# Robustness Analysis for Road Networks

## A framework with combined DTA models

Minwei Li

Delft University of Technology, 2008

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*Cover illustration: Minwei Li*

# Robustness Analysis for Road Networks

## A framework with combined DTA models

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*“则天道变化，不主故常是正”*

《天演论》

严复译

# Preface

Minwei Li, December 2008

In 2001 before I finished my master study in Tsinghua University in Beijing, China, I had two choices to continue my study abroad. Finally I selected TU Delft to explore a brand-new world of traffic and transport because I felt that compared with the conventional directions in civil engineering such as structural mechanics, transport research becomes a more urgent and interesting topic for modern societies. The most important thing I have learned after my five years and nine months studying and research experience in TU Delft is that although there exists lots of uncertainties and difficulties, we *can* make our transportation system better. Besides the way of building more infrastructure to increase the capacity, traffic management measures can improve the traffic states if they are carefully designed grounded on accurately modeling traffic flow and human behavior.

This thesis focuses on building up a systematic framework that is capable of analyzing the ability of road networks against unpredictable and exceptional incidents, such as a severe accident. This ability can be simply treated as the road network robustness. For the performance analysis on a network scale, it is crucial to represent the route choice behavior of travelers and dynamic traffic assignment (DTA). Starting from the analysis of the basic requirements for the complete study of road network robustness, an innovative two-step process is proposed. It's basic idea is that in step one an user equilibrium status of the network is built up to represent the daily traffic pattern; and in step two, based on the equilibrium status, incident scenarios are represented as a non-equilibrium situation or a new equilibrium situation taking into account the effects of the incident. So the framework is also designed with two stages corresponding to these two steps, and our main contribution is to adopt two approaches of DTA models (i.e., user equilibrium (UE) approach and en-route approach) into the framework. Through case studies of two road networks with different size and complexity, the applicability and effectiveness of this framework have been proved for the systematical analysis of a road network robustness against different types of incidents.

As a foreigner living abroad, we should face more difficulties than local people, especially there exist so big differences in the culture and living styles between China and western countries. However, the biggest challenge for me is that transportation was almost a new topic for me when I first came here, which means I had to start from learning the basic knowledge. So I would like to thank my supervisor, Prof. Henk van Zuylen who hired me from China directly, for his patience, encouragement and supervision for my study and research. Thanks also to Dr. Michiel Bliemer and Dr. Yusen Chen, who are both experts of DTA models and gave me lots of valuable advises and critical comments on the final thesis. Particular thanks to my former colleague Henk Taale in TU Delft who developed the MARPLE model, based on which I can realize my idea and finish this PhD research. Particular thanks also to my current colleague Claire Minett, who spent lots of her spare time improving my English writing. Last but not least, I must thank my colleague Maaike Snelder in both TU Delft and TNO for her help in translating the summary from English to Dutch.

During almost six years in TU Delft, I am happy that I have met so many foreign friends, such as Dr. Francesco Viti (my first officemate), Dr. Dong Ngoduy (my officemate for the longest period), Dr. Marc Miska (the best English-speaking German I ever met), and many many others who let me enjoy the feeling of winning in table tennis. Because of you all, I didn’t feel so lonely when I was alone in Delft. The happy times we spent together will be in my memory forever.

Thanks also to my parents in China. I know that in the last 14 years when I was outside for studying and working, you care about me every second. But as your single child, I cannot accompany you so often, even at the moment when you really needed me. This thesis is for you! It is also specially for my devoted grandma and grandmother who passed away during my time in the Netherlands that I couldn’t be with them for the last minute! May they be gratified in paradise!

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# Notation

The main shorthand and symbols that are used in the development of our model (Chapter 4 to Chapter 7) are presented as follows:

## Shorthand

$TA$ : traffic assignment
$DTA$ : dynamic traffic assignment
$UE$ : user equilibrium
$SUE$ : stochastic user equilibrium
$IL$ : influencing length (km)
$IF$ : influencing flow (veh)
$TTD$ : total travel distance (veh*km)
$TTT$ : total travel time (veh*hour)
$TD$ : total delay (veh*hour)
$ETD$ : extra total delay (veh*hour)
$TNA$ : total network arrival (veh)
$NAS$ : network average speed (km/h)
$NL$ : network loading (veh/h)

## Sets

$A$ : Set of directed links in the network
$N$ : Set of nodes in the network
$\Omega_w$ : Set of scenarios related to uncertain variable $w$
$PS^{od}$ : Set of paths from origin $o$ to destination $d$
$EPF(t)$ : Set of equilibrium path flows for interval $t$
$EPC(t)$ : Set of equilibrium path costs for interval $t$
$PF(t)$ : Set of path flows for interval $t$
$PC(T)$ : Set of path costs for interval $t$

## Indices

$t$ : Evaluation interval
$o$ : Origin
$d$ : Destination
$r$ : Route
$u$ : Traveler type
$a$ : Link

# 1

# Introduction

## 1.1 Importance of Road Network Robustness

With the development of economy, transportation system, especially the road system, plays a more and more important role in our society. It undertakes the transport tasks of human beings and goods, which means that most of the social and economic activities (e.g., working, recreation, freight, etc.) should use road networks, and the process and the success of these activities highly depends on the performance of road systems. So on one hand, the existence of a connected road network is essential to the operation of the whole society. For instance, after the occurrence of some exceptional events, such as the catastrophic disasters (e.g. earthquakes and floods) or the malicious targeted attacks, existing road infrastructures may be completely destroyed and large numbers of casualties might need help. To allow for the evacuation of victims and the transport of emergency supplies for the influenced area, the road network needs to function (at least partially) as soon as possible. On the other hand, it also means that any disruption that makes partial or fully failure of the road network might cause remarkable negative social and economic impact, even the disruption of the whole society. For example, (Scarponi, 2004) reported that a fiery accident that destroyed a section of Interstate 95 – the main highway linking New York and Boston – will take millions of dollars and two weeks or more to reopen, which is described as ‘a pain in the neck’. However, these millions of dollars of losses are just for the direct effects of the accident that only include the repairing fee of the infrastructure and covering of police and fire overtime. In fact, all the indirect losses from such an accident might be much higher than the direct losses, and are probably impossible to count completely. Those indirect losses include the extra time losses for the traffic to use alternative paths, the extra time losses for the original traffic on those alternative paths due to the congestion induced by the extra traffic, and the delay and inconvenience to other activities caused by the disruption in the transport of people and goods. Thus, in order to reduce the losses of money and casualties caused by the disruptions in the road network, it is very important for a road network first to maintain its function as much as possible after the disruption; and to recover its function as quick as possible from the partial or complete failure. These two points are exactly what the concept of road network robustness concerns.

Robustness is defined by (Gribble, 2001) as '*the ability of a system to continue to operate correctly under a wide range of operational conditions, and to fail gracefully outside of that range*'. For a road network, its operational conditions can be basically classified into two sides: supply conditions and demand conditions. Any disruption in a road network ultimately results in the changes of its supply (such as the link capacity) or/and its demand. The operation status of a road network is often evaluated with some indicators for its network-level performance, such as the average speed and network throughput. Thus the study of road network robustness can be simply understood as the analysis of the performance of the road network under the situations with considerable changes in its supply or/and demand compared with its normal or desired performance. From this point of view, the concept of network robustness is very easily confused with the concept of network reliability, which also focuses on analyzing the network performance under uncertain operational conditions. So in Section 1.2, road network robustness will be clarified through a thorough comparison with network reliability. Based on the clear definition and delimitation of road network robustness, Section 1.3 presents the main problem formulation for this thesis, including the basic requirements for road network robustness studies and the gaps between the existing researches and these requirements. In Section 1.4 the objectives and scope of the research are described. Contributions of this thesis to modern state-of-the-art of road network robustness study are discussed in Section 1.5. Finally, the set-up of this thesis is outlined in Section 1.6.

## 1.2 Clarification of Road Network Robustness

Network robustness and network reliability are two concepts that are easily confused because they both focus on the analysis of network performance and the changes of the performance caused by the changes in the road network. During the last two decades, network reliability has been widely studied with large numbers of publications, while network robustness has only been given little attention by a limited number of researchers. Thus, it might be the most suitable way to introduce the concept of road network robustness by making clear distinctions with road network reliability. The structure of this section is then organized as follows. In the first two subsections, definitions of network reliability and network robustness are given respectively. After that, the differences between the two concepts are illustrated in detail. Finally the significance of carrying out road network robustness analysis is summarized.

### 1.2.1 Network Reliability

Several understandings about road network reliability exist from different interests in the research objectives. The most accepted definition of the network reliability is given by (Billington & Allan, 1992) and (Wakabayashi & Iida, 1992) as follows:

> Reliability is the *probability* of a road network performing its proposed service level adequately for the period of time intended under the operating conditions encountered.

