000b), (Nagurney & Dong, 2002) and (Han & Yang, 2008) and (Si et al., 2012). They applied mathematical algorithms to address the bi-level problem in different equilibrium conditions through a simple network. Multi-criteria in these studies were used as different values of time and different out-of-pocket pricings.

Second, multiple researchers (e.g. (Tzeng & Chen, 1993), (Rilett & Benedek, 1994)) extended the cost function by adding link-based emission costs. These kinds of studies applied mathematical programming and game theory to evaluating policy from the road authorities' perspective. Their studies had one common characteristic: by taking other traffic-related nuisances into account, the multi-criteria were much more reasonable and suitable than in other conventional approaches. However, it is impossible to realise a simultaneous optimisation in view of MCR strategy and is difficult to implement it in a real network using the analytical methods that were developed in previous studies.

In addition, Gaker et.al (2010) designed some experiments to investigate how travellers' behaviour could be predicted and influenced using personalised information and social influence. Based on stated preference surveys and experiments, they concluded that travellers show sustainable behaviour when they are provided with context- and person-specific information on the environmental impact of their actions. What is even more interesting is that people's CO_2 values are around \$0.50 per pound, which can be considered a value of green (VoG). Therefore, all these facts lead to the conclusion that there is a lack of knowledge about the effect of adding CO_2 emission costs to the traveller route choice function in DTM, which contributes to the research motivation of this thesis.

1.4 Research questions

The purpose of this Master thesis is to reveal the effects of the multi-criteria routing on the network performance.

The **main research question** is: What is the impact of adding vehicular CO_2 emission cost into route choice on the network performance?

Related to this main research question, a set of sub-questions have also been defined to help structure the research process. The idea is that the answers to these sub-questions should lead to an answer to the main question. The sub-questions have been grouped in three clusters based on whether they relate to: 1) the definition of multi-criteria routing; 2) multi-criteria routing methodology and experiments; or 3) evaluation of results from the simulation. These sub-questions are listed below.

Figure 1-2 Sub-questions and methods

1.5 Hypothesis of this thesis

This thesis hypothesises that network performance would be improved by well-designed composite travel costs, including travel time cost and travel CO_2 emission cost.

1.6 Research methodology

1.6.1 Methodology flow chart

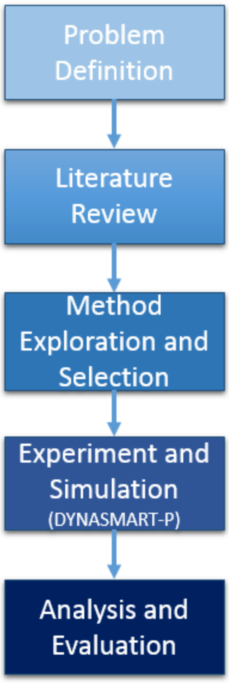


Figure 1-3 Thesis methodology

1.6.2 Methodology description

The methodology used in this thesis contains five major steps. In Step 1, some problems related to current traffic environmental pollution and multi-criteria traffic management were reviewed with some general findings. These problems were further studied through a detailed literature review in Step 2.

In Step 3, the conceptual method—incorporating traffic CO_2 emission cost with travel time cost in route choice cost function—was proposed to achieve consistent MCR. Three different methods were designed based on different levels of integration with the conceptual method. A schematised model was set up in Matlab to demonstrate the feasibility of each method. The results of the simple network model can be used to analyse the meaning of the individual cost and marginal cost and to determine which method should be implemented in Dynasmart-P.

In Step 4, a case study simulation of Helmond (a city in the province of North Brabant in the southern Netherlands) was set up in Dynasmart-P. The results of network performance indicators from the simulation were analysed. Step 5 includes an analysis and evaluation based on the modelling results that answered the research questions and was used to make some recommendations for future research.

1.7 Thesis outline

The framework and outline of this report are provided in Figure 1-4. In general, the report is divided into three parts: background, method and simulation results, and conclusion. Each chapter is associated with a brief objective to the right of the chapter outline.

The structure of the report is as follows. Background blocks include Chapters 1, 2 and 3. Chapter 1 gives a general introduction. The concepts of MCR and DTM are elaborated on in Chapter 2. This chapter also presents a literature review and theoretical framework related to the main topic of this thesis. Chapter 3 introduces Dynasmart-P. Chapters 4 and 5 are the method and results chapters. Chapter

4 explores the methods used for incorporating emission cost and analyses the differences between different cost types. A simple network was then built in Matlab and the feasibility of each method is illustrated in Chapter 5. The most suitable method was selected for Dynasmart-P experiments. Chapter 6 gives the results from Dynasmart-P and draws a conclusion by answering the research question through the network performance results analysis and sensitivity analysis. Finally, Chapter 7 gives the final conclusions and recommendations.

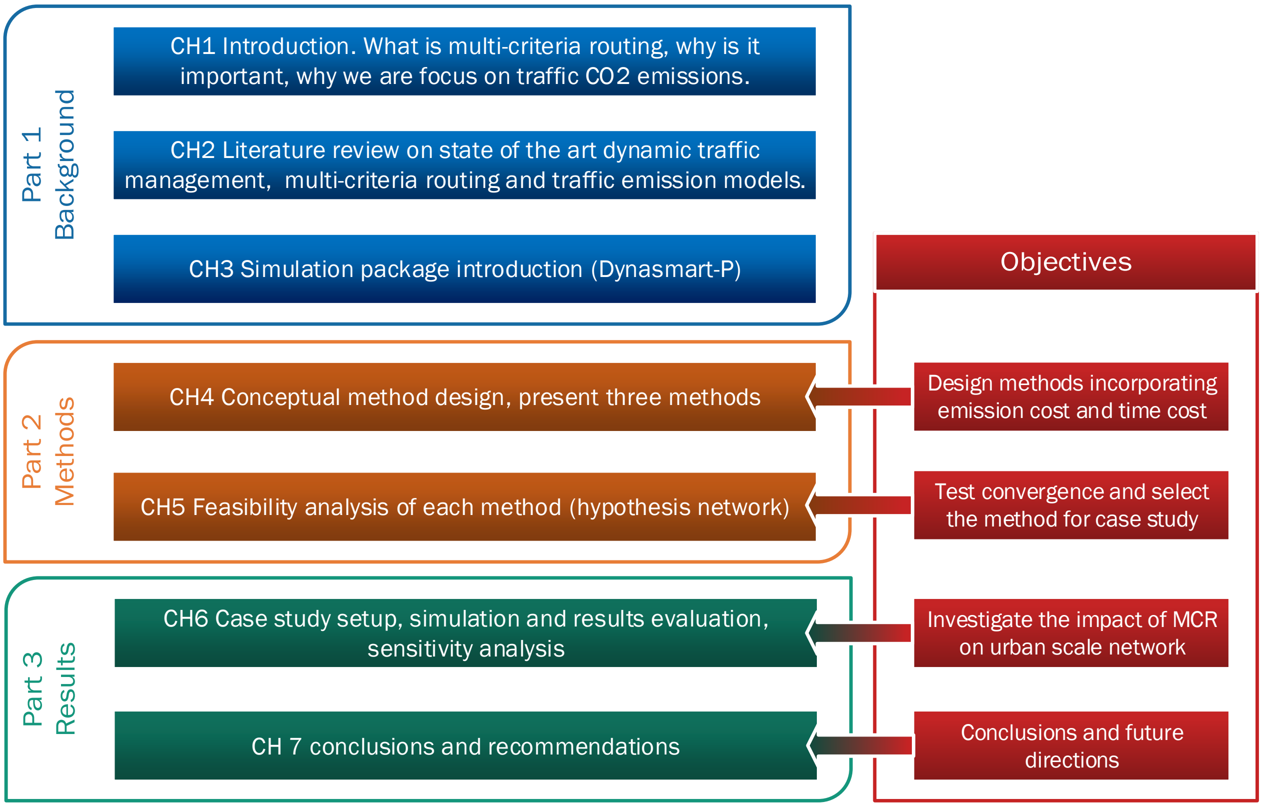


Figure 1-4 Thesis structure and reading guideline

2. Literature review and theoretical framework

This chapter presents the background literature that is relevant to the primary areas of this thesis. Because the goal of this thesis is to improve the network performance of DTM by using MCR, background must be provided on dynamic traffic assignment, MCR and traffic emission models. In this chapter, an overview of the previous studies is given first in the literature review, followed by some relevant theories in the theoretical framework. Subsequently, there is discussion about how this thesis contributes to the current literature.

This section answers the following questions: What is the previous research state on dynamic traffic assignment and MCR? (Section 2.1); How should traffic emissions be calculated and which traffic emission calculation programme is suitable for this study? (Sections 2.1 and 2.2).

This chapter is presented so that readers can have a whole picture of the main theories in this thesis and an understanding of how this thesis contributes to the current literature.

2.1 Literature review

2.1.1 Traffic assignment and multi-criteria routing

As mentioned in Chapter 1, DTM is one way of combating rising congestion and environmental problems. The core of DTM is the control and routing strategy, which is associated with traffic assignment. In general, traffic assignment models can be classified into two categories: dynamic traffic assignment (DTA) models and static traffic assignment (STA) models. These two models represent different realities of traffic assignment, and Section 2.2.3 gives a detailed description and comparison of them. Based on certain decision rules, a traffic assignment model can determine a reasonable trade-off between network supply and traffic demand. These decision rules include routing strategy and route choice behaviour (Ortuzar & Willumsen, 2001). DTA is a more real and precise method to represent travel behaviour than STA, since real-life travel behaviours are dynamic and stochastic.

A lot of research has been done on the traffic equilibrium principles in DTA since the middle of the last century. Vickrey (1969) considered departure time in DTA, and Daganzo and Sheffi (1977) introduced the stochastic on traffic network by assuming that travel time on each link contains a random value. Recently studies focus on the reliability of travel combined with stochastic or dynamic (Shao et al., 2006);(Szeto & Lo, 2006); (Szeto & Wong, 2011);(Chen et al., 2011). Reliability means travel time is uncertain and travellers will leave earlier to avoid travel delays. Peeta and Ziliaskopoulos (2001) created a comprehensive summary of DTA.

Ben-Akiva et al. (1986) first introduced the simulation-based method to solve the DTA problems. Later on, many simulation models were developed. They can be classified into three simulation levels microscopic simulations, mesoscopic simulations and macroscopic simulations. A detailed introduction of DTA simulation will be provided in Section 2.2.

These traditional DTA models normally used travel time as general travel to assign vehicles on the traffic network. In the real travel process, each driver has his own understanding and preference on the traffic network. The trade-off between travel time and out-of-pocket money is necessary and significant for travellers when they make route decisions.

Quandt (1967) introduced the first multi-criteria traffic network model, and Schneider (1968) extended it. In their studies, travellers selected their optimal routes based on several criteria, such as travel time and travel cost. But they assumed these costs were fixed. The flow-dependent cost model was later introduced by Dafermos (1981), who considered congestion effects and obtained an infinitedimensional variational inequality formulation of the multiclass and multi-criteria traffic network equilibrium problem. Adler et al. (1999) used the simulation method to evaluate the impacts of bi-objective routing systems on user and system performance. In their study, travel cost was formulated as the linear weighted additive sum of travel time and cost.

Concerns over environmental impacts and efforts to include them in traffic modelling led to early research in both traffic assignment methods and multi-criteria. Rilett and Benedek (1994) proposed a traffic assignment model with environmental objectives. Using an emission-based assignment method is a kind of extension of Wardrop's user equilibrium principle (Wardrop, 1952) and system optimal principle (Wardrop, 1952). They made two concepts for the pure emission objective assignment. First, travellers were assigned on the network based on their own emission production. This is an extension of user equilibrium, which means no one can further reduce their emission production by changing routes without harming others. Second, travellers were assigned on the network based on the minimum total emission policy, which can be seen as an extension of system optimal. In a later article (Benedek & Rilett, 1998), they found that under congestion conditions, CO_2 emissions in the environment optimum assignment were 7% less than normal user equilibrium and system optimum assignments. They developed a simple macroscopic CO_2 emission model which used the link length and average speed as input. Further research by Sugawara and Niemeier (2002) confirmed that emission reduction depends on the level of congestion. Some relevant papers related to this field are introduced in the following paragraphs.

Tzeng and Chen (1993) proposed a multi-criteria network assignment model with an explicit pollution minimisation criterion in the system optimum framework. This framework included travel time, air pollution and travel distance. A Pareto set of solutions was formulated and the Lagrangian was constructed of equivalent minimisation problems with these weighted objectives. The highlighted objective with large weight directed the assignment towards improvement of the objective. A Frank-Wolfe algorithm was then used to obtain the set of weight that is closest to the optimal solution of an objective. However, the traffic demand in their study was static.

Nagurney (2000a) estimated travellers' CO_2 emissions on each link using a fixed CO_2 emission rate. She showed emission paradoxes by illustrating examples on a Braess network: (1) the addition of a road may result in an increase in total emissions with no change in travel demand; and (2) total emissions may increase with a decrease in total travel demand. She concluded that the network topology, cost structure and travel demand structure are key aspects to consider in making policy towards emission improvement. In her examples, emission is output and is not a component in cost function.

Later, Nagurney et al. (2002) developed an equilibrium model for multi-class and multi-criteria that included travel time, travel cost and emissions. They applied this framework to bi-criteria (cost and emission), resulting in the same conclusion: a unique solution exists as long as the generalised cost satisfies the monotonicity condition. Further extension of this model, including time and route guidance values, was introduced by Jaber and O'Mahony (2009). All these methods are analytical and try to provide proof for the existence of a solution, given the cost monotonicity.

Wismans et al. (2010) used a Pareto set to derive a solution. It consisted of the following objectives: (1) congestion: minimisation of total travel time; (2) traffic safety: minimisation of total number of injuries, by exposure and risk per road type; (3) climate: CO_2 calculated with average speed; (4) air quality: using a CAR model; and (5) noise: using a RMV model. Optimisation is carried out with a bi-level approach: at the upper level is a Network Design Problem (NDP) with the multiple objectives (measures) described above, and at the lower level is DTA, a reaction to these measures. Solution methods include generic algorithms (GA), simulated annealing and grid search. Solution dominance is found if one alternative scores better than the others. However, it is difficult to select a better solution with multiple targets and the method is not suitable for a large network.

Gaker et al. (2010) investigated how to predict and influence travellers' behaviour regarding personalised information and social influence. Different surveys and experiments were carried out, in which they found that many concepts from behavioural economics can be transferred to and have great potential to influence transport behaviour. At the same time, personal and trip-specific information regarding greenhouse gas emissions has significant potential for increasing sustainable behaviour. Based on some surveys and experiments, it was discovered that social influence positively impacts a decision (e.g. to purchase a hybrid car or choose a route). This research indicates that travellers show sustainable behaviour when they are provided with context-specific and person-specific information on the environmental impact of their actions. What is even interesting in their study is that they concluded people's value of green is 0.4 euro per kilogram (of CO_2 emission).

Zhang (2013) investigated the impact of CO_2 pricing on CO_2 emissions on freight transport, but she found that total network emissions do not change significantly until CO_2 pricing is higher than 400 euro per ton (0.4 euro per kilogram). CO_2 emissions decrease more sharply when the CO_2 price is changed at a rate higher than 400 euro per ton. This result is quite similar to Gaker's conclusions, although they involve different types of transportation.

Gao (2012) also established a DTA model where users make strategic route choices in response to real-time information in a stochastic time-dependent network with correlated link travel times. A routing policy is defined as a decision rule which specifies what node to next take out of the current node based on current-time and real-time information. This is essentially a mapping from network states to decisions on the next nodes. A routing policy can manifest itself as different paths depending on the underlying stochastic process that drives a traffic network. A path is purely topological and is a special case of a routing policy where any decision on the next node is not dependent on the current-time or real-time information. This analytical and mathematic DTA method needs large amounts of computing time for a large-scale network. For this reason, this thesis used the DTA simulation method.

Chen et al. (2013) administered several revealed and stated preference surveys to find out what relationship exists between a traveller's profile and ecological routing. User interviews and online surveys with 650 interviewees found results comparable to those of Gaker. Travellers would be able to choose a more environmental friendly route when available alternatives had comparable travel time and out-of-pocket costs.

Studies by Gaker et al. (2010) and Chen et al. (2013) introduced a new dimension in modelling traffic performance: the traveller's perception of environmental concern related to route choice. As vehicular emissions can only be computed after a journey is finished, the introduction of emissions into the cost function needs a consistent framework to take this delayed feedback into account and thus to add the necessary convergence to the simulation.

2.1.2 Traffic emission modelling

Vehicle emissions mainly include hydrocarbons, Carbon Oxides, Nitrogen Oxides, Sulphur Oxides and etc. Many studies have looked at traffic emissions. Two major types of traffic emission models can be identified: microscopic and macroscopic. In a microscopic traffic emission model, emissions are mainly related to factors such as vehicle speed, type, acceleration and deceleration, flow pattern and driving cycles. Abbott et al. (1995) pointed out that the most common emission function is related to average speed. Some later studies (e.g. Joumard et al. (1995); Hickman et al. (1997) successfully improved this idea by considering speed variation. There, the speed-acceleration look-up tables are used as a kind of dynamic emission model. Through the emission matrix, instantaneous vehicle emissions are calculated according to vehicle speed and acceleration rates of different types of vehicles. Later on, some regression-based models were developed to overcome the discretisation problem of speed-acceleration look-up tables. These models needed a lot of data to calibrate and may give non-reasonable values if a situation is not included in the calibration data. In the regression model, traffic emissions are estimated by the continuous emission factor functions. The COPERT 3 model is a kind of regression model that uses a function of average speed (Ntziachristos & Samaras, 2000).

New emission models have continued to be developed. Int Panis et al. (2006) developed an emission model based on instantaneous speed and investigated the influence of speed limit by using the DRACULA microscopic model. Coelho et al. (2006) developed three emission functions based on three different instantaneous speed and speed profiles. Smit et al. (2007) proposed a complex model (VERSIT+) to predict emissions by using several continuous variables. A detailed VERSIT+ model was introduced in a TNO report (2006.OR.PT.016.1/RS). This version of the VERSIT+ model was based on approximately 12,000 emission tests over 153 real-world speed-time profiles. The COPERT model has around 2,800 emission tests. More test data would make the models more accurate. VERSIT+ has already been widely used to estimate vehicle emissions in the Netherlands.

Some research has focused on modelling macroscopic traffic emissions, which are based on microscopic emission models. Barth and Boriboonsomsin (2008) developed a fourth-order polynomial emission function related to average link speed. This model is an approximately fit equitation using real-world experiments or observed data. Smit et al. (2008) applied the VERSIT+^{macro} traffic situation model, which is a simplified emission model from VERSIT+, "It is a quantitative traffic situation model for the assessment of traffic management measures at aggregate network level (e.g., changing speed limits). It consists of a set of composite emission factors (g km-1) for discrete traffic situations, which are defined by predefined ranges of quantitative traffic variables." (Smit et al., 2008).

Recently, a new TNO macro emission model was developed based on VERSIT+. It calculated macroscopic emission rates based on macroscopic traffic variables. According to Klunder et al. (2013), "Emissions were calculated with the TNO emission model VERSIT+ with the individual vehicle data from VISSIM (speed and acceleration) as input on a second-by-second base. Finally, both the emission and traffic data have been aggregated in various ways. This approach led to sets of macroscopic emission rate curves as a function of the mean speed." The model validation shows that when using 10 minutes of aggregated data, the relative difference between the total emissions from VISSIM/VERSIT+ micro-simulations and the total emissions from the TNO macro emission model was less than 0.1%.

2.2 Theoretical framework

This section introduces the theories that underpin and are used to support this research. First, it will introduce DTM. In addition to the DTM framework, route choice behaviour will also be defined in this chapter. Next, an introduction of DTA and dynamic modelling will be presented to demonstrate more insights into the influence of MCR on DTM. This will be followed by a theoretical introduction of individual travel cost and marginal travel cost. Finally, the traffic emission models used in this thesis will be introduced.

2.2.1 Dynamic traffic management

The role of dynamic traffic management is to improve the routing efficiency, to make better use of the existing transport infrastructure and toward sustainable traffic. With the intelligent transportation system development, dynamic traffic management becomes more proactive and is able to provide more accurate and adaptive measurements based on the real-time information.

From the road authorities' perspective, they want to use DTM to obtain optimal traffic distributions on the network, thus achieving system optimum. At the same time, drivers use these DTM measures to minimise their travel time or generalised costs. They are striving for a user equilibrium state. This interaction is often described as a bi-level network design problem (NDP). The routing strategy and the traveller's route choice behaviour are the crucial points in DTM.

2.2.2 Route choice behaviour

Before investigating the impact of the DTM correctly, it is necessary to have some knowledge of drivers' choice behaviour. A conceptual framework for route choice behaviour was introduced by Bogers et al. (2005) and is shown in in Figure 2-1.

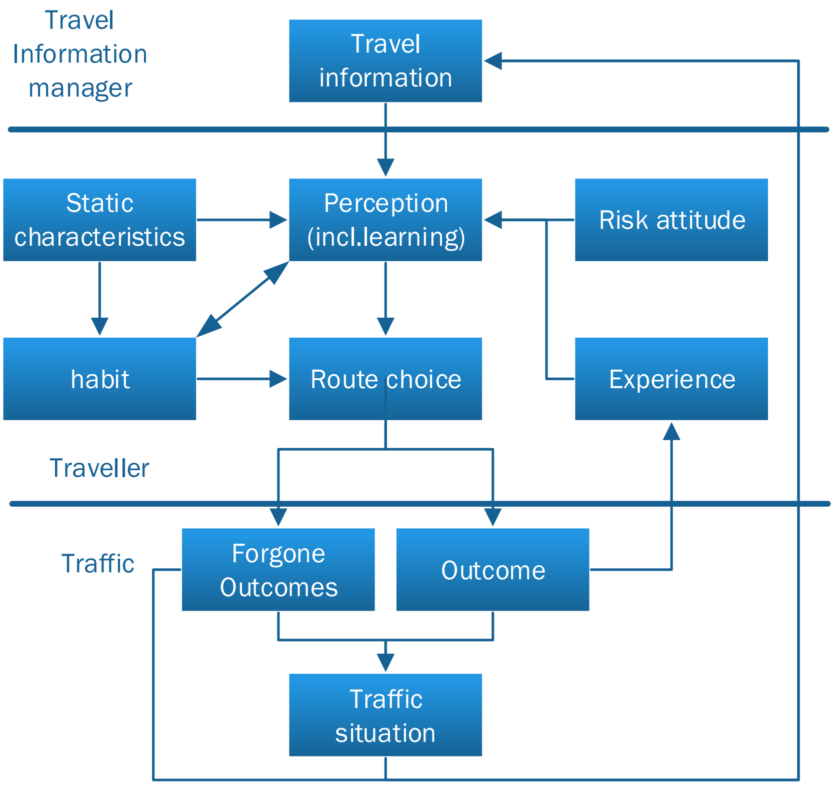


Figure 2-1 Conceptual framework on route choice behaviour (Bogers et al., 2005)

In a traveller's route choice process, various aspects and processes simultaneously play important roles. Travel information externally influences the traveller's perceptions and route choice behaviour. Based on previous route choices, a traveller applies personal habits and experience to the choice of routes. 'Habit' can be defined as a traveller's choice of route based on their previous choices, without comparing alternative routes. Travellers' experiences are based on former route choices, which give them more knowledge about the characteristics of the routes, such as mean travel time and reliability. The 'risk attitude' means that travellers are averse to risks on the route (e.g. travel time variability) that also play an important role in route choice behaviour. The learning process is dynamic and can be considered to include looking for ways to weight recent experiences and information. It plays a smaller role than given information and developed habit. In this framework, route decision making is dynamic and traffic situations that arise after the traveller takes real actions act as feedback to the travel information manager. Drivers choose a route based on some principles (e.g. minimum general travel cost) and criteria related to generalised travel cost (e.g. travel time, travel distance, route familiarity, safety, emission). As seen in Figure 2-1, the acquired information used to choose a route is obtained from the experience of earlier travel choices.

2.2.3 Dynamic traffic assignment

Traffic assignment models are used to represent traffic behaviour and traffic evolution on the network. The number of vehicles on network links is determined by giving the travel demand between different OD pairs based on some given decision rules. There are two types of traffic assignment: static and dynamic (a detailed comparison of these two traffic assignments will be given in the following section). The main property of DTA is that it can represent time variations in traffic flows and conditions and reflect traffic networks more realistically. DTA can show the traffic propagation process on the network, which is not possible in STA.

2.2.3.1 Dynamic versus static traffic assignment

The two types of traffic assignment take different variables into account. If the OD matrix and the demand are assumed to be time independent, the problem is classified as static assignment. If time dependence is taken into account, then the model is dynamic assignment. In general, a traffic assignment model is used to determine the network traffic flows and conditions in an optimal trade-off between network supply and demand. This trade-off is based on both decision rules and equilibrium principles, such as user equilibrium or system optimum.

Static assignment models describe a homogeneous traffic flow pattern and are good at approximating it for certain period like peak hours or workdays. However, an assumption of homogeneity is usually too restrictive to produce realistic model outcomes, particularly when simulating time-dependent DTM measures. The major shortcoming of STA models is failure in the congestion situation. In congested road networks, vehicles queue and spill back upstream. This cannot be represented in an STA model. Another shortcoming is that an STA model assigns demand on the whole network at one time; thus, different routes may have some interactions when they share some links. In reality, vehicles flows vary for different time periods because the transport demand fluctuates at different times. Flows on different routes that share several common links may not hinder each other, because drivers may use the shared links at different times, especially in large networks.

DTA models assign vehicles on a network with multiple dimensions, such as space, time (either continuous or discrete) and user class. They are superior to static models, given the inherent dynamic nature of traffic. This enables DTA to more reliably estimate travel times, yielding more realistic model output (Bliemer, 2001). DTA can represent the dynamic of congestion and the traffic propagation process on the network. More realistic and accurate results are derived from DTA because it is able to portray actual traveller behaviour. The advantages of DTA are listed below:

- DTA can precisely represent a traveller's behaviour, such as choice of route and departure time.
- DTA can explicitly model traffic propagation on the network and time-dependent properties.
- DTA performs much better than STA in reproducing traffic congestion.
- Time-varying traffic control measures can be included in the DTA model.

From the discussion above, we can conclude that DTA is better at simulating the impact of location and time-varying DTM measures. The main goal of this thesis is to investigate the impact of taking CO_2 emissions cost into account in route choice, and CO_2 emissions vary with traffic states, which change over time. Thus, a suitable DTA model should be selected for this purpose. The drawbacks of DTA compared with STA are that DTA needs more detailed and higher-quality input data and longer computing times.

2.2.3.2 Dynamic modelling framework

The framework of the DTA model is illustrated in Figure 2-2. The infrastructure's dynamic features (e.g. nodes, links, traffic control devices, link parameters) determine the dynamic network supply. The time-dependent OD matrices show the dynamic demand profiles from each origin node to each destination node. At each time period, the corresponding demand is assigned to the network based on the current available routes and the routes' performance. The DTA model includes things such as dynamic network loading, a traffic flow simulator, path processing and routing polices. Through the DTA model, route choice, traffic flows, travel times and costs varying with time can be obtained.

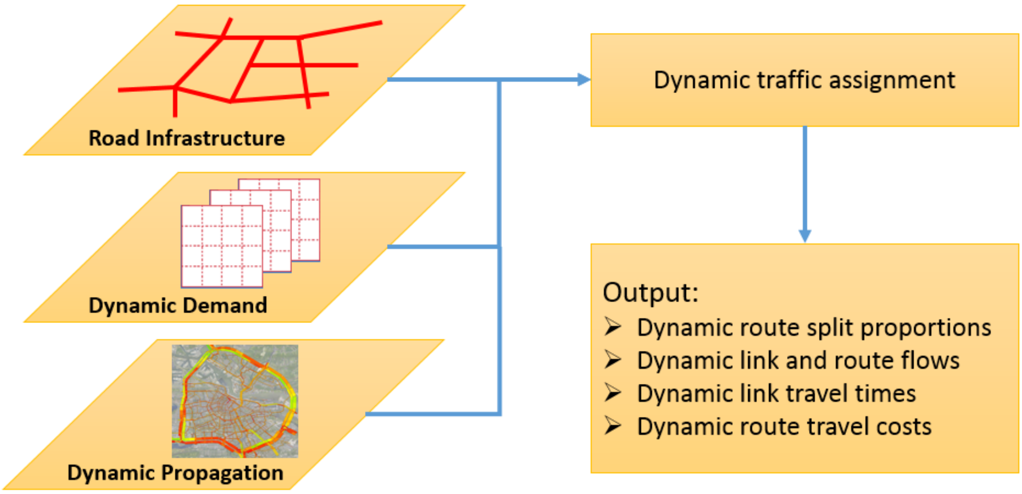


Figure 2-2 General framework of dynamic traffic model (Roelofsen, 2012)

2.2.3.3 Dynamic traffic models

Dynamic traffic models can be classified in two categories: analytical models and simulation (heuristical) models. Many researchers studied on the analytical models such as quasi-dynamic models ((Merchant & Nemhauser,1978a); (Carey, 1987); (Friesz et al., 1989); (Lam & Huang, 1995)) and dynamic analytical models ((Ran & Boyce, 1996);(Bliemer, 2000))

Many different traffic models have been developed for dynamic traffic simulation with different purposes. . They have been designed to focus on different levels (i.e. macroscopic, mesoscopic, microscopic) and scopes (e.g. large, medium and small networks). A summary of current dynamic traffic modelling tools is listed in Table 2-1. This table is not comprehensive, but it includes tools commonly used in traffic research.

Table 2-1 Summary of dynamic traffic simulators

Level / Size	**Macroscopic**	**Mesoscopic**	**Microscopic**
Large	Marple	Dynasmart-P	
Medium	INDY		
Small		Flexsyt	Fosim / Vissim / Paramics

TUDelft TNO

2.2.4 Individual travel cost and marginal travel cost

A DTA model was preferred in this study because it can provide important insights into traveller behaviour in response to dynamics of traffic measures. Two principles of equilibrium are followed in DTA: user equilibrium and system optimum. In dynamic user equilibrium assignment, the traffic system reaches a stable state where travellers choose their routes based on their individual travel costs and make sure they are equal and minimal. In this scheme, travellers only consider their own costs and have no interest in the whole system. In reality, an additional traveller entering a route may impose an additional travel cost on other travellers who are already on the route. This additional cost is considered to be an externality cost or marginal cost.

'Marginal cost' has a number of definitions. From the perspective of economics and finance, marginal cost is the change of total cost that arises when the quantity produced changes by one unit. Mathematically, marginal cost is expressed as the derivative of the total cost with respect to quantity. In traffic area, marginal costs are the extra costs incurred to the system as a result of extra traffic. Marginal costs are applied when considering system optimal traffic assignment or tolling problems (according to Wardrop's second principle with minimal total travel cost).

Marginal costs can be separated into two parts: direct costs and external costs. Direct costs are the actual costs caused by the extra traffic, and external costs are caused by other traffic in the network. Marginal link cost is the total extra cost of one extra vehicle on the link when there are already q_1 vehicles. This relationship is presented in Figure 2-3.

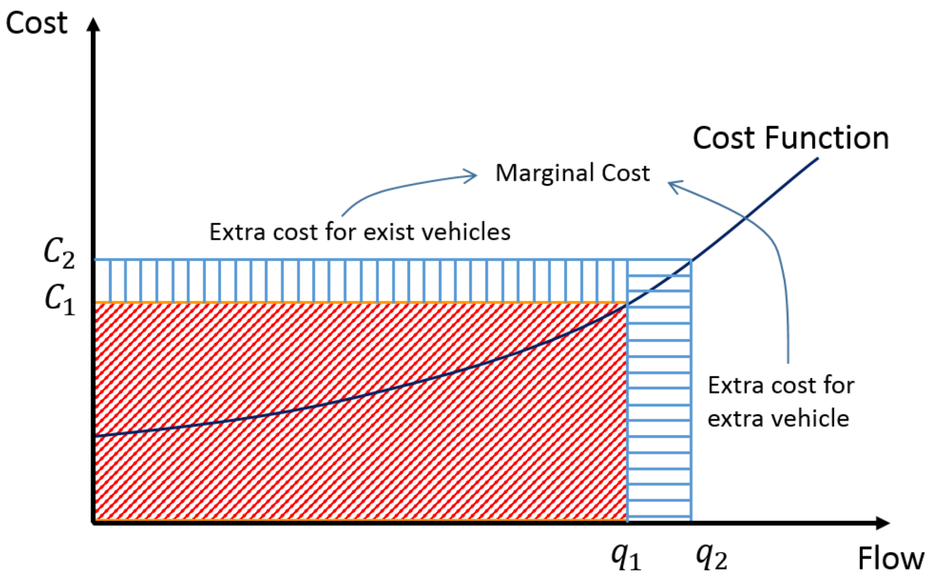


Figure 2-3 Marginal cost (Bovy, 2006)

Normally, the marginal travel time cost is not obvious during the free-flow part because the slope of travel time cost is slight and the marginal cost for others is tiny.

A branch of the literature has addressed marginal costs within traffic modelling. This concept was introduced for road pricing by (Pigou, 1920). Then (Merchant & Nemhauser, 1978b) proposed the marginal travel time function for solving system optimal traffic assignment. If the travel cost only takes travel time into account, the derivative of the travel time function can be separated into two parts: the travel time contribution of an additional user on a link and the additional travel time burden that the user inflicts on all the other users already on the link (Sheffi, 1985). In the system optimum state, the marginal costs of all used routes are equal and minimal. An optimum system can be found by solving a user equilibrium assignment, which uses the marginal cost function. The system optimum can be achieved when all used routes have the same marginal cost, which is in line with the economic competition model.

This thesis supplies information about individual emission cost on the link. A rational traveller is typically interested in making a route choice that minimises his own generalised cost, while ignoring the impact on other traffic participants. Thus, the individual cost was selected in this study, associated with travellers' characteristics and the objectives of MCR management. In Chapter 5, the results from a simple test simulation with different cost types will be compared to show the difference in using each cost type.

2.2.5 Traffic emission modelling

In general, two types of traffic emission models are available. Microscopic traffic emission models (e.g. COPERT and VERSIT+) estimate vehicle emissions based on detailed individual vehicle data such as vehicle speed and vehicle acceleration. The VERSIT+ model uses multivariate regression functions to estimate emission factors. It can estimate emissions on different levels (e.g. road or link, urban, national). The structure of VERSIT+ is presented in Figure 2-4.

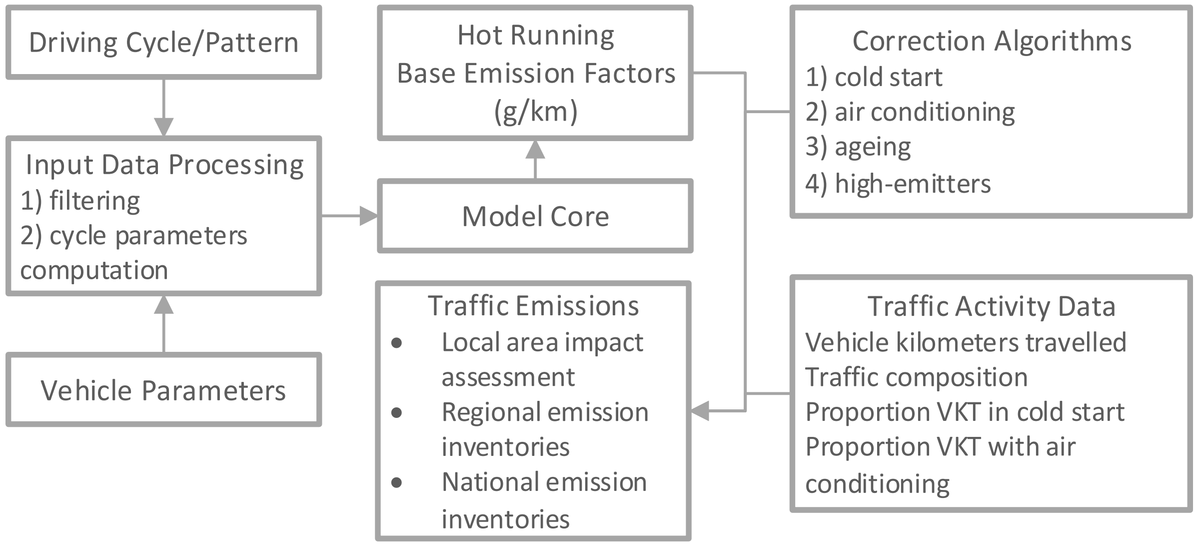


Figure 2-4 VERSIT+ model structure (Smit et al., 2007)

Macroscopic emission models estimate traffic emissions based on the macro averaged emission factors and aggregated traffic data. The TNO macro emission module is used to assess traffic management for macroscopic traffic models that provide emission values for various vehicle exhaust gases (e.g. CO, CO_2, NOx). It focuses on emission estimates for different urban intersection types. The TNO macro emission module's method is based on TNO VERSIT+. According to Klunder, Stelwagen & Woldeab (2013) the TNO module 'is applied and validated in the EU 7th framework project eCoMove and in a macroscopic traffic model of the Ministry of Infrastructure and the Environment of the Netherlands'.

Macroscopic emissions are estimated using macroscopic emission rate curves (emissions in grams per second), which are a function of mean speed on the network component. The network component contains factors such as intersection type, speed limit, link type, link length, number of lanes and vehicle type. Each network component has a specific emission rate curve. In total, there are 260 emission rate curves and 80 link-size-dependent look-up tables in the current emission module. However, there is no all-embracing comprehensive emission module. The closest match will be used for the network situation, which does not have the associated emission rate curve in the emission module. The structure of the TNO macro emission module is shown in Figure 2-5.

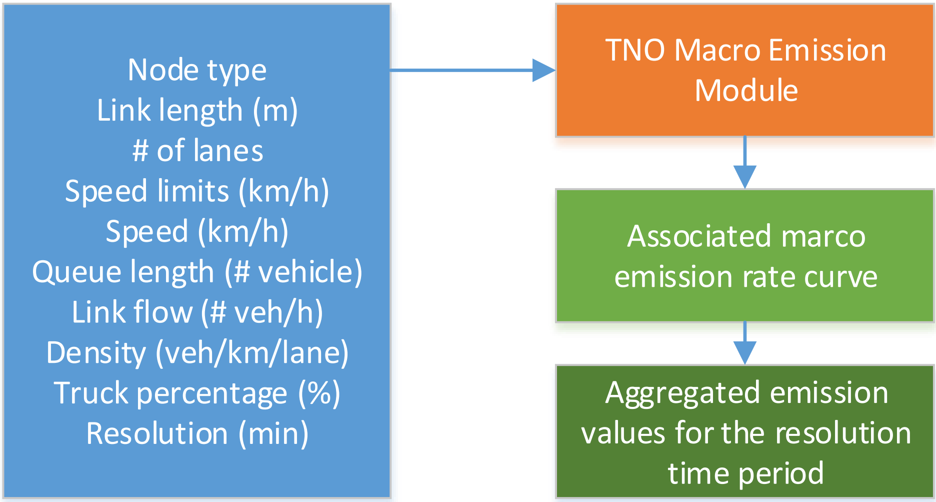


Figure 2-5 Structure of the TNO macro emission module

In this thesis, macroscopic emission models which are the link-based CO_2 emissions are preferred because the macroscopic traffic management objectives and the mesoscopic traffic assignment simulation core are used in the traffic model. This study used two macroscopic emission models. One is the link-based emission model by Barth and Boriboonsomsin (2008). CO_2 emissions are estimated as a function of average running speed on the link, and a fourth-order polynomial is used to fit the data points which are obtained from real traffic observation. This model was used in simple network tests and the detailed introduction will be provided in Chapter 5. The second emission model is TNO macro emission module which calculate the macroscopic emission based on the macroscopic emission rate curves. This emission module was used with Dynasmart-P in the case study in chapter 6. Both emission models adopt the mean vehicle speed as input variables and the link based emission are non-monotonic as a function of the mean vehicle speed on the link.

2.3 Contribution of the thesis and relevant works

In the route choice model, the composite cost function is applied to DTA. This differs from the traditional traffic assignment, in which only travel time and relevant cost are taken into account during route choice. In such an assignment process, emission is not simultaneously taken into account as the output of the traffic process. The methods for incorporating travel time cost and emission cost in a simultaneous and consistent framework would lead to find the possibility for considering emission in new route choice. Therefore, the biggest contribution of this thesis is showing that it is possible to incorporate the travel time cost and traffic CO_2 emission cost in route choice to achieve MCR and to consequently reveal its effects on DTM.

The introduction of CO_2 emission into route choice creates a new dimension in DTM. As vehicle emission can only be computed after a journey is finished, a delayed feedback needs to take into account in order to achieve the necessary convergent simulation. The reviewed models compute all criteria at the same time which means none of the current models considered this delayed feedback.

The simulation-based approach is preferred to explain MCR because the analytical approaches, which consider as the bi-level network design problem and use mathematical formulas to solve optimization problems, cannot bring about such a simultaneous optimisation in view of MCR and implement it in a real network. The case study for this research used the TNO macro emission model with Dynasmart-P mesoscopic traffic simulation. The methods were first tested in a simple Matlab environment during the exploration process.

Finally, the composite cost and a consistent framework were applied in the network assignment, which is greatly different from the existing traffic assignment method. It makes some changes to network performance and offers some solutions for sustainable traffic management.

2.4 Chapter conclusion

In this chapter, a literature study about dynamic traffic assignment, multi-criteria routing and vehicle emissions models is carried out. The literature review gave more detailed insight into currently relevant studies and also into the contributions of this thesis. Previous studies consider the traffic emission only as the output of routing, and try to solve the multi-criteria routing problem in analytical way. These methods are hard to realize such a simultaneous optimization in view of multi-criteria, and difficult to implement in a real network. Thus the simulation approach is selected in this study. A consistent framework is needed because the input in the composite cost (including emission) should be the same as actual output from the traffic simulation, given that emission is the outcome of a finished journey.

Later, the theoretical framework was provided so that readers can gain sufficient understanding of the theories used in this thesis. The reasons for selecting the TNO macro emission module were also illustrated in the theoretical framework. The contributions of this study was provided in section 2.3. The final results will hopefully help road authorities improve the traffic network to create more efficient routing and fewer emissions.

3. Simulation package introduction

As mentioned in Chapter 2, this study chose traffic simulation approach as the first trail to evaluate the effects of MCR traffic management on a network level other than theoretical approach. This chapter will answer the following sub-question: What is the suitable traffic simulation model for MCR on an urban-scale network?