For a given road network in the form of a direct graph $G = (N, A, D, CL, \ldots)$ consisting of a set of nodes $N$, a set of directed edges/links $A$, a set of demands $D$, a set of controls $CL$, and other inputs, a general function to calculate network reliability is to calculate the probability of a measure or indicator of the network performance, $C(G)$, no less than the pre-specified threshold value $C^*(G)$, i.e.

$$Pr\left(C(G) \geq C^*(G)\right) \tag{1.1}$$

It is important to recognize that the value of each input variable set, such as $N$, $A$, $D$, and $CL$, is in fact not deterministic but with variations. Capacities of nodes and links depend highly on the infrastructure itself and the external conditions (e.g., weather, driving behavior of travelers, incidents, and traffic controls, etc.). Demand obviously varies from time to time in a day and from day to day. Traffic controls, especially those dynamic traffic responsive control measures, also vary with the actual flows. Most of the variations result in uncertainties in the network. For instance, stochastic link/path travel time is the result of the combination of stochastic (link) capacity, stochastic traffic demand and stochastic human behaviors. Such variations have been analyzed in reliability studies on traffic and transportation, such as the work of (Asakura & Kashiwadani, 1991) and (Chen et al., 2002).

Network reliability studies are normally categorized according to the chosen measures/indicators for the network performance. Some important categories are briefly introduced as follows:

- Connectivity reliability (terminal reliability nominated by some researchers): is the probability that traffic can reach a given destination at all (Bell & Tida, 1997);
- Travel time reliability: is the probability that a trip can reach its destination within a given period at a given time of day;

- Capacity reliability: is the probability that the network can accommodate a certain traffic demand at a required level of service (e.g., minimum speed), while accounting for drivers' route choice behavior, such as (Chen et al., 1999) and (Chen et al., 2002).

### 1.2.2 Network Robustness

The concept of network robustness is often defined and exemplified in computer systems as the ability of a computer system to cope with errors during execution. It has been an important topic in several types of large-scaled complex networks, such as communication networks (Albert et al., 2000), internet (Tu, 2000), metabolic networks (Jeong et al., 2000), as well as general complex networks (Shargel et al., 2003) and (Beygelzimer et al., 2004). But for transportation networks, such as the road networks, robustness has only attracted very limited attention and it is also difficult to find a unified or widely accepted definition for road network robustness. The following definition summarizes the interpretations from several researchers, such as (Berdica, 2002) and (Gribble, 2001):

> Road network robustness is the *insusceptibility* of a road network to disturbing incidents, and could be understood as the opposite of network vulnerability. In other words, road network robustness is the *ability* of a road network to continue to operate correctly across a wide range of operational conditions.

Since robustness is a relatively new concept in the road network domain, no systematic classifications of its studies have been made yet. Moreover, the existing studies on road network robustness mainly use the methods of network reliability analysis. In the following subsection, the differences between network reliability and network robustness will be analyzed. As the result, the significance of carrying out robustness studies for road networks can then be summarized.

### 1.2.3 Differences between network robustness and reliability

Although both network robustness and network reliability problems focuses on analyzing the network performance taking into account the changes and uncertainties in the network, there also exist clear differences between them, mainly in the following two aspects.

- Primary objects: In the definitions of the two concepts given in the two sections afore, their objects are clearly described as the *probability* (for reliability) and the *ability* (for robustness) of road networks to perform properly. A simple illustration can be found in Figure 1.1. An indicator $C$ for the network performance (e.g. travel time, average speed) is assumed to follow the distribution function $g(C)$. Network reliability researches analyze the probability of $C$ being higher than the expected level $h$ (deterministic here, but could also be dynamic), i.e. $Pr\,(C \geq h)$. For example, researchers can analyze the chances of a trip from A to B to use more than 1 hour in the different periods of a day or by using different paths. So travelers can choose their departure time or path according to such information and their own desired arrival time to reduce the risks of arriving too early or too late. So the *empirical information* or the *experience* of the travel time plays important role in the analysis of reliability. In contrast, network robustness research concerns about the special situations (scenarios) with exceptional events. Researches want to know whether or not the road network can still operate sufficiently to satisfy the expected performance level $h$ in scenario $i$, i.e. $C_i \geq h\,(i = 1, 2, \ldots)$. For example, when an accident occurs on the major link (such as the motorway) between A and B that creates long queues, can travelers still reach B by using alternative route in less than 1 hour to attend the meeting? Different from reliability problem, since the situations are unexpected and exceptional for robustness problem, travelers would face an unacquainted situation so that their experience might not be useful.

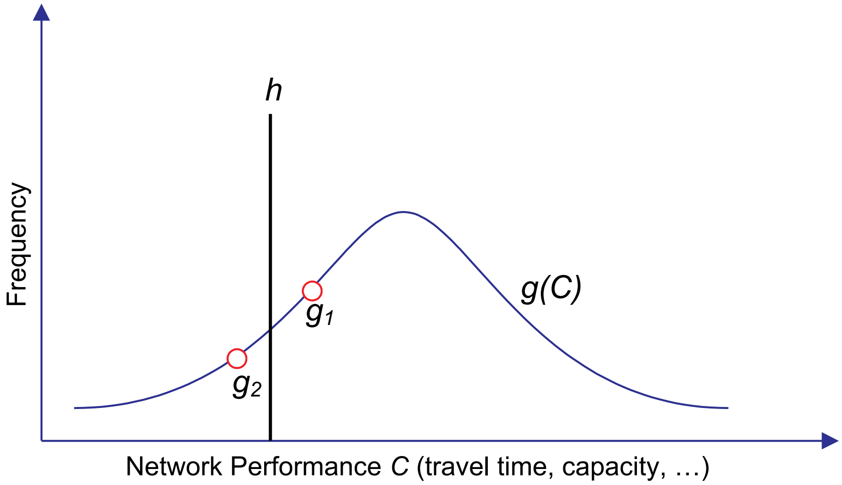

**Figure 1.1: Illustration of the variance of network performance and what reliability and robustness concern**

- Sources of uncertainties in the network: Road networks are the complex system full of changes and uncertainties. Revealing uncertainties in road networks is also an important research topic. (Iida, 1999; Bell & Cassir, 1999; Taylor, 2000; Chen et al., 2002; Nicholson et al., 2003; Immers & Jansen, 2005) categorized, summarized, and analyzed all types of uncertainties and their sources in transportation systems, ranging from irregular and exceptional events to regular fluctuations. They are listed below:
  - Irregular, unexpected and exceptional events

    1. Natural: disasters (e.g. earthquakes, hurricanes, floods, landslides, ...), extreme weather, ...
    2. Artificial: severe traffic accidents, major road works, social events (e.g. football matches, big fairs ...), malicious attacks, ...
    3. Technical: signal failures ...

  - Regular and expected variations in

    1. Demand: fluctuations in times of day, days of the week, and seasons of the year, ...
    2. Capacity: minor road works, ...

  A simple classification might be that network reliability researches mainly involve the effects of those regular and expected variations, while network robustness studies mainly concern the effects of those irregular, unexpected, and exceptional incidents. In Figure 1.2, such differences are illustrated with the analysis of some empirical data. The figure to the right shows the cumulative distribution function of the travel times collected on Kruithuisweg (N470) in The Netherlands from 01/01/2004 to 15/01/2004. Most ($\approx$ 97%) of the travel time for this road stretch is less than 400 seconds, which can be considered as a normal and acceptable scope of the travel time. Generally the analysis on network (travel time) reliability focuses on the variations in the network whose effects on the travel time are within this range, and the collected data beyond this range will be filtered. But as we can see in the figure, still about 1% of the samples have extremely high travel time ($>$ 500 seconds). They are mainly caused by some irregular and exceptional events that temporarily create the situations with exceptional low capacity or exceptional high demand. The occurrence of such situations are with very small probability as illustrated in the figures to the left, but their impact is remarkable. For instance, the event that the bridge opens for more than one boat once can make very high delay up to 5 minutes. Network robustness analysis focuses on the cases or scenarios with such events in the network.

Besides these two major differences, (Immers & Jansen, 2005) later pointed out that (travel time) reliability is normally a user-oriented quality of the system, and robustness is one of the characteristics of the road system itself.