This chapter starts by illustrating the simulation model choice. Next, there is a brief introduction to Dynasmart-P. More detailed information about Dynasmart-P can be found in Appendix A.

3.1 Simulation Software Choice

The three main types of traffic models represent the traffic system with different level of details and traffic entities (Hoogendoorn & Bovy, 2001). A detailed introduction of the three types of traffic models follows.

Macroscopic simulation models are based on the deterministic relationships of the traffic stream's flow, speed and density at high levels of aggregation. These models group vehicles, which means no individual vehicle is explicitly represented. Macroscopic simulation models were originally developed to model traffic on freeways, corridors and urban grid street networks. They run quickly for large-scale networks (especially for evaluating traffic flow on a strategic level) and are widely used in urban traffic network management studies.

Microscopic simulation models are aimed at describing the detailed traffic evolution, each vehicle is modelled on an individual basis, and take specific preference of the vehicle characteristics into account. These models are based on car-following and lane-changing theories. Microscopic simulation includes detailed vehicle movements, interactions and network elements. These models are normally used for local detailed studies, such as a car-following study or a study about the effect of traffic signals at an intersection. This kind of simulation model is time consuming and hard to calibrate.

Mesoscopic simulation models combine characteristics of both microscopic and macroscopic models. According to an FHWA report (2008), "The mesoscopic models' unit of traffic flow is the individual vehicle, and they assign vehicle types and driver behaviour, as well as their relationships with the roadway characteristics. Their movement, however, follows the approach of macroscopic models and is governed by the average speed on the travel link. As such, mesoscopic models provide less fidelity than microscopic simulation tools, but are superior to travel demand models, in that, mesoscopic models can evaluate dynamic traveller diversions in large-scale networks."

Since this study focuses on an urban-scale network, microscopic simulation models require too much computation time to be applicable. Macroscopic simulation models runs quickly on this scale, but vehicle interactions are not explicitly modelled; they move the vehicles in groups, which is inadequate for our evaluation and is not suitable for evaluating routing or control strategies.

Moreover, by implementing MCR measures, we wanted to investigate the individual traveller's response by tracing the rich representation of microscopic details like route choice. Mesoscopic simulation models assign individual vehicles based on link cost, which is suitable for our link-based emission cost model. These models can be used to study travellers' route choices and behaviour in different travel information situations and network conditions. Based on the trade-off between an efficient and a sufficient level of detail, mesoscopic simulation models are the best fit for this thesis.

The typical mesoscopic simulation model is Dynasmart-P. This is a simulation-based DTA system with micro-simulation of individual user decisions as well as a mesoscopic traffic flow simulation approach. According to the manual, Dynasmart-P can provide:

- Reliable estimation of network traffic conditions
- Predictions of network flow patterns and travel times in response to various contemplated traffic control measures and information dissemination strategies.
- Routing information to guide trip-makers in their travels
- Routing information to guide trip-makers in their travels

Dynasmart-P was an available mesoscopic model to simulate traffic management effects in this study. In addition to the main simulation model, DSPEd 2.0 was used to set up the network and prepare the input files (e.g. demand, signal control strategy).

3.2 Introduction to Dynasmart-P

Dynasmart-P (an acronym for ‘dynamic network assignment simulation model for advanced road telematics’) is a dynamic traffic simulation model that was first developed by Peeta and Mahmassani in 1992. The current version of Dynasmart-P is a state-of-the-art dynamic network analysis and evaluation tool that incorporates different information supply strategies, route assignment rules and traffic control measures. Dynasmart-P is categorised as a mesoscopic simulation model because it applies established macroscopic traffic flow models and relationships to model the flow of vehicles on a network, while simulating traffic flows according to individual drivers’ decisions and trajectories and moving vehicles in the network individually. It is a descriptive traffic simulation tool for evaluating traffic control measures, information strategies and route assignment rules. It can also be used for intelligent transportation network design, planning, evaluation, and traffic simulation (Weng, 2010).

Multiple user classes are a central feature of Dynasmart-P. The current version is able to model individual drivers in five predefined classes. According to the user’s manual, Class 1 is unresponsive vehicles, which are not responsive to any information. Classes 2 and 3 are system optimal and user equilibrium respectively: users follow the system optimal assignment rule and user equilibrium assignment rule. These two classes are available if the iterative assignment method is chosen. Class 4 is en-route info, which updates its paths at each intersection based on the prevailing shortest path tree. Since Class 5 users respond to VMS information, this class is called VMS responsive.

3.3 Dynasmart-P model framework

Dynasmart-P simulates vehicle movements according to a modified Greenshields speed-density relationship. It moves individuals or groups of vehicles with the prevailing link speed. There are three major modules for Dynasmart-P: the traffic simulation module, the driver decision modelling module and the path processing module. Apart from these three main components, one main module is used to organise all modules and load the time-dependent OD matrix.

The traffic simulation module is the core of Dynasmart-P. It consists of two primary sub-modules: link movement and node transfer. The link movement sub-module processes vehicle movements on links during each simulation step (time interval) by estimating speeds on the links through the speed-density relationships. The node transfer sub-module determines link-to-link or section-to-section traffic transfer based on the control type at the intersections (Naser & Birst, 2010).

The path processing module is used for calculating the K-shortest path tree and updating trip time for the tree. The driver decision modelling module is used for building the initial path decision. Traveller behaviour in Dynasmart-P is based on boundedly-rational behaviour, which means that drivers alter their routes only if the difference between the new route and current route is over a certain threshold. Decisions from the decision modelling module are sent back to the traffic simulation module. The structure of Dynasmart-P is shown in Figure 3-1.

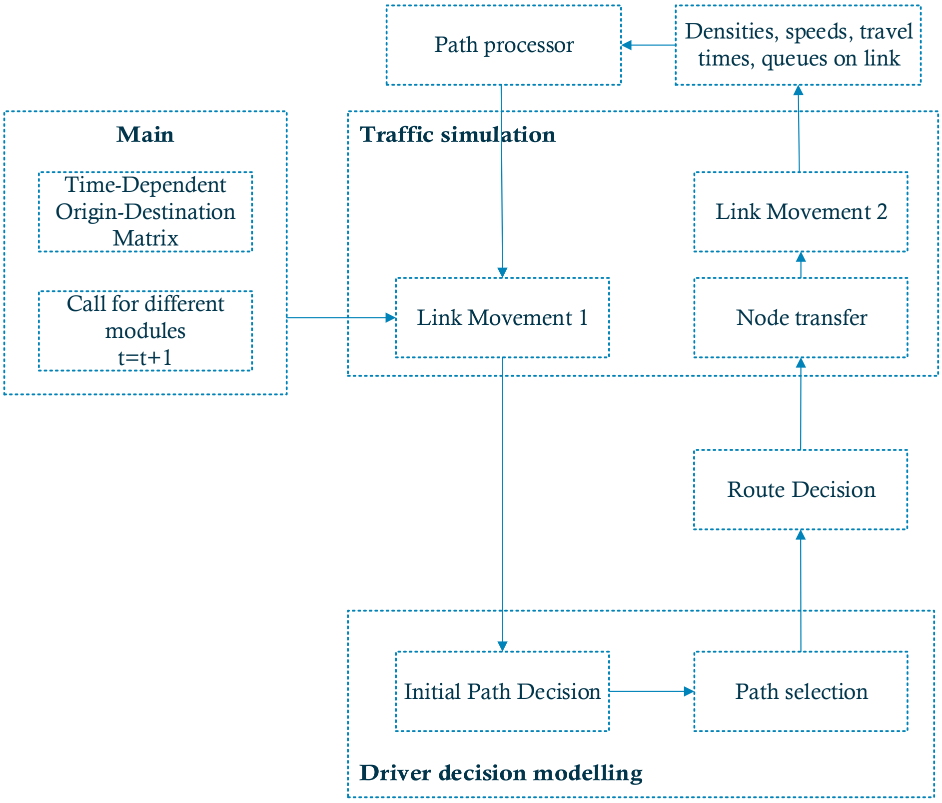


Figure 3-1 Dynasmart-P model structure (Zhang, 2012)

A detailed introduction of the traffic flow model, traffic simulation component, driver decision modelling and path processor, simulation assignment mode and route choice algorithm are given in Appendix A.

3.4 Dynasmart-P evaluation

Previous studies have identified some innate limitations in Dynasmart-P. First, there is no volume capacity constraint on the link because there are no pass constraints set in the algorithm. Second, the traffic model in Dynasmart-P is based on the q-k relationship. In a modified Greenshields equation, a minimum speed is set to prevent a collapse of the simulation. But in the real world, there is no minimum speed for a vehicle and it may stop when it enters traffic congestion. In Dynasmart-P, this minimum speed may cause some incorrect phenomenon: after jam density, the flow values will rise along with the density increase. Third, in reality, vehicles queue at the upstream of the bottleneck link, while in Dynasmart-P, the queue starts from the downstream node of the bottleneck link. Fourth, the link volume is highly sensitive to link length and the saturation flow and service flow do not affect the link's density. Since many previous studies applied Dynasmart-P to DTM, it could be a good candidate tool. However, Dynasmart-P has some problems and does not provide fully satisfying realism and consistency.

We know that Dynasmart-P can be used for a large-scale network and incorporated with various ITS components to simulate a traveller's route choice under different conditions, to move vehicles individually and to give individual vehicle trajectories. Dynasmart-P gives a richer representation of traveller behaviour decisions and network elements than some macroscopic tools and higher computational efficiency than some microscopic models. This study focused on investigating the effects of MCR on DTM. Link-based emission costs were added into route choice cost and changes in travellers' route choice behaviour could cause some changes in network performance. Based on assumed measures of MCR and the features present in this model, Dynasmart-P is suitable for this study.

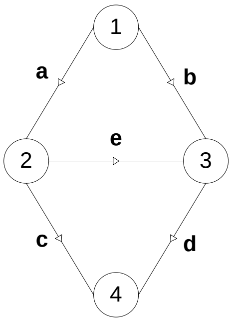
4. Development of multi-criteria routing method

The preceding chapters introduced the current state of research on MCR and the simulation programme Dynasmart-P. This chapter will try to answer the following sub-research questions: How should traffic CO_2 emission cost be incorporated with travel time cost into a consistent dynamic traffic simulation framework? (Section 4.1 and Section 4.2); How should the conceptual method be applied with different extensions for different levels of integration? (Section 4.3)

Since this emission cost is the product of traffic, it will be considered as delayed feedback for the traffic system. Section 4.1 will introduce an example to demonstrate the effect of delayed feedback. The conceptual method will be provided in Section 4.2. Section 4.3 will elaborate on three methods that are extended from the conceptual method. This will be followed in Section 4.4 by a discussion about routing policy with individual and marginal costs.

4.1 Demonstrating the effect of delayed feedback

In order to illustrate the ideas and principles, we designed a Braess network as an example, based on Nagurney (2000a). This network contained four nodes and five single-direction links. There was only one OD pair on the network: from Node 1 to Node 4, with six fixed trips. Three possible paths were found: Path 1 (a-c), Path 2 (b-d) and path 3 (a-e-d). Cost functions are given below, with the emission factor H set to 0.1 for all links.



OD pair: (1,4) = 6 trips		
Link flow	Link cost	Link emission
F_a	$10\ F_a$	$H_a\ F_a$
F_b	F_b+50	$H_b\ F_b$
F_c	F_c+50	$H_c\ F_c$
F_d	$10F_d$	$H_d\ F_d$
F_e	F_e+10	$H_e\ F_e$

Figure 4-1 Braess network by Nagurney

Before opening link e, the equilibrium state was 3 trips on each path (a-c, b-d), after opening link e, the equilibrium for each path was 2 trips. With the network depicted in Figure 4-1, Nagurney illustrated her paradox: adding an extra link e results in an increase in total emission (1.40 now versus 1.2 original without the link 2 to 3) and path travel time (92 now versus 83 original). In her example, emission is the output of travel action and is not the part of the cost function, which is travel time only. All three paths have the same cost 92 (left table). This case is depicted in the left figure in Figure 4-2.

As shown in Figure 4-2, emission on the three paths is not the same: Path 3 has more emission than the other two. Then applying the composite cost which includes travel time and emission cost together with the emission factors (cost = time + perceived emission factor* emission). The results in the centre of Figure 4-2 show a factor of 20. It was obtained by an iterative process that started from Nagurney's one, so that the input emission is converging to its output to guarantee the stability. In this case, all three paths have the same composite cost while travel time and emission in real value per path decrease compared to the corresponding numbers in Nagurney's network (left table). The right table in Figure 4-2 shows the system optimal situation under the Braess network as the reference for other two scenarios.

Finding 1: In this demonstrative network, user equilibrium is not the same with system optimal, when emission is effectively taken into account in the travel cost function, traffic spreads more efficiently over the network and both travel time and emission decrease.

Original Nagurney Solution						
	Path	Flow	Cost	Time	Emission	Total-Time
Path						
a-c	2	6	92	92	0.60	264
b-d	2	6	92	92	0.60	264
a-e-d	2	10	92	92	1.00	344
Link						
a		4	40	40	0.40	160
b		2	52	52	0.20	104
c		2	52	52	0.20	104
d		4	40	40	0.40	160
e		2	12	12	0.20	24
Total			196	196	1.40	552

New Solution with emission in cost function						
	Path	Flow	Cost	Time	Emission	Total-T
Path						
a-c	2.4	6.0	100.4	88.4	0.60	255.4
b-d	2.4	6.0	100.4	88.4	0.60	255.4
a-e-d	1.2	8.4	100.4	83.2	0.84	272.6
Link						
a		3.6	43.3	36.0	0.36	129.6
b		2.4	57.1	52.4	0.24	125.8
c		2.4	57.1	52.4	0.24	125.8
d		3.6	43.3	36.0	0.36	129.6
e		1.2	13.8	11.2	0.12	13.4
Total			214.6	188.0	1.32	524.2

Braess network: optimal						
	Path	Flow	Cost	Time	Emission	Total-T
Path						
a-c	3	6	83	83	0.6	249.0
b-d	3	6	83	83	0.6	249.0
a-e-d	0	6	70	70	0.6	180.0
Link						
a		3	30	30	0.3	90.0
b		3	53	53	0.3	159.0
c		3	53	53	0.3	159.0
d		3	30	30	0.3	90.0
e		0	10	10	0	0
Total			176	176	1.2	498.0

Figure 4-2 Network performance indices in Braess network

The effect of the perceived emission factor is examined in Figure 4-3. A very large factor (meaning more priority for emission) tends to eliminate inefficient path for large emission and close to a system optimal result. As shown in the left table, when the emission factor is 50, there will be no trip on Path 3 because it has the highest emission rate. A very low factor ignores the influence of emission and tends to converge to a Braess solution (Nagurney's), shown in the right figure in Figure 4-3.

Emission factor = 50						
	Path	Flow	Cost	Time	Emission	Total-T
Path						
a-c	3	6	113	83	0.600	249.0
b-d	3	6	113	83	0.600	249.0
a-e-d	0	6	120	63	0.600	180.0
Link						
a		3	50	30	0.300	90.0
b		3	63	53	0.300	159.0
c		3	63	53	0.300	159.0
d		3	50	30	0.300	90.0
e		0	20	10	0.000	0.0
Total			246	176	1.200	498.0

Emission factor = 5						
	Path	Flow	Cost	Time	Emission	Total-T
Path						
a-c	2.12	6.0	93.9	90.9	0.60	261.0
b-d	2.12	6.0	93.9	90.9	0.600	261.0
a-e-d	1.76	9.5	93.9	89.4	0.952	321.8
Link						
a		3.9	40.3	38.8	0.388	150.5
b		2.1	53.6	52.1	0.212	110.5
c		2.1	53.6	52.1	0.212	110.5
d		3.9	40.3	38.8	0.388	150.5
e		1.8	13.3	11.8	0.176	20.7
Total			201.1	193.6	1.376	542.8

Emission factor = 1						
	Path	Flow	Cost	Time	Emission	Total-T
Path						
a-c	2.03	6.0	92.4	91.8	0.600	263.3
b-d	2.03	6.0	92.4	91.8	0.600	263.3
a-e-d	1.95	9.9	92.4	91.4	0.989	338.9
Link						
a		4.0	40.1	39.7	0.397	157.8
b		2.0	52.2	52.0	0.203	105.5
c		2.0	52.2	52.0	0.203	105.5
d		4.0	40.1	39.7	0.397	157.8
e		1.9	12.1	11.9	0.195	23.2
Total			196.8	195.5	1.395	549.9

Figure 4-3 Effect of emission perceiving factor

Finding 2: Emission can be used as feedback in traffic assignment and routing loops and can help improve network routing efficiency when carefully designed.

As mentioned before, traffic emission is the product of a vehicle trip and reflects the performance of a traffic network system. Providing this feedback to the system control would eventually make it possible to correct some system behaviour and performance. The composition of perceived cost also shows the magnitude to which we can influence route choice by emission perceiving factor. This can help policy-makers turn their priority towards sustainable traffic management.

4.2 Conceptual method development

4.2.1 Objectives of the method

Traditionally, in DTM, vehicles choose their routes on the network based on factors such as travel time or travel distance. Since traffic emission is the product of vehicle movement, it can only be computed when a journey is finished. The introduction of emission concern into travellers' route choices requires a traffic model or simulation to take this delayed feedback and the necessary convergence into account. This convergence will be illustrated with a more detailed method test in the next chapter.

As mentioned in Chapter 2, some previous studies have tried an analytical approach, using mathematical formulas to explain MCR. These previous models computed all criteria at the same time, but adding one extra cost component without consistency may cause changes to the network state. None of the previous models used this emission as an output feedback to achieve a consistent framework. Meanwhile, it is difficult to use an analytical approach to realise such an optimisation in view of multi-criteria and it is impossible to implement in a real network. Given these limitations to an analytical approach, a simulation-based approach emerges.

In this thesis we searched for a proper way to incorporate vehicle emission cost into the route choice cost function and to achieve stable traffic assignment. Network performance can be investigated after stable traffic assignment is obtained. The method we used focuses on how the emission cost can be added to the route choice cost function to make traffic assignments and to bring input and output emissions into convergence.

4.2.2 Method structure

The conceptual simulation method structure (see Figure 4-4) was established according to the description of the objectives in the previous section. The simulation starts with just the travel time cost because vehicular emissions can only be computed after a journey is finished. After the simulation, the traffic emission cost can be calculated using the traffic simulation states. The composite cost with travel time cost and the input traffic emission cost are then used for the next simulation step. With the composite cost function, the traffic states from the simulation will differ from those in the previous simulation. The goal of the method is to achieve a traffic state with the same input and output emissions and the same travel cost between the input and end-experienced costs. The moving average process between two successive runs is applied to update the emission cost in the composite cost function, which is used to achieve the consistent and stable state.

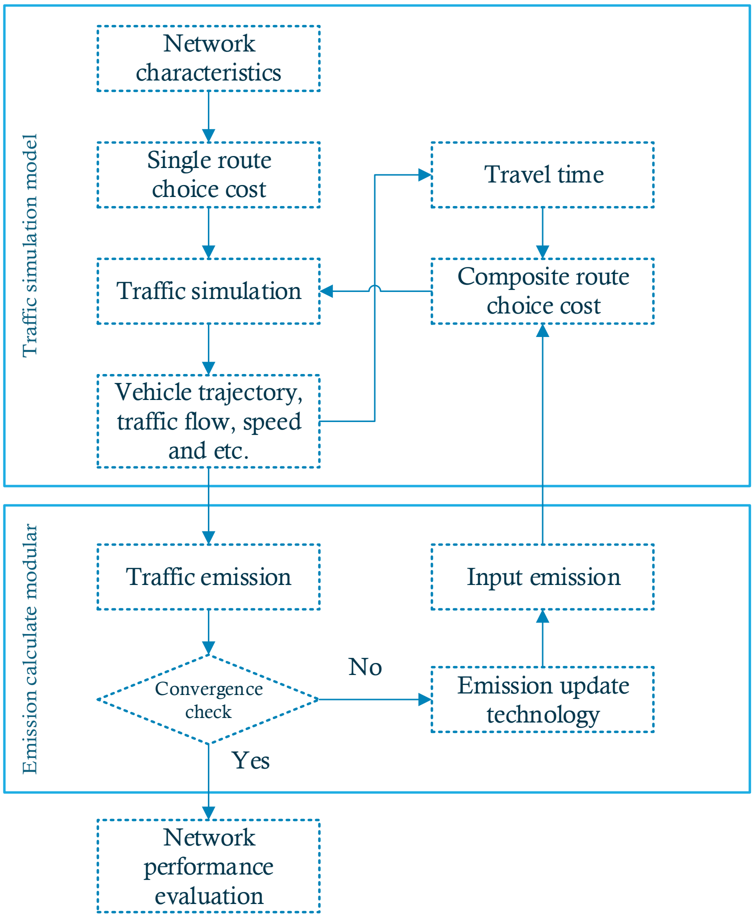


Figure 4-4 Conceptual simulation method structure

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4.2.3 Method application

The conceptual method was designed to create a consistent framework for MCR with the composite cost function. This thesis focuses on travel time cost and link-based emission cost. The conceptual method does not restrict the emission models, which means any emission model could be used in this structure. At the end, the network evaluation was carried out after a consistent framework was achieved.

In general, traffic simulation tools simulate traffic on a network step-by-step and drivers estimate their travel cost and update their route during each simulation step. Equilibrium states can be obtained through iterative assignment, which is processed by several iterations over the whole simulation planning time. According to the traffic simulation model's characteristics, three different methods are able to include the emission cost (these will be introduced in the next section). The fundamental idea of each method is based on the conceptual method (discussed in the previous section). The first method computes and updates the emission cost for each simulation interval. In this case, the emission cost is calculated after each simulation interval.

The second method calculate the emission cost after each intermediate iteration during the iterative equilibrium process. For instance, if the simulation has 60 minutes and 10 iterative assignments, the emission calculation is carried out after every iteration when the simulator finishes 60 minutes of simulation. We can get an emission matrix after each iteration: one dimension is simulation time and the other dimension is link ID. This emission matrix will be updated during the equilibrium process.

The third method derives from implementable consideration. The outer emission approximation loops are adopted, which means the emission matrix is calculated and updated according to the final user equilibrium state. A detailed introduction of these three methods is provided in the next section.

4.3 Development of three methods

Investigating the impact of adding traffic CO_2 emissions into route choice is the main research goal of this thesis. CO_2 emissions are the output of traffic throughput. A consistent framework needs to be found to address the discrepancy between input and output of CO_2 emissions. For this purpose, three simulation methods were designed, focusing on how to integrate emissions into route choice cost.

As mentioned in Chapters 2 and 3, the user equilibrium process in dynamic traffic simulation has two dimensions: the simulation time horizon and the iterative assignment. The following three methods incorporate emission cost in different ways.

4.3.1 Method 1

Method 1 computes and updates the emission cost for each simulation interval which is a simultaneous emission calculation and update method. As mentioned in Chapter 3, in Dynasmart-P, user equilibrium (UE) and system optimum (SO) travellers will calculate the shortest path for a certain simulation interval. Through the traffic flow model and assignment method used in Dynasmart-P, vehicles will calculate and update their path based on the new shortest path tree. Emission is unknown as the output of the traffic.

Only travel time costs are used to calculate shortest path in the initial step. From the second step, the emission cost from the previous step can be used as an input for the general travel cost. Then the emission cost used for the next simulation interval can be calculated based on the current interval emission and the previous interval emission. It is a kind of method of successive average improvement. In this case, emission cost can be expressed as the following equation.

$$Ei_i(\tau + 1) = (1 - \alpha)Eo_i(\tau - 1) + \alpha Eo_i(\tau) \quad \text{Equation 4-1}$$

Where, $Ei_i(\tau)$ means input emission cost on link i during the simulation step τ.

$Eo_i(\tau)$ means calculated emission cost on link i after the simulation step τ.

α is the weight factor. If $\alpha = 1$, the emission cost on the link i for the step $\tau + 1$ is just the actual emission from step τ .

For each simulation step, the input emission cost can be added in the general cost based on the traffic throughput in previous steps except the first step (which only used travel time). The network performance evaluation will be made when the network reach the equilibrium state through the iterative procedure.

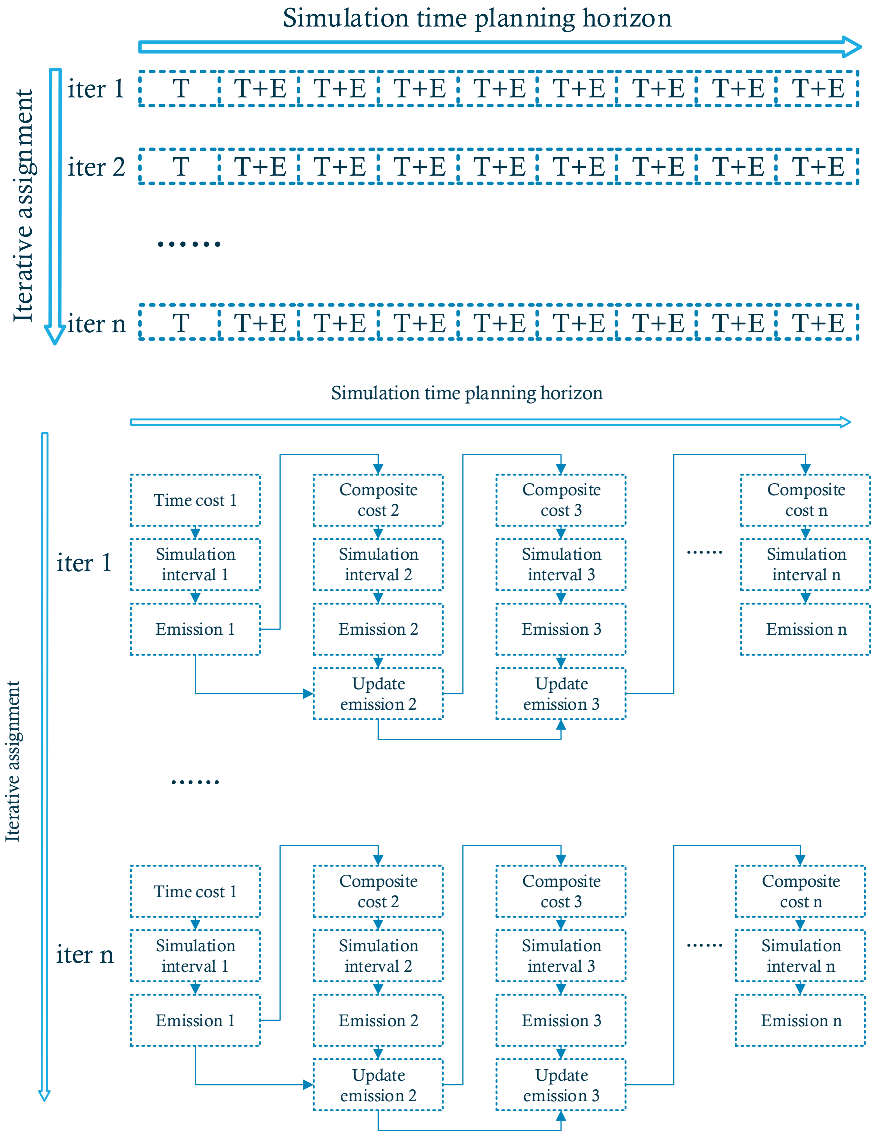

Figure 4-5 Method 1 structure

Following is a detailed explanation of the steps involved in Method 1:

Step 1. Select the values of VoT and VoG.

Step 2. Use travel time as the route choice cost for the first K-shortest path algorithm calculation (first simulation interval). Perform a dynamic simulation for this simulation interval.

Step 3. Calculate the link based emission on the basis of the traffic state in this interval. Update the link based emission cost for the next simulation interval.

Step 4. Perform the dynamic simulation in the following simulation interval with the composite cost.

Step 5. Repeat Steps 3 and 4 until the whole simulation time period is complete.

Step 6. Perform the iterative traffic assignment until it reaches the equilibrium state.

Step 7. Evaluate network performance with the final equilibrium state and compare the result with the reference scenario.

Method 1 calculates emission cost and updates the composite cost internal of the simulation itself. The link emission cost is calculated immediately in Method 1 based on the short simulation interval. This is an idealised method and closes to the real-time DTA.

4.3.2 Method 2

Method 2 calculates and updates the emission cost after each intermediate iteration during the iterative equilibrium process. The iterative assignment method is selected in the simulation to find the user equilibrium traffic state on the network. This user equilibrium state is a more reasonable starting point for investigating the impact of adding CO_2 emissions in the general cost function.

There are many intermediate iterations during the iterative assignment process. Since traffic emissions is an output of traffic throughput, the start iteration only uses travel time cost in the cost function. After the first iteration is finished, the link-based emission cost can be calculated at each simulation interval on the basis of the traffic state in the first iteration. Then the composite route choice costs for the next iteration at each simulation interval are based on the relevant emission costs from previous iterations and the time cost. Through the parameters of VoT and VoG, emission cost and time cost can convert to each other. In the following iterations, the emission cost can be calculated and updated after each intermediate iteration is finished.

The link-based emission cost for the next iteration is based on the emission cost in the previous and current iterations. Input emission is calculated as follows:

$$Ei_{\mathrm{i,t}}(n+1) = (1-\alpha)Eo_{i,t}(n-1) + \alpha Eo_{i,t}(n) \quad \text{Equation 4-2}$$

Where, $Ei_{i,t}(n+1)$ means the input emission cost on link i at the simulation time t in the n+1th iteration

$Eo_{i,t}(n)$ means the calculated emission cost on link i at the simulation time t in the nth iteration.

When the user equilibrium assignment stops, the emission is calculated based on this final state and the network performance is evaluated according to this final network output.

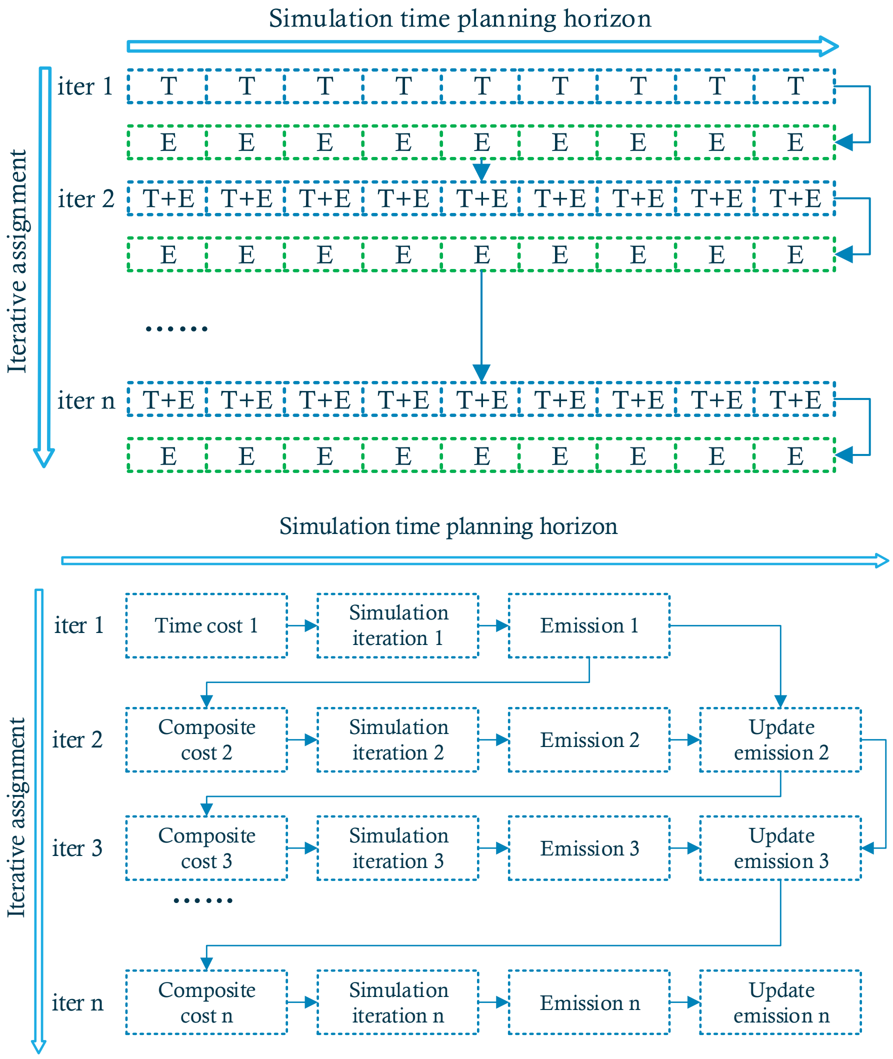

Figure 4-6 Method 2 structure

Following is a detailed explanation of the steps involved in Method 2:

Step 1. Select the values of VoT and VoG.

Step 2. Finish the first iteration for the whole simulation time with only travel time cost in the route choice cost function.

Step 3. Calculate the link based emissions on the basis of the current simulation and prepare the new emissions cost for the next iteration.

Step 4. Perform the next simulation iteration with a composite cost (travel time and emission cost)

Step 5. Repeat Steps 3 and 4 until the user equilibrium iterative simulation is complete.

Step 6. Perform the iterative traffic assignment until it reaches the equilibrium state.

Step 7. Evaluate network performance with the final equilibrium state and compare the result with the reference scenario.

Method 2 also calculates and updates emissions for each simulation interval internal; it is only one intermediate step lag behind. This method calculates emissions based on the completed vehicle trajectory of the iteration, which is easy to aggregate.

4.3.3 Method 3

Method 3 computes and updates emissions after finishing the user equilibrium assignment in the simulation. The user equilibrium simulation procedure and the emission approximate procedure are processed in two directions. In the first run, only the time cost is taken into account for the iterative assignment process. Then the emission cost is calculated based on this equilibrium traffic output. In subsequent runs, this emission cost is added in the composite route choice cost and the user equilibrium state is obtained through the iterative assignment process. The new input emission cost for the next run is based on the emission cost from previous and current runs. The input and output emissions convergent are checked. If the input and output emissions convergent and the traffic state converge, the emission updating will be exit and the network performance will be evaluated; else it will be continue.

$$Ei_{i,t}(r+1) = (1-\alpha)Eo_{i,t}(r-1) + \alpha Eo_{i,t}(r) \qquad \text{Equation 4-3}$$

Where, $Ei_{i,t}(r+1)$ means the input emission cost on link i at the simulation time t in the r+1th run

$Eo_{i,t}(r)$ means the calculated emission cost on link i at the simulation time t in the rth run.

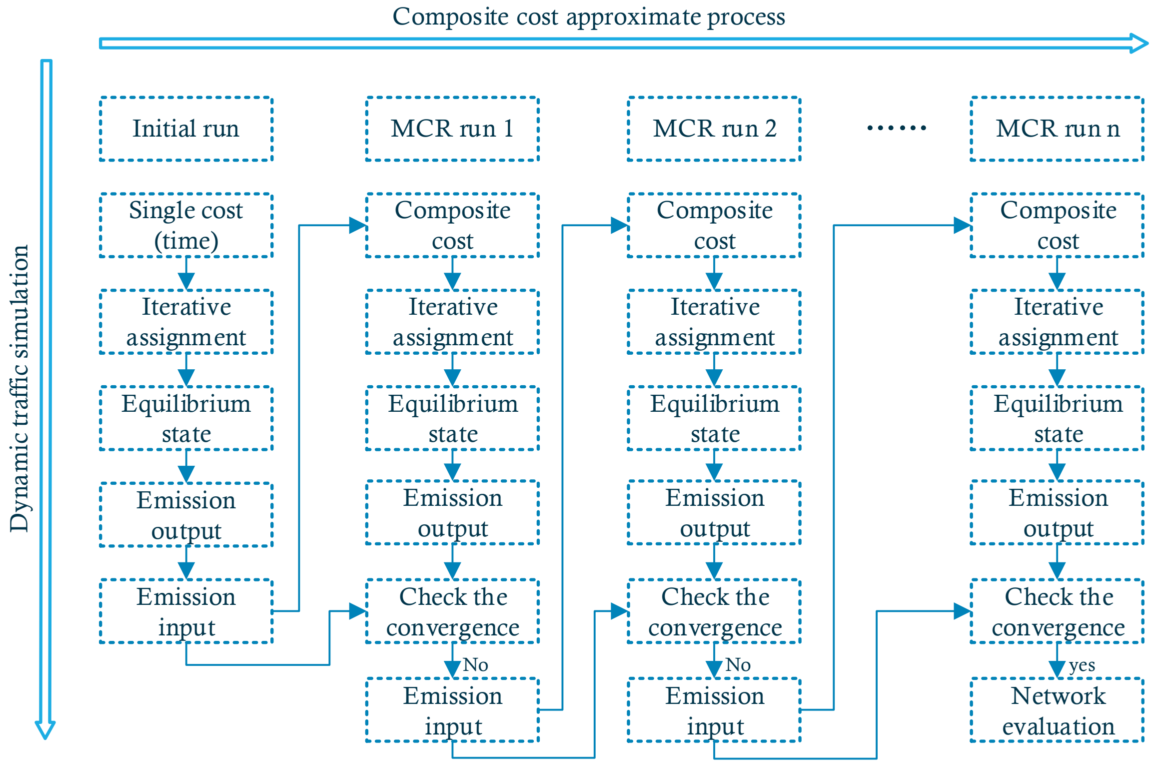

Figure 4-7 Method 3 structure

Following is a detailed explanation of the steps involved in Method 3:

Step 1. Select the values of VoT and VoG.

Step 2. Perform a single criteria routing (time cost only) and user equilibrium iterative assignment simulation in the initial run.

Step 3. Calculate the link based emission cost depending on the traffic state from the reference scenario and prepare for the next multi-criteria simulation.

Step 4. Perform a multi-criteria simulation with composite cost and finish the user equilibrium iterative assignment with this composite cost.

Step 5. Calculate the link based emission cost in the current simulation and prepare the new emissions cost for the next run.

Step 6. Repeat Step 4 and 5 until the convergence of input emissions and output emissions and the convergence of traffic state on the network are checked.

Step 7. Evaluate network performance and compare it to the reference scenario.

Method 3 applies the outer loop iterations for updating emission cost to achieve convergent input and output emission states. The emission updates through the moving average method which can make emission input changes based on previous runs. The outer emission calculation method is suitable when using some well-packaged simulation tools because there is no need to access the traffic simulation model itself.

4.4 Routing policy with Individual travel cost and marginal travel cost

As introduced in Chapter 2, individual travel cost and marginal travel cost are used for different equilibrium purposes. Individual travel cost represents a user's preference and marginal travel cost refers to optimum levels over the whole system. In this research, the cost function contains two components (travel time and travel emissions) illustrated in the previous section. There are four scenarios for different equilibrium purposes, which are listed in the following table:

Table 4-1 Scenarios with different cost types

		Emission cost	
		Individual	Marginal
Travel time cost	Individual	Scenario 1 IT/IE	Scenario 2 IT/ME
	Marginal	Scenario 3 MT/IE	Scenario 4 MT/ME

TC denotes the traveller's travel cost, and vot and vog represent travellers monetary value of time and emission. $TT(q)$ is the travel time function and $E(q)$ is the individual vehicle emission function related to traffic flow q. $TT'(q)$ and $E'(q)$ are the derivative of travel time function and emission function with respect to flow.

Scenario 1: individual travel time cost and individual emission cost

$$TC = vot \cdot TT(q) + vog \cdot E(q) \quad \text{Equation 4-4}$$

Here, road users consider the personal travel time that they have experienced and the emissions they have produced themselves. Users would be charged based on the emissions they generate. Following this cost scheme, traffic would be assigned on the network based on the user equilibrium principle. This is the general situation of travellers.

Scenario 2: individual travel time cost and marginal emission cost

$$TC = vot \cdot TT(q) + vog \cdot E(q) + vog \cdot E'(q) \cdot q \quad \text{Equation 4-5}$$

Here, road users consider their own travel time and their own emissions, as well as the extra emissions that they induce from other users. In this situation, people not only think about the emissions they produced themselves, but also about extra emissions produced by others because of their traffic. This situation is realistic since some environmentalists' aware people are concerned emissions from the whole system perspective.

Scenario 3: marginal travel time cost and individual emission cost

$$TC = vot \cdot TT(q) + vot \cdot TT'(q) \cdot q + vog \cdot E(q) \quad \text{Equation 4-6}$$

Here, road users consider not only their own travel time and emissions, but also the extra travel time imposed on others due to their traffic. Thinking logically, this kind of traveller is rare. This scenario can be calculated mathematically, but it is not realistic.

Scenario 4: marginal travel time cost and marginal emission cost

$$TC = vot \cdot TT(q) + vot \cdot TT'(q) \cdot q + vog \cdot E(q) + vog \cdot E'(q) \cdot q \quad \text{Equation 4-7}$$

This is the system optimal for composite cost from a road authority perspective. Here, road users consider both their time cost and their emission cost from a system optimum perspective. This travel cost scheme can give a system optimum traffic assignment with respect to travel time and emissions.

4.5 Chapter conclusion

In this chapter, the conceptual structure of multi-criteria routing method is developed. Later on, three methods are designed to determine a consistent traffic assignment framework with composite route choice cost based on the conceptual method structure. Each method has its own features and uses different techniques to incorporate emission cost. They are represent simultaneous, one intermediate iteration lagging and one iteration lagging emission calculation. Methods 1 and 2 are internal emission calculate and update methods, while Method 3 uses the outer loop to calculate and update emission cost. Thus Methods 1 and 2 need to be closely integrated with the traffic simulators in contrast to Method 3, which can be easily implemented with other traffic simulation tools because it does not change the traffic models in the simulation. Methods 1 and 2 calculate and update emissions in each simulation iteration during the user equilibrium process. Stable emissions are found when user equilibrium is achieved. In contrast, Method 3 has two directions: one for user equilibrium and one for emission approximation. It uses the final user equilibrium state to calculate and update emissions for the next run. A feasibility analysis of these three methods is given in the next chapter, with a simple test network in Matlab. Routing policy with individual travel cost and marginal travel cost is also introduced, which can be used for different traffic assignment objectives.

5. Method implementation

Three methods for incorporating travel time cost and traffic CO_2 emission cost were introduced in the previous chapter. The research question to be answered in this chapter is: what is the feasibility of each method? In this chapter, the feasibility of these three methods will be tested. We also investigated whether the solutions from the three methods are unique or identical. In order to answer these questions and select the suitable method for the case study, a simple DTA model was built in Matlab, which is similar to Dynasmart-P, because the selected method will be used in Dynasmart-P to investigate network performance through a larger, and real network.