### 1.2.4 Significance of robustness analysis for road networks

After the comparisons given in Section 1.2, the definition of road network robustness is clear for us, including its domain and objectives. Thus the significance of having a robust road network also becomes clear. For road authorities, a more robust road network has higher capability against the unpredicted and exceptional disturbances,

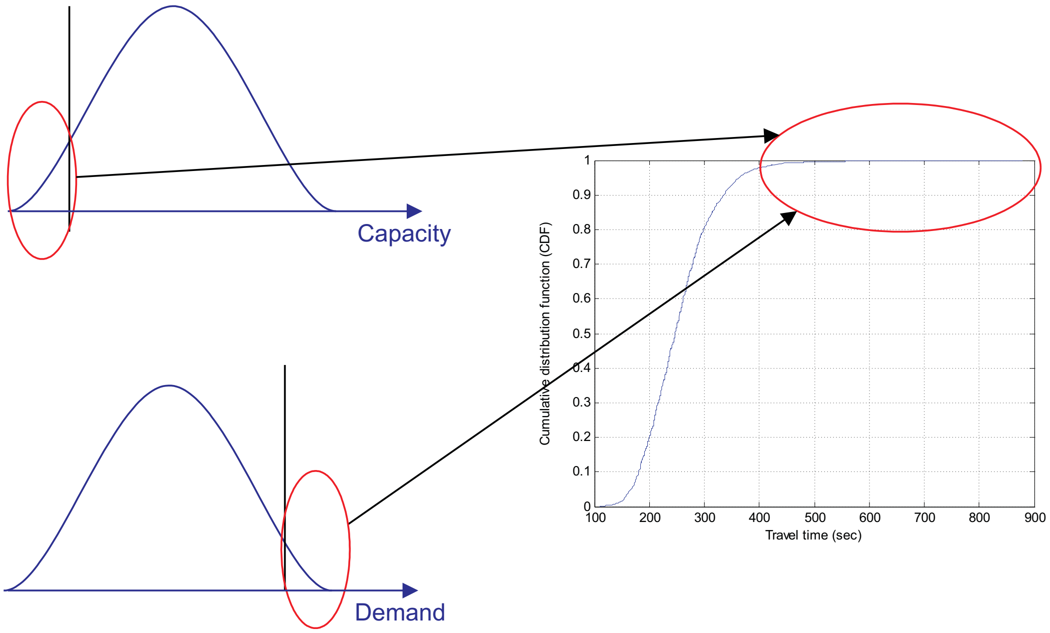

**Figure 1.2: Illustration of research domain of network robustness**

which means the whole society will be less affected by these disturbances. For travelers, they can also benefit from a robust road network with less losses of time when they encounter such disturbances. But the fact is that till now the amount of studies on road network robustness are quite limited, and its concept has not been widely and well known because it is easily confused with network reliability, even to some researchers of transportation systems. In order to make the concept of network robustness be recognized by more specialists in transportation field, such as planners and engineers, we feel it necessary to first make a better understanding of this topic due to the following two reasons:

1. For road planners, a better understanding of road network robustness and its relationship with the structure will allow them to easily consider network robustness in the planning;
2. For traffic engineers, a better understanding of road network robustness and its major influencing factors besides the network structure will support them in making suitable control schemes and measures to improve the robustness of the existing road network.

The main target of the research work in this thesis is to supply valuable information to traffic engineers about the characteristics of road network robustness and the major influencing factors to it. To do this, some systematic and comprehensive analysis will be carried out based on a suitable methodology. In the next section, we will formulate the road network robustness problem and the process of the solutions to this problem in detail.

## 1.3 Problem Formulation

In this section, several basic requirements for a systematic study on road network robustness will be given according to its definition and characteristics. After that, some basic influencing factors of road network robustness will be summarized. Finally, some gaps in the methodology and methods for road network robustness analysis are listed.

### 1.3.1 Basic requirements for road network robustness analysis

From the analysis in the sections above, road network robustness problem has the following characteristics: a physical road network with supply and demand, performance of the road network, disturbances in supply or demand, and travelers' reactions. Thus several primary requirements for a systematical analysis of road networks robustness can be summarized as follows:

1. A reference status that reflects the normal/daily network performance, i.e. the state without exceptional disturbance, is required;

2. Modeling the disturbances to the road network, including the disturbances on the supply (capacity) and on the demand, is required;

3. Representation of the interaction between network performance and travelers' (route) choice behavior is required. As mentioned before, in the situations with and without unexpected and exceptional disturbances, travelers' choice behavior might change based on their experience can help or not. This phenomenon is one of the fundamental characteristics of the transport system and also one of the reasons for the complexity of road network studies;

4. A valid network model is required, which means that the network performance, such as the travel time, can be correctly calculated. One of the key submodels is the queuing model that describes the build-up, spillback, and dispersion of queues because queuing is an inevitable phenomenon in most of the scenarios with disturbances. (Knoop, V.L. and Hoogendoorn, S.P. and van Zuylen, H.J, 2007) pointed out that modeling of queuing behavior is very crucial for modeling road network performance and route choice behavior of travelers.

These four primary requirements are the basis of all the works we will describe in this thesis, especially for the design of the methodology (Chapter 3). Thus they will be mentioned and emphasized several times in the following contents.

### 1.3.2 Influencing factors of road network robustness

As mentioned above, the major objectives for this study include achieving a better understanding about road network robustness and if possible, quantitatively describing road network robustness. We also know that robustness is considered as one of the characteristics of road networks. So the geometric structure of a road network fundamentally decides its robustness. Besides that, several other factors that can be qualitatively described as follows:

- Capacity: most of the incidents directly reduce the capacity of the road network, regardless of whether on links or at nodes. For the same level of capacity reduction, the road network with higher reserved capacity obviously has higher robustness;
- Demand: demand of a road system is the user of its capacity. For an existing road network with fixed capacity, less demand means a relatively higher reserved capacity and thus higher robustness against the same disturbances;
- Control: control measures are normally designed for the efficient use of the network capacity and/or other objectives of road managers, such as safety. From this point of view, suitable traffic control measures will improve the road network robustness to a certain extent.

### 1.3.3 Gaps in road network robustness analysis

Based on the above-mentioned requirements and influencing factors for the analysis of road network robustness, we are now confronted with several gaps in the adopted methodology and methods in the existing studies after a thorough literature study (Chapter 2).

1. Gap in the methodologies for road network robustness studies. Most of them are borrowed from reliability studies, but distinct differences exist between those two concepts, as well as the suitable methodology;
2. Gap in the suitable indicators of road network performance that can display the robustness of a road network against all kinds of disturbances, and if possible, quantify the robustness of road networks;
3. Gap in the models that can describe travelers' (route) choice behavior in both situations that without disturbances, i.e. daily normal states, and with disturbances on supply or/and demand;
4. Gap in the case study of network robustness with real-sized road networks fully considering the dynamics in the network performance and travelers' choice behavior.

Thus in the following two sections, our major objectives and contributions of this thesis work are listed corresponding to these gaps.

## 1.4 Research Objectives

The objectives of this thesis research include following points:

- Developing a generic framework or methodology for systematical network robustness studies;
- Developing suitable models that are able to represent network behavior under both normal situation without disturbances and exceptional situation with disturbances;
- Testing the validity of the developed methodology and models through case studies with a hypothetical road network and a real-sized road network;
- Searching for suitable network-level indicators that are convenient for estimating network performance, and suitable time-dependent indicators that can clearly represent the dynamics of road network performance. These indicators should be able to quantify network performance as well as network robustness;
- Finding critical elements (such as links) in a road network by using the proposed methodology.

## 1.5 Thesis Contributions

This thesis contributes to the state-of-the-art in building up a generic framework as the methodology for road network robustness analysis. In this framework, a model is developed to represent the network performance under both normal situation and exceptional situation with disturbances. Detailed information about the contributions of this thesis work are listed as follows.

1. Contribution to the knowledge of road network robustness: A better understanding of road network robustness, including its definition, significance, characteristics, and influencing factors can be achieved;
2. Contribution to the methodology and methods for road network robustness studies: a comprehensive framework has been built up. With this framework, network performance in different scenarios with all kinds of situations, i.e. without disturbances or with various exceptional disturbances, can be compared for the analysis of network robustness.

3. Contribution to the modeling approach. As parts of the framework, different models with a common traffic loading module are developed to be able to describe different (route) choice behavior of travelers under various situations. Thus the dynamics of the network performance and corresponding travelers' choice behavior after exceptional disturbances can be represented in a logical and consistent way.

4. Contribution to the suitable indicators to evaluate network robustness: These indicators can accurately illustrate the changes in the network performance taking into account travelers' (route) choice behavior.

5. Contributions to the application of network robustness: Through two case studies, some preliminary understanding about the robustness of road networks with hierarchical structure can be drawn, especially the knowledge about the critical links in a network. Several criteria for a preliminary scan of critical links in a road network are also proposed;

6. Contribution to the road network management: The influence of the information service to the robustness of road network has been analyzed. The delay in the information service proves to be negative to the network robustness. Furthermore, there exists an optimal compliance rate within the travelers to the real-time traffic information, which means that it is not always good for the network performance when the percentage of the travelers who always choose the fastest path increases.

## 1.6 Thesis Outline

This section provides an outline of this thesis and briefly gives information about each chapter.

Chapter 2 presents an overview of the state-of-the-art of (road) network robustness studies. In this chapter, we first review related robustness studies in the general complex networks and several other network domains (e.g. communication, biological). Special interest is devoted to the methods in these research works. After analyzing the characteristics of road networks distinguished from other types of networks, a detailed review of existing road network robustness studies is given, including their strengths and weaknesses. At the end, some basic requirements, especially the requirements for the suitable TA models for road network robustness studies, are derived from the review.

Chapter 3 summarizes the general features of a TA model, which is the core of road network robustness studies. Two approaches of TA models, UE assignment and en-route assignment, are compared and their possible applications for network robustness analysis are discussed. Based on the general requirements presented in Chapter 1 and particular requirements for TA models in Chapter 2, the final TA model for our road network robustness analysis is chosen at the end of this chapter.

In Chapter 4, a generic two-step simulation-based framework is designed for the systematic network robustness researches. Both TA approaches used in the framework are discussed, especially the en-route assignment models. Moreover, the other basic methodology used for network robustness analysis in this research work, scenario-based methodology, will also be introduced in detail.

Chapter 5 and Chapter 6 present the applications of the framework in road network robustness studies by testing respectively a hypothetical simple network and a real-sized network in each chapter. More specifically, the tests with a small network in Chapter 5 are mainly for the face validation of our framework and TA models; and the tests with a large road network in Chapter 7 are more for practical purpose.

Chapter 7 proposes a preliminary investigation study on the influence of real-time traffic information to road network robustness. In this study, a number of scenarios with different percentages of travelers who would respond to the real-time traffic information are simulated. The differences in the network robustness clearly demonstrate that the effects of the real-time traffic information are affected remarkably by the response of travelers.

Chapter 8 summarizes the whole thesis work and proposes several suggestions for the future work.

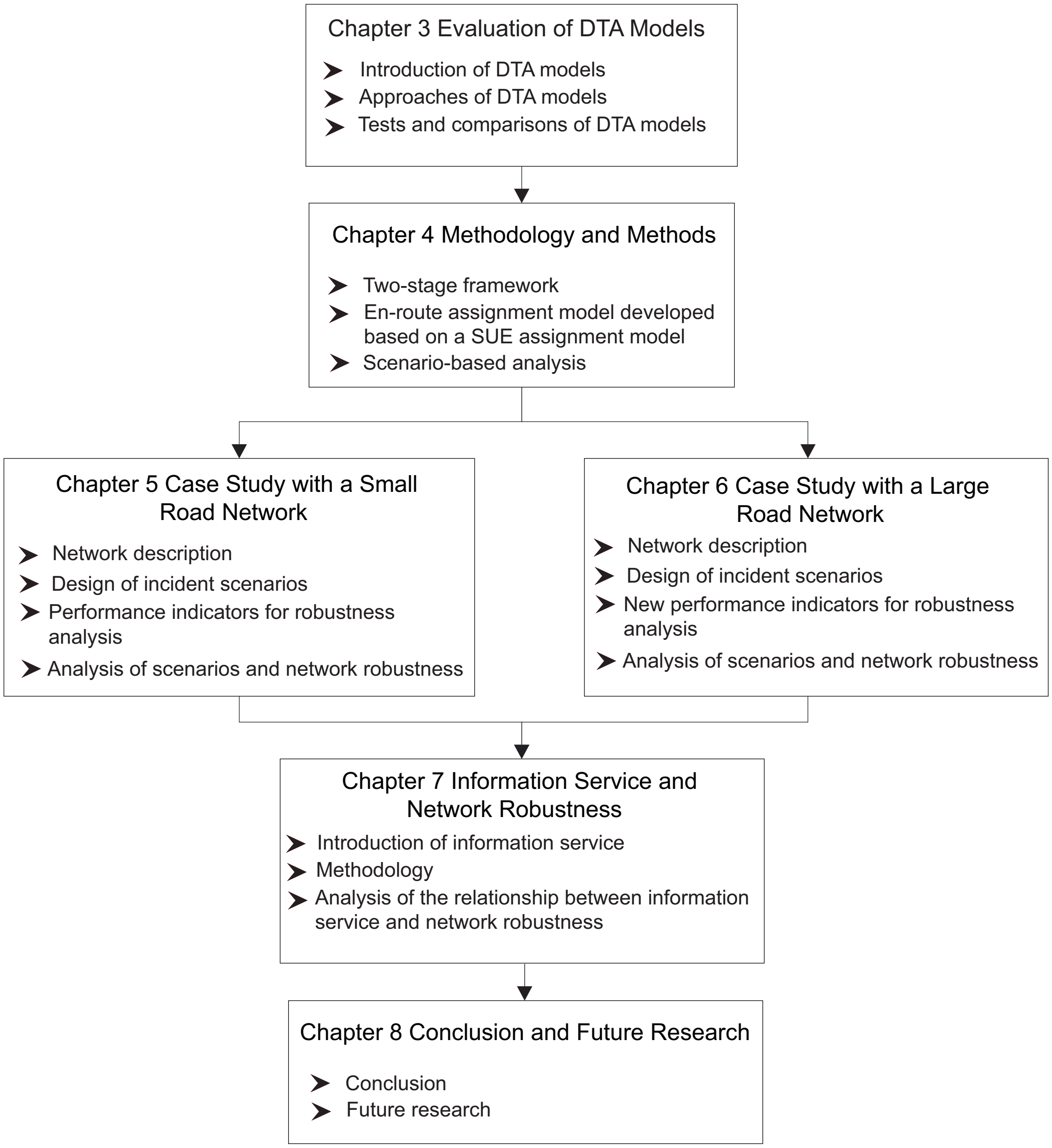

**Figure 1.3: Structure of the main contributions in this thesis**

# 2

# State-of-the-Art of Robustness Studies for Networks

In Chapter 1, road network robustness is introduced along with its importance to the economy, safety and the quality of traveling. However, the concept of road network robustness is so new and related studies are so rare that no systematic and well-rounded methodology could yet be found. To solve this problem, a good understanding of the existing studies on road network robustness are important and necessary.

Road networks form parts of the transportation network, which together with the electrical power systems, the World Wide Web (WWW), internet etc, are all examples of so-called *complex networks* that play important roles in maintaining the quality of modern society. Studies on the robustness of general complex networks and some specific types of networks have been developed more systematically than that of road networks, for instance (Albert et al., 2000), (Tu, 2000), (Shargel et al., 2003), (Beygelzimer et al., 2004), (Dekker & Colbert, 2004) etc. Before reviewing the existing robustness studies on road networks, it is valuable to first analyze the similar or related studies on the robustness of other network domains and, if possible, to use them as references in choosing or designing methodologies and methods. According to this idea, Chapter 2 comprises three major parts as follows. Section 2.1 summarizes the studies on the robustness of general networks and several specific types of networks. In Section 2.2, the features of road networks are listed and analyzed compared to other complex networks. According to the analysis in this section, we found that the road network robustness problem is quite different from that of other network categories, which means it needs new and specific methodology and methods. Section 2.3 discusses and evaluates existing road network robustness studies with particular focus on the ways of representing network performance and travelers' behavior in them. In the end, Section 2.4 outlines some lessons learned and gains derived from the reviews.

## 2.1 Robustness Studies of General (Complex) Networks

Network robustness has received much attention for networks in general or for several specific types of network domains, such as the WWW, internet and electronic networks. The subjects of these studies mainly cover the following areas:

- The analysis of the robustness (also referred to as tolerance in some contributions) of a network to random but serious errors and targeted attacks;
- The search for approaches to improve the robustness of the studied networks against a selective deletion of nodes (e.g., attacks on network hubs);
- The optimization design or improvement of complex networks considering robustness, as well as other objectives and constraints.

### 2.1.1 Classification of complex networks

For large and complex networks, the connectivity distribution function $P(k)$ is often used to describe the characteristic of a network. It is defined as the percentage of the nodes in the network being connected to $k$ other nodes. According to the types of the distribution, networks can be divided into the following two major classes.

1. The first class of networks, which are called *exponential networks*, is characterized by a $P(k)$ that peaks at an average $\langle k \rangle$ and decays exponentially for both smaller and larger $k$. In particular cases, the connectivity follows a Poisson distribution as shown in the right-hand figure of Figure 2.1. The most investigated examples of such exponential networks are fairly homogeneous, in which each node has approximately the same number of connected links as $k \simeq \langle k \rangle$.