5.1 Design of the simple test network

A small simple network DTA simulation was created in Matlab to test the feasibility of each method. As illustrated by Chiu et al. (2011) "The characteristics of DTA are: (1) vehicle departing at different time are assigned on the routes based on their minimum cost. (2) DTA simultaneously determines travellers' choice route. (3) Traffic propagation on the link followed with some constraints and the fundamental relationship of traffic flow variables." The design of the simple test network was based on the general DTA algorithmic procedure from (Chiu et al., 2011), shown in Figure 5-1.

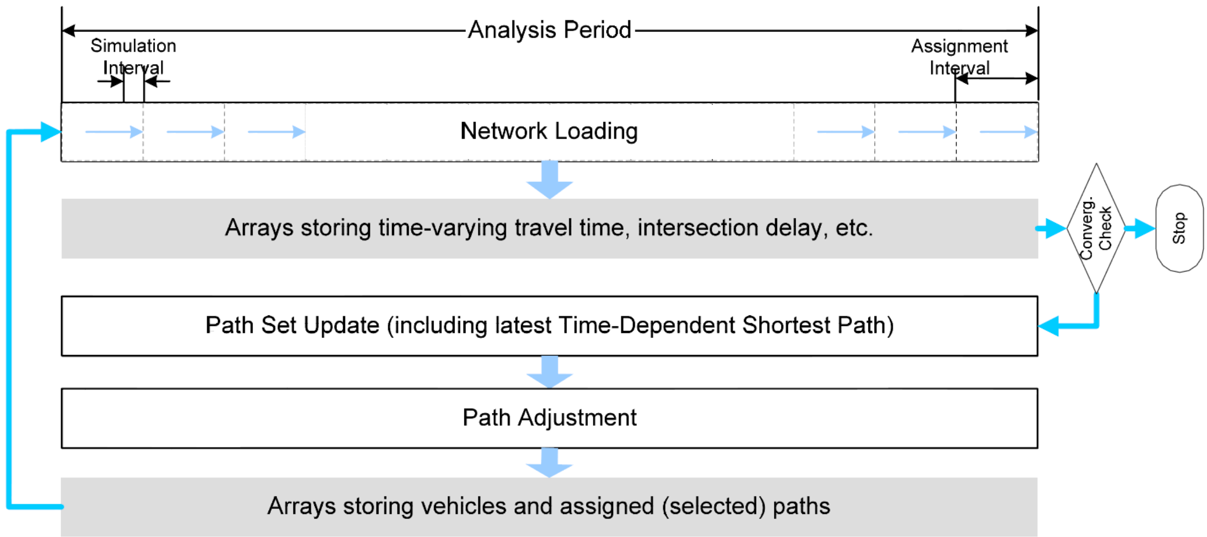

Figure 5-1 General DTA algorithmic procedure (Chiu et al., 2011)

As shown in Figure 5-1, there are three major components: network loading, path set update and path assignment adjustment. Network loading is used to determine the result of vehicles following a given set of route choices. Path set update is used to discover the new shortest routes. Path adjustment follows the path set update and assigns vehicles closer to equilibrium. These three components iterate in succession until the converge check is satisfied.

The physical structure of the network is shown in Figure 5-2. This physical structure contains only one O-D pair and three direct routes. It adopts the characteristics of DTA and the basic computational framework in Dynasmart-P. Each route contains only one directly link. The reason for designing this kind of network is that the real large network can always be divided into small sub-networks that contain several direct routes that connect two points and have no switching opportunity among different routes.

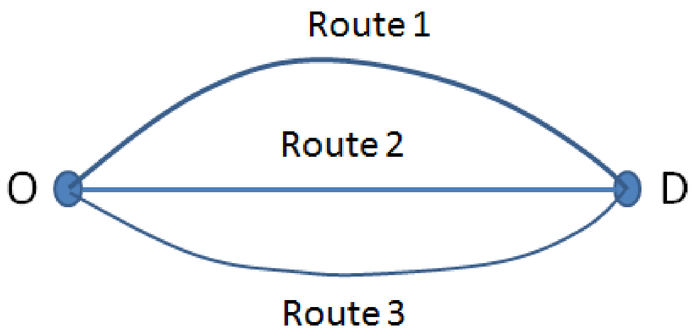

Figure 5-2 Test network

5.1.1 Traffic flow models and emission models

In the test network, a dynamic demand profile was predefined with a certain time interval for the whole horizontal analysis time period.

Like the modified Greenshields traffic model in Dynasmart-P (mentioned in Chapter 3 and Appendix A), the traffic model in the test network was a one-regime Greenshields model with minimum speed constraint (shown in Figure 5-3). In this traffic model, traffic states on a specific link are determined by three variables: free flow speed u_f, jam density k_{jam} and the minimum speed constraint u_{min}. The \ minimum speed here is computational required because travel time on the link at a specific simulation interval is calculated by link length over link speed. The minimum speed constraint is used to avoid zero travel speed. Travel speed can be derived from the equation below.

$$u = \begin{cases} (v_f - v_{min}) \cdot \left(1 - \frac{k_i}{k_{jam}}\right)^{\alpha} + v_{min}, & 0 \le k < k_{jam} \\ u_{min}, & k \ge k_{jam} \end{cases} \quad \text{Equation 5-1}$$

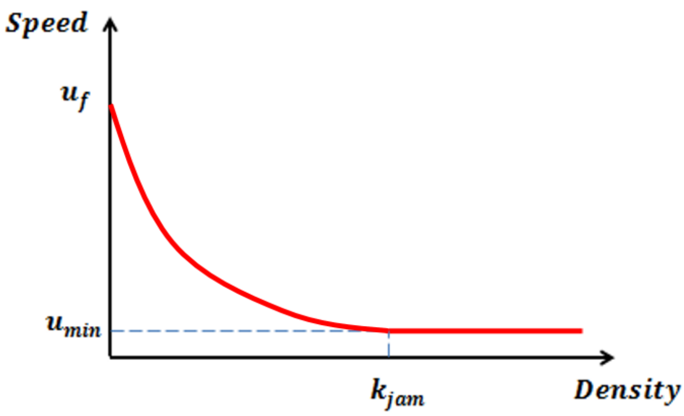

Figure 5-3 Modified Greenshields traffic flow model in test simulation

Each route represents a different kinds of road type such as expressway, freeway and arterial road through the different value of variables.

The emission calculation model is from Barth and Boriboonsomsin (2008). CO_2 emissions were estimated as a function of average running speed on the link. A fourth-order polynomial was used to fit the data points which were obtained from real traffic observation, shown as a blue solid line in Figure 5-4 . The polynomial function is shown in Equitation 5-2.

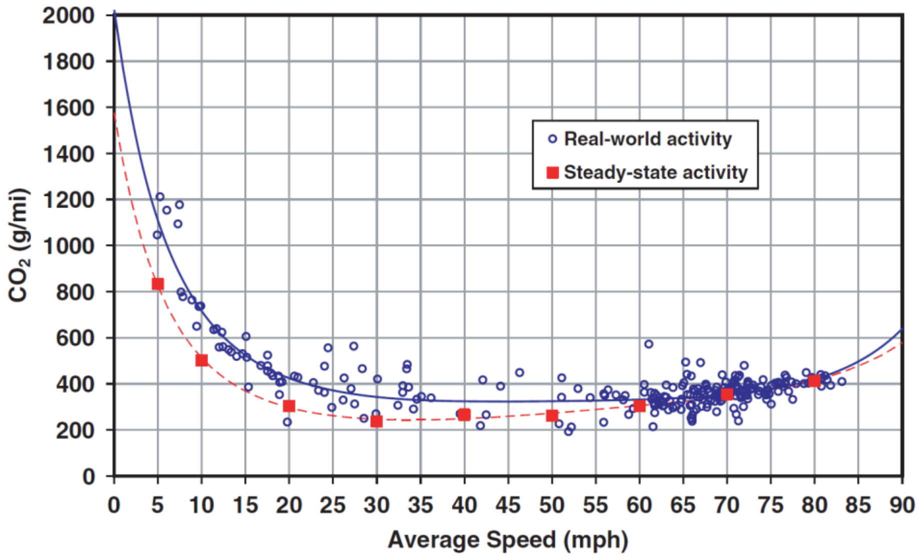

Figure 5-4 CO2 emissions function on the link (Barth & Boriboonsomsin, 2008)

$$ln(y) = b_0 + b_1x + b_2x^2 + b_3x^3 + b_4x^4 \qquad \text{Equation 5-2}$$

Where, y is the CO_2 emission in grams per mile and x is the average trip speed in miles per hour. The coefficients are b_0=7.613534994965560; b_1= -0.138565467462594; b_2=0.003915102063854; b_3= -0.000049451361017; b_4=0.000000238630156.

The red line in Figure 5-4 is the CO_2 emissions for steady-state speeds. This line is the approximate lower boundary of CO_2 emissions for real travel activity, because vehicles must experience some accelerations and decelerations in real traffic, which will leads to higher CO_2 emissions.

5.1.2 Assumptions for the test simulation

The following assumptions were made for the test simulation:

1) The simulation interval is one minute and the demand profile is changed dynamically for a predefined time interval.

2) Vehicles generated at the same simulation interval on the same route are considered to be a pattern, which means that vehicles in a pattern will have the same travel state.

3) Vehicles are spread evenly and immediately on the link when they are generated on the link. Thus density on each link is calculated by the number of vehicles over link length.

4) Vehicles' speeds are determined by the prevailing speed on the link during each simulation interval. This means that all the vehicles on the same link in the same simulation have the same travel speed, and this prevailing speed refers to the link density at each simulation interval.

5) The number of vehicles on the link is calculated based on the travel distance of each vehicle pattern. If the travel distance is larger than the link length, these vehicles are excluded from the vehicle numbers on the link.

6) To make the simulation result more comparable, simulation conditions were predefined. The parameters in the same trial group were strictly uniform for each method. The reference scenario, which only contains travel time cost in the cost function, was used to represent the traditional assignment. There are four scenarios in this section: reference scenario (time only), MCR scenario 1 (Method 1), MCR scenario 2 (Method 2) and MCR scenario 3 (Method 3).

5.1.3 Value of time and value of green

Value of time and value of green are two coefficients to represent the travellers' monetary values on time and CO_2 emission. Travel time cost and CO_2 emission cost are able to combine together in one route cost function through these two coefficients.

Value of time (VoT)

From a traffic economic perspective, the VoT is the opportunity cost of the time that a traveller spends on his journey. In some cases, VoT is considered to be the money that people would like to pay in order to save time or the monetary value of their own time. The VoT depends on personal characteristics and the purpose of the trip. In general, the VoT is divided into two categories: working purpose and non-working purpose. Some studies use the state preference surveys to estimate the VoT (Segone (1998); Boiteux (2001); Fontan (2003); Axhausen et al. (2007); Jong (2012); Börjesson and Eliasson (2012)). The summary of their results are listed in Table 5-1:

Table 5-1 Value of time survey result

	Value in Euros/hour	Purpose
Segonne, 1998	7.27	Commuting
	7.76	Professional travel
	6.33	Other purpose
Boiteux, 2001	9.5	Commuting
	10.5	Professional travel
	5.2	Other purpose
Fontan, 2003	21.03	Commuting
Axhausen et al., 2007	30.6	Business
	18.7	Commuting
	17.8	Leisure
	14.8	Shopping
Jong,2012	9.25	Commuting
	26.25	Business
	7.5	Other
Börjesson and Eliasson,2012	12.1	Commuting
	7.8	Other

As we can see from the previous studies, the reasonable VoT ranged from around €5 per hour to €30 euro per hour, with varying purposes and researchers. The newest research, conducted by Jong (2012) in the Netherlands and Börjesson and Eliasson (2012) in Sweden, shows that the VoT for commuters is around €10 per hour. Thus, in the initial test experiment, the default VoT was set as €10. In the later section, the robustness analysis will use different values of time and values of green. In the next chapter, the sensitivity analysis will be carried by using different combinations of VoT and VoG.

Value of green (VoG)

VoG is the travellers' environmental concerns. Gaker et al. (2010) used some surveys and experiments to study travellers' behaviour regarding the values of greenhouse gas emissions. Zhang (2013) investigated the impact of CO_2 pricing on CO_2 emissions in freight transport: she found that total network emissions do not change significantly until the CO_2 pricing is higher than €400 per ton (€0.4 per kilogram). CO_2 emissions decrease more sharply when the CO_2 price is changed at a rate higher than €400 per ton. In this study, the initial VoG was set at €0.4 per kilogram.

5.2 Feasibility of each method

There are three routes in the network and a dynamic demand profile was used for each simulation interval. This chapter describes four scenarios: SCR (travel time only), MCR1 (Method 1), MCR2 (Method 2) and MCR3 (Method 3). The SCR scenario is the traditional traffic assignment method that only considers travel time cost in the route choice cost set. Methods 1, 2 and 3 were applied in MCR1, MCR2 and MCR3 scenarios where travel costs were determined by individual travel time and individual emissions. At the end of this chapter, the results of using the different combinations of individual cost and marginal cost are provided.

There are two ways to stop iteration during the UE process: the duality gap and the sufficient numbers of iterations based on the test experiment and performance from the simulation. Boyce et al. (2004) noted that: 'whether the solutions obtained after 10, 50 or even 500 iterations are a useful basis for transportation planning decisions depends upon their discrepancies from a highly converged solution that approximates the true user equilibrium'. They compared the results from 25, 92, 534 and even more than 2,000 iterations, and found that the relative gap will be less than 1% after 25 iterations and 0.1% after 92 iterations. Some initial tests have been done to determine the maximum iterations in both two cases considering the trade-off between getting enough convergence of the simulation and computing efficiency. The maximum iteration was 60 times for normal traffic condition and 190 times for congested traffic condition in this simple network simulation test based on the trial tests. The duality gap was also checked for during these iterations.

The methods proposed in this section try to create a consistent way to incorporate emission cost into the traffic assignment cost function. It means that actual emission value is approximately the same with input emission values in the simulation. The normal statistical summary and the root-mean-square error (RMSE) test were employed to check the differences between the input emission values and actual emission values for each simulation interval during the whole simulation period.

RMSE is a frequently used measure for finding the difference between values predicted by a model or an estimator and the values actually observed. These individual differences are called residuals when the calculations are performed over the data sample that was used for estimation, and are called prediction errors when computed out-of-sample. The RMSE serves to aggregate the magnitudes of the errors in predictions for various times into a single measure of predictive power. RMSE is a good measure of accuracy and is calculated as follows:

$$\text{RMSE} = \sqrt{\frac{\sum_{t=1}^{n}\left(y_{1,t}-y_{2,t}\right)^2}{n}} \qquad \text{Equation 5-3}$$

Where, n is the number of data.

$y_{1,t}$ and $y_{2,t}$ are the two time series,

Then the coefficient of variation of the root-mean-square error (CVRMSE) can be measured based on RMSE. CVRMSE measures the differences between values predicted by a model and values actually observed. A lower value indicates less variance and hence higher quality.

$$\text{CVRMSE} = \frac{RMSE}{\bar{x}} \qquad \text{Equation 5-4}$$

Where, $\bar{x}$ is the mean value of the first time series.

CVRMSE is usually presented as a percentage. Reddy et al. (1997) pointed out that models with a CVRMSE of less than 5% are considered to be excellent, those less than 10% are considered to be good, those less than 20% are considered to be mediocre and those greater than 20% are considered to be poor.

The feasibility of each method was analysed through two perspectives: the convergence and the results. The maximum iteration was predefined as 60 in normal traffic conditions and 190 in congested traffic conditions. The convergence was checked in each scenario. The differences between input emission and actual emission, duality gap, total travel time, total emission cost, flow split rate and travel cost on each route were used for convergence check. Since the number of vehicles on the network was the same in each scenario, the results from the total level and average level should have the same trend. Thus, this test focused on total level performance. This chapter uses three kinds of performance indicators: total travel time, total emission and trip completion rate. The feasibility analysis of each method was based on these two aspects.

The objective of these three MCR methods is to discover a framework with consistent input and output in the equilibrium. In the simple test network, the input emission and output emission values were checked between the last two successive iterations (i.e. iterations 59 and 60 in normal traffic conditions and iterations 189 and 190 in congested traffic conditions). Through this comparison, we identified whether the consistence between expected emission values and actual emission values was achieved. The general statistic summary, RMSE and CVRMSE were adopted to represent the consistence.

Duality gap was used for the convergence check. In case of a deterministic equilibrium, the duality gap should become zero over iterations. In the stochastic case, the duality is likely to converge to a certain value. The duality gap in dynamic traffic simulation is calculated by summing the duality gap for each simulation time interval. The duality gap in each simulation time is determined by the difference between total travel time on each route and total minimum travel time of this OD pair over the total minimum travel time of this OD pair. If the duality gap converges to a certain value during the iterations, then the simulation goes to a convergence state followed by the assignment rules.

$$\mathrm{DG} = \sum_t \left(\frac{\sum_k (f_k^t \tau_k^t - d_i^t u_i^t)}{d_i^t u_i^t} \right) \qquad \text{Equation 5-5}$$

Where,DG is the duality gap, i is the OD pair, $k$denotes the set of used routes connecting the OD pair i. f_k^t represents the flow on route k departing at assignment interval t. τ_k^t is the experienced travel time on route k for assignment interval t. d_i^t is the total flow for the OD pair i at time interval t and u_i^t is the shortest route travel time for OD pair i at time interval t.

Total travel time and total emission are calculated by:

$$\text{Total travel time} = \sum_{i \in P,t} q_{i,t} T_{i,t} \qquad \text{Equation 5-6}$$

$$\text{Total Emission} = \sum_{i \in P,t} e_{i,t} N_{i,t} D_{i,t} \qquad \text{Equation 5-7}$$

Where: i is route from OD pair P.

t is the simulation interval.

$q_{i,t}$ is the vehicle number that departs at time t on route i.

$T_{i,t}$ is the travel time of the vehicle that departs at time t on route i.

$D_{i,t}$ is the travel distance on route i during the simulation time interval t.

$N_{i,t}$ is the vehicle numbers on route i during the simulation time interval t.

$e_{i,t}$ is emissions on route i during the simulation time interval t.

Split rate in this simple simulation means the choice percentage on the route in each simulation interval. For instance, at a particular simulation interval, there are 10 vehicles that try to enter the network. If the spilt rate for route 1 is 0.3, it means that three vehicles of total demand at that particular departure time choose route 1. Split rate is an ideal indicator for the traffic network statement because, according to Wardrop's equilibrium principle, at the user equilibrium state, no one can improve himself by switching routes without harming others. The split should be strictly converged in the STA. In DTA, split rate also can be used as a statement indictor that is approximately stable when approaching user equilibrium state. In the simple test simulation network, the split rate is compared with the previous iteration at the same simulation interval. The absolute difference is applied for convergence check because the difference between two successive iterations may be positive or negative in every simulation interval. As a result, the sum of these absolute differences for all simulation intervals allows you to clearly see the changes between two successive iterations.

5.3 Case 1 (normal traffic condition)

In Case 1, the traffic intensity was normal and there was no serious traffic congestion during the simulation period. The parameters were set so that the link prevailing speed was higher than 40 km/h in the equilibrium state. There were three routes in the network, and the route parameters are shown in Table 5-2.

Table 5-2 Route parameters for Case 1

	L (km)	U (km/h)	Umin (km/h)	Kj (Veh/km)	Shape term	Iter (number)	VoT (euro/h)	VoG (euro/kg)
Route 1	20	90	1	150	1.5	60	10	0.4
Route 2	24	105	1	170	1.5	60	10	0.4
Route 3	28	120	1	220	1.5	60	10	0.4

(L= length; U= maximum speed intersection; Umin= minimum speed; Kj= jam density; iter= maximum iteration number)

The traffic flow model on each route based on modified Greenshields model is shown in Figure 5-5:

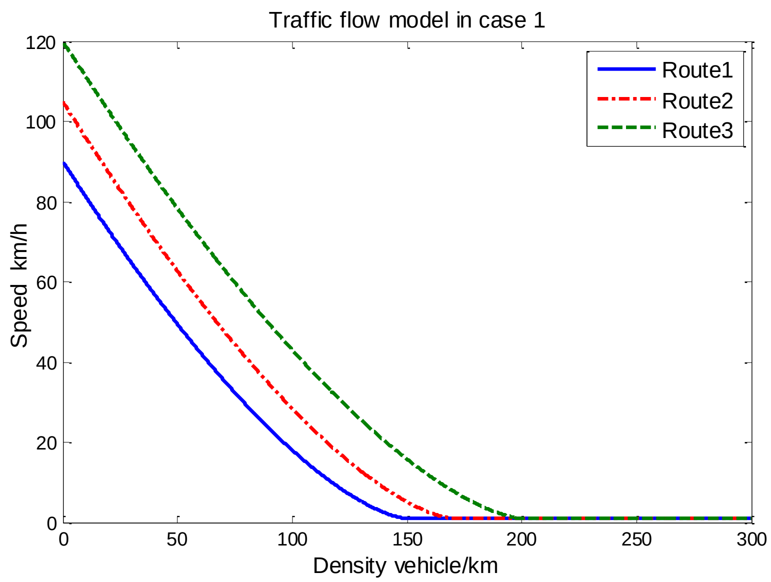

Figure 5-5 Traffic flow model on each route in Case 1

The demand profile is shown in Figure 5-6:

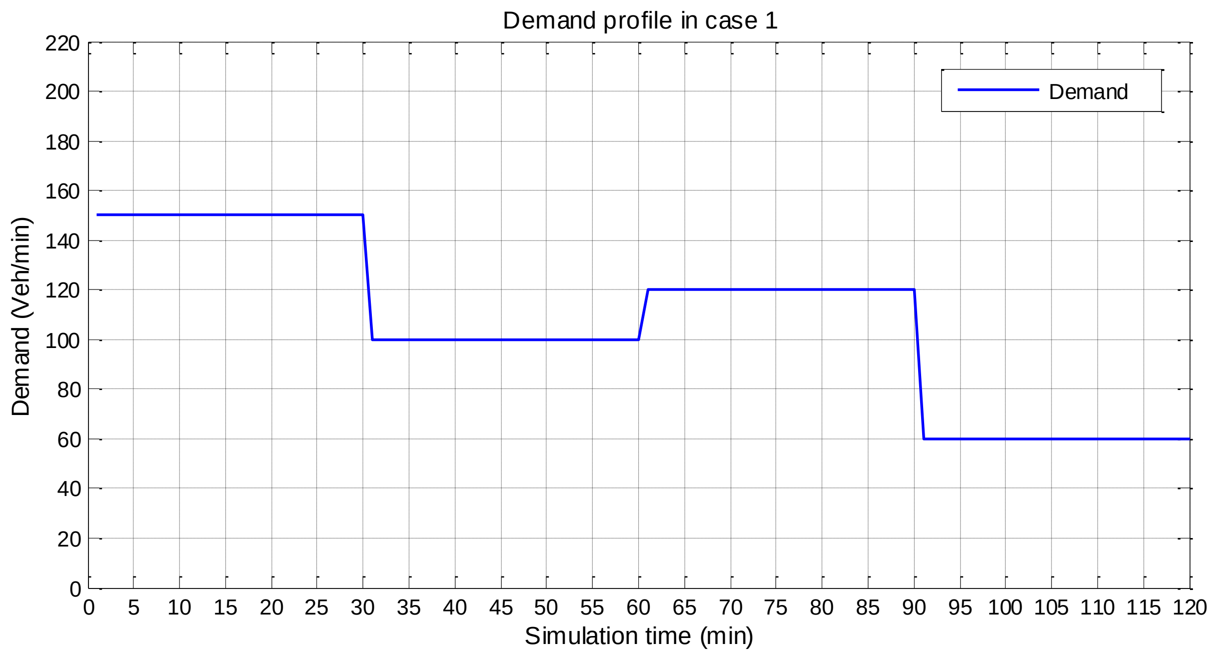

Figure 5-6 Demand profile in Case 1

In this test simulation, the simulation time interval is 1 minute. The numbers of vehicles entering network at each minute are used to represented traffic demand.

5.3.1 Convergence check

Input and output emission check

The input emission and output emission checks were performed in different ways in Methods 1, 2 and 3. Methods 1 and 2 contained one user equilibrium iterative process, so the convergence check was performed in the last iteration. In Method 3, we first needed to check the out loop convergence and then checked the input emission and output emission values in the last run. This check was used to determine how many out loops were needed in Method 3.

i. Emission check in Method 1

In Method 1, the emission update within the iteration and the input and output emission check started at the second simulation interval because there was no emission cost in the first simulation interval. Thus, the sample size was 119. The statistical summary for Method 1 is shown in Table 5-3.

Table 5-3 Statistic summary of Method 1 in Case 1

		Route 1	Route 2	Route 3
Sample size (# of simulation interval)		119	119	119
Difference between input and output emission	Sum Value	-0.0469	-0.2820	-0.0682
	Mean	-0.0004	-0.0024	-0.0006
	Standard Deviation	0.0212	0.0141	0.0610
	Sample Variance	0.0004	0.0002	0.0037
Emission value	RMSE	0.0211	0.0142	0.0607
	CVRMSE	0.0052	0.0029	0.0102

ii. Emission check in Method 2

Statistical summary:

Table 5-4 Statistic summary of Method 2 in Case 1

		Route 1	Route 2	Route 3
Sample size (# of simulation interval)		120	120	120
Difference between input and output emission	Sum Value	-0.7217	0.0154	-0.2459
	Mean	-0.0060	0.0001	-0.0021
	Standard Deviation	0.0133	0.0016	0.0079
	Sample Variance	0.0002	0.0000	0.0001
Emission value	RMSE	0.0145	0.0016	0.0081
	CVRMSE	0.0035	0.0003	0.0013

The mean value, standard deviation and sample variance for the difference between input and output emission were quite small on these three routes. This finding indicates that the difference for different simulation intervals was very tiny. For the emission values themselves, RMSE was calculated to determine the average magnitude of the errors between input and actual emissions. A lower value indicates less variance and hence higher quality. Normally acceptable CVRMSE is lower than 0.05 (5%). In the Method 2 statistical test, the RMSE and CVRMSE on each route were lower than the acceptable level, which means the input emission and output emission values in Method 2 have higher similarity.

iii. Emission check in Method 3

There are two steps in Method 3: check whether the numbers of out loops is sufficient and then test the difference between input emission and actual emission in the last run. These two steps are illustrated here with a detailed explanation. First, the total input emission and output emission were checked. The results are shown in Table 5-5.

Table 5-5 Input emission and output emission in different runs of Method 3 in Case 1

Run	Emission in	Emission out	Difference
0	0	1763.522	1763.522
1	1763.522	1787.745	24.223
2	1775.633	1783.802	8.169
3	1779.718	1788.129	8.411
4	1783.923	1783.084	-0.840
5	1783.504	1783.494	-0.010
6	1783.499	1784.537	1.038

As seen in the above table, the difference between emission in and emission out was reduced by multiple runs. Run 0 was the first run, so the input emission cost was zero. Then the input emission was updated each run. In the sixth MCR condition, the emission input and output difference was quite small compared with the beginning.

Next, the absolute emission difference compared with the previous iteration for each interval was calculated for all three routes. The results are shown in Figure 5-7.

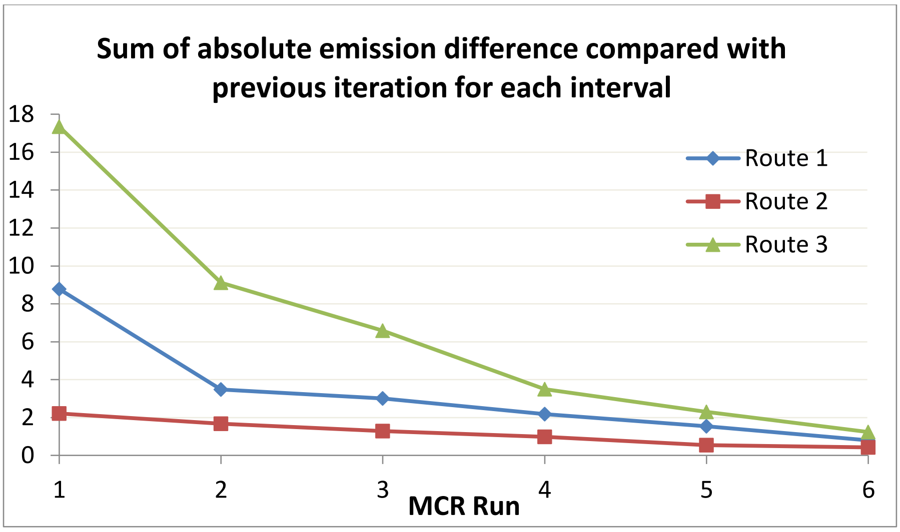

Figure 5-7 Sum of absolute emission difference for each interval in Case 1

In Figure 5-7, the sum of absolute emission difference at the sixth Run was closed to 0 for each route with 120 counts. This the output emissions and input emissions are almost convergence. Then the statistical feature was calculated in the sixth run. This result is shown in Table 5-6.

Table 5-6 Statistic summary for the last run of Method 3 in Case 1

		Route 1	Route 2	Route 3
Sample size (# of simulation interval)		120	120	120
Difference between input and output emissions	Sum value	0.4581	-0.0631	0.6433
	mean	0.0038	-0.0005	0.0054
	Standard Deviation	0.0133	0.0053	0.0244
	Sample Variance	0.0002	0.0000	0.0006
Emission value	RMSE	0.0136	0.0053	0.0249
	CVRMSE	0.0033	0.0011	0.0042

The general statistical summary shows that the difference between input and output emissions for three routes was very small. The RMSE and CVRMSE were sufficient for the acceptable level. This indicates that in the sixth MCR loop in Method 3, the output emission (actual emission) was close to the input emission (expected emission).

The RMSE and CVRMSE in Method 2 were less than those in Method 3, but both methods met the acceptable level. Input emissions in Method 2 were calculated and updated according to each intermediate step in the whole user equilibrium. In Method 3, the emissions were calculated and updated based on the previous user equilibrium state and there were six out loops to update the input emission. The following tests for Method 3 are based on the results from the stable state (sixth run).

Duality gap

The duality gap for each iteration was calculated as a sum of duality gaps for every simulation interval. The duality gaps for four scenarios are shown in Figure 5-8. All of these scenarios converged after 20 iterations.

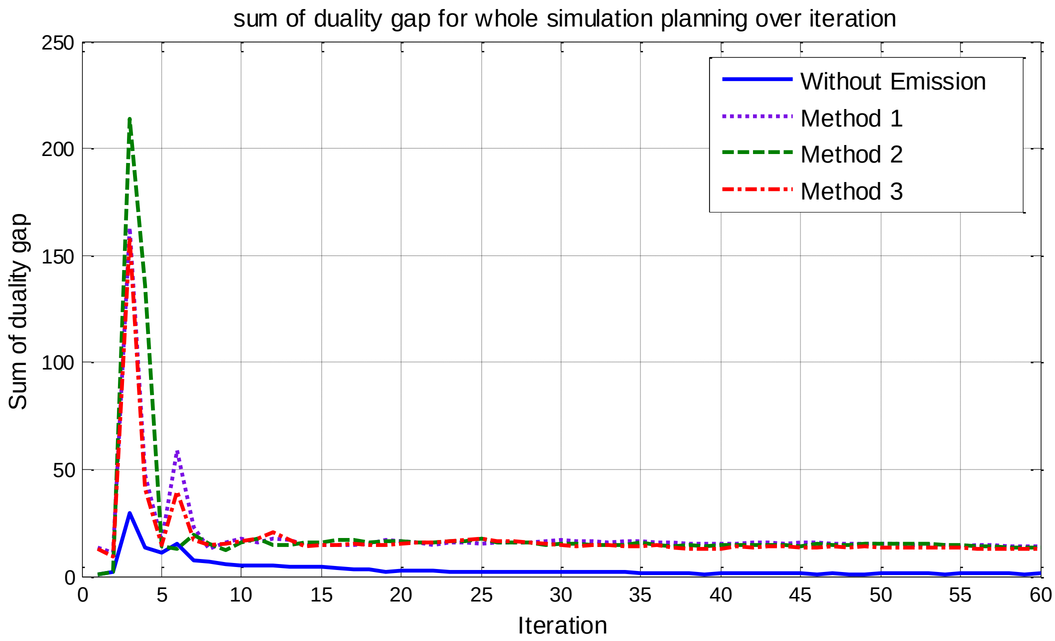

Figure 5-8 Duality gap in Case 1

Method 2 had the highest amplitude at the beginning and had some small fluctuations from iterations 5 to 15. The reference case, Method 1 and Method 3 all had two obvious fluctuations at the beginning. The amplitudes of Methods 1 and 3 were similar and the amplitude of the reference case was quite small compared to that of the other three. The duality gaps of the three methods reached a stable value after approximately 20 iterations. All the three methods reach a stable state in the end.

Total travel time and total emissions

The simulation iterated 60 times in each method. The total travel time (left figure) and total travel emissions (right figure) on the network for four scenarios are shown in Figure 5-9, the total travel time and total emission in all scenarios are approximately stable after 20 iterations. Another observation is that the total travel time and total emission fluctuations in Method 2 were more serious than those in the other three scenarios, because it had the biggest amplitude at the beginning. All of the three methods are almost have the similar total travel time and total emission in the end which means the quality of these three method are almost same and all of them reach a stable state after 60 iterations.

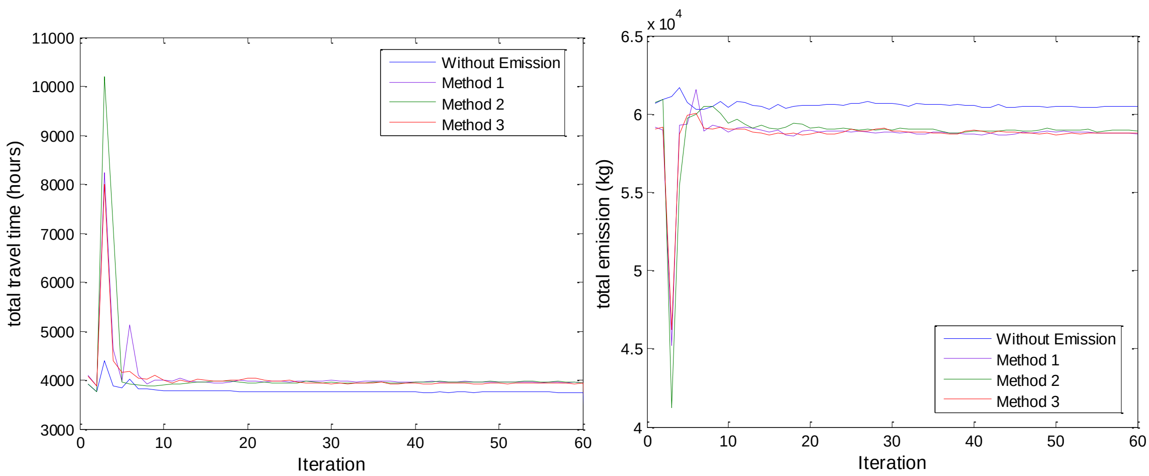

Figure 5-9 Total travel time (left) and total emissions (right) over iterations in Case 1

Split rate

The split rate results from these three scenarios in Case 1 are shown in Figure 5-10 and the absolute split rate difference was calculated based on every two successive iterations. Case 1 had 120 simulation intervals in the whole simulation period. In the first 10 iterations, the sum of absolute split rate difference on each route had huge fluctuations. However, in all four scenarios, the fluctuations became steady after 30 iterations. In the end, the total 120 values of absolute split were almost zero, which indicates that the vehicle split on the network was already stable. There are two explanations for this fact: (1) in the equilibrium state, the cost on each route was approximately the same and no one wanted to change his routes; and (2) the step length decreased with the iterations due to the MSA heuristic method itself.

There is no big difference between these four scenarios and there was only higher oscillation in Method 2 in the beginning iterations. The possible reason for this is that the input emission cost was updated in every iteration in Method 2, but was stationary in Method 3 for every iteration in one simulation run. This may lead to huge oscillations in an unstable state, though all three methods can achieve a stable state like base scenario. The conclusion from the split rate check is that Methods 2 and 3 can achieve an approximately stable state on network assignment.

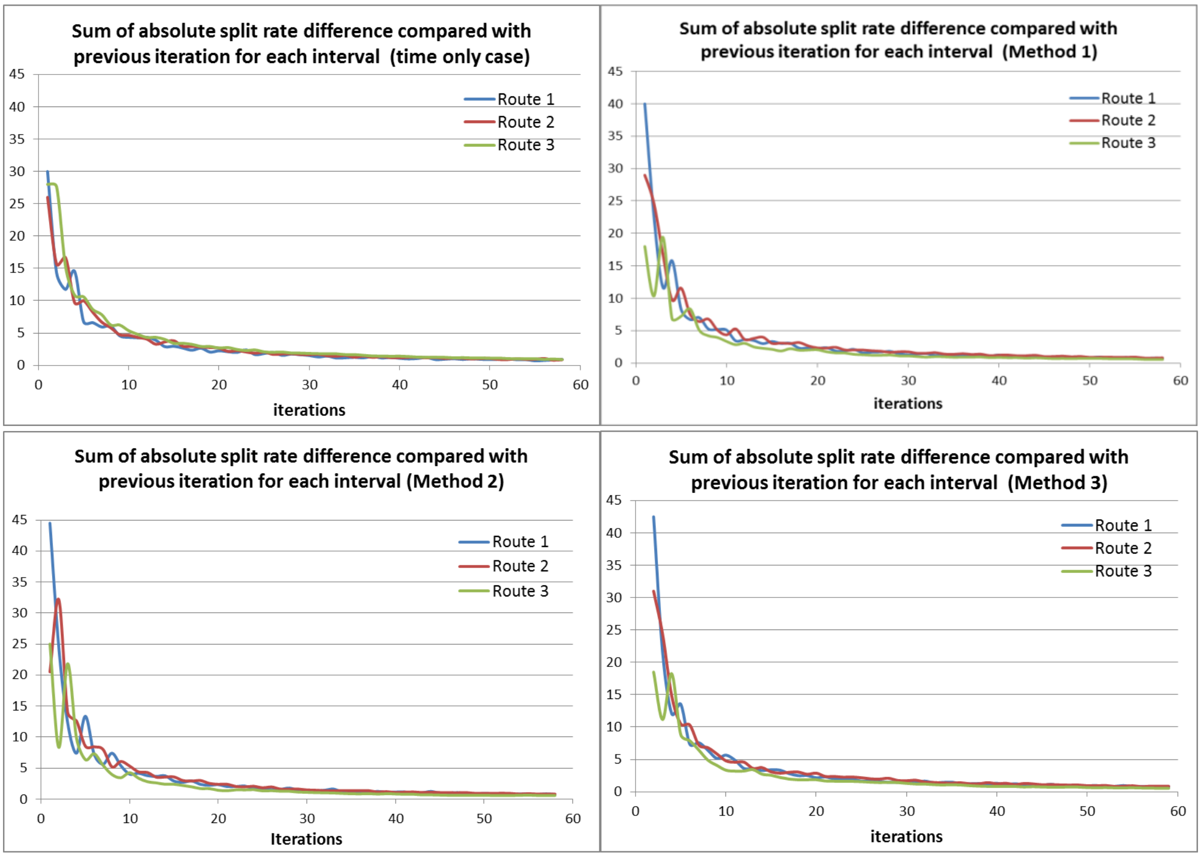

Figure 5-10 Sum of absolute split rate difference in Case 1

The split rate for each route under three methods for the whole simulation time period are shown in Figure 5-11, Figure 5-12 and Figure 5-13. It is apparent that the split rates on each route under different methods were close to each other and the tendency of each method's split rate curve on one route is similar. This means under the different method, travellers have the same split rate on the network. These completely illustrate that all three methods have approximately the same results with enough iterations.

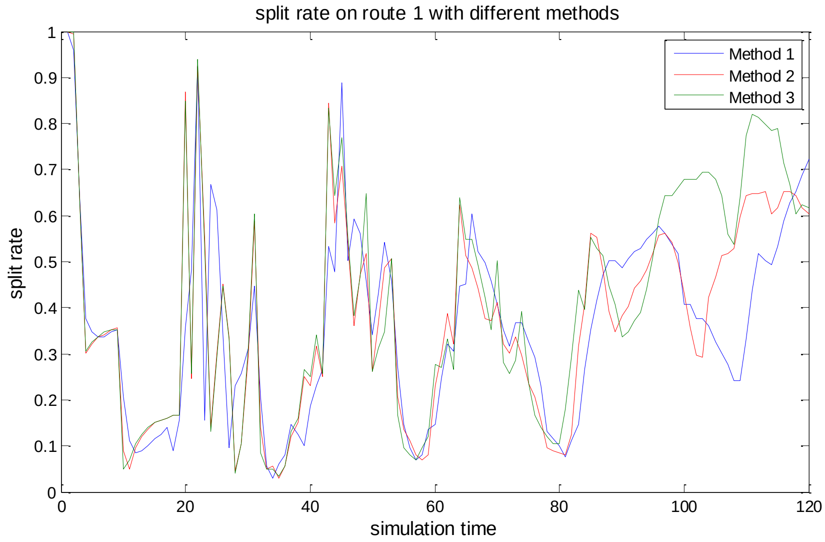

Figure 5-11 Split rate on route 1 under three methods in Case 1

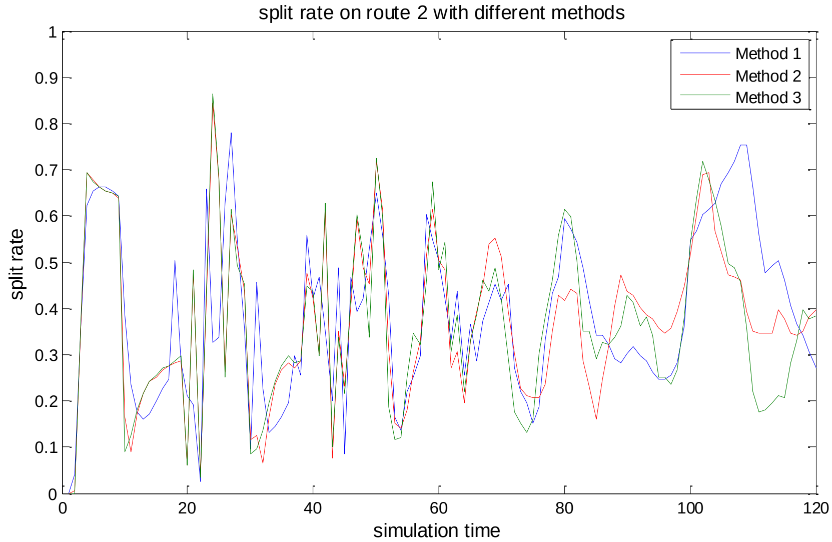

Figure 5-12 Split rate on route 2 under three methods in Case 1

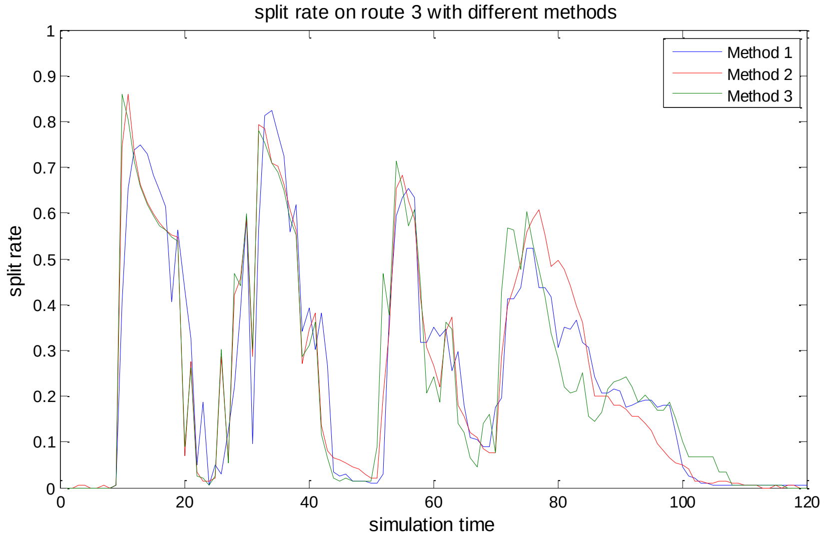

Figure 5-13 Split rate on route 3 under three methods in Case 1

Travel cost

The travel cost on each route at each simulation interval in the approximate user equilibrium state are shown in Figure 5-14. In the reference case, only travel time was converted to monetary cost, while in Methods 1, 2 and 3 both travel time and traffic emissions were transformed into monetary costs. Travel costs on the three routes had the same tendency in the three methods for the whole simulation period. From the Figure 5-14, it could be concluded that all the three methods have the approximately same quality. In the last iteration, the travel cost on three routes are almost the same during the simulation time period, all the travellers on the network have approximate same cost on three routes. This conforms the traffic assignment archives an approximate user equilibrium state after the last iteration.