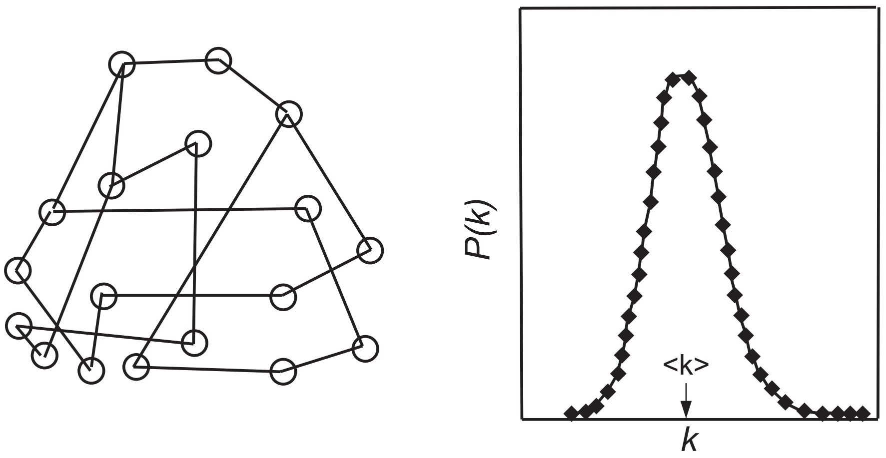

**Figure 2.1: Representative structure of exponential networks**

2. In contrast, analysis on the topology of the WWW (Albert et al., 1999), the Internet (Faloutsos et al., 1999), social networks (Barabasi & Albert, 1999), and metabolic networks (Jeong et al., 2000) indicates that many systems belong to the class of heterogeneous networks, called *scale-free networks*. In such networks, $P(k)$ decays as a power-law $P(k) \sim k^{-\gamma}$ with a characteristic scale $\gamma$, such as $\gamma = 2.2$ for the metabolic network analyzed by (Jeong et al., 2000). Whereas the probability that a node has a very large number of connections $(k \gg \langle k \rangle)$ is practically prohibited in exponential networks, highly connected nodes are statistically significant in scale-free networks such as hubs (see solid circles in Figure 2.2).

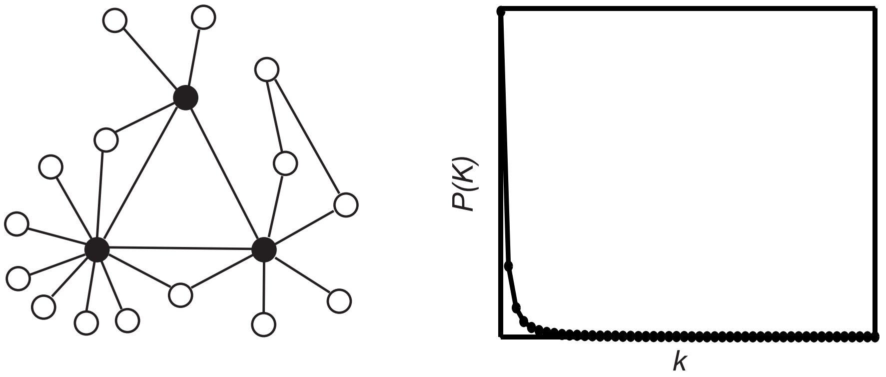

**Figure 2.2: Representative structure of scale-free networks**

### 2.1.2 Connectivity robustness of complex networks

A number of studies have been carried out for the analysis on the connectivity robustness of the two basic classes of networks. In these studies, the diameter **d** of the network, which is the average length of all the shortest paths between the pairs of nodes in the network, is widely used as the indicator for the quantitative connectivity performance of a network. The values of **d** of the studied network are calculated before and after the disturbances are introduced to the nodes in the network. Generally, if the value of **d** of a road network does not increase significantly after the disturbances, the network can be considered as robust against such disturbances. Thus, **d** is a static indicator to describe the connectivity robustness of the network because only the static length values are taken into account, i.e. the influence of the utilization of the links is not considered.

Disturbances to the nodes in the network are classified into the following two types: one is the randomly occurring errors, which are caused by random malfunction of the nodes; the other one is the intentional attacks, which are aiming at the most connected nodes, i.e. hubs. Some interesting conclusions have been drawn from analyzing the values of **d** of the network with these two types of disturbances:

- For an exponential network, the accumulation of errors, whether random or intentional, has the same deteriorating effect on the network connectivity performance. Each deletion of a node destroys some local paths, which leads to an increase in the distance between the nodes involved in these deleted nodes;
- For a scale-free network, the connectivity performance is almost unchanged by the random removal of nodes up to a large deletion rate. So such a network has immunity to random errors;
- A scale-free network is vulnerable under hostile attacks, which means that the effects of targeted attacks to those highly connected nodes (hubs) are much more severe than those to exponential networks.

Based on studies on the two basic classes of the general networks, robustness studies of specific large networks such as the WWW, the Internet, and metabolic networks usually take the following two steps. The first step is to identify the structure of the studied network best described by or closer to either exponential network class or scale-free network class. In the second step, general robustness characteristics of such a network class mentioned above are first tested. Then the unique characteristics of the studied networks are also addressed. The same method of using simulations of node removal disturbances are implemented and the same indicator **d** is used in these studies. Besides general conclusions of the network robustness, different degrees of robustness against two types of perturbations can be found in those specific types of networks. However, these studies are limited by the following assumptions:

1. Links, which are important elements for most of the large networks, are assumed to be homogenous with the same characteristics (e.g. capacity and speed) in these studies, which is not valid for all types of networks;

2. Only node removal has been considered as the source of perturbation scenarios in these studies, while the degradation or removal of links are ignored;
3. Only static indicators for network connectivity are studied, such as **d**. The changes of network performance, such as the throughput and delays, have not been reflected.

So questions about the reference values of these network robustness studies for that of road networks arise: are the conclusions of these network connectivity robustness also valid in the context of road networks? Can the methodologies and algorithms be directly implemented for analyzing road networks? Before giving the answers, the next section characterizes road networks and compares them with the two basic network classes presented above.

## 2.2 Characteristics of Road Networks

Transportation networks, as one type of the large and complex networks, may be distinguished in a number of ways from the two basic classes of networks. Several assumptions in the above reviewed network robustness studies are not appropriate for road networks at all because road networks have the following characteristics:

- The first and the most important characteristic of road networks is that human beings are basic ‘components’ forming the ‘flows’ in the network. So human behavior (e.g., car-following behavior, lane-changing behavior, and route choice behavior et al.) on one hand plays an important role in determining the performance of the network, and on the other hand human behavior is also influenced by the network performance. This makes road network performance more variable and unpredictable than the performance of other types of networks;
- Links in road networks are more important for robustness studies than nodes, especially for motorway networks where no grade crossings (i.e. physical nodes) are allowed. Due to this reason, most of the destructive perturbations on road networks appear on the links;
- Links in road networks are normally treated as one-directional, especially motorway links because they are structurally separated from the reverse direction by natural or artificial barriers;
- Physical road networks are hierarchically structured, in which several levels of subnetworks exist containing different types of nodes and links with different characteristics. This kind of layered structure has not been addressed in other types of complex networks. Here the classification of road networks in The

Netherlands is used as an example. In a hybrid road network, motorway subnetworks form the top level since its links have the highest desired speed (up to 120 $km/h$), the highest priority. Urban arterial subnetworks comprise the bottom level since its links are with the lowest desired speed ($\leq 50\,km/h$). Between these two subnetworks there exist the rural road links (connecting towns with medium speed at 80 $km/h$) and ramps (connecting motorway with lower level subnetworks). As mentioned before, physical nodes are rare in motorway networks. But in other lower level subnetworks, controlled or uncontrolled junctions are naturally treated as nodes, and they have remarkable influence on capacity (Viti, 2006).

When a physical road network is studied, it is normally modeled in a certain level of details according to the purpose and interest of the research. In Figure 2.3, two modeled road networks with different levels of details are presented to illustrate the particular characteristics of road network modeling. The left figure is the motorway network model of The Netherlands, and the figure on the right is a smaller but more detailed road network model around and inside city of Delft in The Netherlands.

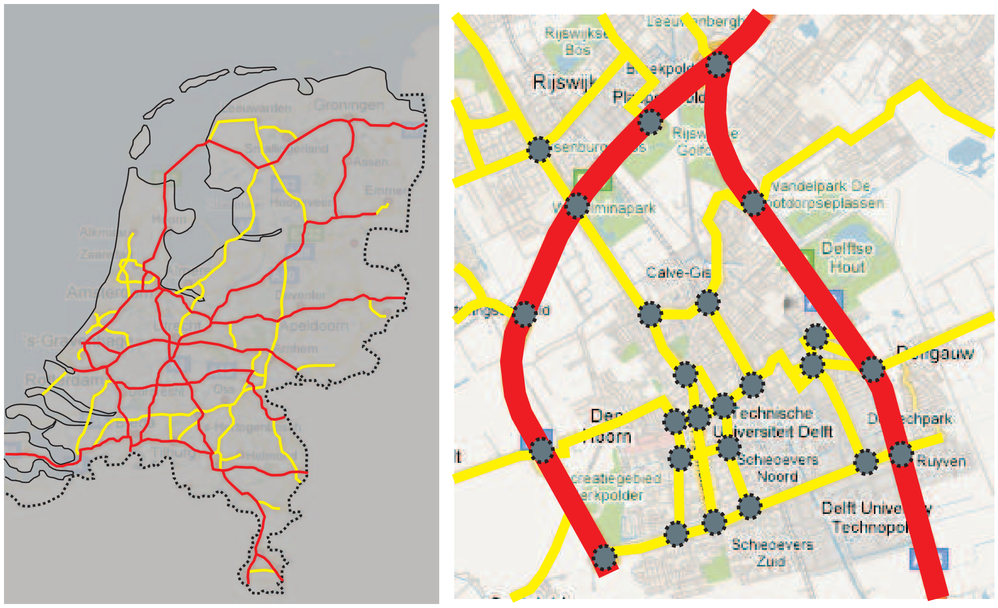

**Figure 2.3: Motorway network of The Netherlands (left) and Delft network (right)**

- Dutch motorway network: motorway forms the links, and junctions are treated as abstract nodes because travelers can shift from one motorway to another at these points, although there are no grade crossings. Cities also can be considered as nodes if lower level subnetworks are ignored, but they are either surrounded by rings of the motorway or beside the motorway joined with ramps. Most of the nodes in such large-scale motorway networks have 3 or 4 connected nodes. Here the tailend nodes have only 1 or 2 connected nodes, while the highly connected nodes are connected to 5 or 6 nodes.

- Delft network: urban and rural roads form the links, and nodes become more meaningful by representing physical junctions with or without signal controls. The majority of the nodes in the network have 3 or 4 connected nodes except for the tail end nodes, such as at residential areas. A node seldom has more than 4 connected nodes.

From those two networks with different scales and details, it is clear that the distribution of connections of a road network as shown in Figure 2.4 is more similar to that of the exponential network shown in Fig. 2.1 with $\langle k \rangle = 3$. According to the research work of (Albert et al., 2000), this kind of network is fragile to random perturbations, but robust to targeted attacks. On the other hand, we have to notice that links in road networks have capacities that can accommodate a certain amount of traffic as buffers. Lower level subnetworks can act as a temporary replacement for the motorway network when its functions have deteriorated. This could increase the robustness of road networks to a certain extent.

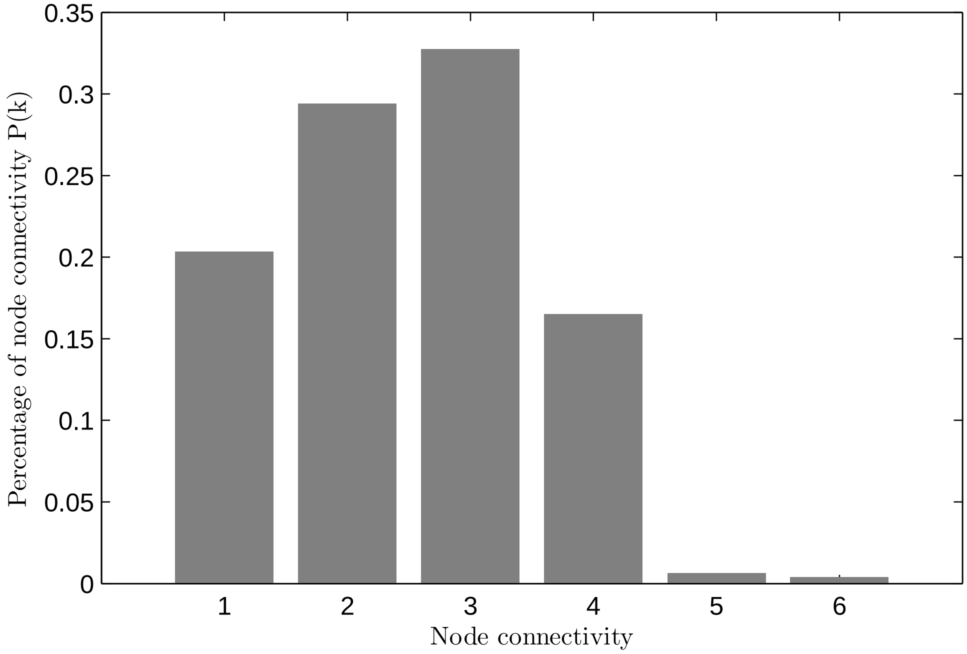

**Figure 2.4: Connection distributions of an integrated network A10-West that has 782 nodes and 1405 links. This network has been studied in (Taale, 2004) with the MARPLE model**

Considering the characteristics of road networks mentioned above, especially the importance of human (choice) behavior, the methodologies and the static performance indicator(s) in the studies introduced in Section 2.1 thus are not suitable for road networks. So it is necessary to develop a suitable methodology and corresponding methods and indicators specifically for the robustness study of road networks.

## 2.3 Robustness Studies of Road Networks

In this section, literatures of the existing studies on road networks robustness will be reviewed in detail. As stated before, the number of relevant studies is limited and they are scattered over different objectives, such as identifying vulnerable links or sections of a road network, analyzing accessibility of the whole network or certain zones after natural disasters and so on. In Table 2.1, an overview of some representative studies and relevant scenarios are listed. These studies will be discussed in more detail in the following part of this section.

**Table 2.1: Overview of road network robustness studies**

| Objective | Reference | Scenarios |
|---|---|---|
| Identifying vulnerable links/sections | (Scott et al., 2005) | single link removal |
| | (Kaysi et al., 2003) | single point damaged |
| | (Visser & Molenkamp, 2004) | single link damaged |
| | (Yperman & Tampère, 2006) | single link removal |
| | (Bell, 2000; Cassir & Bell, 2000) | single link removal |
| | (Murray-Tuite & Mahmassani, 2004) | 1 or 2 links damaged |
| Accessibility robustness | (Berdica & Eliasson, 2004) | single link removal |
| | (D'Este & Taylor, 2003) | single link removal |
| Post-disaster analysis | (Chang & Nojima, 2001) | earthquake |
| | (Sakakibara et al., 2004) | earthquake |
| Critical network | (Dekker & Colbert, 2004) | nodes attacked |
| Improvement of robust network | (Yin et al., 2005) | link capacity increase |
| | (Zhang & Levinson, 2004a) | network design |

### 2.3.1 Identifying vulnerable links/sections in a road network

A vulnerable network element (e.g., link or section) is a part of the network responsible for a sharp decrease in traffic operation performance caused by capacity restrictions due to an incident or circumstances of unusually high traffic demand (Yperman & Tampère, 2006). Searching for vulnerable elements of a road network aims to identify potential weak points in a network and determine the consequences in case of failure of one of these elements. It is the most important topic of network robustness studies at this moment. Performance indicators that are used for identifying vulnerable elements and relevant methods to calculate the indicators are summarized below:

- Travel time/cost based measures

    1. (Kaysi et al., 2003) use average travel time (*tt*) and average stopped time (*st*) as indicators for network performance, and the differences between

the base case and Hot Spot (HS: defined as the points in time and space on the road network at which a certain abnormal traffic behavior occurs, causing nonrecurring congestion) scenarios are used to identify HS characteristics (e.g. location, type, duration, severity) and the effectiveness of traffic management. The authors use mesoscopic simulation software package DYNASMART (Mahmassani et al., 2004b) to calculate *tt* and *st* in all HS scenarios.

2. Network Robustness Index (NRI) defined by (Scott et al., 2005) is the difference between the system-wide travel-time costs derived from the base case ($c$) with all links present and from the incident case ($c_a$) when link $a$ is removed. The lowest value of ($c - c_a$) identifies the most important link $a$ for the network. The authors use a dynamic UE (user equilibrium) assignment approach to calculate both $c$ and $c_a$ based on the following two assumptions. One is that the network can achieve a status named user equilibrium (more discussion in Chapter 3 and Appendix B). The other assumption is that that the removal of link $a$ is a long-term event and travelers therefore have full information about the whole network performance with and without link removal so that user equilibrium status can always be achieved.
3. In the research of (Visser & Molenkamp, 2004), two steps of network vulnerability (as opposed to network robustness) evaluation are carried out. The first step is to identify the potential vulnerable segments by assessing the probability of an incident occurring as well as the number of cars that will be blocked, which is derived from a static UE assignment. The second step is to rank the link vulnerability taking into account the rerouting effects resulting from the incidents. This is done by calculating extra travel time through an extra iteration of reassignment with link closure after the baseline assignment. The reassignment is also a static procedure with fixed values of turning fraction for each link, which is computed as the share of the cars above capacity.
4. (Bell, 2000) and (Cassir & Bell, 2000) are the first to introduce game approach into road network performance reliability studies. A game is envisaged between a network user and an ’evil entity’. On one hand, The user seeks a path to minimize the expected trip cost. On the other hand, the ‘evil entity’ impose link costs on the user (by breaking the link) so as to maximize his expected trip cost. This is assumed to be a two-player, non-cooperative, zero sum game. The user guesses what link costs will be imposed and the evil entity guesses which path will be chosen by the user. The authors assume that multiple users for one OD pair have the same probability in choosing links, as well as paths. When multiple OD pairs exist, different probabilities for different OD pairs may be considered, even if a common link for two or more OD pairs is broken. In each scenario the evil entity only breaks one link.