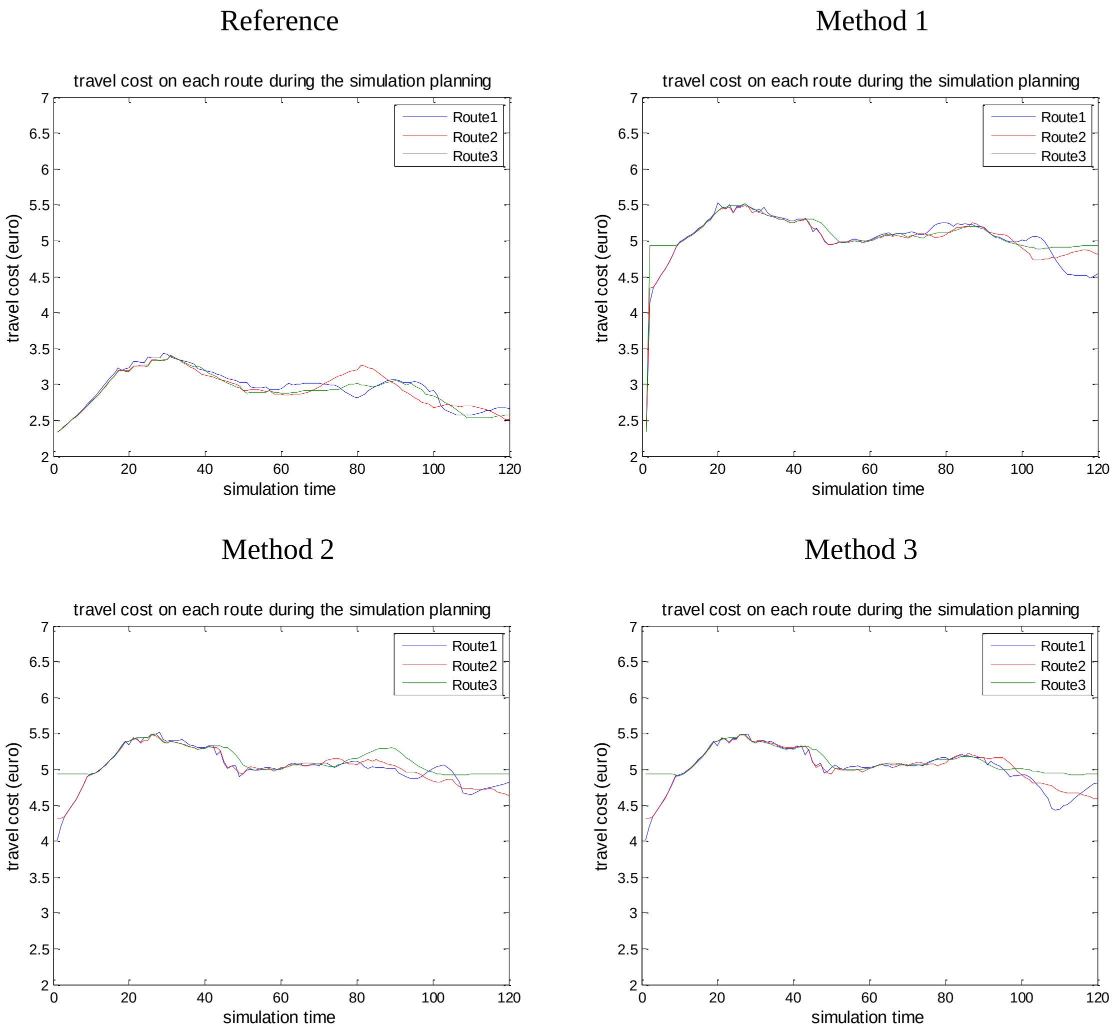

Figure 5-14 Travel cost on three route during the simulation time in Case 1

Other network characteristics such as prevailing speed and vehicle number on each route under three methods can be found in Appendix B.

5.3.2 Aggregate network performance

The numerical network performance from an aggregate level is summarised in Table 5-7. Three criteria were adopted: total travel time, total emissions, and trip completion rate. The percentage comparisons between the MCR and SCR are shown in brackets.

Table 5-7 Network performance in Case 1

	SCR (time only)	MCR 1 (Method 1)	MCR 2 (Method 2)	MCR 3 (Method 3)
Vehicle number (#veh)	12900	12900	12900	12900
Total travel time (hour)	3756.1	3949.7 (+5.15%)	3949.2 (+5.14%)	3933.3 (+4.72)
Total Emission (kg)	60489	58742 (-2.89%)	58936 (-2.57%)	58756 (-2.86%)
In-network vehicle (#veh)	900	1024	1018	1010
Trip completion rate	0.9302	0.9206 (-1.03%)	0.9211 (+0.98%)	0.9216 (+0.92%)

In Case 1, the numerical network performance in Methods 1, 2 and 3 were close to each other's on these three criteria. This result may indicate that the results from all three methods were equivalent in the Case 1 test. Compared with SCR and MCR performance, the total travel time in MCR scenarios was higher than in the SCR scenario, and the trip completion rate in MCR scenarios was lower than in the SCR scenario. Total emissions in MCR was less than in SCR because the emission cost was taken into account in the MCR situation. Because the economic emission speed was around 40–90 km/h, vehicles with lower and higher speeds in this economic range will emit more CO_2 emissions and experience higher emission costs. Thus the MCR will force people to lower their speed in the free-flow condition in order to achieve the best trade-off between time cost and emission cost.

5.3.3 Conclusions for Case 1

Based on the results in the previous two sections, Methods 1, 2 and 3 are quite close to each other. From the functional perspective, all these methods can achieve a convergence state with several iterations. From the technique perspective, Method 1 is expected to perform well and be reasonable. Method 3 is more complicated than Methods 1 and 2 because it has two directions in the user equilibrium iteration and emission approximation during the whole procedure. From the stability perspective, in the normal traffic condition and in the simple road network, all three methods can achieve stability in the end. The results from the normal traffic condition test show that all three methods can reach similar levels of network performance, which means the results of these three methods are almost the same.

5.4 Case 2 (congested traffic condition)

Case 2 represents the congested traffic condition by changing demand profile and network parameters. The route parameters were set as in Table 5-8. In the congested case, the length of the three routes were shorter than normal case. The maximum speed and the jam density on three routes decreased. The higher shape term on Routes 1 and 2 means the decrease slope of speed-density curve become sharply. A small increase in density on the link will cause more speed reduction than before. The demand in the congested case was higher than in the normal case, so there would more vehicles on the network.

Table 5-8 Route parameters for Case 2

	L (km)	U (km/h)	Umin (km/h)	Kj (Veh/km)	Shape term	Iter (number)	VoT (euro/h)	VoG (euro/kg)
Route 1	15	80	5	120	1.8	190	10	0.4
Route 2	18	100	5	150	1.6	190	10	0.4
Route 3	20	120	5	200	1.4	190	10	0.4

(L= length; U= maximum speed intersection; Umin= minimum speed; Kj= jam density; iter= maximum iteration number)

The traffic flow model for each route, based on a modified Greenshields model, is shown in Figure 5-15:

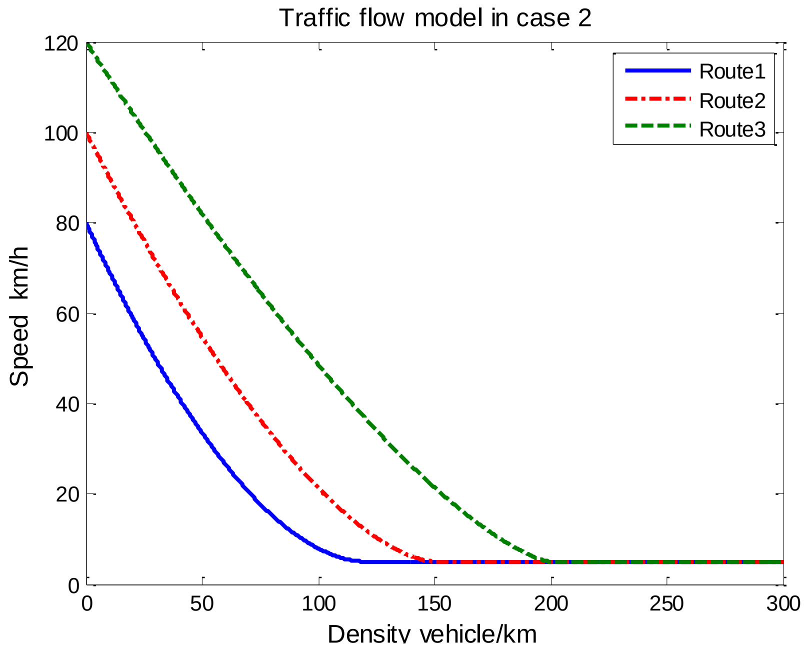

Figure 5-15 Traffic flow model in Case 2

The demand profile in Case 1 and Case 2 are shown in Figure 5-16:

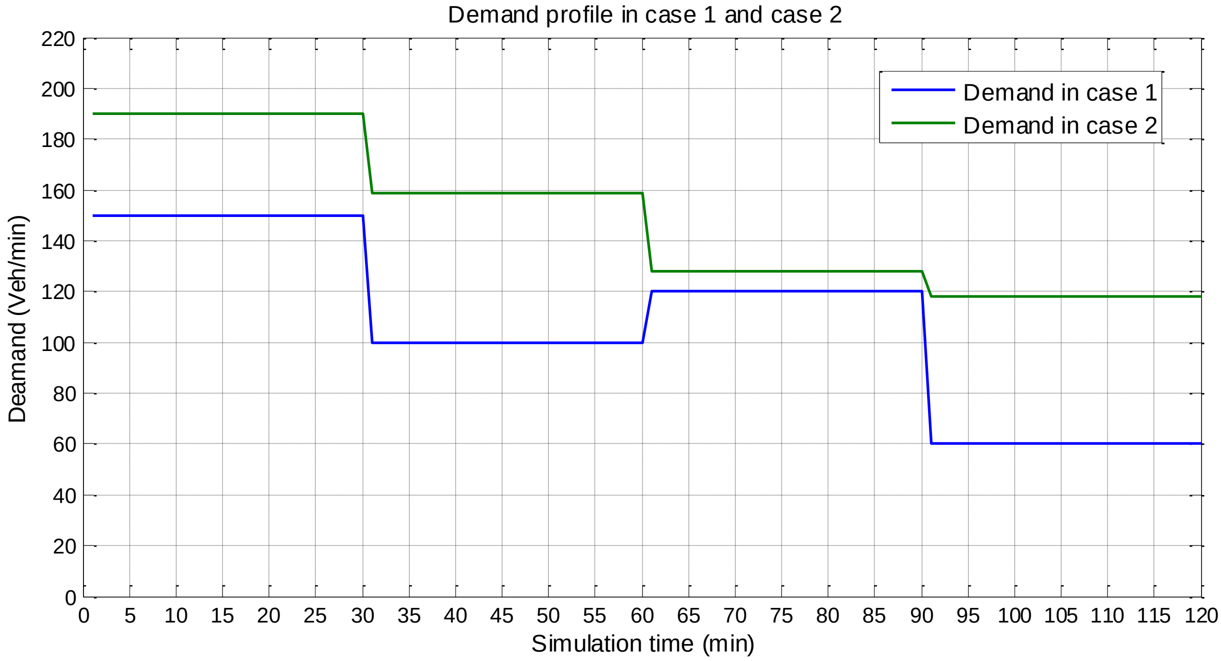

Figure 5-16 Demand profile in Cases 1 and 2

As shown in Figure 5-16, traffic demand in case 2 (Green line) is higher than in case 1 (Blue line). There are more vehicles on the network in case 2.

5.4.1 Convergence check

In the congested traffic condition, the maximum iteration was one for each scenario. The convergence check was the same as in Case 1. The number of iterations in the congested traffic condition was 190, which is more than three times that in Case 1.

Input and output emission check

i. Emission check in Method 1

The statistical summary for Method 1 is shown in Table 5-9.

Table 5-9 Statistic summary of metho1 in Case 2

		Route 1	Route 2	Route 3
Sample size (# of simulation interval)		119	119	119
Difference between input and output emission	Sum Value	3.7494	3.4907	3.7303
	Mean	0.0315	0.0293	0.0313
	Standard Deviation	0.1677	0.1980	0.2297
	Sample Variance	0.0281	0.0392	0.0527
Emission value	RMSE	0.1699	0.1993	0.2308
	CVRMSE	0.0479	0.0494	0.0551

As the statistical summary shows, in the congested traffic condition the CVRMSE for the input and output emissions in Method 1 were around 5%, which means the input and output emissions during each interval were almost the same.

ii. Emission check in Method 2

Statistical summary:

Table 5-10 Statistic summary of method 2 in Case 2

		Route 1	Route 2	Route 3
Sample size (# of simulation interval)		120	120	120
Difference between input and output emission	Sum Value	1.6551	3.5063	-0.7271
	Mean	0.0138	0.0292	-0.0061
	Standard Deviation	0.0340	0.0487	0.0102
	Sample Variance	0.0012	0.0024	0.0001
Emission value	RMSE	0.0365	0.0000	0.0118
	CVRMSE	0.0102	0.0566	0.0028

The statistical summary shows that difference between the input and output emissions was quite small and the CVRMSE for the emission values themselves met the acceptable level.

iii. Emission check in Method 3

The total input emission and output emission were checked, and the results are shown in Table 5-11.

Table 5-11 Input emission and output emission in different runs of Method 3 in Case 2

Run	Emission in	Emission out	Difference
1	0	1416.744	1416.744
2	1416.744	1425.771	9.027
3	1421.257	1427.228	5.971
4	1421.743	1425.275	3.532
5	1423.509	1426.416	2.907
6	1424.962	1422.471	-2.491
7	1422.716	1420.851	-1.866
8	1420.784	1417.816	-2.967
9	1419.3	1420.384	1.084
10	1424.842	1423.988	-0.854

In the table above, the difference between input emission and output emission was reduced, followed by multiple runs. Run 1 was the first run in which the emission cost was zero and can be considered the traditional situation. Then the input emission was updated on every run. The differences in the input and output emissions converged to zero over the multiple runs. These differences for all the three routes are shown in Figure 5-17. Since these differences almost converge in the tenth run, the statistical summary was checked in this run.

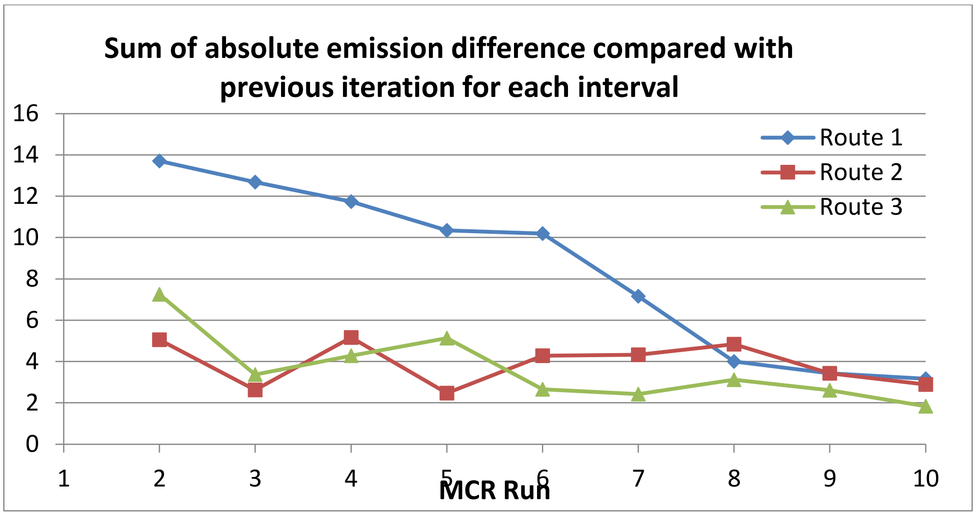

Figure 5-17 Sum of absolute emission difference for each interval in Case 2

Statistical summary:

Table 5-12 Statistic summary for the last run of method 3 in case 2

		Route 1	Route 2	Route 3
Sample size (# of simulation interval)		120	120	120
Difference between input and output emissions	Sum Value	-10.6533	2.1833	0.6160
	Mean	-0.0888	0.0182	0.0051
	Standard Deviation	0.1292	0.0378	0.0251
	Sample Variance	0.0167	0.0014	0.0006
Emission value	RMSE	0.1563	0.0000	0.0255
	CVRMSE	0.0423	0.0418	0.0060

The CVRMSE on three routes was lower than 0.05, which meets the acceptable level. Compared to the results from Method 2, the CVRMSE in Method 3 was lower. This indicates that the convergence of input emission and output emission in Method 3 was of a higher quality than in Method 2 when iterating 190 times.

Duality gap

Compared with Case 1, the duality gap in the congested traffic condition still fluctuated at the sixtieth iteration, but it showed the convergent trend. After 100 iterations, the duality gaps fluctuated within a small range. Although it did not show the absolute convergence at the end, it can still be used as an approximate convergence in DTA.

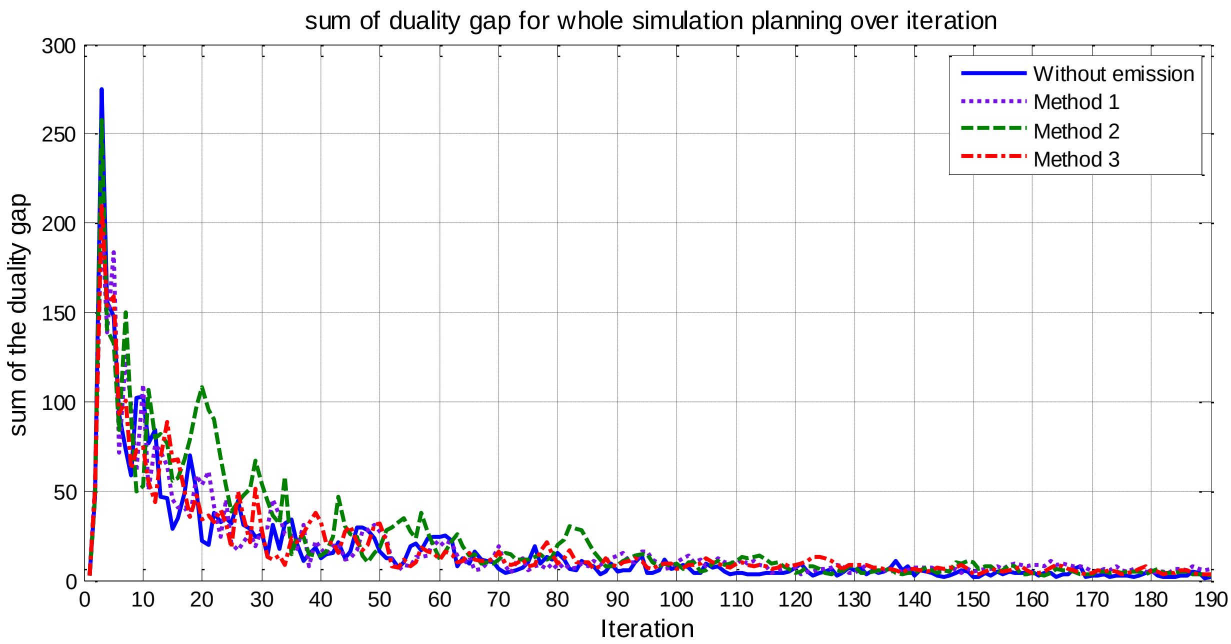

Figure 5-18 Duality gap in Case 2

Method 2 had a higher amplitude at the beginning than Method 1 and Method 3. Looking over all iterations, the duality gaps in all four scenarios show the convergent trend over iterations. All the three methods reach a stable state in the end.

Total travel time and total emission

The simulation iterated 190 times in each method. The total travel time (left figure) and total emission (right figure) on the network for four scenarios are shown in Figure 5-19. Both of these calculations fluctuated slightly at the end and were reasonably close to each other. As shown below, during the first 90 iterations, Method 2 (green line) appeared to have larger oscillations in both total travel time and total emissions. The oscillations on the other three lines were close to each other.

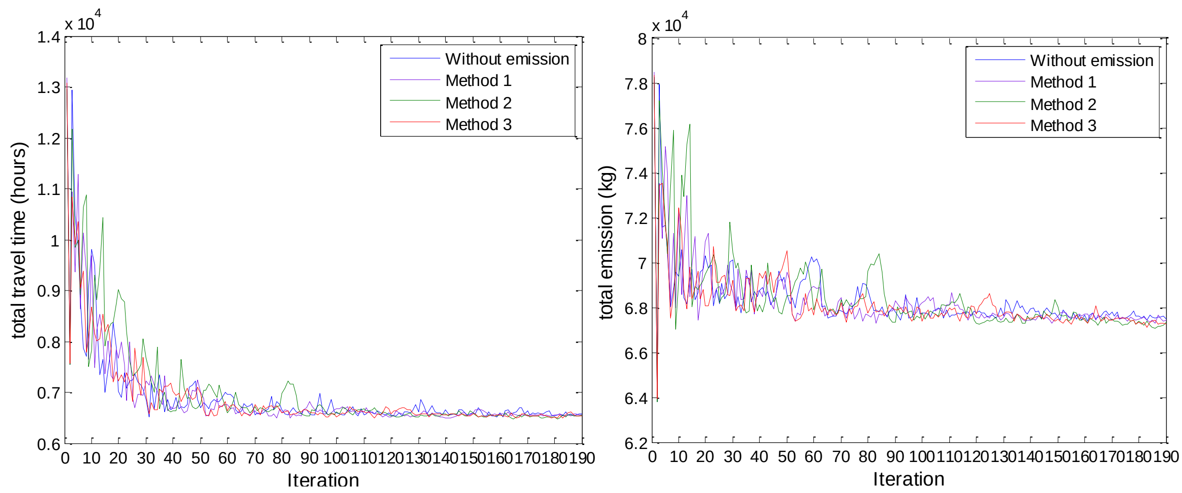

Figure 5-19 Total travel time (left) and total emission (right) over iterations in Case 2

Split rate

The split rates resulting from these three scenarios in Case 2 are shown in Figure 5-20. The absolute split rate difference was calculated based on every two successive iterations and both of them had quite small values at the end. This indicates that traffic flow patterns on the three routes were approximately stable.

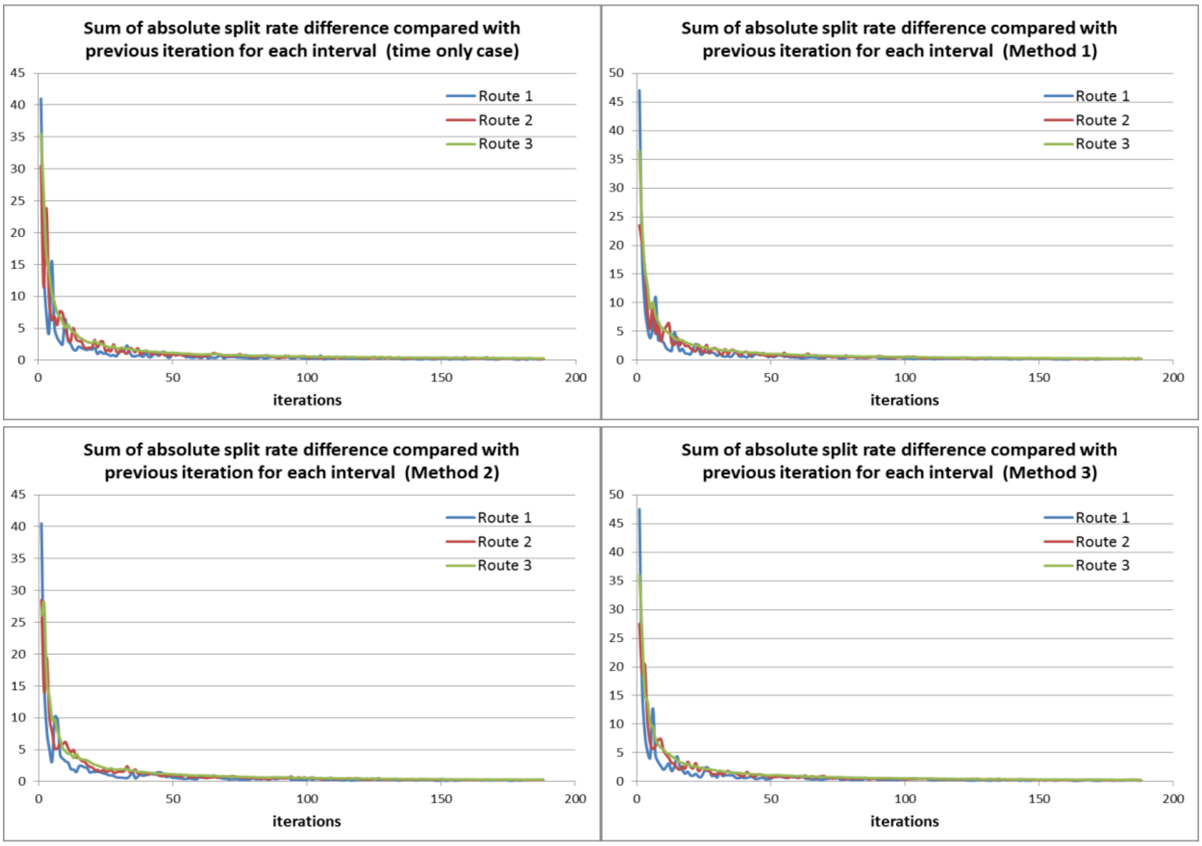

Figure 5-20 Sum of absolute split rate difference in Case 2

The split rate for each route under the three methods for the whole simulation time period in Case 2 are shown in Figure 5-21, Figure 5-22 and Figure 5-23. It is apparent that the split rates on each route under different methods were close to each other and the tendencies of split rate curves for each method on one route were similar; this result is in line with Case 1. These findings completely illustrate that all three methods have the same approximate results with enough iterations for congested traffic conditions.

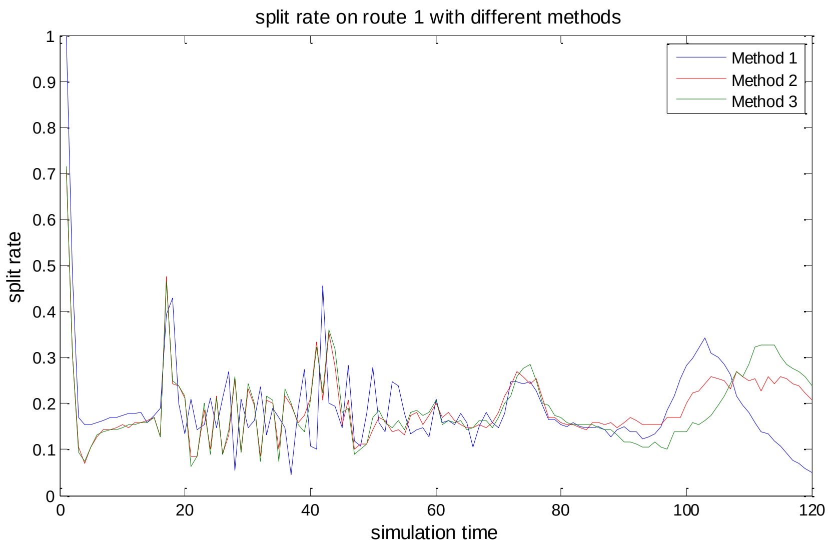

Figure 5-21 Split rate on route 1 under three methods in Case 2

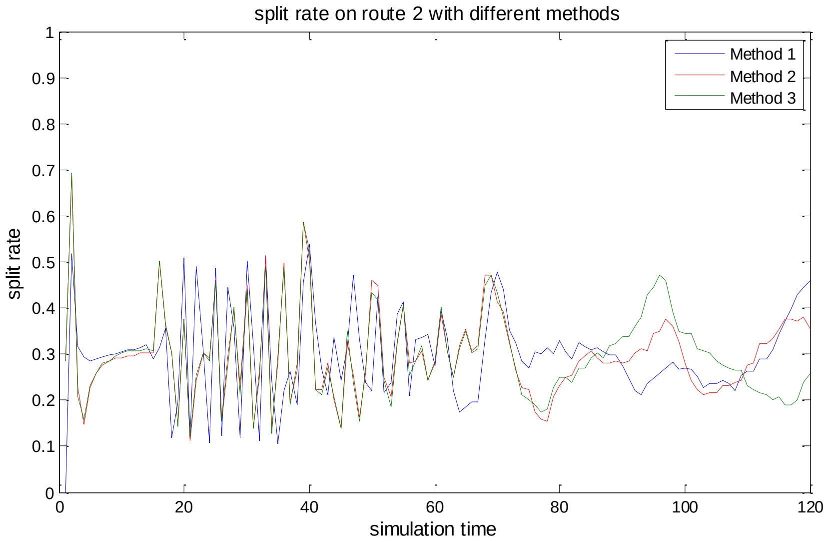

Figure 5-22 Split rate on route 2 under three methods in Case 2

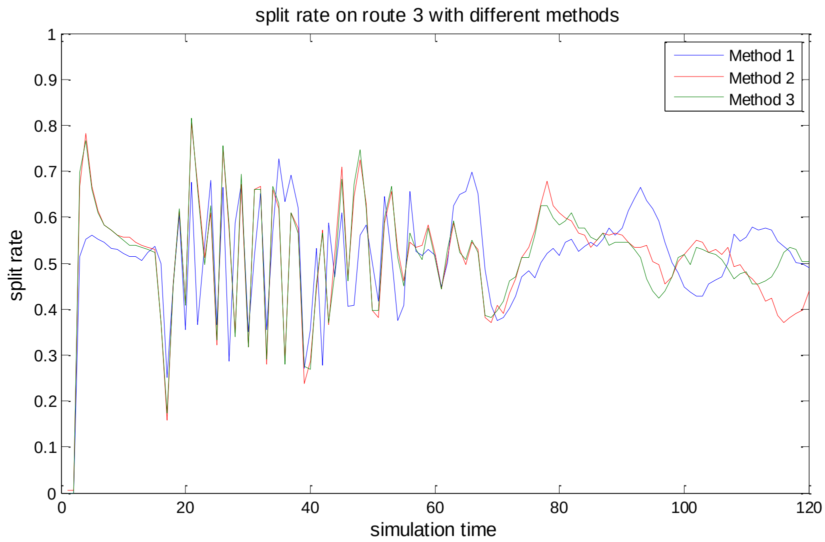

Figure 5-23 Split rate on route 3 under three methods in Case 2

Travel cost

Travel cost on each route at each simulation interval in the approximate user equilibrium state in case 2 are shown in Figure 5-24. Travel cost on the three routes had the same tendency in the three methods for the whole simulation period. This confirms that all three methods could have approximately the same quality under congested traffic conditions. In the last iteration, the travel cost on three routes are almost the same during the simulation time period, all the travellers on the network have approximate same cost on three routes. This conforms the traffic assignment archives an approximate user equilibrium state after the last iteration.

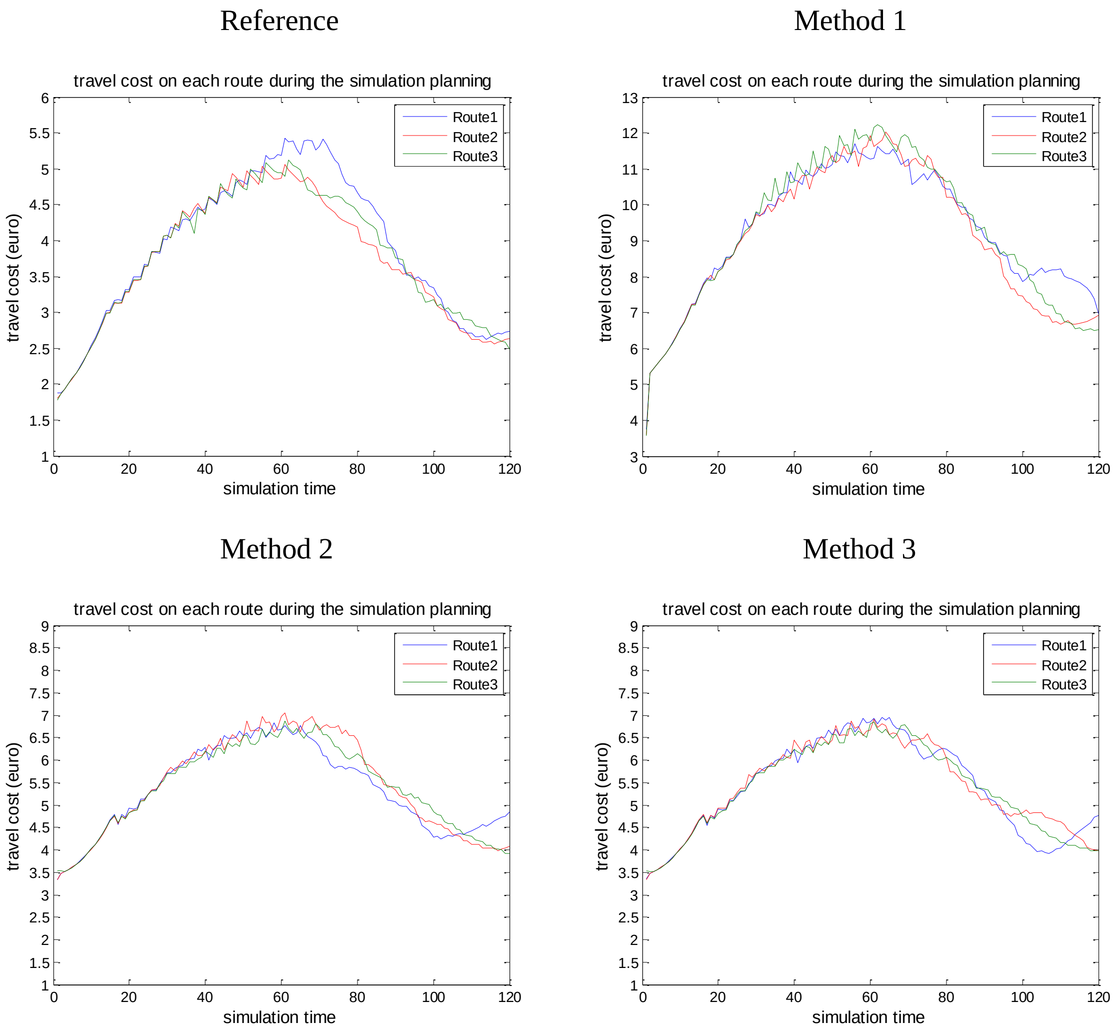

Figure 5-24 Travel cost on three route during the simulation time in Case 2

Other network characteristics such as prevailing speed and vehicle number on each route under three methods can be found in Appendix B.

5.4.2 Aggregate network performance

The numerical network performance on an aggregate level is summarised in Table 5-13. Three criteria were used, as in Case 1. The percentage comparisons between MCR and SCR are shown in brackets.

Table 5-13 Network performance in three scenarios

	SCR (time only)	MCR 1 (Method 1)	MCR 2 (Method 2)	MCR 3 (Method 3)
Vehicle number (#veh)	17850	17850	17850	17850
Total travel time (hour)	6526.4	6549.7 (+0.36%)	6551.5 (+0.39%)	6539.2 (+0.20%)
Total Emission (kg)	67997	67482 (-0.76%)	67333 (-0.98%)	67268 (-1.07%)
In-network vehicle (#veh)	1856	1868	1912	1883
Trip completion rate	0.8960	0.8953 (-0.08%)	0.8929 (-0.35%)	0.8945 (-0.17%)

In Case 2, all three methods almost reached user equilibrium after 190 iterations. The numerical results were similar in all four scenarios. Total emissions in MCR scenarios were slightly less than in SCR because emission cost was taken into account. Compared with the network performance in Case 1, the prevailing speeds in the congested condition were between 30–50 km/h where the emission curve was flat, so the emission reduction was less than in Case 1.

5.4.3 Conclusions for Case 2

The congested traffic condition may need more iterations to achieve convergence than the normal traffic condition. All three methods can reach the stable state and the network performance results did not differ greatly over the three methods. As in Case 1, all three methods showed a convergent tendency over iterations, which means that all the methods can reach a stable state if there are enough iterations in different traffic demand conditions.

5.5 Individual travel cost and marginal travel cost in test network

As introduced in Chapter 4, there are two types of travel costs from different perspectives. In this section, the differences from a dynamic network will be investigated.

In the reference case, only travel time cost is considered in the cost function. In the multi-criteria case, travel cost contains travel time cost and travel emission cost. Let $E = E(v)$ denote the macroscopic emission model as a function of the link prevailing speed. $v = V(k)$ is the Greenshields traffic flow model on the link, where the speed v is the link prevailing speed. Traffic density k is calculated according the definition $k = K(n) = \frac{n}{L}$, where n is the number of vehicles on the link for a simulation interval. In a unit simulation interval, this number of vehicles n can be seen as the flow on the link. The marginal time cost and marginal emission cost for each vehicle in one simulation interval can be calculated as follows.

$$\text{Marginal Emission } (n) = \frac{\partial E}{\partial n} \cdot n = \frac{\partial E}{\partial v} \cdot \frac{\partial v}{\partial k} \cdot \frac{\partial k}{\partial n} \cdot n \qquad \text{Equation 5-8}$$

$$\text{Marginal Time } (n) = \frac{\partial T}{\partial n} \cdot n = \frac{\partial T}{\partial v} \cdot \frac{\partial v}{\partial k} \cdot \frac{\partial k}{\partial n} \cdot n \qquad \text{Equation 5-9}$$

Through the same set in Case 1 and Case 2, network performance in the two methods is shown in Table 5-14 and Table 5-15. Because the reference case only contains time cost, the individual emission cost or marginal emission cost do not have impact on the route choice cost function. The results are same for each kind of time cost, regardless of the type of emission cost that is implemented.

Table 5-14 Network performance in Case 1

		Reference case (time cost only)	Method 1	Method 2	Method 3
Individual time cost & individual emission cost	Total travel time (hour)	3756.1	3949.7 (+5.15%)	3949.2 (+5.14%)	3933.3 (+4.72%)
	Total emission (kg)	60489	58742 (-2.89%)	58936 (-2.57%)	58756 (-2.86%)
Individual time cost & marginal Emission cost	Total travel time (hour)	3756.1	3878.9 (+3.27%)	3885.9 (+3.46%)	3872.5 (+3.10%)
	Total emission (kg)	60489	59342 (-1.90%)	59158 (-2.20%)	59283 (-1.99%)
Marginal time cost & individual emission cost	Total travel time (hour)	3753.8	3931.3 (+4.73%)	3940.1 (+4.96%)	3937.3 (+4.89%)
	Total emission (kg)	60407	58881 (-2.53%)	58911 (-2.48%)	58744 (-2.75%)
Marginal time cost & marginal emission cost	Total travel time (hour)	3753.8	3876.2 (+3.26%)	3881.6 (+3.40%)	3847.6 (+2.50%)
	Total emission (kg)	60407	59128 (-2.12%)	58973 (-2.37%)	59311 (-1.81%)

Table 5-15 Network performance in Case 2

		Reference case (time cost only)	Method 1	Method 2	Method 3
Individual cost	Total travel time (hour)	6526.4	6549.7 (+0.36%)	6551.5 (+0.38%)	6539.0 (+0.19%)
	Total emission (kg)	67997	67482 (-0.76%)	67333 (-0.98%)	67268 (-1.07%)
Marginal Emission cost	Total travel time (hour)	6526.4	6661.7 (+2.07%)	6704.8 (+2.73%)	6680.0 (+2.35%)
	Total emission (kg)	67997	68216 (+0.32%)	67870 (-0.19%)	67945 (-0.08%)
Marginal time cost	Total travel time (hour)	6516.3	6551.8 (+0.54%)	6540.3 (+0.37%)	6536.0 (+0.30%)
	Total emission (kg)	67975	67523 (-0.66%)	67439 (-0.79%)	67321 (-0.96%)
Marginal time cost & marginal emission cost	Total travel time (hour)	6516.3	6623.6 (+1.65%)	6683.3 (+2.56%)	6715.0 (+3.05%)
	Total emission (kg)	67975	67941 (-0.05%)	67736 (-0.35%)	67898 (-0.11%)

Table 5-14 and Table 5-15 show the network performance in the reference case and the three methods with different cost types. The reference case with individual cost is equal to the traditional user equilibrium state with time cost only, and the reference case with the marginal time cost should be the system optimum state with time cost only in the traditional assignment. The numbers in brackets in the three methods show the relative percentage changes with corresponding reference cases. Compared to the results from reference cases, the total emissions were improved with the composite cost function in the three methods. These improvements are more obvious in normal traffic conditions than in congested conditions; since the prevailing speeds in congested conditions range from 30–50 km/h where the slope of the emission curve is flat, there is less space to improve. Network performance using the three methods with different types are close to each other, especially in normal traffic conditions. This will be further analysed in the next section. The increase in total travel time occurs because the emission function is a convex function with the link prevailing speed and people may lower their speed in the free-flow part in order to find an optimal trade-off between time cost and emission cost.

5.6 Method assessment

There are three methods for incorporating travel time cost and travel emission cost, and each method has four combinations with different types of cost. In total, there are 12 combinations in this section. Several criteria are proposed to assess the methods: technique criteria (stability, iterations to converge), quality criteria (quality of the results, split rate and robustness), operational criteria (emission update, implementable in other simulations) and policy criteria (perspective of management, realism).

In this thesis, stability means the ability to achieve a stable network traffic state, which can be seen through the duality gap. Iterations to converge means the number of iterations needed to reach the consistent stable state. The duality gaps in all three methods exhibit a decreasing trend with some fluctuations, especially in Case 2. An index was set up to represent the reduction of the duality's value and amplitude. In this thesis, this index was defined by a variant of mean squared error, which is calculated by the following equation:

$$VMSE = \frac{\sum DG_n^2}{n} \quad \text{Equation 5-10}$$

Where: DG is the duality gap values and n is the iteration numbers

If the continuous percentage changes of VMSE are less than 5% in Case 1 and 1% in Case 2 for all iterations after one specific iteration are satisfied, the specific iteration number is the value of iteration numbers to converge.

Method 1 is the method that is closest to a logical and ideal methodology and to real-time traffic management. The quality of the results can be measured by comparing the results from Methods 2 and 3 to Method 1.

The split rate here is the sum of the absolute split rate difference compared with the previous iteration for each interval. For each scenario, it is the sum value of 120 counts. If the sum of the split rate changes close to zero, it means the method can reach an approximate stable state (i.e. there are not many travellers who change their routes over the continuous iterations). This value is related to iteration times: more iteration times equal fewer split rate changes.

Robustness means that a system does not break down easily or is not wholly affected by a single application failure. It also refers to a model or system's ability to effectively perform when its variables are changed. This feature can be tested by the duality gap and the quality of the results when the traffic conditions or the parameters (VoT and VoG) vary. If the method can still reach a stable duality gap with different parameters and the quality of the results is in line with the previous results, then the method itself is robust.

The operational criteria show the operating characteristics of the three methods. Emission update is the way to update the emission cost. There are two methods: inner update and outer update. Inner update means the emission updates in each intermediate stage during the simulation process. The outer update means that the emission update is not included in the traffic assignment model itself and the emission updates by using the final state from the simulation process.

The implementable in other simulation means the level of complexity with which the method is applied with the current traffic simulation programmes. Most current traffic simulation tools are well packaged and it is difficult to make some modifications to these models' simulations.

The perspective means the departure point for using each different type of travel cost. As mentioned before, there are four travel cost types combinations in each method. The individual travel cost is based on the users' perspectives and the marginal travel cost is based on the road authorities' perspectives or the whole system's perspective. This is related to the objectives of traffic management.

In this thesis, these four combinations of the cost types can also be used to represent four different kinds of users. Realism refers to whether these four groups of travellers exist in reality. A detailed introduction of each kind of traveller can be found in Section 4.4.

The results are listed in Table 5-16.

Table 5-16 Methods assessment form

		Method 1				Method 2				Method 3			
		InT+InE	InT+MaE	MaT+InE	MaT+MaE	InT+InE	InT+MaE	MaT+InE	MaT+MaE	InT+InE	InT+MaE	MaT+InE	MaT+MaE
Stability		yes	yes	yes	yes	yes	yes	yes	yes	yes	yes	yes	yes
iterations to Convergence		17 (93)	18 (96)	17 (95)	18 (95)	18 (97)	19 (98)	18 (98)	18 (98)	17 (96)	15 (97)	18 (96)	15 (97)
Quality	Total travel time	0	0	0	0	-0.01% (0.03%)	0.18% (0.65%)	0.22% (-0.17%)	0.14% (0.9%)	-0.41% (-0.16%)	-0.17% (0.27%)	0.15% (-0.24%)	-0.74% (1.38%)
	Total emission	0	0	0	0	0.03% (-0.22%)	-0.31% (-0.51%)	0.05% (-0.12%)	-0.26% (-0.30%)	0.02% (-0.32%)	-0.10% (-0.40%)	-0.23% (-0.30%)	0.31% (-0.06%)
	Completion rate	0	0	0	0	0.05% (-0.27%)	0.02% (0.02%)	-0.40% (-0.32%)	-0.12% (-0.25%)	0.11% (-0.09%)	0.20% (0.11%)	0.04% (0.10%)	0.46% (-0.27%)
Sum of split rate		<0.5 <0.3	<0.5 <0.3	<0.5 <0.3	<0.5 <0.3	<0.5 <0.3	<0.5 <0.3	<0.5 <0.3	<0.5 <0.3	<0.5 <0.3	<0.5 <0.3	<0.5 <0.3	<0.5 <0.3
Robustness		yes	yes	yes	yes	yes	yes	yes	yes	yes	yes	yes	yes
Emission update		inner	inner	inner	inner	inner	inner	inner	inner	outer	outer	outer	outer
Implementable in Simulation		–	–	–	–	–	–	–	–	+	+	+	+
Perspective		user	User & authority	User & authority	authority	user	User & authority	User & authority	authority	user	User & authority	User & authority	authority
realism		++	+	–	+	++	+	–	+	++	+	–	+

- Numbers without brackets are results from the Case 1, numbers in brackets are results from Case 2.

Through the duality figures in both the normal traffic condition and the congested traffic condition, all three methods can reach a stable state. In general, all three methods had similar iteration numbers. The iterations to convergence prove that Method 2 needs more iterations to reach convergence but the differences are not so great.

The quality of the results contains three components: total travel time, total emissions and completion rate. As shown in Table 5-16, the percentage changes compared with Method 1 were lower than 1% (only the total travel in Method 3, Case 2 is 1.38%). This means Methods 2 and 3 had results similar to Method 1. Judging the quality of the results, all three methods in this simple network test could be considered to be similar.

The sum of the absolute split rate changed for each simulation interval. In both the normal and congested cases, the values were less than 0.5, which is the sum of 120 counts. It shows that for each simulation interval, the changes of split rate were almost zero, which illustrates the convergence of each method.

With different demands and different VoT and VoG, the duality gap for all three methods can reach a stable state. The quality in Methods 2 and 3 is quite close compared to that in Method 1, so the robustness of each method was sufficient. (The figures can be found in Appendix B).

As introduced in Chapter 4, Method 1 updated the emissions at each simulation time interval and Method 2 updated the emissions following the user equilibrium procedure. These means both Methods 1 and 2 applied the inner loops to calculate and update the emissions. In this inner emission calculate and update method, we needed to make some modifications to the source code, which were hard to implement. Method 3 applied the outer loops to calculate and update the emissions. From an applicability perspective, Method 3 could be easily implemented with other traffic simulation software. Therefore the lack of implementable features in Methods 1 and 2 is a drawback and their presence in Method 3 is an advantage.

The choice to use individual travel cost and/or marginal travel cost is based on the traffic management objectives. Since it is in the nature of road users to only consider their individual travel costs, using both individual travel cost and individual emission cost reflects the users' perspective. This kind of road user is quite common in the real world. In addition to their own travel time and emissions, some environmentally friendly travellers also consider the extra emissions that they induce in other road users. In this case, adopting individual travel cost and marginal emission cost reflects both users' and road authorities' perspectives. This kind of road user does exist in the real world, but there are few of them. Using the marginal travel time cost and individual emission cost can also reflect both the users' and authorities' perspectives, but this sort of traveller rarely exists in reality. Using both marginal cost in travel time and emissions is reflects authorities' perspectives and can lead to optimal solutions for traffic assignment, but it is hard to induce users to behave in this way. This kind of traveller is rare in the real world, unless the road authority applies some enforcement measures.

The choice of cost combinations should be based on traffic management objectives. This thesis aims to investigate the impact of drivers considering their CO_2 emission cost on network performance. On the other hand, some technique limitation existed to calculate the marginal time cost and emission cost with the Dynasmart-P and TNO macro emission model. Therefore, individual travel time cost and individual emission cost were used in this thesis.

5.7 Chapter conclusion

The objective of this simple network test was to discover which methods were feasible and suitable for Dynasmart-P. The results showed that all three methods can reach the stable state and that network performance is almost the same in both cases in the simple network. From a functional perspective, all three methods can be used to answer the main research question. From implementable perspective, Method 3 is easy to combine with current traffic simulation tools while Methods 1 and 2 need to access the traffic model and make some modifications. As mentioned in Chapter 2, mesoscopic traffic simulation are preferred and Dynasmart-P was selected in this multi-criteria study. Since Dynasmart-P does not integrate the emission calculation and it is difficult to access its core traffic flow model, we selected Method 3, which has one simulation state lag method and an outer emission update method. If future simulation tools integrate the emission calculation within the traffic model, Method 1 is recommended for this sort of research.

The objective of this thesis is to investigate network performance when incorporating travellers' perceptions of environmental concerns into the route choice cost function. Previous studies (eg. Gaker et al.2010) on the prediction and influence of travellers' behaviour regarding personalised information and social influence have found that personal and trip-specific information regarding greenhouse gas emission has significant potential for increasing sustainable behaviour. The social influence such as CO_2 emission cost can be transformed to travellers' personal costs through the VoG, and it can have some impacts on travellers' route choice decisions. Their surveys indicated that people exhibit sustainable behaviour when they are provided with context-specific and person-specific information on the environmental impact of their actions.

Applying the different kinds of cost type represent the different traffic management perspectives, either user or system. Dynasmart-P deals with the marginal travel time in an approximation way and the TNO macro emission model calculates emission rate curves based on the different lookup tables. Thus the marginal time from Dynasmart-P is not accurate and the marginal emissions on the link are not available in the current version of TNO macro emission model.

In general, travellers make their decisions based on their own costs. Since marginal costs are not available in the simulation and emission models, Method 3 with individual costs was selected for this case study. We used Method 3 to incorporate the individual travel time cost and individual travel emission cost into a simulation model and to link the control objectives and travellers' experiences back to the simulation core, so that network performance could be corrected and measured.

6. Application to real network: Helmond case study

In contrast to the analytical approach, real test, this thesis chose a simulation approach as the first trail to evaluate the effects of MCR on DTM. This chapter discusses how MCR methodology was applied to a study area located in the city centre of Helmond in the province of North Brabant in the southern Netherlands. The case study network was built in Dynasmart-P, in line with the real physical characteristics of the study area.

The following questions will be answered in this chapter: How should the case study experiments be carried out to test the impact of applying MCR? (Section 6.1); which indicators are preferred to represent the network performance? (Section 6.1); what is the effect of using different random seeds? (Section 6.2 and Section 6.3); how does network performance change when traffic CO_2 emission cost is added into travellers' routing? (Section 6.3 and Section 6.4); what are the network performance impacts when the cost components' weight changes? (Section 6.4).

The purpose of these experiments was to investigate the impact of composite cost on network performance. The case study setup is first introduced in this chapter. Then the SCR and MCR case experiments and results analysis are described, followed by a sensitivity analysis of the scaling factor between VoT and VoG. Finally, the results and conclusions of the MCR by composite route choice cost function are discussed.

6.1 Case study setup

6.1.1 Network description

This section describes the case study's traffic network. The case study region covers an area of 7.8 km^2: 2.0 km from south to north and 3.8 km from west to east. A general map of this area is shown in Figure 6-1.

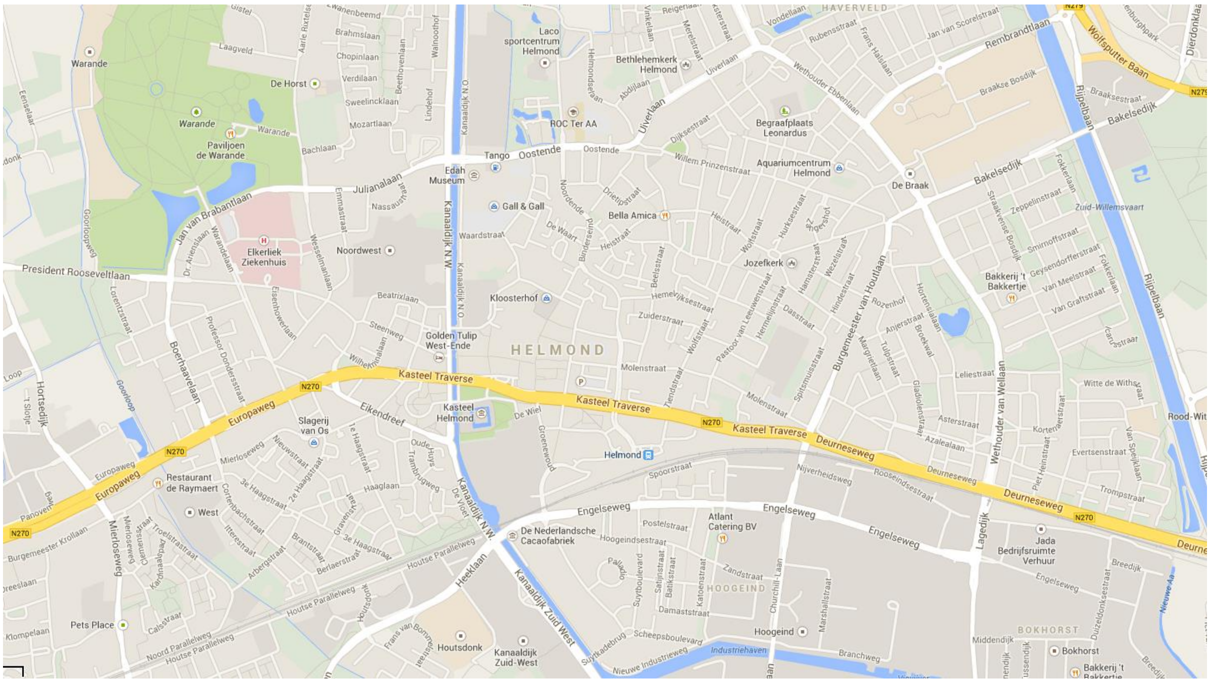

Figure 6-1 Study area map (via Google map)

This area includes one freeway (N270), which runs across Helmond's city centre from west to east, two urban beltways in the north and south, and several urban roads. Table 6-1 summarises the major roads.

Table 6-1 Major roads in the case study area

Road sections	Function	Speed limit (km/h)
N270	Freeway	110
Boerhaavelaan-Oostende-Wethouder van Wellaan	Urban-belt way	50
Binnendongenstraat-Heeklaan-Engelseweg-Lagedijk	Urban-belt way	50
Eikendreef	Arterial road	50
Kanadldijk N.W.	Arterial road	50
Churchill-Laan	Arterial road	50
Burgemeester van Houtlaan-Bakelsdijk	Arterial road	50

The basic network was built in Dynasmart-P, based on the eCoMove project by TNO. The links in the simulation network were based on the roads in the real network. Figure 6-2 shows the basic network features in Dynasmart-P: there were 78 zones, 171 nodes and 378 links. Two links were usually connected between two nodes by a two-direction road. Each link could represent corresponding road characteristics by setting parameters such as the link type, length, number of lanes, speed limit, service flow rate or saturation flow rate. These parameters mirrored the real situation.

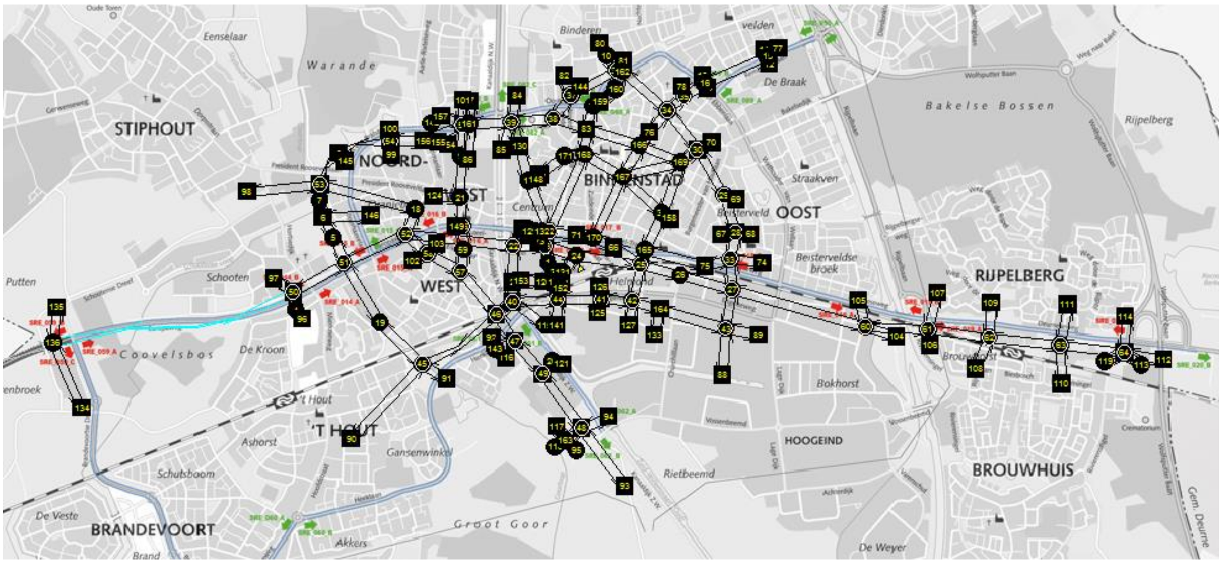

Figure 6-2 Research network in Dynasmart-P

Traffic flows were obtained from loop detectors on the roads and flows were converted to a 2 hours OD matrix using an OD estimate programme. For 78 zones in the Helmond network, the total number of vehicles was around 31,000 during the two peak hours in the morning. The user class percentages were 100% for UE class with the iterative consistent assignment (definitions of each class were introduced in Chapter 3). In Dynasmart-P, the maximum iteration number for user equilibrium is 40 and the convergence threshold is 100.

The simulation period is the morning peak hours from 8:00 till 10:00 (workday). The 120 minutes simulation planning horizon follows the 6 seconds simulation interval in Dynasmart-P, which means the vehicles and the network states are updated every 6 seconds.

The case study included five link traffic flow models that responded to different road types. The parameters for these models are listed in Table 6-2. Flow model 1 was a one-regime modified Greenshields traffic model; the other four were all two-regime modified Greenshields traffic models.

Table 6-2 Traffic flow models in the case network

Flow model	1	2	3	4	5
Regimes	1	2	2	2	2
Breakpoint density	30	-	-	-	-
Intercept speed	92	-	-	-	-
Minimal speed	6	10	10	10	10
Jam density	200	160	120	90	90
Shape term	2.0	1.0	2.0	3.0	3.0

6.1.2 Basic input file

The link characteristics and traffic models used in the reference case were introduced in Section 6.1.1. The detailed intersection control time plan for all the signalised intersections in the case study area were provided by Peek Traffic. However, there were some obvious errors or missing data that were corrected manually according to experience. For instance, the green time was longer than 3-5 minutes in some directions during one cycle time or there was a zero-second clearance time. Such settings would cause severe spillback or unsafe conditions that are unrealistic.

The OD matrix was generated by an OD estimate programme (Chen, 1993-2013) based on the traffic flow counts on the links. The morning peak hours are used in this study. The final OD demand contained two hours and 10 time slices which means there are 12 OD matrices and each of them represents 10 minutes of traffic demand on the network.

The iterative assignment method was used to close the real user equilibrium state and the maximum iteration was 40. Other factors, such as K-shortest path calculation and update interval, freeway bias or indifference band, were set as default values respectively.

6.1.3 Simulation time period

In the case study, the vehicles load on the network by using a time dependent O-D demand matrix. It has 12 demand matrixes for every 10 minutes, thus in total, we have 2 hours O-D demand. In Dynasmart, vehicle's route routing according to the traffic assignment and the shortest path calculation. The generalised cost function is not only based on travel time, but also calculated by generalised cost function. Dynasmart-P can capture the time-dependent costs for different link types. The link-based emission cost from the TNO macro emission model is a time-dependent emission cost. Both travel time cost and emission cost comprise the composite generalised travel cost.

When the vehicles generate on the network, they calculate the K-shorted path from their origin to their destination according to all the alternative routes' costs based on the link cost at that time. There is no predictive cost information in the current simulation method, that is to say there are two cost maps on the network at each simulation time, one is the travel time cost map for all the links and other is the emission cost for all the links. Vehicles choose their route according to the least generalised cost combination of all the links in each alternative route to their destination. In Dynasmart-P, vehicles can update their shortest path tree at each update simulation interval, which was every 30 seconds in this case study. This updating also moves them towards to their destination, according to the cost maps at the update simulation interval. Thus we used a two-hour simulation time period; even if the vehicles were generated at the last minute, they would make their route choice decision towards their destination for all the link costs in each alternative route at that time.

On the other hand, a traffic state is not realistic if there are longer simulation times than the demand OD matrix. Without the demand, the traffic state on the link will change because no more vehicles will enter the network. This has some influence on the Greenshields traffic flow model applied in Dynasmart-P. Meanwhile, if there are no target vehicles leaving the network for 10 minutes, Dynasmart-P will automatically stop. In a complicated urban network, some serious congestion or intersection overflow can lead to a full gridlock. In this case, extension of the simulation time period will be useless because it will automatically stop and some of the vehicles will be left on the network.

In summary, we applied a two-hour simulation time period based on the routing algorithm and the operational features of Dynasmart-P.

6.1.4 Experiment scenarios

Scenario 1: reference scenario

Scenario 1 is the traditional traffic assignment and was considered the reference scenario. In this scenario, vehicles are assigned on the network based only on travel time cost. Scenario 1 is a control experiment for the MCR experiments.

Scenario 2: multi-criteria routing scenario

Scenario 2 is the MCR scenario which contains travel time cost and travel emission cost in the cost function. These two components are summed through the transfer parameters VoT and VoG. Normally, there are no uniform values for VoT and VoG because they vary with different traveller characteristics. In this thesis, all the travellers obeyed the user equilibrium behaviour with the same VoT and VoG. The different scaling factors were used for the sensitivity analysis.

6.1.5 Performance indicator

The objective of this research was to investigate the impact of adding CO_2 emissions in the cost function on the network performance. Therefore, performance indicators were needed to quantify and analyse the impact of this MCR. Four major measures of effectiveness for the evaluation of network situations under different scenarios were used: average travel time, average trip distance, average CO_2 emission and trip completion rate.

Average travel time (min/vehicle)

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 the running time and stop time.

Average trip distance (mile/vehicle)

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.

Average CO_2 emission (kg/vehicle)

Traffic emissions on the network are calculated from TNO macro emission model, the average CO_2 emission is the average of CO_2 emission per vehicles.

Trip completion rate (percentage)

The number of exit network vehicles divided by the number of total vehicles during a fixed period equals the trip completion rate. A higher trip completion rate means there is a lower congestion level and more vehicles arrive at their destinations during the simulation period.

This chapter introduced the case study designs. The next chapter will present the simulation results from these case study designs.

6.1.6 Scaling factor between Value of Time and Value of Green

This research used two components in the general cost function (introduced in Section 5.1.3). Both of them can be transferred to each other or to monetary units through the factors of VoT and VoG. In addition to the exact time cost and emission cost, which are derived from the travel time function and emission function, the general cost is also influenced by VoT and VoG. The scaling factor is used to represent the relationship between them and is calculated as VoT over VoG. If the scaling factor is the same, the weight of travel time cost and emission cost is also the same for different sets of VoT and VoG pairs. The scaling factor can be used for sensitivity analysis. The scaling factors and the corresponding VoT and VoG in this research are listed in Table 6-3.

Table 6-3 Scaling factors and corresponding VoT and VoG

VoT/VoG	VoT (Euro/hour)	VoG (Euro/kg)
0.001	10	10000
0.01	10	1000
0.1	10	100
0.2	10	50
0.5	10	20
1	10	10
2	10	5
5	10	2
10	10	1
25	10	0.4
37.5	15	0.4
50	20	0.4
75	30	0.4
100	40	0.4
500	200	0.4
1000	400	0.4
Infinite	10	0

6.1.7 Assumptions for the model

This research began with several assumptions:

- Only car traffic was considered in the model and all the vehicles were user equilibrium class.
- The generation links had more lanes than in reality to make the traffic load more smoothly.
- All the vehicles were considered to be homogenous and to have the same VoT.
- Vehicles were assigned on the network based only on the time cost.
- The random seeds were same in both cases.

6.1.8 Model calibration

As mentioned in the section 6.1.1, the case study adopted a network from the TNO eCoMove project. The network link characteristics and traffic control strategies at the signalised intersections were already calibrated before the experiments. Some errors or unreasonable values were identified and adjusted. The main processes are shown in Figure 6-3.

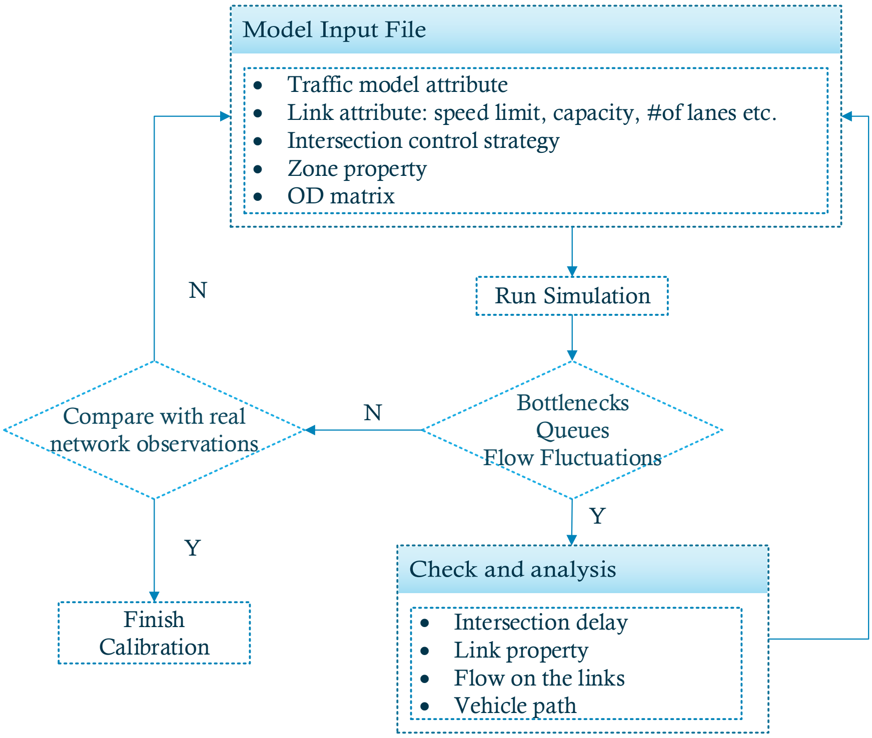

Figure 6-3 Network calibration structure

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 (Bezembinder, 2009). It is not easy to calibrate a simulation model to an exact real situation, because the vehicle composition in the simulation is not the same as the in real network and signal timing has a big influence on vehicle assignment in the simulation.

Three indicators were checked after running the simulation: bottlenecks, queues and flow fluctuations. If some unexpected indices are observed from the simulation result, then we need to check and analyse the reasons for these unexpected phenomena. Some changes should then be made to the input files and the simulation should be run again until the results are close to the real network observations.

After trials and repetitive adjustments, the final network model can better mimic the real network traffic conditions on critical links. Then it is successfully prepared for the case study. This calibrated network was used in both the reference case and the multi-criteria case.

6.2 Reference case experiments

6.2.1 Random seeds in Dynasmart-P

In Dynasmart-P, the vehicles' loading process is determined probabilistically via the use of random seed number. Identical scenarios with identical random number seeds will yield the same results. The random seeds have some effect on the vehicle fractional generation values, which may cause some uncertain variations in the final network statistic summary. The more random seeds used in the simulation, the more accurate it is for average results. Considering the trade-off between accuracy and efficiency, this study used 10 different random seeds that were generated randomly in Excel. The network performance indicators were examined for different random seeds in both the reference case experiment and the MCR experiment.

6.2.2 Reference case experiment results

In the reference case experiment, 10 parallel experiments with different random seeds were investigated. These random seeds were generated in Excel. As mentioned in the model assumption, vehicles were homogeneous within the same vehicle class (UE class) and VoT. Vehicles were assigned on the network using only the time cost, which could be considered a single-criterion routing (SCR). In SCR experiments, the different VoT have the same results. In order to make parallel comparisons with MCR experiments, VoT in the SCR experiments was set at €15/hour. The random seeds were also the same in both case studies. The iterative assignment algorithm was applied to achieve user equilibrium in the simulation. Network performance after the simulation is shown in Table 6-4.

Table 6-4 Network performance in reference experiments

Random Seed Number	Average Travel Time (mins)	Average Trip Distance (miles)	Average CO_2 Emissions (kg/vehicle)	Trip Completion Rate	Total Vehicle Number
179	8.217	1.597	0.957	91.28%	30413
923	8.000	1.616	0.957	91.84%	30305
1073	7.983	1.601	0.960	92.18%	30292
1232	7.851	1.619	0.949	91.49%	30275
1391	7.906	1.594	0.952	92.06%	30362
1601	8.193	1.597	0.949	92.13%	30446
1942	7.979	1.612	0.939	92.11%	30408
1586	8.201	1.604	0.971	91.96%	30232
1846	8.046	1.616	0.969	91.13%	30240
2012	8.107	1.601	0.943	91.38%	30417
Average	**8.048**	**1.606**	**0.954**	**91.75%**	**30339**

On the average level of reference case scenario, there are 30339 vehicles were generated on the network and 91.75% vehicles arrived at their destinations during the simulation period. The trip completion rate indicates the network's congestion level: the less congestion on the network, the higher the trip completion rate in the end. The average vehicle travel time was 8.048 minutes and the average vehicle trip distance was 1.606 miles. Considering that the area of Helmond is 2.0 km from south to north and 3.8 km from west to east, this average trip distance is quite reasonable. The total CO_2 emissions on the network divided by the total number of vehicles on the network equals the average CO_2 emissions per vehicle. In the reference case, the average vehicle CO_2 emission was 0.954 kg/vehicle.

Different VoT settings were also tested in the reference case. The same network performance results confirm that VoT does not influence network performance in the reference case.

6.3 Multi-criteria routing experiments

MCR experiments were carried out to test changes in network performance when composite costs were applied in the cost function. As mentioned in Chapter 5, Method 3 with individual travel time and individual emission cost was used for the MCR experiments. The initial VoT was €15/hour and VoG was €0.4/kg. This section will first discuss the MCR experiments design. Then the network performance from 10 random seeds will be illustrated. The results evaluation will be provided in the end of this section.

6.3.1 Multi-criteria routing experiments design

The MCR simulation-based optimisation in this research consists of the following steps, followed using a bi-level approach:

1) Construct a composite cost, including multi-criteria such as travel time, cost, and emission. The weight to each criterion is determined by the scaling factor. The cost uses Value of Time and Value of Green to travel time and CO_2 emission to convert:

$$\mathrm{COST} = \mathrm{VoT} \cdot \mathrm{TravelTime} + \mathrm{VoG} \cdot \mathrm{CO_2\ Emission} \qquad \text{Equation 6-1}$$

2) Perform a dynamic simulation with this composite cost (equilibrium assignment) and obtain relevant output for control objectives, such as throughput, cost and emission;

3) Check the convergence of between the input and output objectives. If the result is convergent, then continue to evaluate the network performance; otherwise Update the cost based on newly performed simulation and then compute an averaging composite cost of previous one and newly-updated one;

4) Iterate from the previous step within the same simulation;

5) Evaluate the network performance

6.3.2 Network performance results

Network performance should be investigated after achieving a consistent framework since the simulation has delayed feedback. A consistent framework means that the traffic states on the network are stable between two successive runs. An example of a detailed convergence check can be found in Appendix D. It is hard to achieve absolute convergence on a larger-scale network. Considering the trade-off between accuracy and efficiency, the maximum update iteration was 30 in this case study. The results were obtained through the approximately convergent state.

There were also 10 parallel MCR experiments with the same random seeds as in the SCR experiments. The VoT in MCR experiments was set at €15/hour and the VoG was €0.4/kg. The iterative assignment algorithm was applied to achieve user equilibrium in the simulation. Network performance after the simulation is shown in Table 6-5.

Table 6-5 Network performance in MCR experiments

Random Seed Number	Average Travel Time (mins)	Average Trip Distance (miles)	Average CO_2 Emissions (kg/vehicle)	Trip Completion Rate	Total Vehicle Number
179	7.590	1.625	0.923	94.25%	30328
923	7.537	1.636	0.928	93.91%	30241
1073	7.518	1.620	0.929	94.33%	30301
1232	7.467	1.638	0.921	93.68%	30353
1391	7.542	1.620	0.926	93.71%	30434
1601	7.534	1.624	0.911	94.79%	30313
1942	7.431	1.637	0.912	94.51%	30392
1586	7.611	1.621	0.938	94.43%	30330
1846	7.556	1.643	0.931	93.68%	30500
2012	7.497	1.618	0.915	93.32%	30336
Average	**7.528**	**1.628**	**0.923**	**94.06%**	**30353**

On average in the MCR scenario, 30,353 vehicles were generated on the network and 94.06% vehicles arrived at their destinations during the simulation period. The average vehicle travel time was 7.528 minutes, the average vehicle trip distance was 1.624 miles and the average vehicle CO_2 emission was 0.924 kg/vehicle.

6.3.3 Evaluation of the Multi-criteria routing impacts

The MCR impacts were investigated by comparing the network performance of the MCR scenario and SCR scenario. The relevant change percentage was calculated based on the following equation, which represents the relevant change between MCR and SCR results.

$$relative\ change = \frac{(MCR_{value} - SCR_{value})}{SCR_{value}} \times 100\% \quad \text{Equation 6-2}$$

Total vehicle numbers

The total vehicle numbers during the simulation period are shown in Figure 6-4.

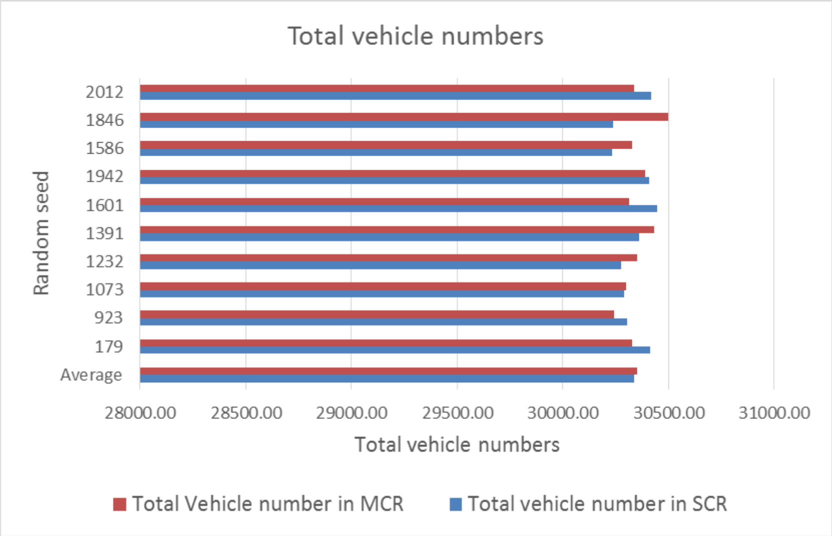

Figure 6-4 Total vehicle numbers in both scenarios

The average total vehicle number from 10 different random seeds under MCR was 30,353 and under SCR it was 30,339. The mean value of the relevant change was 0.05%, which means the total vehicle numbers in both scenarios were similar. The average values of the performance indicators from the simulations are in line with the total values of the performance indicators because the difference of total vehicle numbers in both scenarios could be ignored.

Average travel time (mins/vehicle)

The average travel time with different random seeds in SCR and MCR experiments is shown in Figure 6-5. The vertical axis indicates the different random seeds: the red bar is the result from MCR experiments and the blue bar is the result from SCR experiments. The last group on the bottom is the average values of these 10 random seeds. The statistical summary is shown in Table 6-6.

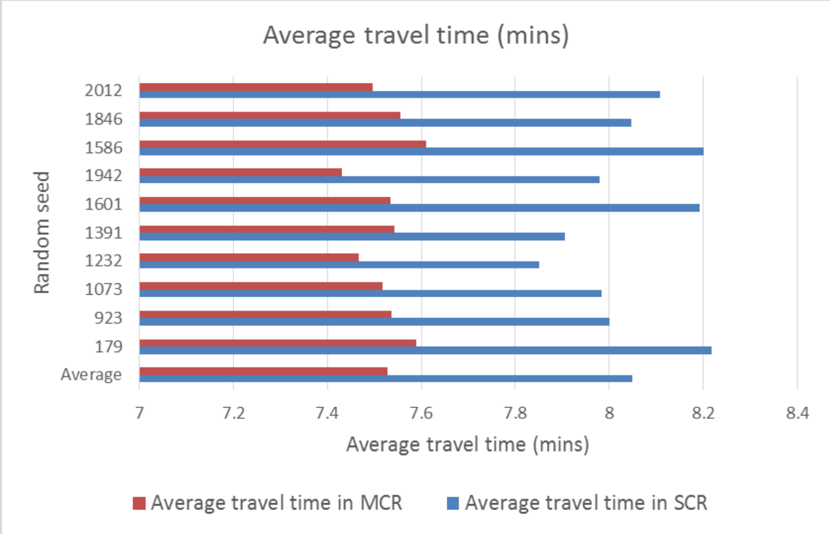

Figure 6-5 Average travel time in both scenarios

Table 6-6 Statistical summary of average travel time in both scenarios

Random seed	179	923	1073	1232	1391	1601	1942	1586	1846	2012	**Mean**	**Standard Deviation**
Average travel time in SCR (mins)	8.217	8.000	7.983	7.851	7.906	8.193	7.979	8.201	8.046	8.107	**8.048**	**0.128**
Average travel time in MCR (mins)	7.590	7.537	7.518	7.467	7.542	7.534	7.431	7.611	7.556	7.497	**7.528**	**0.054**
Relative changes	-7.63%	-5.79%	-5.83%	-4.88%	-4.60%	-8.04%	-6.86%	-7.20%	-6.09%	-7.53%	**-6.46%**	**1.19%**

As seen in Figure 6-5 and Table 6-6, the average travel time in the MCR scenario apparently fell in each random seed compared with the SCR scenario. The average relevant changes for these 10 random seeds were -6.46%, meaning the average travel time in MCR had about a 6.46% saving compared to the SCR scenario.

Average trip distance (miles/vehicle)

The average trip distance with different random seeds in SCR and MCR experiments is shown in Figure 6-6 and the statistical summary is shown in Table 6-7.

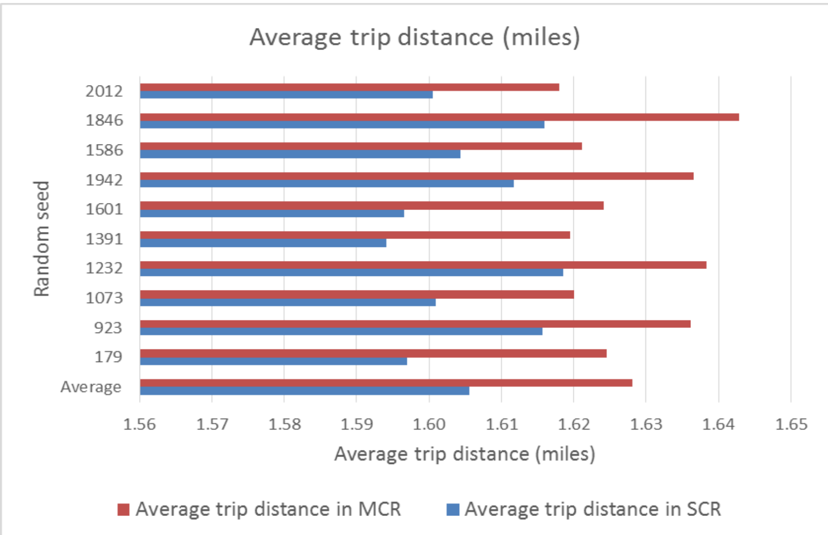

Figure 6-6 Average trip distance in both scenarios

Table 6-7 Statistical summary of average trip distance in both scenarios

Random seed	179	923	1073	1232	1391	1601	1942	1586	1846	2012	**Mean**	**Standard Deviation**
Average trip distance in SCR (miles)	1.597	1.616	1.601	1.619	1.594	1.597	1.612	1.604	1.616	1.601	**1.606**	**0.009**
Average trip distance in MCR (miles)	1.625	1.636	1.620	1.638	1.620	1.624	1.637	1.621	1.643	1.618	**1.628**	**0.009**
Relative changes	1.72%	1.27%	1.20%	1.22%	1.59%	1.72%	1.54%	1.05%	1.66%	1.09%	**1.41%**	**0.27%**

As seen in Figure 6-6 and Table 6-7, the average trip distance in MCR is 1.41% longer than it in reference experiment, which is only a lightly increasing.

Average emissions (kg/vehicle)

The average trip distance with different random seeds in SCR and MCR experiments is shown in Figure 6-7 and the statistic summary is shown in Table 6-8.