- Flow-capacity based measures
  1. An incident impact factor is proposed in the research work of (Yperman & Tampère, 2006). Given that $I$ is the inflow rate into a link and $C$ is the clearing rate of the incident on the link, which is also the initial capacity of the link, the incident impact factor is calculated as $I/(1-I/C)$. A dynamic UE assignment approach in the INDY model (Bliemer et al., 2004) is used to derive $I$ of each link.
  2. A vulnerability index $V_a^{od}$ for link $a$ with respect to OD pair $(o,d)$ is presented by (Murray-Tuite & Mahmassani, 2004). $V_a^{od}$ takes into account the utility of alternate path(s) of $(o,d)$, in which the 'utility' $g_j$ of alternative path $j$ is specified as the combination of the relative capacity and the ratio of the free-flow path travel time to the marginal path travel time for path $j$. Finally, the disruption index $D_a$ for link $a$ is the sum, over all OD pairs, of the vulnerability indices of link $a$. The higher value of $D_a$, the more vulnerable link $a$. The authors take a bi-level programming formulation between an 'evil entity' and a traffic management agency (TMA) with four different interactions between the players.

From the above-mentioned studies on the identification of vulnerable links in road networks, their strengths are summarized as follows:

- Differences in the values of system-wide performance indicators between a base case and incident cases are adopted to evaluate the impacts of the incidents;
- Incident scenarios are based on links, which are more important for road networks than nodes;
- The process of pre-selecting or pre-ranking the vulnerability of links is adopted based on their performance in the base case.

The weaknesses in these studies mainly exists in the unsuitable assignment approaches or models for calculating network performance after the incidents, which can be classified from the following two points:

- Static UE models with fixed values of splitting rates for the assignment in several studies (e.g., (Visser & Molenkamp, 2004)) are not suitable for modeling reassignment phenomena in road networks with incidents;
- Dynamic UE approaches that are used in most studies only make sense for long-term disruptions to the network and for planning purposes. They are not suitable for unpredictable and non-recurrent incidents because no equilibrium can be established after an unique incident.

Using unsuitable traffic assignment models will achieve incorrect assignment results, leading robustness analysis to incorrect as well. So in our proposed methodology and methods, they will be modeled in a more realistic way.

### 2.3.2 Studies of regional accessibility/connectivity robustness

Accessibility, or connectivity analysis is the most traditional topic in the network-level studies. Before, these studies (such as the ones discussed in Section 2.1) only considered network connectivity status and ignored the cost of traveling. Some new research works have noticed this problem and introduced some performance variables into the accessibility problems.

1. (Berdica & Eliasson, 2004) developed a network based analysis method for systematically studying regional accessibility from a vulnerability perspective, i.e. how the accessibility of an area $r$ is affected when part of the road network for some reason becomes completely or partly impossible to use. The new accessibility measure consists of three components:

    - average travel time $\bar{t}$ for an inhabitant in the area;
    - average travel cost $\bar{c}$ for an inhabitant in the area; and
    - the value of suppressed travel $\bar{T}$ compared to a reference area (indexed as 1).

    Hence, the accessibility $\Omega_d$ of area $d$ in scenario 0 is the sum of the these components, expressed as:

    $$\Omega_d = \theta \bar{t}_d^0 + \bar{c}_d^0 + \bar{T}_d^0 \tag{2.1}$$

    where

    $$\bar{t}_d^0 = \frac{\sum\limits_{om} T_{odm}^0 t_{odm}^0}{\sum\limits_{om} T_{odm}^0}$$

    $$\bar{c}_d^0 = \frac{\sum\limits_{om} T_{odm}^0 c_{odm}^0}{\sum\limits_{om} T_{odm}^0}$$

    $$\bar{T}_d^0 = \frac{1}{2} \sum_{om} \left( \frac{T_{1om}^0}{\sum\limits_{om} T_{1om}^0} - \frac{T_{odm}^0}{\sum\limits_{om} T_{odm}^0} \right) \left( c_{odm}^0 + c_{1om}^0 + \theta t_{odm}^0 + \theta t_{1om}^0 \right)$$

    using the following notation:

    | | |
    |---|---|
    | $T_{odm}^0$: | number of trips between $(o,d)$ with mode $m$ |
    | $t_{odm}^0$: | travel time between $(o,d)$ with mode $m$ |
    | $c_{odm}^0$: | travel cost between $(o,d)$ with mode $m$ |
    | $\theta$: | value of time |

    Accessibility to an area $d$ is larger when $\Omega_d$ is lower. With this measure, accessibility can be calculated during normal circumstances and the distribution of trips and/or volumes on the network gives some idea of which links are the most ‘popular’ and consequently central to traveling in the region. To measure the accessibility changes due to some alteration in circumstances, i.e. another scenario 1, the reference area is no longer needed. So define

$$\bar{T}_d^1 = \frac{1}{2}\sum_{om}\left(\frac{T_{odm}^0}{\sum\limits_{om} T_{odm}^0} - \frac{T_{odm}^1}{\sum\limits_{om} T_{odm}^1}\right)\left(c_{odm}^0 + c_{odm}^1 + \theta t_{odm}^0 + \theta t_{odm}^1\right) \tag{2.2}$$

and the change in accessibility for area $d$ ($\Delta\Omega_d$) between scenarios 1 and 0 is

$$\Delta\Omega_d = \theta\left(\bar{t}_d^0 - \bar{t}_d^1\right) + \left(\bar{c}_d^0 - \bar{c}_d^1\right) - \bar{T}_d^1 \tag{2.3}$$

Using this definition, a positive value for $\Delta\Omega_d$ means an improvement (increase) in accessibility.

The authors also propose that by using the so-called ‘select link’ procedure, trips using each specific link can be distinguished by their origin/route/destination relation, which gives an idea of how ‘widely’ an area would be ‘affected’ if the link in question is not available. So it can result in greater in depth knowledge of how interruptions in different parts of the transport system affect accessibility using different modes of transport, which indeed is a kind of robustness study of network accessibility.

2. (D’Este & Taylor, 2003) have proposed a definition of network connectivity robustness. The system robustness value for a given OD pair $(o,d)$ between origin $o$ and destination $d$ could be calculated through the structure function $\phi_{(o,d)}(X)$, in which $X = (x_1, x_2, \ldots)$ is the status vector of the used links for the paths of $(o,d)$. $x_a = 1$ if link $a \in A$ works, otherwise $x_a = 0$. Similarly, if $(o,d)$ is connected for most of $X$, i.e. $\phi_{(o,d)}(X) = 1$, the connectivity of $(o,d)$ can be considered robust.

   The authors also proposed a new probability variable $P_{ijod}$ for the probability of the link joining node $i$ to node $j$ to be used by a trip from $o$ to $d$. So the matrix of link probabilities $P_{od}$ provides an indicator for the overall vulnerability, as well as robustness, of trips between the given OD pair $(o,d)$ and also for the location of the key links. In general, the higher a link probability is, the greater the adverse impact if that link is broken. For example, if a link is the common link of all the possible paths of the OD pair $o,d)$, then its probability is 1, which means if it was broken, then all the paths fail and 100% of the demand is influenced. On the contrary, if a link is only used for one of the five equal paths of an OD pair, its probability is 0.2, which means if it was broken, only 1/5 of the demand would be influenced. Two methods could be used to calculate these link probabilities, which are Bell’s Algorithm by (Bell, 1995) and Conditional Probability Method proposed by (Dial, 1971).

| | Strength | Weakness |
|---|---|---|
| (Berdica & Eliasson, 2004) | Network performance variables (e.g. $t_{odm}$, $c_{odm}$) are introduced into accessibility studies | No numerical studies are given to testify the methods. |
| (D'Este & Taylor, 2003) | Route choice is considered in calculating link probability. | Route choice are static, which cannot represent the dynamic behaviors of travelers, thereby ignoring the changes in network performance. |

The strengths and weaknesses of each study in this section are summarized in the following table:

Compared with the conventional studies on the static connectivity robustness of networks, these two research works made great improvement in analyzing connectivity robustness by introducing route choice and network performance. Such changes grasp the characteristics of road networks and make the methods more suitable for road network analysis.

### 2.3.3 Measuring post-disaster transportation network performance

In a natural disaster situation such as an earthquake or flooding, the road infrastructure plays a critical role in maintaining routes for evacuation and logistics. Several researches have been done on analyzing the post-disaster network performance (mainly in the network connectivity) and try to derive valuable knowledge for the design and planning of road networks that can increase the post-disaster network performance. Such studies can also be categorized as a type of road network robustness analysis.

1. (Chang & Nojima, 2001) proposed three system performance indicators to evaluate a partially functional network after earthquake disasters, which also grasp the robustness of an entire network system. Those three indicators are:

    - total length of network open
    - total distance-based accessibility
    - areal distance-based accessibility

    Each of the measures is estimated as the ratio of post-earthquake to pre-earthquake conditions and ranges from 0 (system non-functional) to 1 (system fully functional). The first two proposed indicators pertain to the overall performance of the system, while the last indicator is specific to individual subareas within the study region, such as neighborhoods, and can indicate spatial disparities in transportation performance. The indicators are specific to time $t$ after the earthquake. Analysis of these performance indicators using the case of Kobe City in Japan after the 1995 earthquake shows that they provide very useful means of summarizing the earthquake's effects - especially for quantitatively assessing the loss of transportation service in the region, evaluating the spatial and temporal dimensions of the service loss, and making comparisons with the performance of other urban lifeline systems. The authors apply the same measures to two other earthquake cases: 1989 Loma Preita and 1994 Northridge, both in the United States. The comparisons among the three cases show that the impacts of the earthquakes in the extent of transportation damage, level of system disruption, and restoration time frames differ significantly. Overall post-disaster highway system performance was somewhat better in Northridge than in Loma Preita, partly due to the the availability of detours and the greater redundancy of the network.