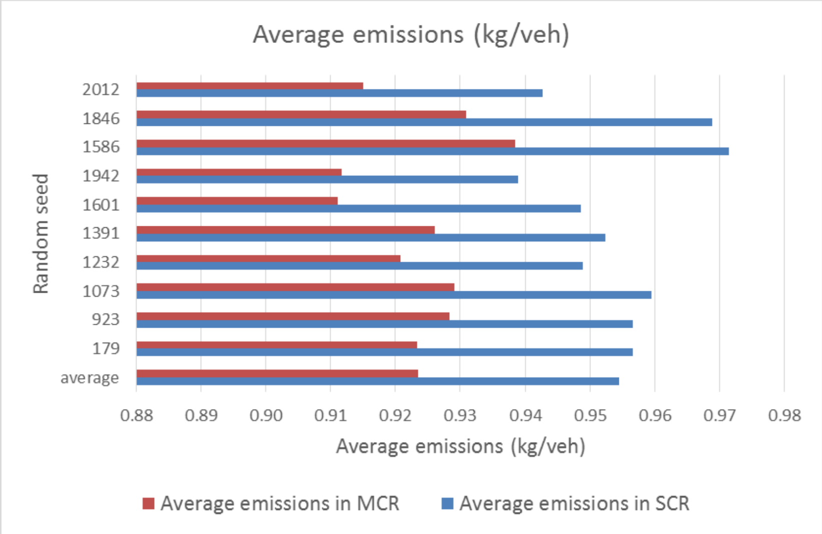

Figure 6-7 Average emissions in both scenarios

Table 6-8 Statistical summary of average emissions in both scenarios

Random seed	179	923	1073	1232	1391	1601	1942	1586	1846	2012	**Mean**	**Standard Deviation**
Average emissions in SCR (kg/veh)	0.957	0.957	0.960	0.949	0.952	0.949	0.939	0.971	0.969	0.943	**0.954**	**0.010**
Average emissions in MCR (kg/veh)	0.923	0.928	0.929	0.921	0.926	0.911	0.912	0.938	0.931	0.915	**0.923**	**0.009**
Relative changes	-3.48%	-2.96%	-3.17%	-2.98%	-2.76%	-3.95%	-2.91%	-3.40%	-3.91%	-2.94%	**-3.25%**	**0.42%**

As seen in Figure 6-7 and Table 6-8, in all 10 random seeds condition, the average emissions showed some improvement in MCR experiments. The average emissions in MCR was 3.25% less compared with reference experiment.

Trip completion rate (percentage)

The trip completion rate with different random seeds in SCR and MCR experiments is shown in Figure 6-8and the statistic summary is shown in Table 6-9.

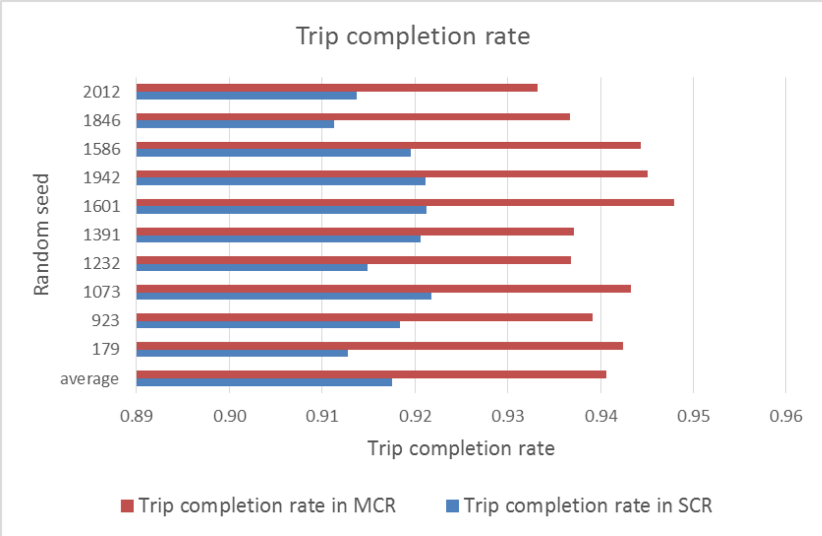

Figure 6-8 Trip completion rate in both scenarios

Table 6-9 Statistical summary of trip completion rate in both scenarios

Random seed	179	923	1073	1232	1391	1601	1942	1586	1846	2012	**Mean**	**Standard Deviation**
Trip completion rate in SCR	91.28%	91.84%	92.18%	91.49%	92.06%	92.13%	92.11%	91.96%	91.13%	91.38%	**91.75%**	**0.40%**
Trip completion rate in SCR	94.25%	93.91%	94.33%	93.68%	93.71%	94.79%	94.51%	94.43%	93.68%	93.32%	**94.06%**	**0.47%**
Relative changes	3.25%	2.25%	2.33%	2.40%	1.79%	2.89%	2.61%	2.69%	2.80%	2.13%	**2.51%**	**0.42%**

The trip completion rate increased in all 10 different random seeds conditions and the mean relevant improvement in MCR was 2.51% compared to that in SCR. The increasing trip completion rate means more vehicles will reach their destinations during the fixed simulation time and the congestion level on the network is reduced in the MCR scenario.

In summary, compared with the SCR experiments, MCR can save about 6.46% average travel time and reduce vehicle CO_2 emissions by 3.25%. The average trip distances increased by 1.41% and the trip completion rate also increased by 2.51%.

The comparisons between the results of SCR and MCR experiments in 10 different random seeds illustrated that the network performance indicators evolved in the same direction in different random seed sets. The results show some similar properties with those of Boyce and Xiong (2004), who conducted some experiments about UE and SO route choice for a large network. They found that in the large and congested road network, shifting flows from UE behaviour to SO behaviour can save 5% total travel time with a 1.5% increase in travel distance.

By adding the reasonable emission cost to perform the MCR, the total network performs better with reduced congestion, travel time and emissions and increased usable network capacity. This result confirms our experiments with the Braess network, described in the beginning of Chapter 4. The introduction of emissions into a multi-criteria composite route choice cost function improved the network performance and network routing efficiency in this case study setting, which requires a careful design of multi-criteria route choice cost function. Travel time cost and emission cost may influence each other in the composite cost. The next section analyses the impacts of the different combinations of VoT and VoG.

6.4 Sensitivity analysis

Sensitivity analysis aims to investigate how changes in the model output could be apportioned to different model inputs. The result in Section 6.3 is only one case of MCR where the VoT is €15/hour and VoG is €0.4/kg; these values were derived from previous studies using travellers' state preference surveys. The result illustrates that network performance shows some improvements with this VoT and VoG combination. These results may change when the weighting between time cost and emission cost is changed.

As introduced in Section 6.1.6, the scaling factor between VoT and VoG was used to investigate the sensitivity of network performance with a different weighting of VoT and VoG. By comparing the output changes, the reasonable combination of VoT and VoG in the Helmond case could be obtained.

This section will examine the network performances from the Dynasmart-P simulation with different scaling factors. The scaling factor is defined as VoT over VoG. A larger scaling factor means the weight of the time cost is higher and people are more likely to consider travel time. Some surveys have found that a reasonable, realistic VoT ranges from €10–40/hour and a reasonable, realistic VoG is around €0.4/kg. The scaling factors in this section include some extreme values used to investigate some extreme conditions, such as drivers who are really concerned with emissions and never mind the travel times.

Different scaling factors were set in Dynasmart-P through different combinations of VoT and VoG. As shown in the previous section, throughout the experiments, network performance fluctuated in a small range that was approximate to the convergence. The same method was used for different scaling factors and the network performance was picked up in the end. Although the end of each experiment was not an exactly convergent state, the network performance was quite close to convergence. Detailed results are shown in Table 6-10.

Table 6-10 Network performance in different scaling factors

Scaling Factors	VoT (euro/hour)	VoG (euro/kg)	Average Travel Time (minutes)	Average Trip Distance (miles)	Average CO_2 Emissions (kg/vehicle)	Trip Completion Rate
0.001	10	10000	19.670	0.704	1.332	0.421
0.01	10	1000	18.739	0.731	1.271	0.458
0.1	10	100	16.268	1.074	1.219	0.674
0.2	10	50	11.347	1.390	1.061	0.816
0.5	10	20	8.634	1.490	0.944	0.901
1	10	10	8.223	1.502	0.942	0.915
2	10	5	7.495	1.599	0.913	0.934
5	10	2	7.547	1.603	0.914	0.935
10	10	1	7.550	1.608	0.924	0.933
25	10	0.4	7.414	1.613	0.912	0.945
37.5	15	0.4	7.497	1.618	0.915	0.932
50	20	0.4	7.631	1.616	0.929	0.936
75	30	0.4	7.652	1.611	0.924	0.938
100	40	0.4	7.663	1.610	0.925	0.933
500	200	0.4	7.847	1.613	0.933	0.926
1000	400	0.4	8.052	1.603	0.942	0.916
Infinite	10	0	8.107	1.601	0.943	0.914

The results from the reference case are listed in the last row with an infinite scale. To give a clear overview of the sensitivity analysis and better interpret the above results, a visualisation comparison of network performance between the different scales and the reference case is presented in Figure 6-9.

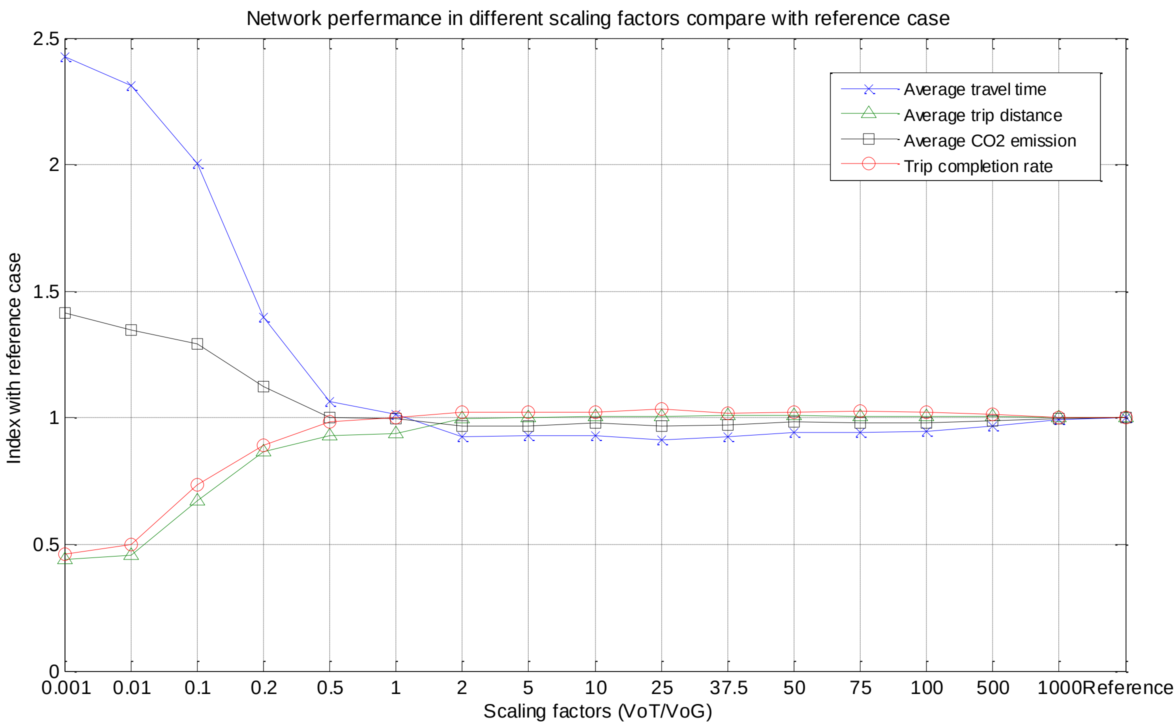

Figure 6-9 Network performance in different scaling factors (Dynasmart-P network)

Some conclusions can be drawn from Table 6-10 and Figure 6-9. When the scaling factor is larger than two, both the average travel time and average CO_2 emissions decrease. At the same time, the average trip distance increases slightly with the higher trip completion rate in the two-hour simulation period.

Specifically in this range, when the scaling factors increase, the average travel time and average CO_2 emissions also increase. The reason is that when the scaling factor goes up, the travel time cost will account more for the route choice function, and therefore network performance will be close to the reference case.

When the scaling factor is smaller than 1, MCR has a negative impact on network routing efficiency and network performance becomes worse than in the reference case. As seen in Appendix E, compared with scaling factor 10, when the scaling factor is 0.001, several intersections are fully blocked because the queue length is 100% after a few minutes. Most of the links had the lowest speed and highest density in the 0.001 scaling factor case, which means that the congested level was higher on most links. The trip completion rate in this case was 42.1%, which means that almost 60% of the vehicles were still on the network at the end of the simulation. It also confirms the high congestion level on the network and that most vehicles were fully jammed due to the serious gridlock. The emission cost function is a convex function with the average link speed in the TNO macro emission model and there are minimum speed limits in Dynasmart-P traffic model. Therefore, due to the high level of congestion in the 0.001 scaling factor, the average emission was 1.332 kg/vehicle, which is the worst among all the conditions.

Another reason for the left part in Figure 6-9 is the routing algorithm used in Dynasmart-P. It is not a model predictive routing algorithm, where the shortest path is calculated based on the whole network on instantaneous cost. The route updating is also based on instantaneous cost toward destination. Without the cost prediction, it will cause gridlock on the urban network because travellers make their route choices without considering the future states and travellers may hard to quite from the congestion due to some physical restrictions on the network. The model predictive traffic simulation will provide more accurate results.

In this case study, with the current traffic simulation model and particular emission model, the scaling factors from 2 to 100 can obviously reduce average travel time and average CO_2 emissions. The better performance appears when the scaling factors from 2 to 37.5. The results from the sensitivity analysis indicated that the weighting of VoT and VoG have important impacts on network performance. Adding CO_2 emissions in the route choice cost function can make traffic spread more efficiently over the network and enhance the routing efficiency and network usable capacity.

Traffic emission costs were not only determined by VoG, but also by the values themselves. For the same traffic state, the emission values may different through different emission estimation models. The reasonable scaling factors are model based, so different emission models may produce different ranges of reasonable scaling factors. In the Helmond case study using the TNO macro emission model, the reasonable scaling factors ranges from 2 to 100.

6.5 Chapter conclusion

The multi-criteria routing method was applied to an urban-scale network in Helmond using Dynasmart-P, which used real data from the field loop detectors. The results from the Helmond case study were briefly presented. Although Dynasmart-P has some limitations in this research, such as the unreal traffic model in the high density range and the minimum travel speed, the case study still showed some positive impacts of MCR.

The simulation model was built in line with the real network's physical characteristics and some reasonable aggregation. Several assumptions were made for the simulation model when designing the case study network. The basic input data were prepared for all scenarios. In order to compare the results, four network performance indicators were defined. Ten random seeds were used in both scenarios. Comparisons of the results were made between the SCR and MCR. The result analysis confirmed that when traffic emission is effectively taken into account in the route choice cost function, traffic spreads more efficiently over the network and both average travel time and average emissions decrease while average vehicle distances slightly increase. The emissions can be used as feedback in an assignment and routing loop and can help improve network routing efficiency. The effective composition of cost influences travel behaviour and, thus, route choice.

The sensitivity analysis of the scaling factors demonstrated that the cost components should be combined with reasonable VoT and VoG. The rational scaling factors were based on emission values calculated by the emission model. In this study using the TNO macro emission model, the rational scaling factors ranged from 2 to 100. The network routing efficiency could be improved with a carefully designed MCR system.

7. Conclusions and recommendations

Green traffic is a hot topic in traffic management that will be highlighted in the near future. Many questions will challenge our conventional modelling and traffic operations: for instance, how should traffic be managed and guided with MCR that includes factors such as traffic throughput or emissions, and what is the effect of MCR on DTM? In the current situation, most DTM systems assign traffic based only on travel time. As vehicular emissions can only be computed after a journey is finished, the introduction of emission into the cost function requires a traffic model or simulation to take into account this delayed feedback and, thus, the necessary convergence.

In this study, we investigated whether and how MCR would influence network performance compared with a traditional travel time oriented approach. The main objectives of this Master's thesis were to conceptually design a consistent method for incorporating travel time cost and traffic emission cost in the travellers' route choice function, and investigating the network performance impact of adding travellers' traffic CO_2 emissions concerns into route choice. The objectives were met by answering several sub-questions.

This final chapter presents the main findings and conclusions of the thesis. Section 7.1 briefly reviews the research process. Section 7.2 summarises the main findings of this thesis. Section 7.3 provides the conclusions and Section 7.4 makes some recommendations.

7.1 Research process review

The first two chapters of this thesis gave the readers a background overview of multi-criteria routing. In this thesis, the concept of MCR means routing traffic while consistently considering traffic throughput and traffic emissions within a framework. Since more attention has been paid to traffic emissions and they are closely related to the network's traffic, this study applied the composite route choice cost, which includes travel time and traffic emissions. The literature review and theoretical framework used in this study were introduced in Chapter 2.

Chapter 3 introduced the simulation package used in this study. It included a brief introduction to the Dynasmart-P simulation software, which is a mesoscopic traffic simulation tool that uses the link-based TNO macro emission model.

Chapter 4 described the development of the MCR method. To answer the main research question, we created a conceptual method that incorporated the traffic CO_2 emission cost with travel time cost in a consistent framework. This was described in Section 4.2. This method considered emission as a delayed feedback in the control loop. Three methods were derived from the conceptual method with different integration levels. A discussion about individual travel cost and marginal travel cost was also presented after the three methods were introduced.

Chapter 5 answered the question of which method was suitable for this study. A simple simulation network was built in Matlab to analyse the feasibility of each method. With the different cost type combinations and three methods, there were 12 scenarios in the multi-criteria assignment. Four groups of assessment criteria were examined: technique criteria, quality criteria, operational criteria and policy criteria. All three methods could achieve an approximately stable state in the simple simulation test. Based on the objectives of the thesis and the technique limitations, Method 3 was selected for the case study. This method has a bi-level structure and includes individual travel cost. The outer loop was used to find a consistent framework in the simulation, and it used the method of successive average to update the emission costs. The inner loop applied the iterative assignment method to achieve an equilibrium state based on the composite cost function.

After the method development and implementation, Chapter 6 introduced the case study of Helmond to answer the main research question. Two scenarios were compared in the case study network: traditional traffic routing, which only takes travel time cost, and multi-criteria traffic routing, which uses the composite cost. After that, a sensitivity analysis of the scaling factor between VoT and VoG was made.

7.2 Main research findings

The most important findings of this thesis are as follows:

1) A Brasses paradox network can be corrected by adding emission to the travel cost function.

A new perspective of Brasses paradox network is illustrated. Nagurney considered the emission just as the output of the traffic assignment and illustrated her paradox as “adding an extra link results in an increase in total emission”. The same example network as Nagurey’s are applied. Under the original solution, the total travel time is 522 and emission is 1.4 in user equilibrium state. While the system optimum state had the 498 total travel time and 1.2 emission. The new solution with emissions in the cost function shows that when the emission factor is 20, the total travel time is 524.2 and total emission is 1.32. We found that providing this delayed feedback to the traffic assignment eventually made it able to correct some behaviour and improve the network routing efficiency. This finding can be extended to the normal network when the user equilibrium state and the system optimum state are not the same.

2) Vehicular emission can be included in the route cost function by using VoT and VoG.

The composite route cost function can incorporate the travel time cost and emission cost though the VoT and VoG. These two values can be obtained from the stated preference survey.

3) The three methods have similar quality, but the obvious differences are in the implementable features.

Three methods were derived based on the conceptual method: a simultaneous emission calculation (Method 1), one intermediate iteration lagging emission calculation (Method 2) and one iteration lagging emission calculation (Method 3). Chapter 5 presented a feasibility analysis of each method based on several criteria. The assessment showed that there are no obvious differences in technique criteria and quality criteria; the obvious differences are in operational criteria and policy criteria (Table 5-16). Method 3 was selected for the case study experiments because it is the only method that can be implemented with Dynasmart-P without modifying the simulation software.

4) With multi-criteria routing, both travel time and travel emissions decrease while trip distance and the trip completion rate slightly increase.

In the Helmond case study, 10 different random seeds were implemented in the simulation in both reference experiments and multi-criteria routing experiments. All the experiments found the same trend between reference experiments and multi-criteria routing experiments. Averaging all the results from different random seeds provides an overview of changes. It shows that the multi-criteria routing can save about 6.5% average travel time and reduce vehicle CO_2 emissions by 3.2%, while average trip distances increase by 1.4% and the trip completion rate increases by 2.5%. These means that MCR increased routing efficiency and reduced network congestion in this case study.

5) VoT and VoG have important impacts on multi-criteria routing

The sensitivity analysis of the scaling factor between VoT and VoG illustrated that MCR needs a well-designed composite cost. Based on the Dynasmart-P simulation and TNO macro emission model used in the case study, when the scaling factor is smaller than one, MCR has a negative impact on network routing efficiency and network performance becomes worse than in the SCR experiments. When the scaling factor is larger than two, network performance is better than in the SCR experiments: both average travel time and average CO_2 emissions are reduced, while average trip distance increases slightly with the higher trip completion rate in the two-hour simulation period.

7.3 Conclusions

The aim of this research was to perform a preliminary evaluation of the effects of MCR in order to see whether it is helpful in simultaneously improving network routing efficiency and reducing negative environmental impact. In this thesis, MCR means consistently considering traffic throughput and traffic CO_2 emissions within a policy framework. A bi-level structure method of incorporating travel time cost and traffic CO_2 emission cost in route choice cost was proposed and analysed. An urban-scale simulation model was then developed to evaluate the feasibility and consistency of MCR and its effects on the real network in Dynasmart-P. Network performance indicators were introduced to quantify the effects of MCR on the network. A sensitivity analysis was performed to assess the influence of VoT and VoG changes.

Based on the results of this study, the following conclusions have been made:

1. Multi-criteria routing can be achieved by using a bi-level structure that applies one iteration lagging emission calculation.

We designed a bi-level structure of the conceptual method of MCR. By considering the different integrated levels and operational methods, we proposed three different multi-criteria methods based on the conceptual method. Methods 1 and 2 need to be highly integrated with the traffic simulation model and the emission model, while Method 3 applies an outer loop emission model that combines with the traffic model. Two types of travel cost were introduced: individual travel cost and marginal travel cost. There were 12 scenarios for the different combinations of method and cost type.

The feasibility of each method was tested by a simple dynamic traffic simulation in Matlab. All three MCR methods can reach an approximately consistent framework. The technique and quality assessments found no big differences between these three methods. The differences between the different combinations of cost type in one method were quite small. Different cost types determined whether the assignment went to user equilibrium or system optimum, and they also represented the different kinds of travellers. A robustness test showed that all three methods are robust with different demands and parameters of VoT and VoG. Since Dynasmart-P dose not integrate the emission calculation and it is hard to access its core traffic flow model, Method 3, which includes one simulation state lag method and outer emission update method, was selected for the case study. The current version of the TNO macro emission model is not able to provide the marginal emission cost on a link, so individual time cost and individual emission cost were adopted using Method 3 in the case study.

2. Four indicators were defined to represent network performance

Network performance indices were applied to quantify the effects of MCR on traffic management. An OD demand matrix was fixed during the simulation period: the total vehicles on the network were close to each other in different scenarios but not the same, so the average values of indicators more precisely represented network performance. Altogether, four indices were introduced: average travel time, average trip distance, average CO_2 emissions and the trip completion rate during the statistical period.

3. Multi-criteria routing can improve the urban scale network's performance

An urban-scale simulation model was set up to simulate the MCR in Helmond. The simulation model was calibrated using real network data observed by field detectors, which included bottlenecks, queues and flow fluctuations. Calibration of the model showed that the final network model could better mimic the real network traffic conditions on critical links and it was successfully prepared for the case study. Ten different random seeds were implemented in both SCR and MCR experiments to eliminate the random seed effect of the simulation software.

The results from the MCR scenario showed that the consistent simulation can be achieved using the MCR method we used in this case study. The results showed that MCR can save about 6.46% average travel time and reduce vehicle CO_2 emissions by 3.25%. The average trip distances increased by 1.41% and the trip completion rate also increased by 2.51%.

In MCR experiments, some vehicles take a longer but less emission route during the simulation, which can spread vehicle more efficiently and reduce network congestion. Through MCR, we improved vehicle distribution and network utilisation. Some vehicles made a detour during the simulation and increased the link travel speed; this decreased the average travel time and vehicle emissions while slightly increasing trip distance. When there is lower travel time, better vehicle distribution and less congestion on the network, more vehicles reach their destinations during the simulation period.

The results show some similar properties to those of Boyce and Xiong (2004), who conducted some experiments about UE and SO route choice for a large network. They found that in a large and congested road network, shifting flows from UE behaviour to SO behaviour can save 5% total travel time with a 1.5% increase in travel distance.

By adding the reasonable emission cost to performing the MCR experiment, the total network performed better with reduced congestion, travel time and emissions and increased usable network capacity. Introducing emissions into a multi-criteria composite route choice cost function improved network performance and network routing efficiency in this case study, which needed a careful MCR design.

4. VoT and VoG have important effects on network performance

There are two components in the general cost function and both can be transferred to each other or to a monetary unit using the factors of VoT and VoG. The sensitivity analysis of the scaling factors between VoT and VoG demonstrated that the cost components should be combined with the reasonable values of VoT and VoG. The rational scaling factors were based on the emission values calculated by the emission model. In this study, using the TNO macro emission model, the rational scaling factors ranged from 2 to 100. Network routing efficiency can be improved with a carefully designed MCR.

The network performance become worse than reference when the scaling factor was quite small. This may be due to the current routing algorithm in Dynasmart-P. Because there is no predictive cost for the routing algorithm, travellers must make their decisions about their destinations according to the instant network link cost. This may cause serious congestion at some intersections, and lead to a fully blocked urban network. We found that when the scaling factor is 0.001, there is a lot of serious congestion a few minutes after the simulation begins.

In summary, this study investigated the effects of MCR on DTM by adding traffic CO_2 emissions into the traveller’s route choice in the simulation. A conceptual structure was designed and extended to three different operational methods. The results from the case study show that when the traffic emission is effectively taken into account in the route choice cost function, the traffic spreads more efficiently over the network and both average travel time and average emission decrease while average vehicle distances slightly increase. Emission can be used as a feedback in assignment and the routing loop and can help improve network routing efficiency. The effective composition of costs influences travel behaviour and, thus, route choice.

7.4 Recommendations

The report proposed a method of multi-criteria routing traffic management that incorporated travel time and traffic emissions in the composite route choice cost function, which shows some positive impact on MCR. By adding a reasonable CO_2 emission cost to the cost function, better use can be made of the network. One recommendation is that MCR is an effective way to manage green traffic.

For TNO these results are an addition to their knowledge of the multi-criteria routing. The multi-criteria method can be used for TNO green traffic research. This method applies Dynasmart-P traffic simulation model incorporated with TNO's macro emission model. For the road authority these results can help them reduce traffic emission and traffic congestion and can help them design their green traffic management policy.

Considering this study is just a starting point in MCR and the current technique restriction, a number of simplifications and assumptions were made in developing the method and the case study simulation. Since the work done in this thesis is a very initial phase of researching MCR, doing more in-depth research is essential for its application.

Some improvements can be made in further research:

1. Investigate the theoretical mechanism of multi-criteria routing on dynamic traffic management.

This thesis applied the simulation approach to investigating the effects of MCR on network performance in a consistent framework. It found some positive impacts on traffic management. While the theoretical mechanism of MCR is not examined in this thesis, more theoretical and analytical research can be done to reveal the depth mechanism of multi-criteria routing.

2. More comprehensive multi-criteria routing with more criteria.

Evaluation of MCR requires further study with more criteria, such as reliability, safety or comfort. Due to the time limitation and lack of information about other criteria, in this thesis, the composite route choice cost function included travel time cost and CO_2 emission cost. Future research should look at MCR with more criteria.

3. Improve traffic simulation tools.

Dynasmart-P is considered to be a good tool for testing various DTM measures. However, the simulation has some drawbacks and limitations and the emission model is not integrated in the traffic simulation. These issues forced us to apply Method 3 (with a one iteration lagging method and a bi-level structure) to update the emissions back to the simulation. However, this method is more complicated. In future studies, the emission calculation and update could perhaps be highly integrated in the new traffic simulation, which is an efficient way to deal with emission as delayed feedback into travel cost.

4. Make routing decisions with a predictive network state.

The current routing algorithm calculate route cost based on the instant link cost at the calculation and updating simulation interval. In the sensitivity analysis, some odd results may have been caused by this routing algorithm. Using the predictive cost information may give better and more accurate route guidance than the current routing algorithm.

5. Marginal cost and system and user optimum

Computation of system optimum and user optimum is simplified in each of available simulation packages, which has impact on précised assessment of multi-criteria routing. Improving and making the calculation of marginal cost of indicators (travel time, emission, etc.) as well as the system optimum and user optimum would allow to see exact influence of the methodology for multi-criteria routing.

6. Determine how best to implement multi-criteria routing in a real traffic network.

The current study implemented MCR in a dynamic traffic simulation. With the fast-developed ITS approach, the information communication is extended from vehicle to infrastructure to vehicle to vehicle. A real-time MCR framework for the urban network in the traffic management centre should be built in the future and should contain three basic systems: a real-time network monitoring system, a driver decision support system and a real-time network operations system. The real-time network state should be used as the input for the advanced traffic models that can give the predicted network traffic state. The driver decision support system can give the drivers optimum route choice with MCR based on the current and predicted network states. This kind of information can be disseminated through a roadside information panel or an in-vehicle device. Implementing MCR in a real traffic network requires various advanced ITS traffic systems and a fast and reliable decision support system.

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Appendix A. Dynasmart-P introduction

This part is an introduction of the Dynasmart-P which is mainly based on Mahmassani (1994).

A.1 Dynasmart-P Traffic-flow model

As we mentioned in pervious section, Dynasmart-P is referred as mesoscopic simulation because it combines some features of both macroscopic and microscopic simulation models. Dynasmart-P uses a modified Greenshields to model the flow of traffic propagate on the network. The original Greenshields model is the most simple macroscopic stream model which assumes a linear relation between speed and density. This relationship is shown graphically in Figure A-1.

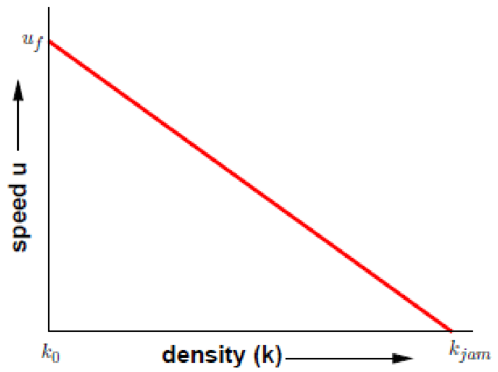


Figure A-1 Greenshields traffic flow model

The equation for this relationship is shown in equation in below according to Figure A-1.

$$v = v_f - \left[\frac{v_f}{k_j}\right] \cdot k$$

Where,

v = mean speed on the link at the density k

v_f = free flow speed

k_j = jam density

Two types of the modified Greenshields family models are available in the current version of Dynasmart-P. The elaborate introduction is in H.S. Mahmassani and Sbayti (2007).

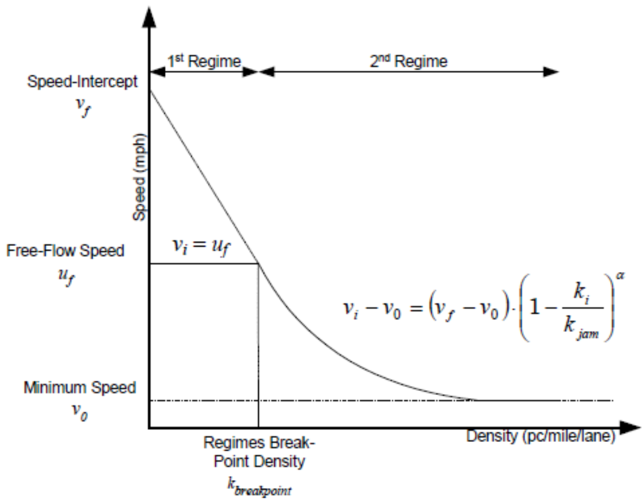


Figure A-2 Two regime Greenshields traffic flow model (Hani S Mahmassani, 2007)

As shown in Figure A-2. Type one is a dual-regime model in which constant free-flow speed is specified for free-flow conditions (1st regime) and a modified Greenshields model is specified for congested flow conditions (2nd regime). This dual-regime model is used for freeways in Dynasmart-P, because freeways typically have more capacity than arterials and can accommodate dense traffic (up to 2300 pc/hour/lane) at near free flow speeds. There are less or no traffic lights on the freeway and the speed of vehicles is only limited by the maximum speed limit in the free flow conditions. The current speed on link i (v_i) can be calculated according the equation which is a piecewise function as follows:

$$v_i = \begin{cases} u_f & , \quad 0 \le k_i \le k_b \\ (v_f - v_{min}) \cdot \left(1 - \frac{k_i}{k_{jam}}\right)^{\alpha} + v_{min} & , \quad k_b \le k_i \le k_{jam} \end{cases}$$

Where, v_i = speed on link i

v_f = speed intercept

u_f = free flow speed or speed limit on link i

v_{min} = the minimum speed on link i

k_i = density on link i

k_{jam} = jam density on link i

k_b = breakpoint density

α = a parameter used to indicate the sensitivity of speed to the density

Type two uses a single-regime to model speed-density relations for both free flow part and congest flow part. This model is used for arterials, because there are many signalized intersections that the free flow speeds and the capacity on arterials are lower than the capacity on freeways. Hence, the prevailing speeds on the aerials are more easily influenced by a slight increase of traffic than in the case of freeways. This single-regime model is shown in Figure A-3 and expressed by equation as follows:

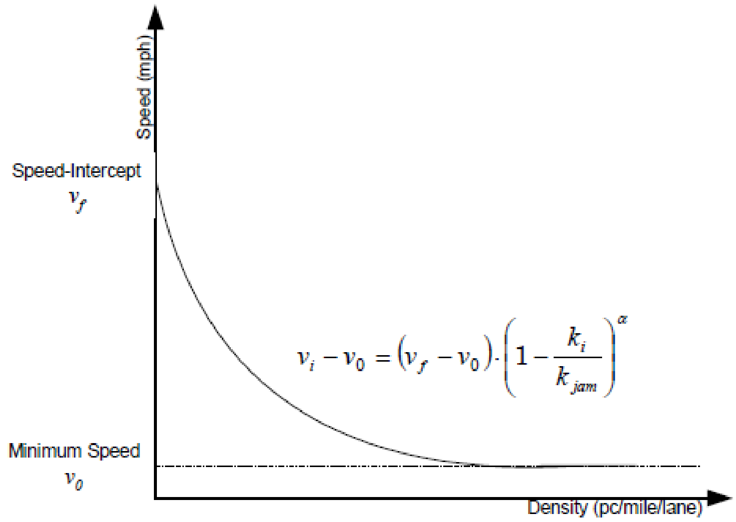


Figure A-3 One regime Greenshields traffic flow model (Hani S Mahmassani, 2007)

$$v_i = (v_f - v_{min}) \cdot \left(1 - \frac{k_i}{k_{jam}}\right)^{\alpha} + v_{min}$$

A.2 Traffic simulation component

Dynasmart-P moves vehicles in discrete bunches or macro particles at the prevailing local speeds determined from the speed-density relations and keeps track their positions, which means the vehicle flux across link boundaries is based simply on the number of vehicles reaching the link boundary during each time step. The vehicle movements on the network in the traffic simulation module and queue propagation model in Dynasmart are introduced in (Hu, 2009). The basic macroscopic equation of traffic flow conservation equation is formed in below:

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

Step 1: update density on the link

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

$$k_{i,t+1} = \frac{NV_{i,t+1}}{l_i \times nol_i}$$

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 based on the speed-density model in Dynasmart-P.

For two-dual regime model:

$$v_{i,t+1} = \begin{cases} u_f & , \quad 0 \le k_{i,t+1} \le k_b \\ (v_f - v_{min}) \cdot \left(1 - \frac{k_{i,t+1}}{k_{jam}}\right)^{\alpha} + v_{min} & , \quad k_b \le k_{i,t+1} \le k_{jam} \end{cases}$$

For single regime model:

$$v_{i,t+1} = (v_f - v_{min}) \cdot \left(1 - \frac{k_{i,t+1}}{k_{jam}}\right)^{\alpha} + v_{min}$$

Step 3: estimate the vehicle location

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

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

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

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

Step 4: calculate the transfer flow from link i to link i+1

Demand should be the vehicle in the queue list and the supply is the downstream remain capacity.

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

Step 5: update vehicle location and queue list

$$R'_{i+1,m,t+1} = l_{i+1} - \left[\Delta t - \left(\frac{R_{\mathrm{i,m,t}}}{v_{i,t+1}}\right)\right] \times v_{i+1,t+1} \ , \quad queue\ list \leq q_{i,t+1}$$

Else,

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

Reference:

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

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

Δt : Simulation time interval

l_i : Length of link i.

nol_i : Number of lanes of link i.

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

$v_{i,t+1}$: Mean speed on 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.

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

$q_{i,t+1}$: Transfer flow from link i to link i+1 during the t^{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.

A.3 Driver decision modelling

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:

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

Where, for vehicle j:

$\delta_j(\mathrm{k})$: 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 $\eta_j$decides users' responses to the supplied information and their propensity to switch.

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.

A.4 Path processor

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).

A.5 Dynasmart-P operational steps

According to X. Zhang (2012), the steps of the Dynasmart-P operation are introduced as followed:

1. Main module initializes the input OD and network data, such as link characteristics and control strategies.
2. The traffic simulation module process the vehicle movement on the links and the node transfer movement according to the control strategies.
3. The driver decision modelling module provides all path and route decisions to the traffic simulation module during its processes of link movement and node transfer.
4. 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 in user behaviour component of the driver decision modelling module.
5. The path selection component gives route decision to the node transfer 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.

A.6 Dynasmart-P simulation assignment mode

There are two distinct modes can be used in Dynasmart-P, namely one-shot simulation and iterative consistence simulation.

One-shot simulation assignment

In one-shot simulation assignment, Dynasmart-P is operated as a fixed time interval. Vehicles are assigned to current-best-paths, random paths or any pre-determined paths (historical paths) at the beginning of the simulation. 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 (H.S. Mahmassani & Sbayti, 2007). There are no grantees that the assigning best paths to the vehicles when they are generated will remain optimal at the end of “one-shot” simulation, because such assignment method does not take traffic evolution in the network into account for future time intervals. This kind of simulation only simulates user classes 1, 4 and 5. 3

Iterative simulation assignment

The second simulation assignment mode in Dynasmart-P applies a heuristics iterative procedure, in which the user equilibrium or system optimal flow pattern is provided. After initialization, Dynasmart-P loads OD matrix and assigns initial paths to vehicles. Then the simulator calculates travel costs under the set of departure time and path assignment. Time-dependent shortest path algorithm is used to determine the shortest path. Then all-or-nothing assignment will be executed to assign all travel demands and generate an auxiliary number of vehicles on current path. The new paths should be included into the path set to update the path assignment. The method of successive average is used to perform convergence checking. If yes, then the simulation is stopped. Otherwise, the simulation goes back and starts for the next iteration." (X. Zhang, 2012).There is also the maximum iteration numbers for the simulation. When the iteration numbers larger than this per-set upper bound, no matter when the convergence is satisfied or not, the simulation will be terminated. In iterative mode, there must have some vehicles in class 2 and class 3. If no vehicles are coded as UE or SO classes, then the iterative assignment procedure is replaced by a one-shot simulation assignment.

A.7 Route choice algorithm in Dynasmart-P

The K-shortest path calculations in Dynasmart-P are based on generalized link impedance, allowing development of route assignments responsive to travel times and costs. In this case, the generalized cost function is not only based on the travel time, but also calculated by generalized cost function. The current Dynasmart-P can capture the time-dependent costs for different link types.

The number of shortest paths is depended on the planning application. According to the manual, for pure UE or SO runs, one path is recommended. For en-route information planning applications, three paths are recommended in order to provide alternative paths. For advanced traffic information system (ATIS) scenario, two paths are recommended.

The simulation interval in Dynasmart-P is fixed at six seconds. The K-shortest paths calculation algorithm is executed every 30 simulation intervals which is 3 minutes, and the K-shortest paths updating algorithm is executed every 5 simulation intervals (30 seconds). The number of simulation intervals for calculating the K-shortest path refers to how often the K-shortest path routine will be executed. If 30 simulation intervals were selected, Dynasmart-P will solve for the K-shortest paths tree every 3 minutes. This is different than the number of simulation intervals for updating the shortest path, a process that does not solve for a new shortest path tree. Instead, the travel times for the current shortest paths tree will be updated based on prevailing link travel times. The freeway bias factor defines the fraction by which real freeway travel times are reduced according to the driver's perception (H.S. Mahmassani & Sbayti, 2007).

The marginal cost can be used for the system optimum simulation, According to the report of Mahmassani (1994), Dynasmart-P calculates the marginal travel time cost in an approximate way which ignores some of the spatial and temporal interactions in the network. The definition of the marginal cost means the extra cost for the whole system imposed by an additional vehicle. Dynasmart-P applies an elaborate procedure to estimate the marginal cost. The path marginal total travel times are obtained by a summation of the time-dependent marginal link travel times for all links on that path. At the end of the current simulation, the time-dependent link travel times and the number of vehicles present on each link are obtained from Dynasmart-P. The marginal link travel times are obtained according to the following equation.

$$mltt(a,t) = tt(a,t) + itt(a,t) \cdot x(a,t)$$

Where,

$\mathrm{mltt}(\mathrm{a},\mathrm{t})$ = marginal travel time in period t for link a

$\text{tt}(a,t)$ = travel time in period t for link a

$\text{itt}(a,t)$ = increment in travel time in period t to trveler already on link a due to the additional traveller

$x(a,t)$ = number of vechiles on link a at time t

The incremental travel time function $\text{itt}(a,t)$ is the derivative of travel time function $\text{tt}(a,t)$ with respect to $x(a,t)$. The method to calculate $\text{itt}(a,t)$ in Dynasmart-P is shown in Figure A-4.

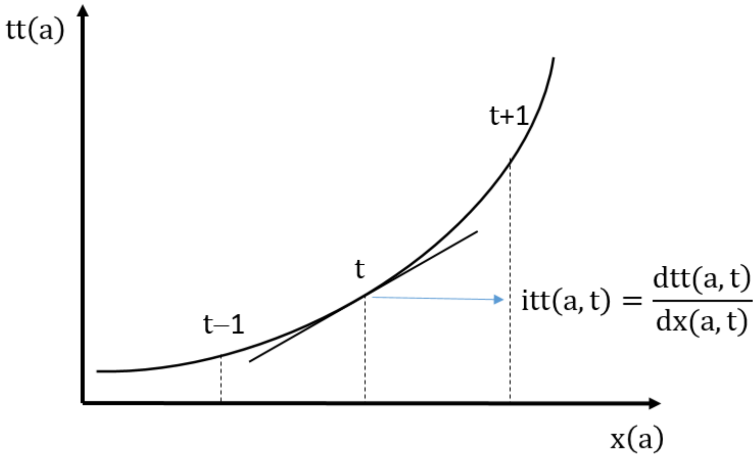


Figure A-4 Computation of marginals (Mahmassani, 1994)

In dynamic traffic case, the number of vehicles and the associate travel time on a link are time-dependent. The approach in Dynasmart-P assumes that the time-dependency of the derivative is due to "time-dependent" link performance functions. This means the travel time and the vehicle numbers for a link depend on the traffic conditions on the link at that time. The link-performance curve changes gradually over time which is expected due to the dynamic nature of the problem. The $\text{itt}(a,t)$ is evaluated by the slope of a quadratic fit and by using the three successive time points at the time t. the time-dependent link performance curves are obtained assuming that three successive time periods are relatively close to each other. However, the consideration of small time intervals may cause some instability in the curves because the values of travel time and the number of vehicles in successive intervals may show jumps at times. Hence, there is a trade-off between the approximate correctness of the curves and the robustness of the curves with the use of very short time intervals (Mahmassani, 1994).

As mentioned before, the marginal costs are used for the SO assignment, the structure of Dynasmart-P for UE and SO assignment is shown in the Figure A-5.

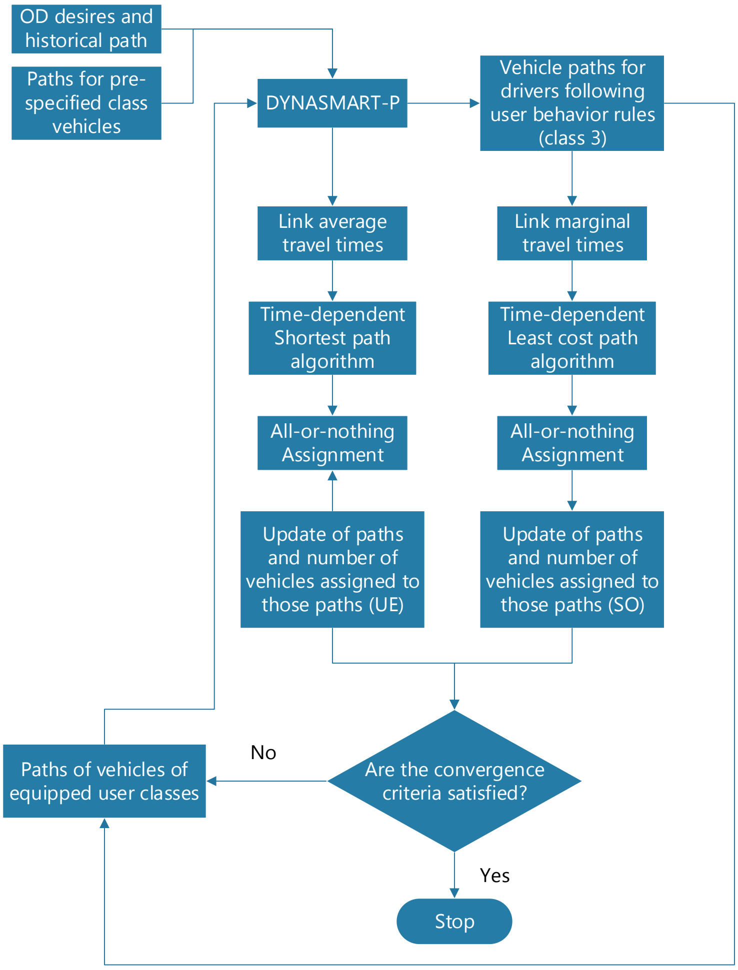


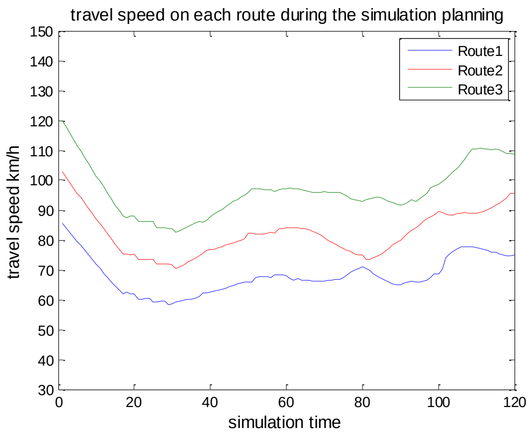
Figure A-5 UE and SO structure in DYNSMART-P

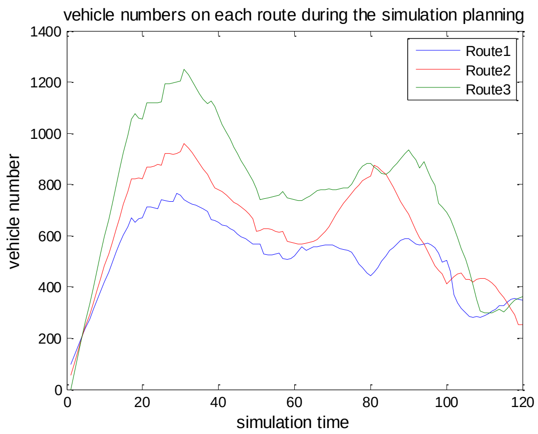
Appendix B. Prevailing speed and vehicle numbers during simulation

B.1 Prevailing speed and vehicle numbers in case 1

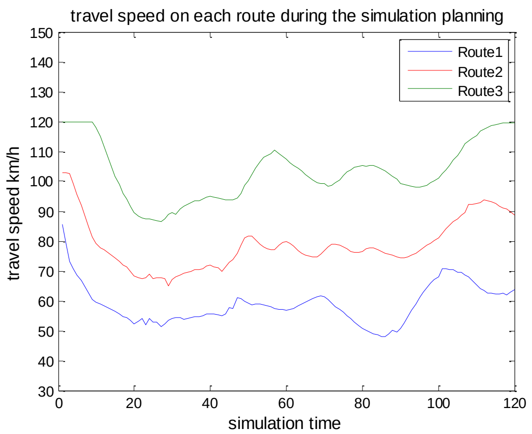
The Prevailing speed, travel cost and vehicle numbers on each route at each simulation interval in the approximate user equilibrium state are shown in Figure B-1. In the normal traffic condition, the prevailing speeds on each route are higher than 50 km/h for the whole simulation period. Because the prevailing speed is determined by the modified Greenshields traffic model, the speed changes are reversed with the vehicle number changes on the link.

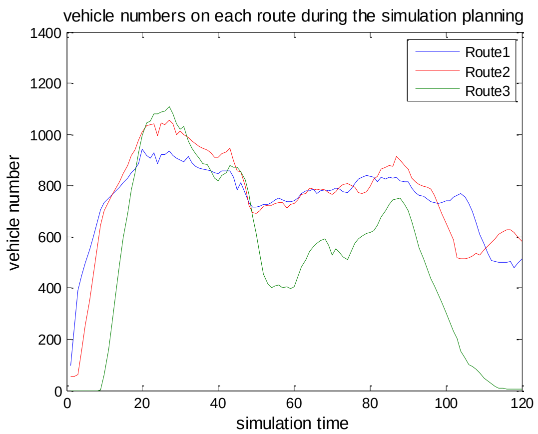
Reference case



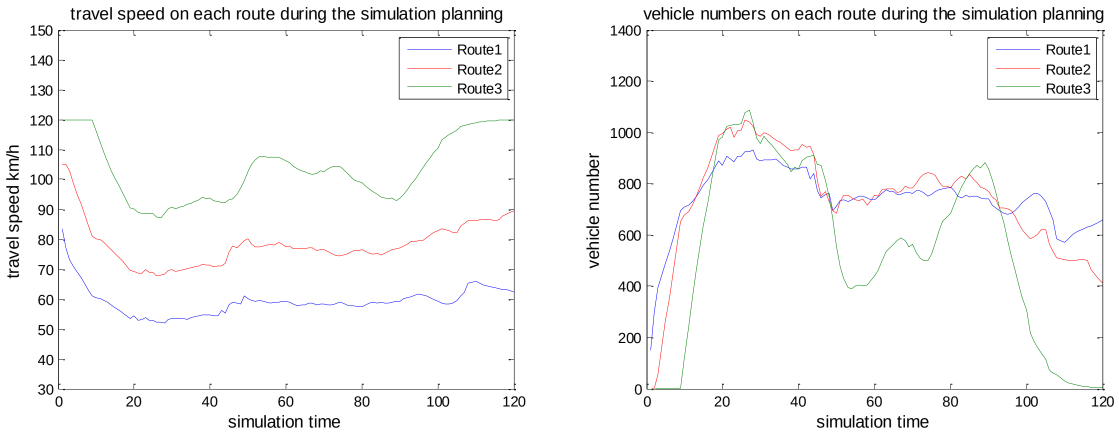


Method 1





Method 2



Method 3

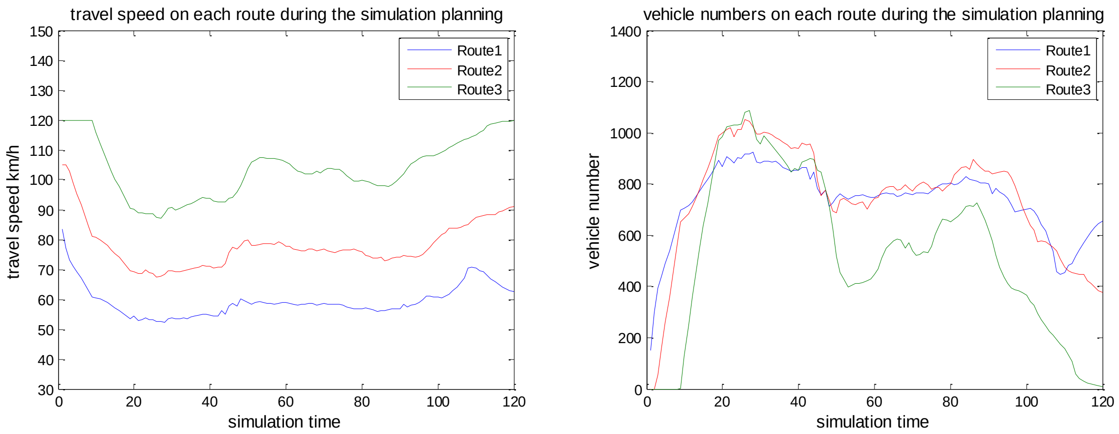
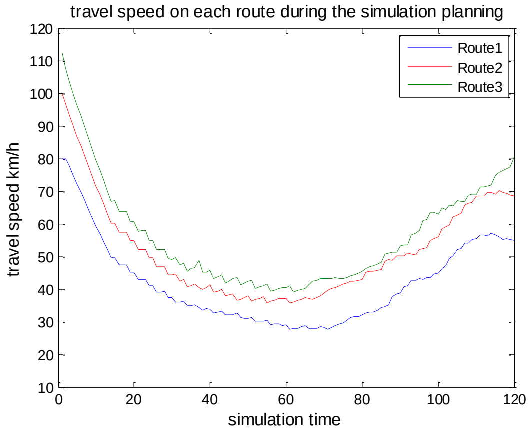


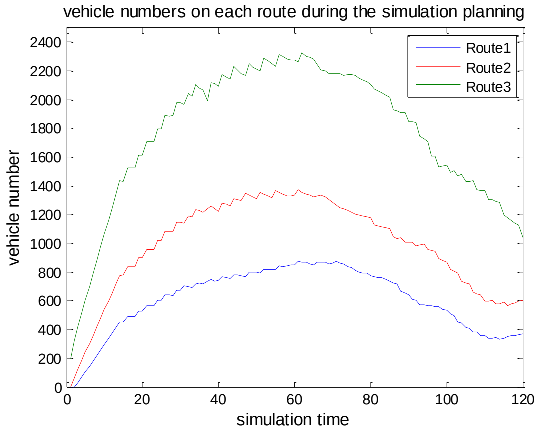
Figure B-1 Prevailing speed and vehicle numbers in case 1

B.2 Prevailing speed and vehicle numbers in case 2

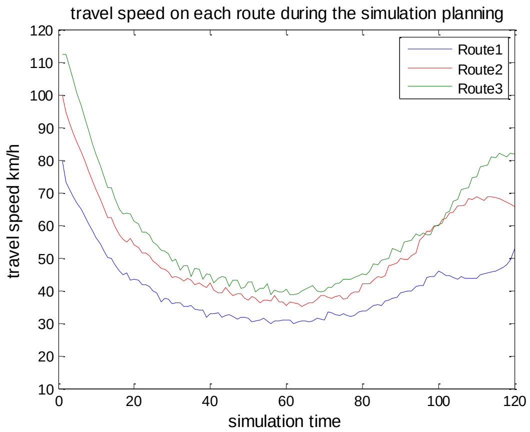
From Figure B-2, the prevailing speeds on three routes are apparently lower than which in normal traffic conditions. The lowest prevailing speed is on route 1 in all scenarios, which is around 30 km/h. It is quite in evidence that the speed changes are revised with the vehicle number changes on the link.

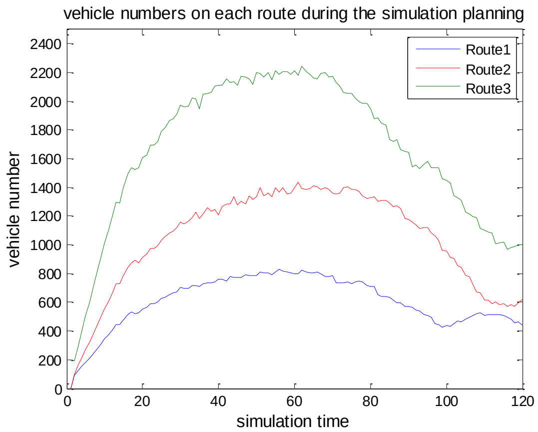
Reference case



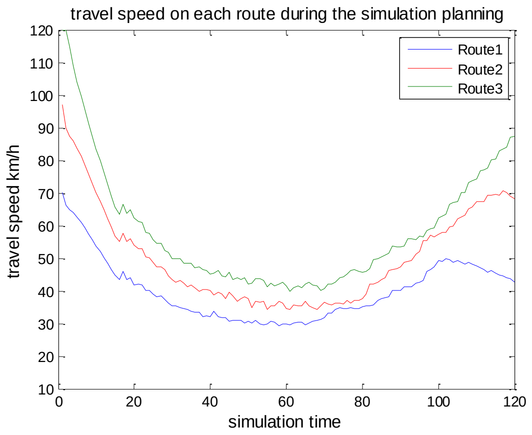


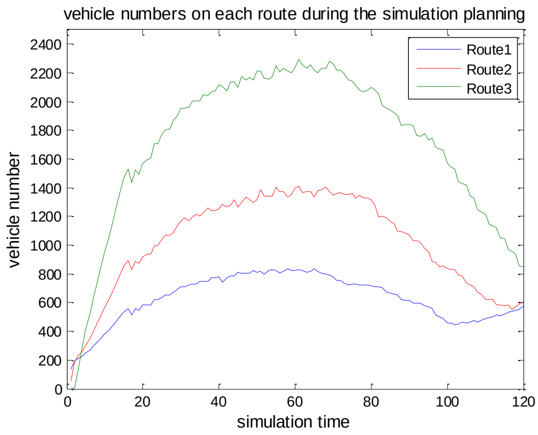
Method 1



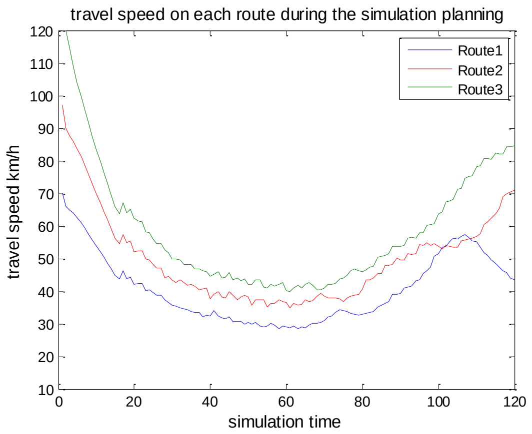


Method 2:





Method 3:



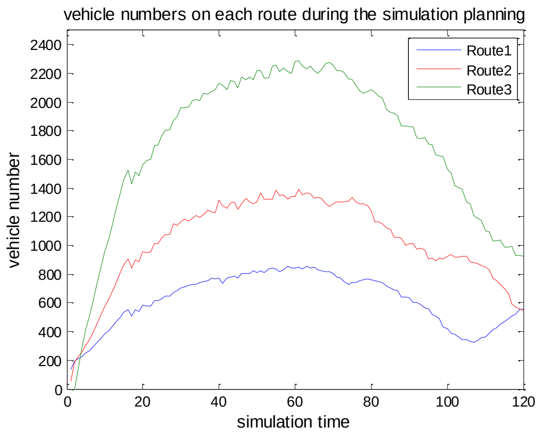


Figure B-2 Prevailing speed and vehicle numbers in case 2

Appendix C. Robustness check for the three methods

C.1 Case 1 Duality gap in normal traffic condition

Individual time cost and individual emission cost

VoT=10 euro/h, VoG =2.0 euro/kg

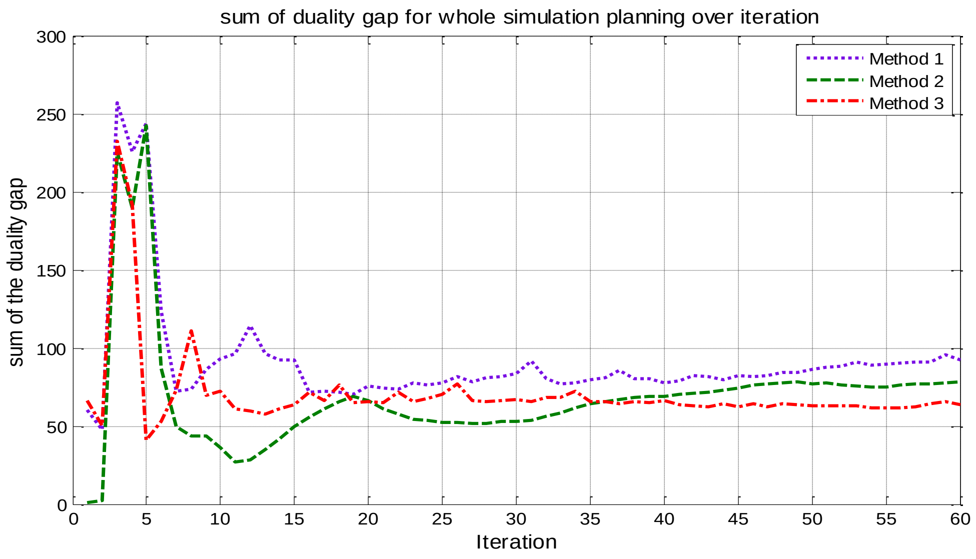


Figure C-1 Duality gap in ITIE in case 1 (VoT=10 euro/h, VoG=2.0 euro/kg)

VoT=20 euro/h, VoG =0.4 euro/kg

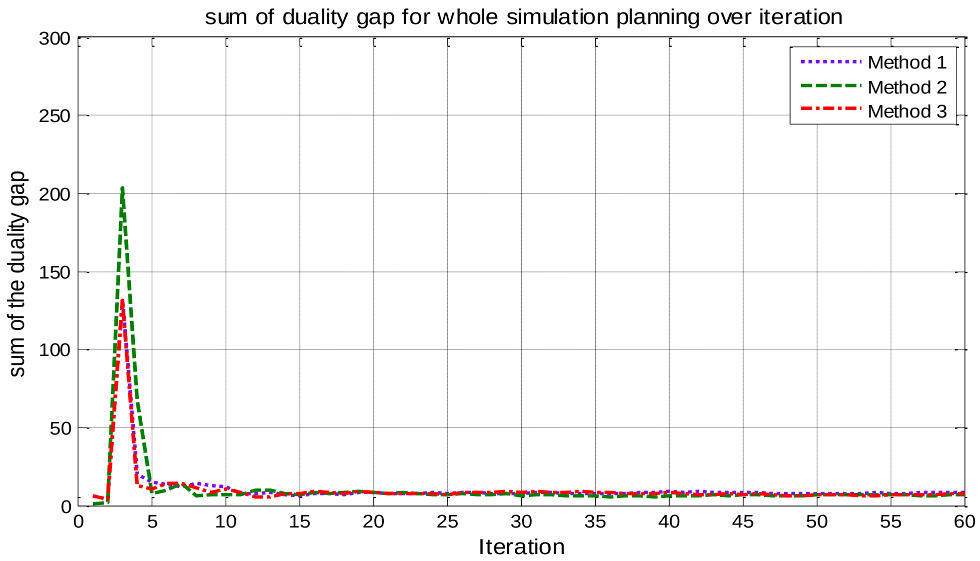


Figure C-2 Duality gap in ITIE in case 1 (VoT=20 euro/h, VoG=0.4euro/kg)

Individual time cost and marginal emission cost

VoT=10 euro/h, VoG =2.0 euro/kg

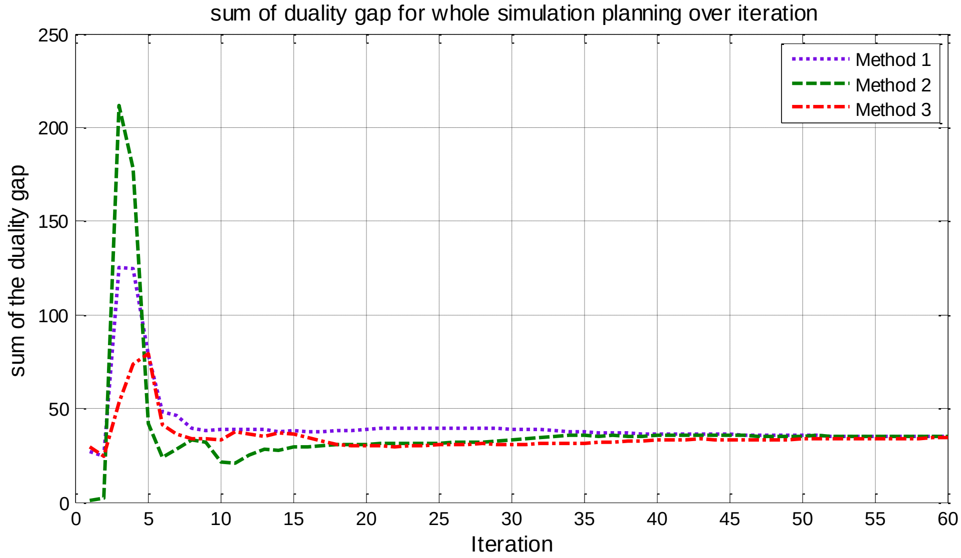


Figure C-3 Duality gap in ITME in case 1 (VoT=10 euro/h, VoG=2.0 euro/kg)

VoT=20 euro/h, VoG =0.4 euro/kg

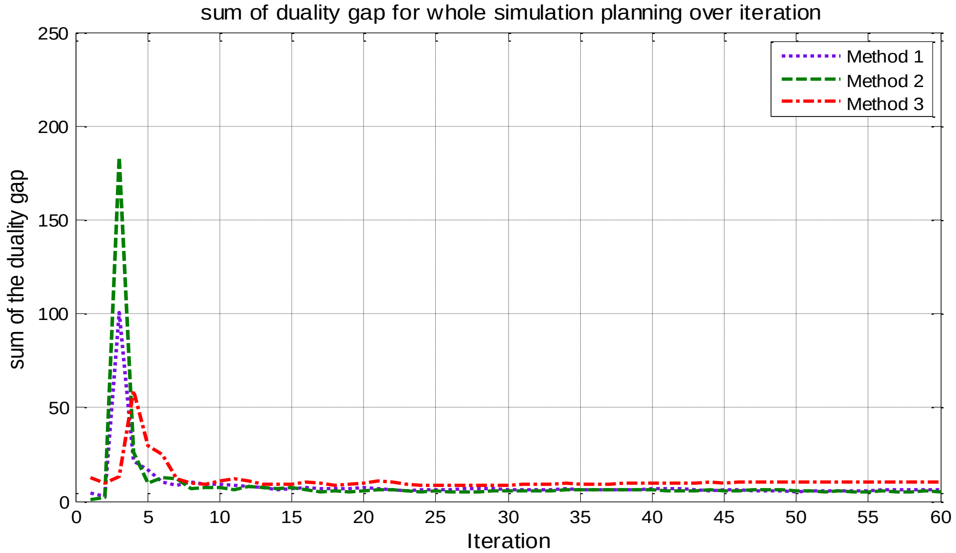


Figure C-4 Duality gap in ITME in case 1 (VoT=20 euro/h, VoG=0.4euro/kg)

Marginal time cost and individual emission cost

VoT=10 euro/h, VoG =2.0 euro/kg

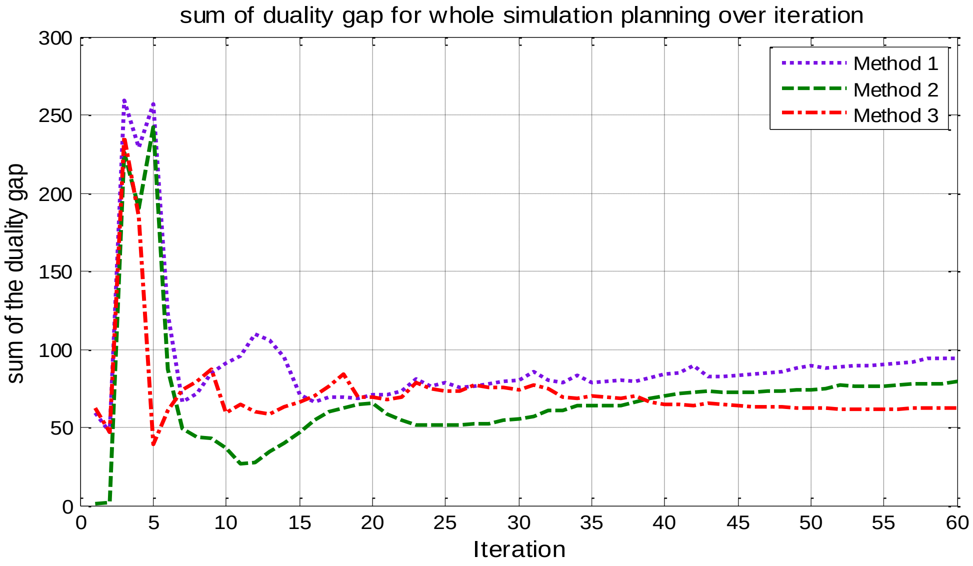


Figure C-5 Duality gap in MTIE in case 1 (VoT=10 euro/h, VoG=2.0 euro/kg)

VoT=20 euro/h, VoG =0.4 euro/kg

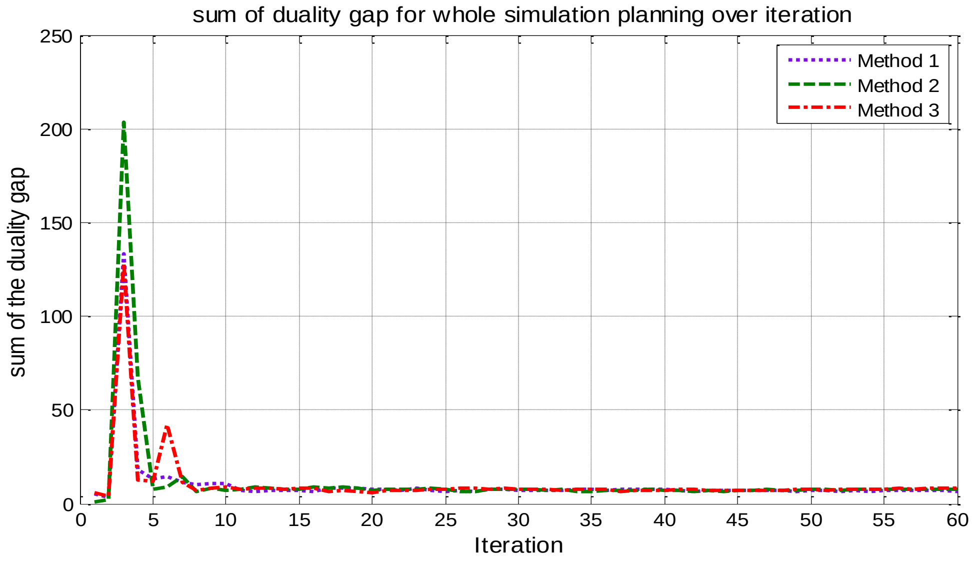


Figure C-6 Duality gap in MTIE in case 1 (VoT=20 euro/h, VoG=0.4euro/kg)

Marginal time cost and marginal emission cost

VoT=10 euro/h, VoG =2.0 euro/kg

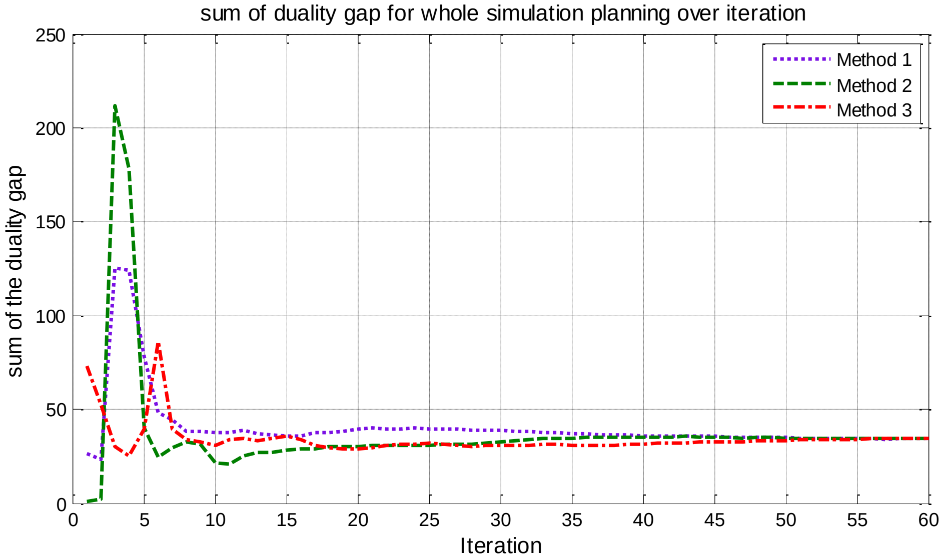


Figure C-7 Duality gap in MTME in case 1 (VoT=10 euro/h, VoG=2.0 euro/kg)

VoT=20 euro/h, VoG =0.4 euro/kg

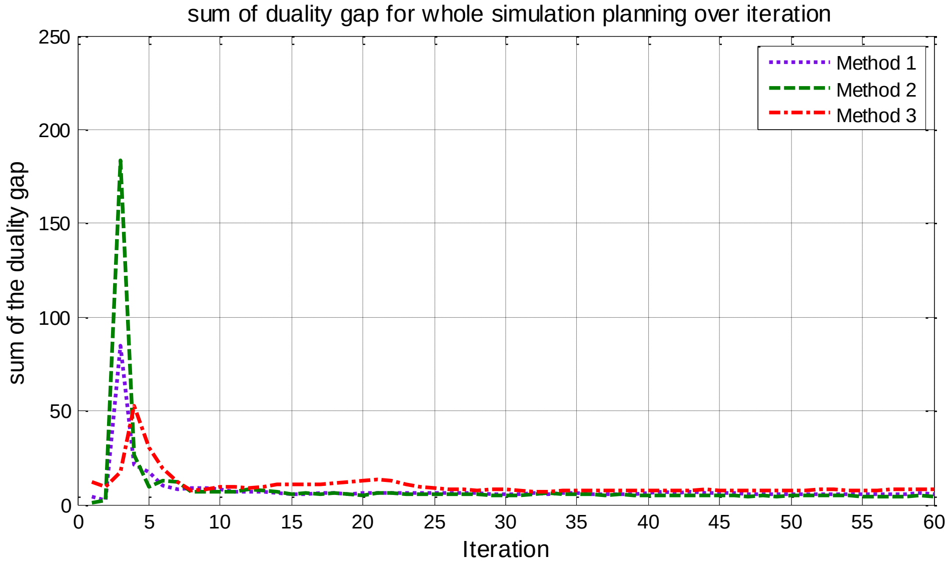


Figure C-8 Duality gap in MTME in case 1 (VoT=10 euro/h, VoG=2.0 euro/kg)

C.2 Case 2 Duality gap in congested traffic condition

Individual time cost and individual emission cost

VoT=10 euro/h, VoG =2.0 euro/kg

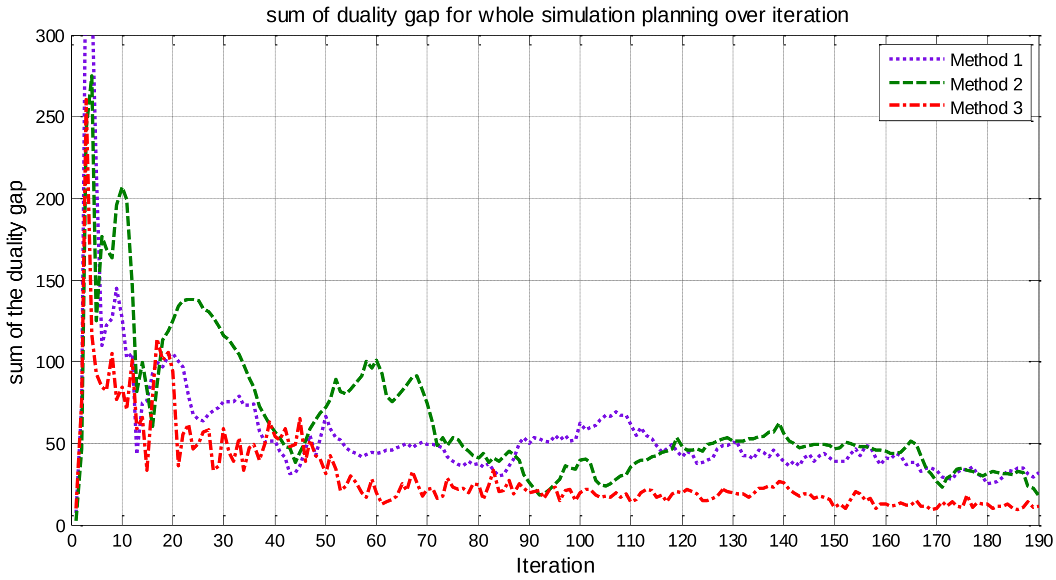


Figure C-9 Duality gap in ITIE in case 2 (VoT=10 euro/h, VoG=2.0 euro/kg)

VoT=20 euro/h, VoG =0.4 euro/kg

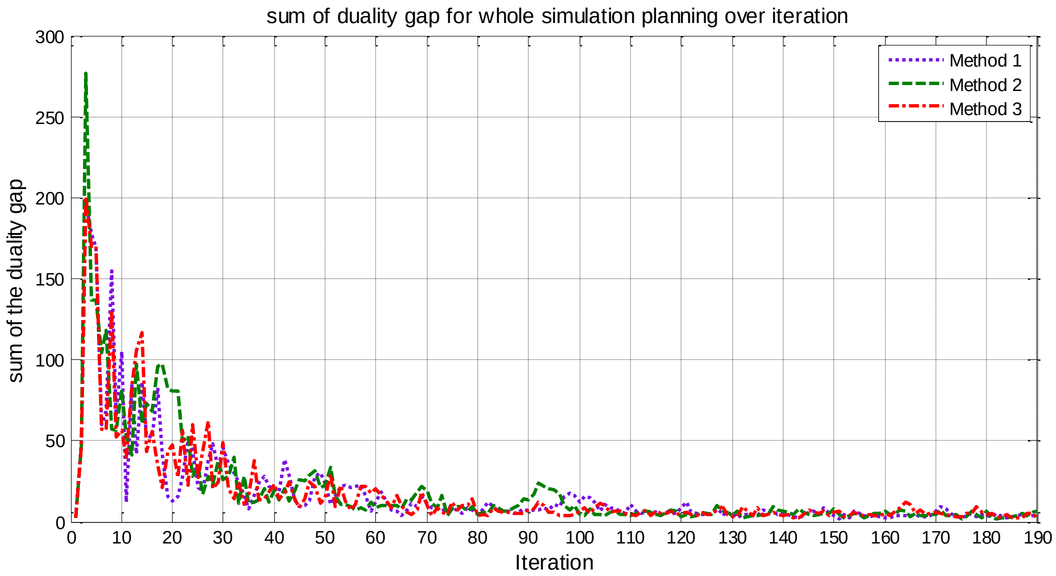


Figure C-10 Duality gap in ITIE in case 2 (VoT=20 euro/h, VoG=0.4 euro/kg)

Individual time cost and marginal emission cost

VoT=10 euro/h, VoG =2.0 euro/kg

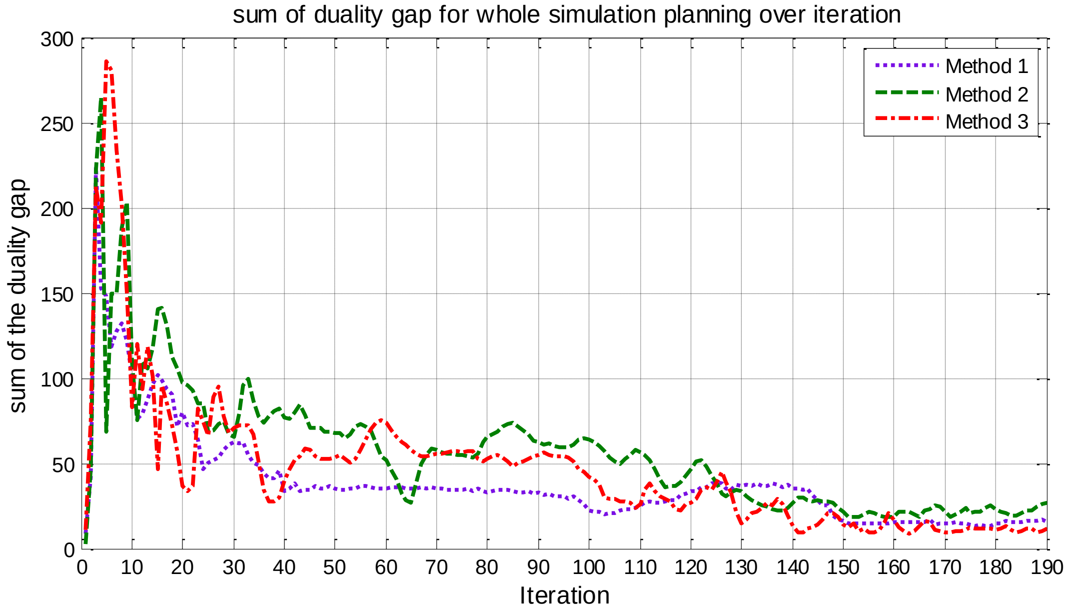


Figure C-11 Duality gap in ITME in case 2 (VoT=10 euro/h, VoG=2.0 euro/kg)

VoT=20 euro/h, VoG =0.4 euro/kg

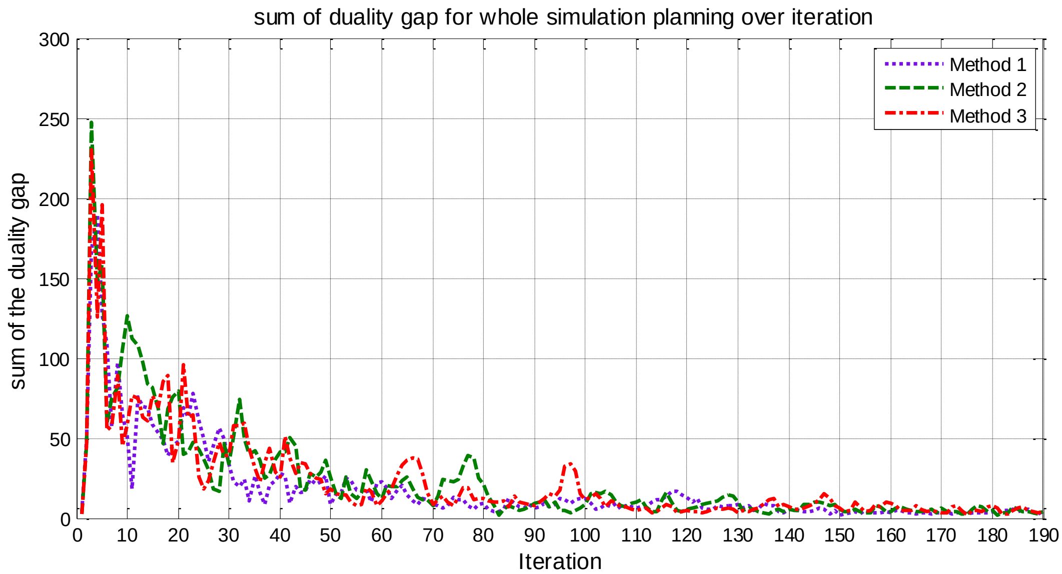


Figure C-12 Duality gap in ITME in case 2 (VoT=20 euro/h, VoG=0.4 euro/kg)

Marginal time cost and individual emission cost

VoT=10 euro/h, VoG =2.0 euro/kg

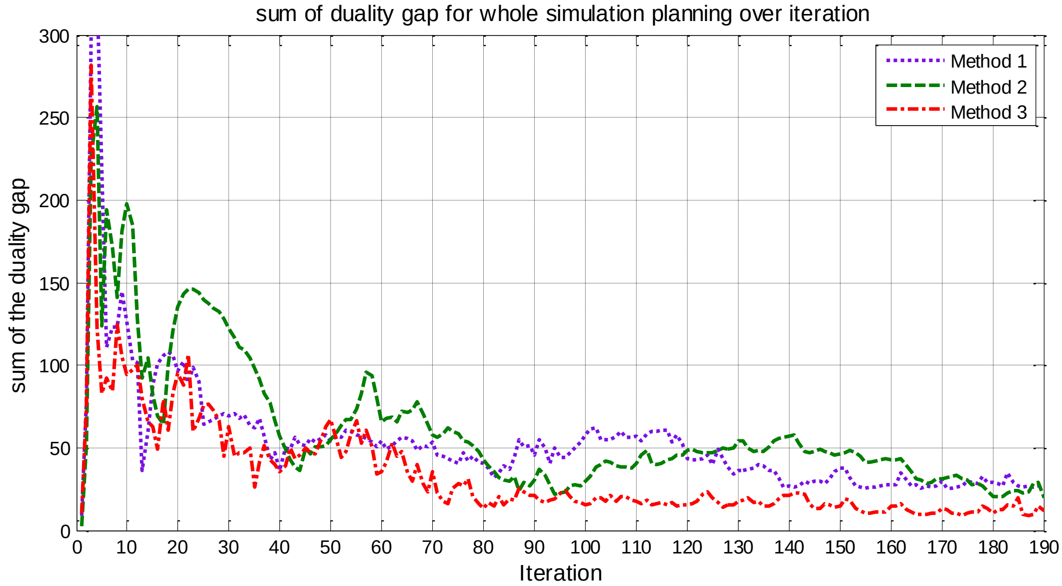


Figure C-13 Duality gap in MTIE in case 2 (VoT=10 euro/h, VoG=2.0 euro/kg)

VoT=20 euro/h, VoG =0.4 euro/kg

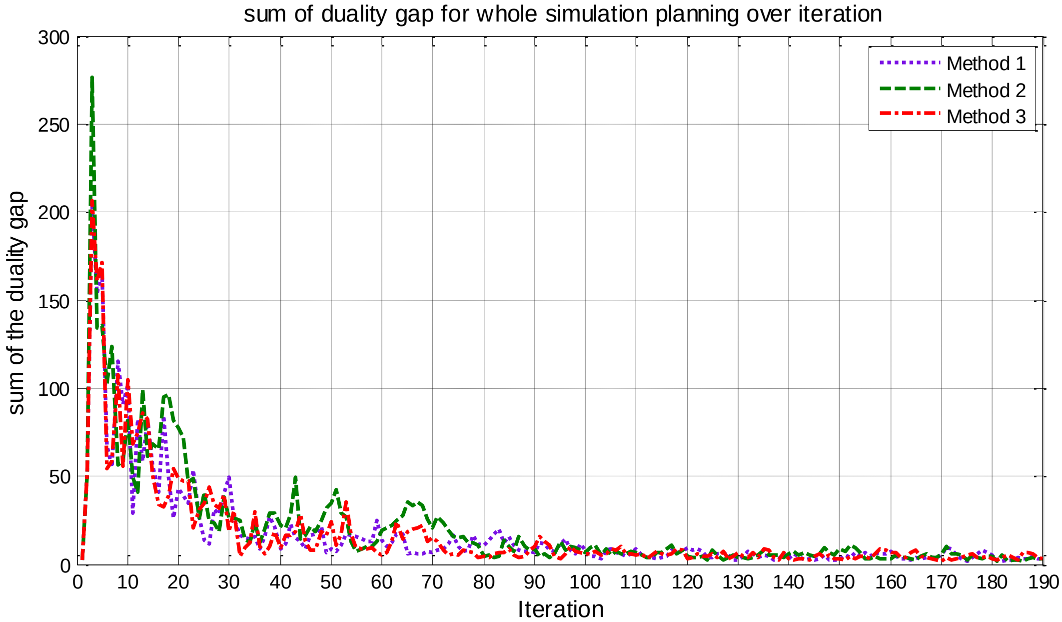


Figure C-14 Duality gap in MTIE in case 2 (VoT=20 euro/h, VoG=0.4 euro/kg)

Marginal time cost and marginal emission cost

VoT=10 euro/h, VoG =2.0 euro/kg

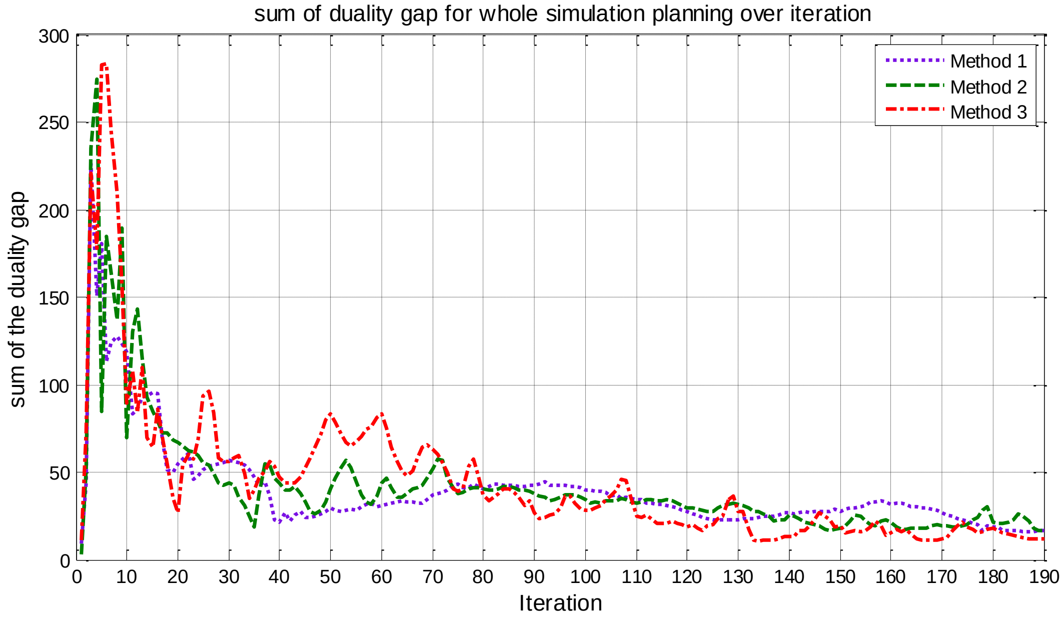


Figure C-15 Duality gap in MTME in case 2 (VoT=10 euro/h, VoG=2.0 euro/kg)

VoT=20 euro/h, VoG =0.4 euro/kg

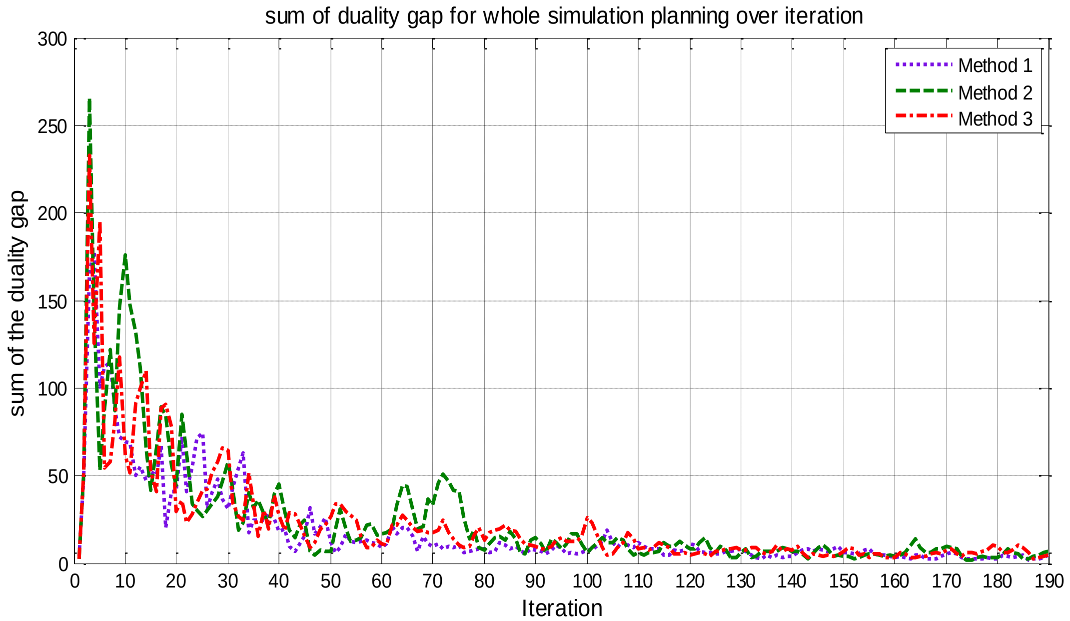


Figure C-16 Duality gap in MTME in case 2 (VoT=20 euro/h, VoG=0.4 euro/kg)

C.3 Quality check

The table in below shows the relative percentage changes of quality from method 2 and method 3 with method 1.

VoT=10 euro/h, VoG =2.0 euro/kg

Table C-1 Quality check (VoT=10 euro/h, VoG=2.0 euro/kg)

	Method 2				Method 3			
	InT+InE	**InT+MaE**	**MaT+InE**	**MaT+MaE**	**InT+InE**	**InT+MaE**	**MaT+InE**	**MaT+MaE**
Total travel time	-0.93%	0.57%	0.71%	0.45%	-1.24%	-1.37%	0.64%	-0.59%
	(-1.67%)	(-1.78%)	(-1.64%)	(-0.75%)	(-1.36%)	(-1.51%)	(-1.44%)	(-1.24%)
Total emission	0.43%	-0.42%	0.33%	0.26%	0.38%	0.63%	0.11%	0.26%
	(-1.56%)	(-1.26 %)	(-1.31%)	(-0.67%)	(-1.35%)	(-1.47%)	(-1.21 %)	(-0.93%)
Completion rate	0.92%	0.53%	-0.23%	0.31%	0.52%	0.47%	0.37%	0.71%
	(-1.69%)	(-1.73%)	(-1.67%)	(-0.93%)	(-1.38%)	(-1.29%)	(-1.33%)	(-1.04%)

VoT=20 euro/h, VoG =0.4 euro/kg

Table C-2 Quality check (VoT=20 euro/h, VoG=0.4 euro/kg)

	Method 2				Method 3			
	InT+InE	**InT+MaE**	**MaT+InE**	**MaT+MaE**	**InT+InE**	**InT+MaE**	**MaT+InE**	**MaT+MaE**
Total travel time	-0.03%	0.28%	0.19%	0.14%	-0.27%	-0.67%	0.35%	-0.64%
	(-0.17%)	(-0.35%)	(-0.37%)	(-0.90%)	(-0.26%)	(-0.42%)	(-0.14%)	(-1.07%)
Total emission	0.13%	-0.32%	0.23%	-0.06%	0.04%	-0.54%	-0.12%	0.15%
	(-0.32%)	(-0.21%)	(-0.61%)	(-0.14%)	(-0.12%)	(-0.70%)	(-0.29%)	(-0.39%)
Completion rate	0.09%	0.13%	-0.27%	-0.22%	0.11%	0.23%	0.32%	0.26%
	(-0.13%)	(-0.19%)	(-0.64%)	(-0.18%)	(-0.09%)	(-0.20%)	(-0.19%)	(-0.37%)

Appendix D. Convergence check in Dynasmart-P case study experiment

In the multi-criteria routing scenario, the network performance should be investigated after achieving a consistence framework since there is a delayed feedback in the simulation. The consistent framework means the traffic states on the network between two successive runs are stable. For instance in ideal condition, for each OD pair, the split rate for all the used routes should be same for every simulation interval. This is the absolute convergence which needs a lot of time and enough iterations in the large and complex dynamic traffic simulation network with heuristic improvement. In this case study, the convergence check is not that strict, because of the balance trade-off between the efficiency and accuracy. If there is a trend which goes to convergence, then an approximate convergence after a certain runs is acceptable. In this case study, the convergence is represented by the traffic flows on some major roads and the total network emissions. Although the different traffic assignments on the network may produce the same average traffic volume (per minute) on the road and may emit the same amount of CO_2 emissions, there is no OD split rate output file from Dynasmart-P, and these two criteria are used to roughly represent the convergence. In this appendix, an example of the convergence check is introduced by using the random seed 2012.

The important intersections which are used as the decision nodes and the major links are selected to check the traffic flow profiles in different runs. Two important decision nodes and three representative road sections which are shown in the Figure D-1. Node 51 is the first intersection entering the urban area if vehicles come from the west N270, and Node 27 is the first intersection entering the urban area if vehicles come from the east N270. Link 155 is the approaching link for Node 51 and link 191 is the approaching link for Node 27. Four exit links are selected which are link 158, 159, 68 and 69. Three road sections are selected, which are represented urban across way (link 60 and link 58), south urban belt road (link 132 and link 117) and north urban belt road (link 115 and link 341). The locations of these links on the network are shown in Figure D-1.

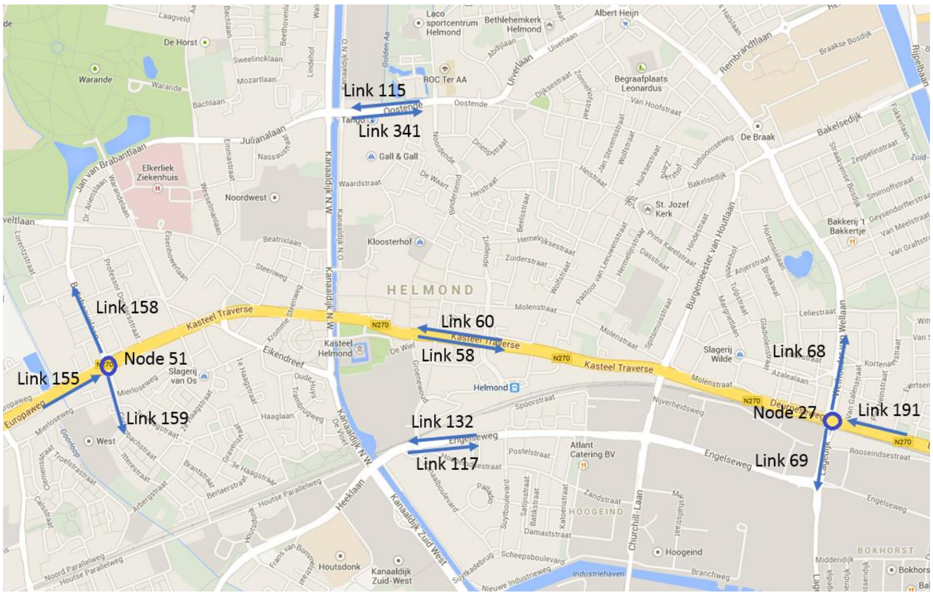


Figure D-1 Represented links for the convergence check on the network

In this experiment, the maximum runs is set as 30. The reference case is the run 1. After the first run, the composite cost function will be used as multi-criteria routing. The average traffic volume (per minute) on the representative links are shown in Figure D-2.

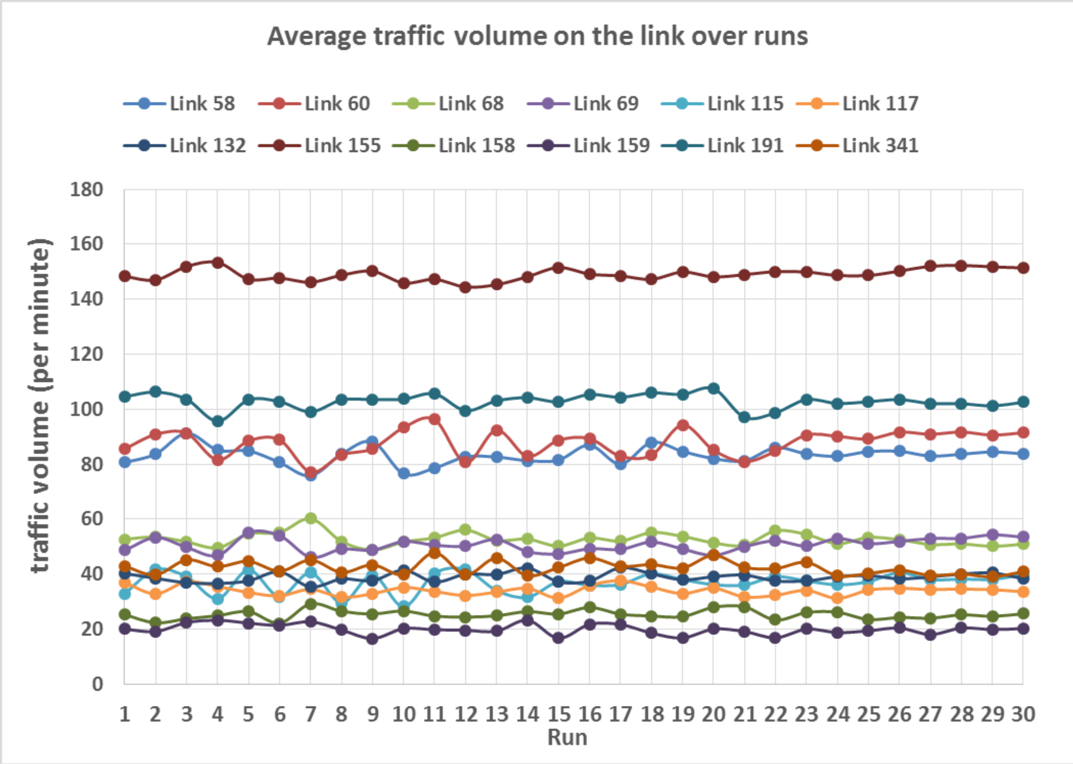


Figure D-2 Average traffic volume on the link over runs

The Figure D-2 shows the average traffic volume (per minute) on the links during the simulation with multiple runs. At the beginning, the average traffic volume on the representative links fluctuates over runs, after the 26th run, these fluctuations become stable. Then the total emissions over multiple runs are investigated and the result is shown in Figure D-3.

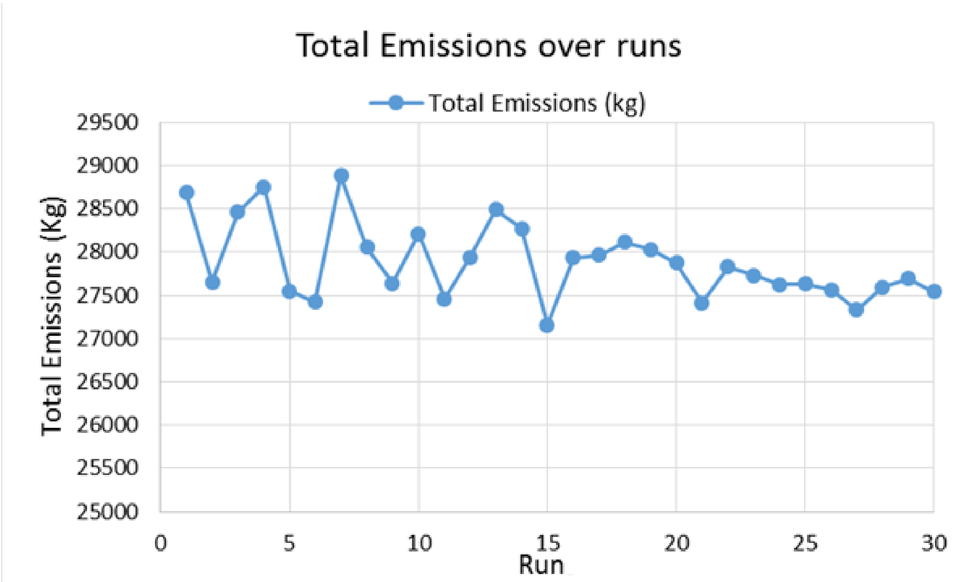


Figure D-3 Total emissions over runs

The total emissions also have huge fluctuations in the beginning. Although there are some points are higher than the initial point, the overall trend goes down with more runs. It is interesting that the fluctuation of the total emission became slightly after 20th run. This is in line with the result from traffic volume check. The total emissions is less than the reference case.

According the results from both link traffic volume check and the network total emissions, a confidence of the convergence arise. There is trend of convergence followed with the multiple runs. As found by Boyce et al. (2004), it may needs more than thousands iterations to close the convergence in a dynamic traffic simulation. The end of the simulation here is not achieve the real convergence.

Considering the trade-off between the efficiency and accuracy, and the future development for the road authority traffic management. This roughly convergence is enough to answer the research questions and give a green traffic management not far off the best solution.

As explained in chapter 4, the first run of the multi-criteria experiment with method 3 is the reference case, the results from the multi-criteria routing simulation is compared with the reference case. The relative changes of the network performance indicators over the multiple runs is shown in Figure D-4.

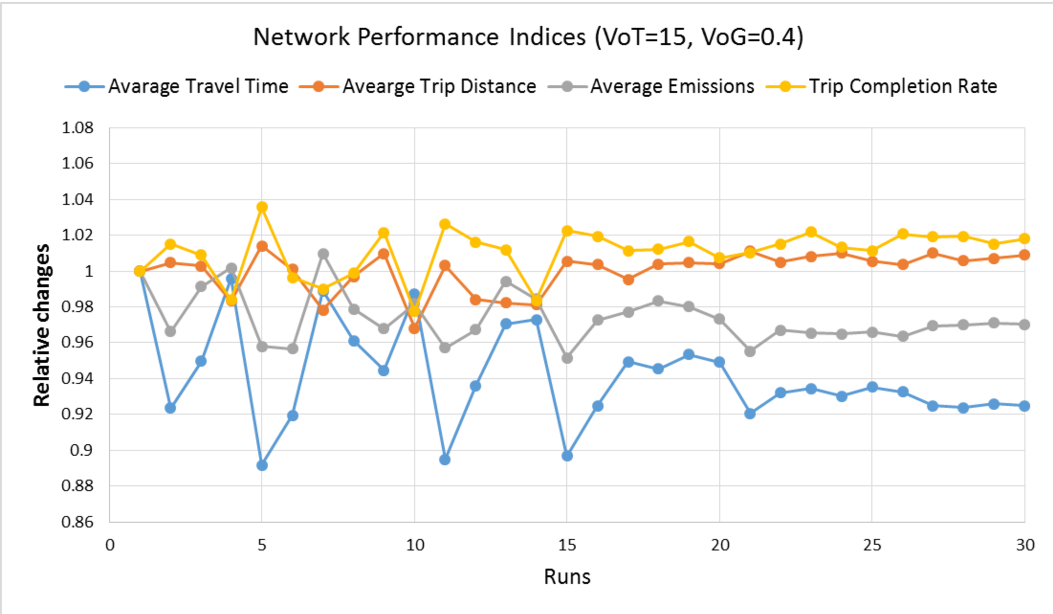


Figure D-4 Network performance indices

In Figure D-4, network performance indices compare with the reference case during the consecutive runs are shown. It's not the absolutely converge in the end, but the network performances fluctuate within a small range after 21th runs. Four network performance indicators go to the convergent state with multiple run, it is apparently that the fluctuations become smooth and slight in the end. The simulation convergence check is finished, and the simulation researches an approximately convergent state.

Appendix E. Network results from Dynasmart-P

E.1 Scaling factor 0.001

Speed of the whole network at 100 minute

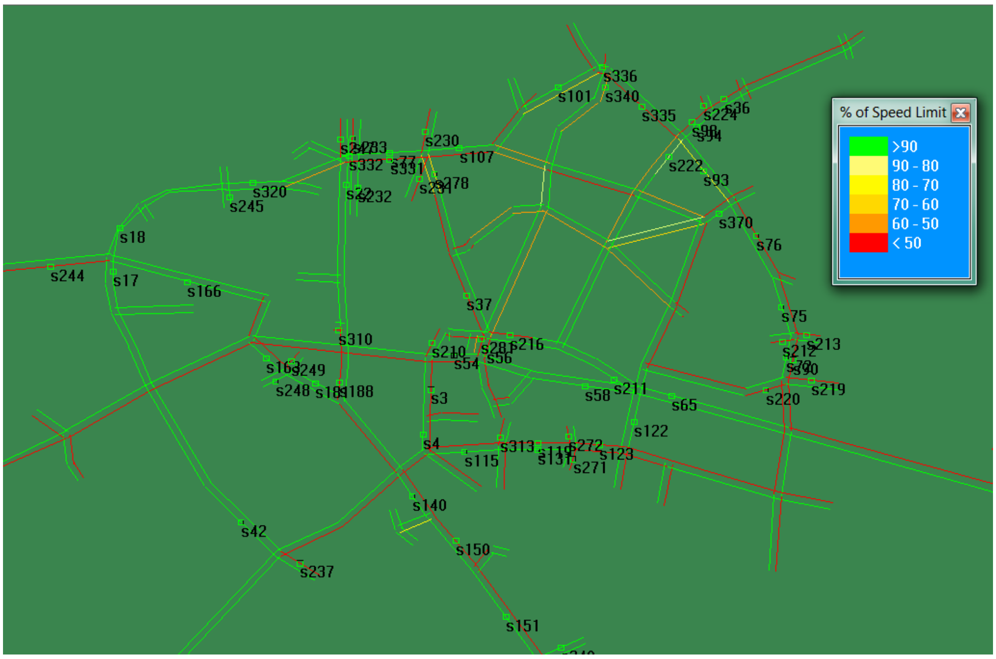


Figure E-1 Speed of the whole network at 100 minute (Scaling factor 0.001)

Density of the whole network at 100 minute

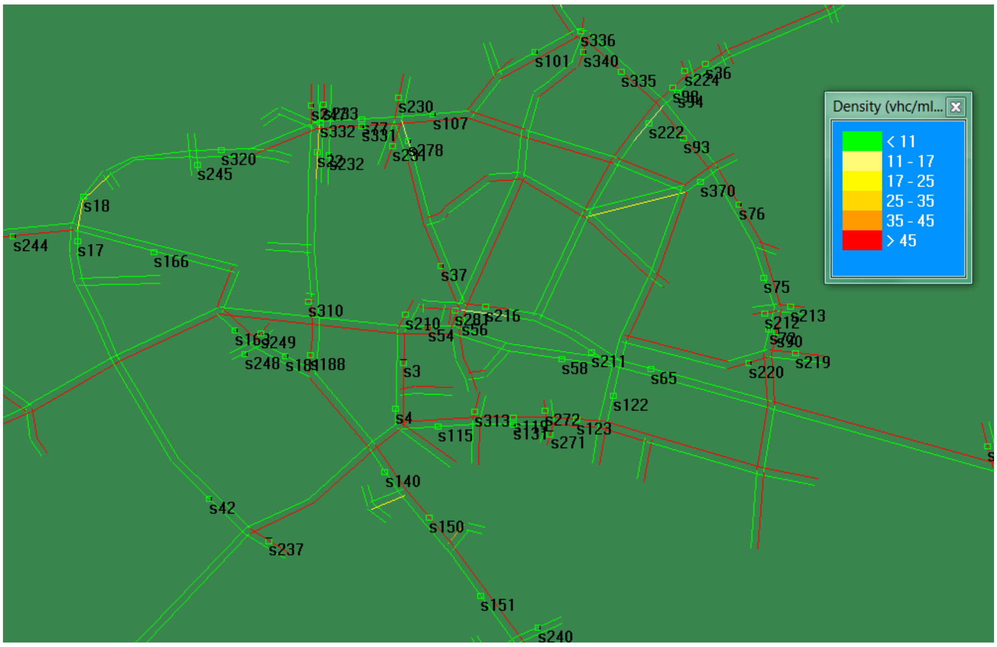


Figure E-2 Density of the whole network at 100 minute (Scaling factor 0.001)

Queue length of the whole network at 100 minute

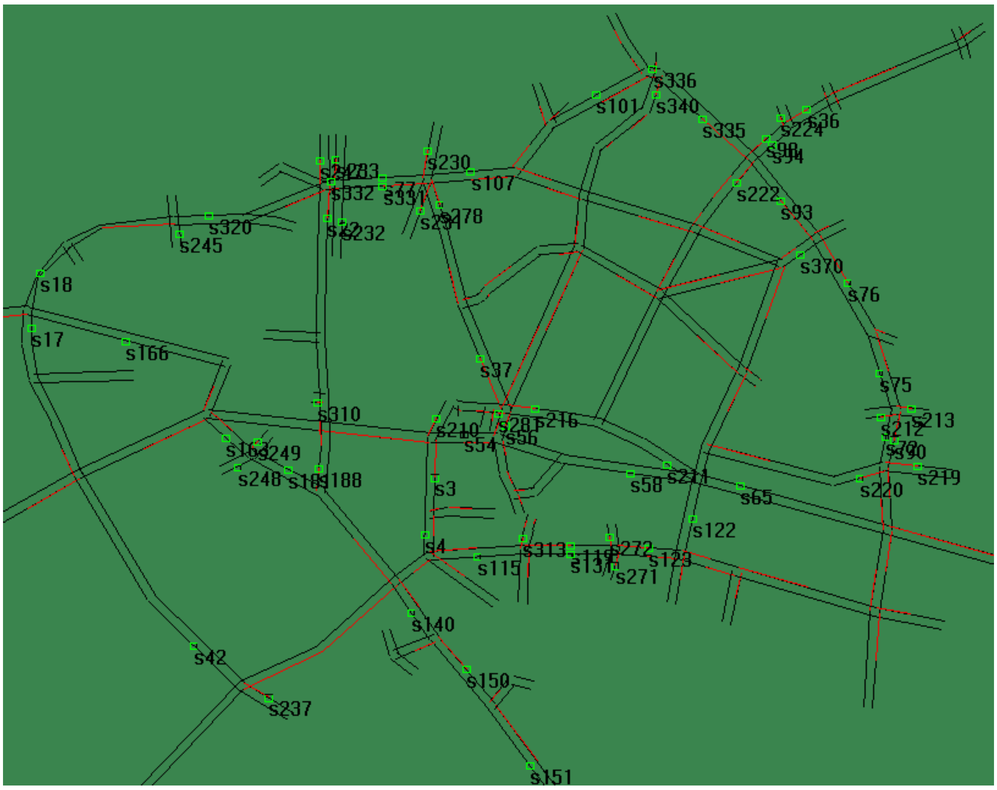


Figure E-3 Queue length of the whole network at 100 minute (Scaling factor 0.001)

Queue length at Node 46

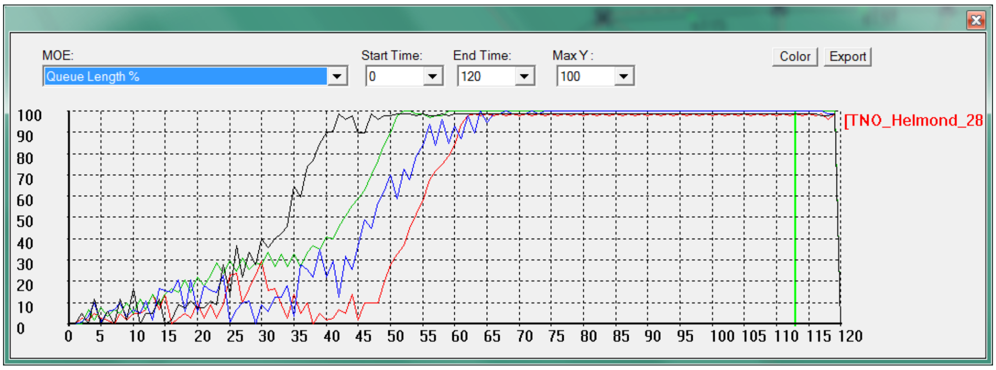


Figure E-4 Queue length at Node 46 (Scaling factor 0.001)

Queue length at Node 52

Figure E-5 Queue length at Node 52 (Scaling factor 0.001)

Queue length at Node 22

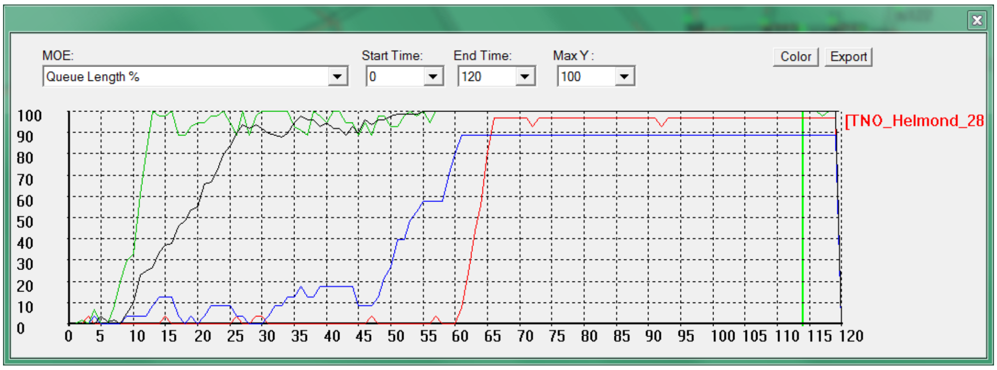


Figure E-6 Queue length at Node 22 (Scaling factor 0.001)

E.2 Scaling factor 10

Speed of the whole network at 100 minute

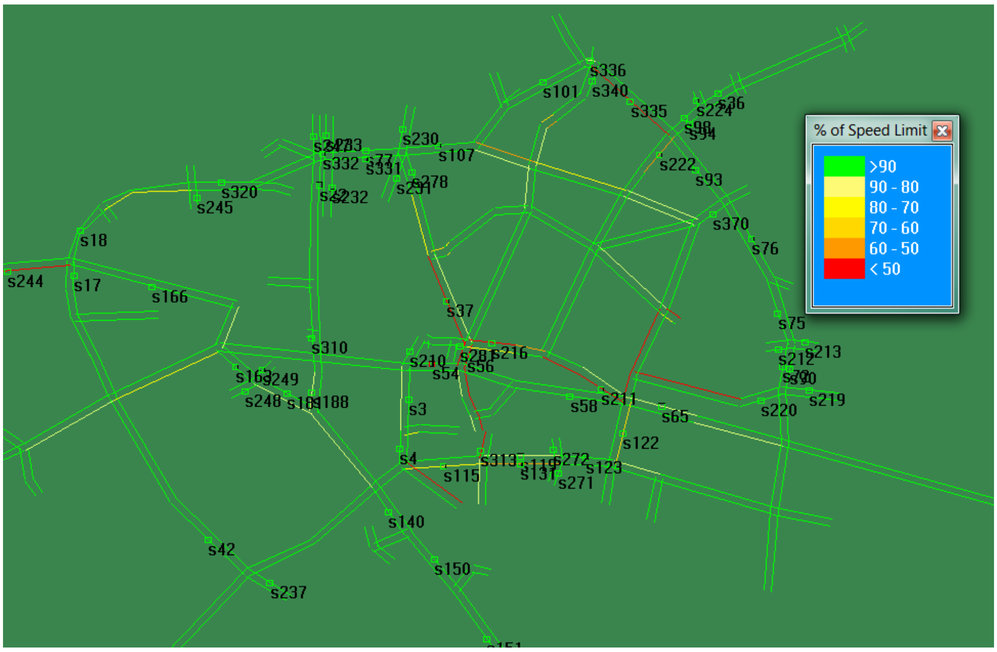


Figure E-7 Speed of the whole network at 100 minute (Scaling factor 10)

Density of the whole network at 100 minute

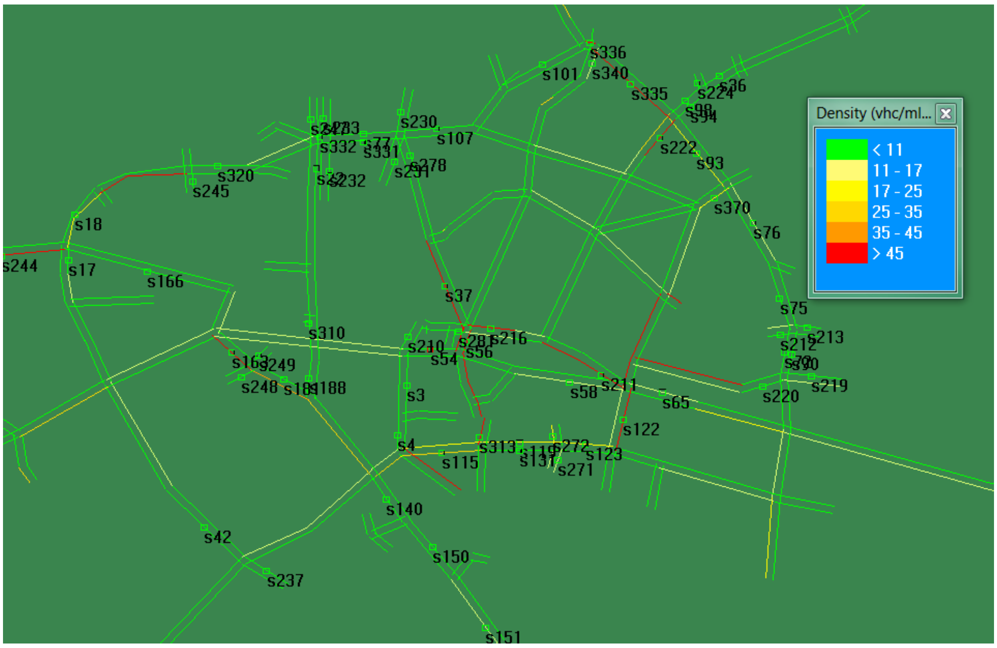


Figure E-8 Density of the whole network at 100 minute (Scaling factor 10)

Queue length of the whole network at 100 minute

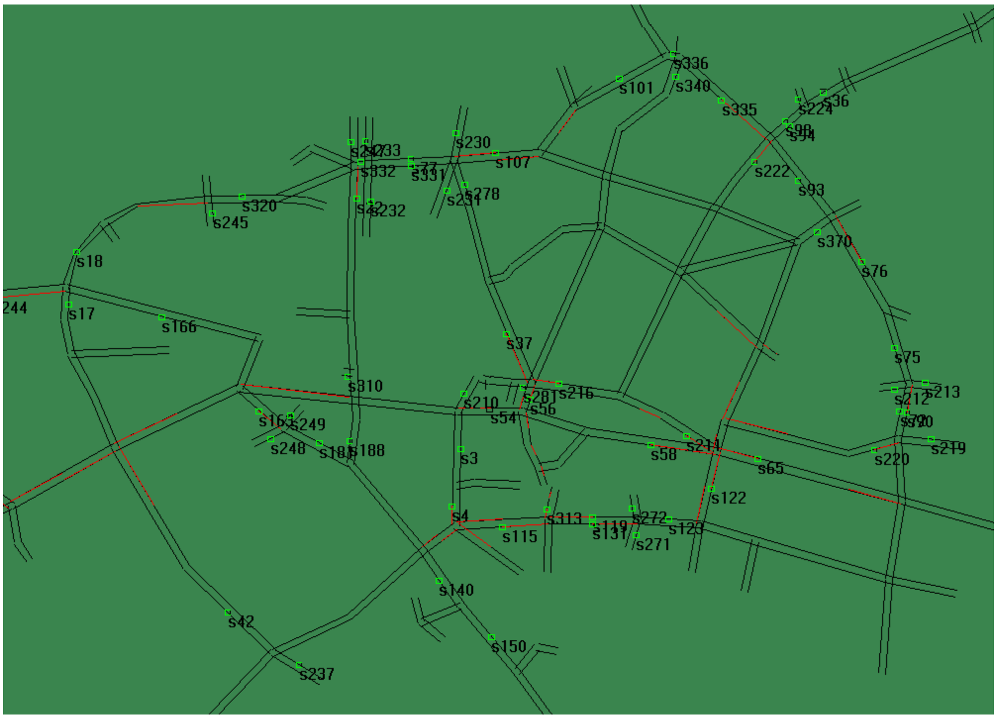


Figure E-9 Queue length of the whole network at 100 minute (Scaling factor 10)

Queue length at Node 46

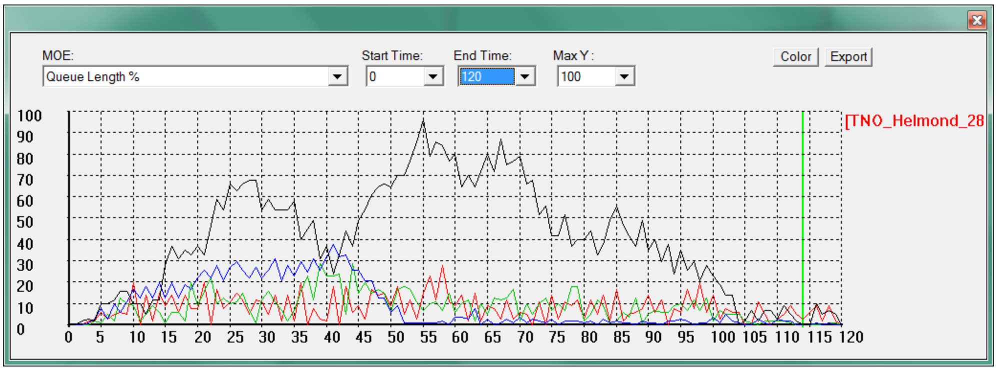


Figure E-10 Queue length at Node 46 (Scaling factor 10)

Queue length at Node 52

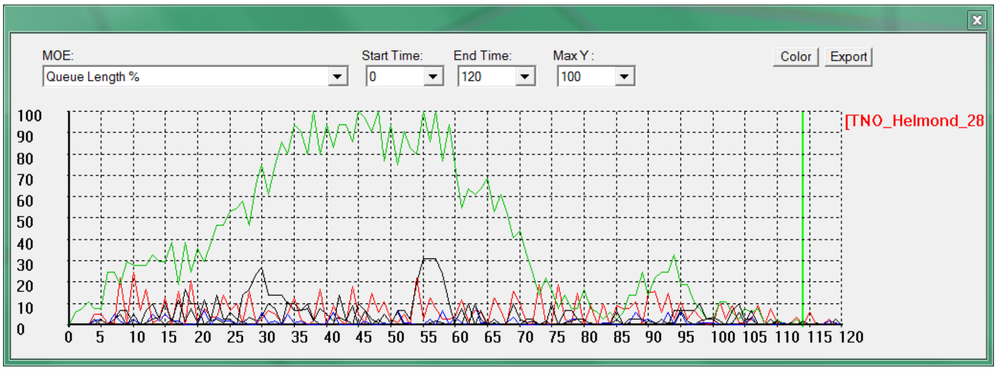


Figure E-11 Queue length at Node 52 (Scaling factor 10)

Queue length at Node 22

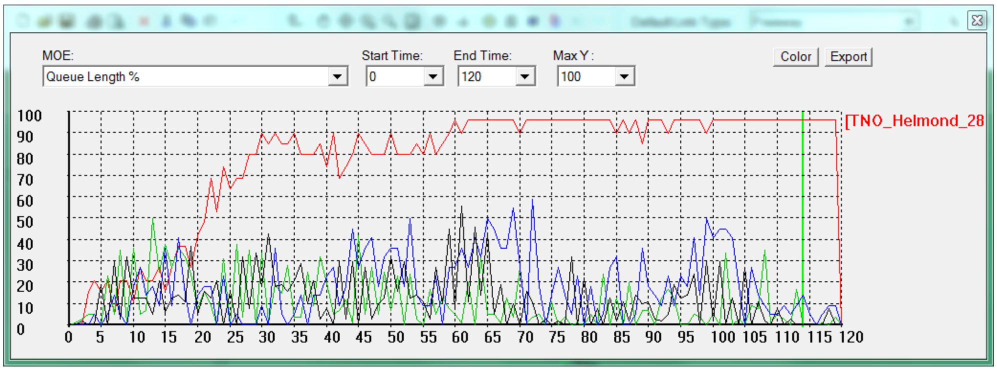


Figure E-12 Queue length at Node 22 (Scaling factor 10)