2. (Sakakibara et al., 2004) propose using a topological index ($TI$) as an indicator of road network dispersiveness/concentration from a topological point of view. When a disaster happens followed by the collapse of road networks, people are forced to choose their destinations from the remaining accessible districts. A network that minimizes the isolation of districts can be defined as the most robust network against catastrophic disasters. The authors distinguish networks with small possibility of isolation as the *dispersed* networks. On the contrary, networks that are easily isolated are referred to as *concentrated* networks. The topological index $TI$ of graph $G = (N,A)$ with $n$ nodes and $l$ links is defined as follows:

$$TI(G) = \sum_{k=0}^{m} P(G,k) \tag{2.4}$$

where $m = n/2$ if $n$ is even and $m = (n-1)/2$ if $n$ is odd. When two or more links do not share the same node, such links are *non-adjacent*. $P(G,k)$ is defined as the number of subsets of link set $A$ consisting of $k$ nonadjacent links. For two networks with the same numbers of nodes and links, the $TI$ value of a dispersed network is larger than that of a concentrated network. Therefore the $TI$ can be used as a quantitative index of dispersiveness/concentration of the road network.

By applying this methodology to the actual highway network in the Hanshin Region in Japan, which was heavily damaged by the Hanshin-Awaji earthquake in 1995, the following remarks are drawn by the authors:

- $TI$ provides guidance on how the network is connected, i.e. connectivity robustness in a disaster situation in terms of node isolation;
- An increment of $TI$ can be calculated for each additional link, which means that for improving the robustness of the road network, a link with a larger increment should be added with a higher priority;
- Reinforcement of infrastructure needs to be performed on critical links in order to avoid functional isolation, and critical links can be ranked using

the values of $TI$. Basically, a link is more critical if its degradation results in a higher value of $TI$.

It is understandable that for a post-disaster transportation network, connectivity is a more important issue than the network performance, such as the travel cost. That is the reason for all the adopted connectivity indicators (e.g. *TI*) are static without considering the demand but only the geometry of the network. However the travel cost, especially the travel time, is also very important for assessing post-disaster situations because less time spent on traveling means more timely rescues and less casualties. This can be considered as a possible improvement for the future post-diaster analysis of transportation networks.

### 2.3.4 Robustness studies for critical networks

(Dekker & Colbert, 2004) and (Dekker, 2005) developed a tool named CAVALIER to study the effect of terrorist attacks on so-called critical infrastructure networks, such as communication, electrical power, rail and fuel distribution networks. Failure of any of these critical infrastructure networks can bring the ordinary activities of work and recreation to a standstill, which makes these networks targets for terrorist attacks. An important aspect of critical infrastructure networks is their *interdependence*. Attacks on the electrical power and communication networks in particular have a ‘force multiplier’ effect on other services. Another important aspect is that each ‘link’ has a fixed *capacity*. The authors examine the robustness of critical infrastructure networks incorporating link capacities, specifically the aspects that relate to the network topology. But before that, critical networks are usually verified not scale-free at a physical level. Since there exist spatial constraints for large numbers of connections to a single spot, hubs of high degrees (connections) are not generally possible.

A terrorist attack simulator, which is included in CAVALIER, is used to study the effect of destroying nodes in a network which sends “packets” of traffic back and forth along links. The simulator assumes that the same number of packets are sent between every pair of nodes, and each link has just enough capacity to handle the load. The simulator uses a shortest-path routing algorithm, which means packets are sent along the shortest path or paths. If there is more than one shortest path, the simulator balances traffic between them. The simulator also assumes that if all the shortest paths are loaded to maximum capacity, traffic is *lost* rather than re-routed on longer paths in order to avoid cascading failure through the whole network as a result of re-routing. So the measure of performance is the average percentage of packets that successfully reach their destinations. Two types of terrorist attacks, targeted and random, are simulated for all networks with between 1 and 6 nodes being destroyed.

The simulations are done through 61 networks that all have 60 nodes. These networks have different topology features, such as different average degrees (i.e. the average number of incoming links of the nodes) and different symmetry ratios calculated by finding the different eigenvalues of a network. The higher symmetry a network is, the lower symmetry ratio it has. The results show that with targeted attacks, most networks began to fail either because of the disconnection or because of the overloaded links when the number of attacks was equal to the average number of node connections. But some highly symmetrical and well-connected networks did not fail even with up to six attacks. On the other hand, randomly generated networks and networks containing large loops are not robust.

The strengths and weaknesses of the studies for critical networks in this section are summarized as follows:

- Strengths: Terrorist attacks on nodes are simulated taking into account link capacities, which is an improvement on the studies in Section 2.1.
- Weaknesses:
  - Only the incidents of nodes are considered, which neglects the fact that links are also essential in road networks;
  - In these studies, the over-capacity traffic is simply assumed ‘lost’, while not re-routed. This assumption is unrealistic because queuing and re-routing of the over-capacity traffic are two basic characteristics of road networks.

The studies listed in this subsection attempted to use the methodology and methods for general complex networks that are introduced in Section 2.1 for road network robustness analysis. Some adjustment and improvement have been done by the authors, but the weakness shows that such methodology and methods still cannot fully satisfy the basic requirements of road network robustness studies. For instance, the travelers’ route choice behavior is not considered at all.

### 2.3.5 Improvement of robust road networks

The concept of robustness has been introduced into network design or network improving problems, i.e. in the objective functions for designing or improving road networks, network robustness is one of the components to be considered. Two studies could be found on such a topic.

1. (Yin et al., 2005) attempt to determine an improvement scheme that minimizes the expected total system travel time as well as the variance of total travel time, i.e. an efficient and robust network. The authors use the sum of total travel time and the sensitivity of the total travel time with respect to uncertain demand (which can also be extended to uncertain capacity and so on) as the objective function for designing a robust network improvement scheme as follows:

$$\min_{c^+} Z = \beta \sum_{s\in\Omega} \pi_s T_s + (1-\beta) \sum_{s\in\Omega} \pi_s \left(T_s - \overline{T_s}\right)^2 \tag{2.5}$$

where $Z$ is the objective function; $c^+$ is a vector of the continuous capacity increases of all links, i.e. network improvement scheme; $\beta$ is a parameter that represents the trade-off between mean (effectiveness) and variance (robustness), $0 \le \beta \le 1$; $\Omega$ is the scenario set to represent uncertain demand, and each scenario $s \in \Omega$ has the occurrence probability $\pi_s$; $T_s$ is the total travel time in scenario $s$; and $\overline{T_s}$ is the expected total travel time and $\overline{T_s} = \sum\limits_{s\in\Omega} \pi_s T_s$. So the objective function includes two parts: the expected total travel time ($\overline{T_s}$) that identifies the effectiveness of the road network and the sensitivity of the travel time ($(T_s - \overline{T_s})^2$) that identifies the robustness of the road network.

A bi-level programming model is implemented to solve the problem in (2.5), in which the upper level problem is to search for optimal $c^+$ to minimize $Z$ and the lower level problem is the SUE assignment problem to achieve $T_s$ for each scenario $s$.

2. (Zhang & Levinson, 2004b) build up a model to first evaluate the reliability and robustness of existing road networks with hierarchical structures, then to search for suitable policies to create a network form that is reliable and robust. The efficiencies of the networks that are developed based on two approaches - bottleneck removal and benefit cost analysis - are evaluated by calculating total vehicle hours of travel (VHT) from the results of equilibrium assignment. To analyze the reliability and robustness of different networks, three failure scenarios are considered, including: (1) random link failure where the probability of a link losing its flow-carrying function is purely random; (2) volume-dependent failure where a link carrying more traffic is more likely to breakdown than its low-volume peers and the failure rate is proportional to traffic volume; (3) the most important links, defined as those with the highest capacity, are destroyed by deliberate attacks.

   Monte-Carlo simulation with thirty runs for each scenario is carried out and the average performance of VHT increase is calculated to identify the reliability and robustness of the network. The authors concluded that the flatter road networks under the benefit cost investment rule are more efficient and also display advantages in all three failure scenarios, especially under the targeted attacks. The highly hierarchical networks (as most existing road networks are now) created by bottleneck removal policy appears to be extremely vulnerable.

The two studies introduced in this section have very high reference value for our road network robustness analysis because of the following strengths:

- The robustness of road networks is analyzed by comparing the network performance through different scenarios;

- The network performance is calculated taking into account travelers' choice behavior;

However, the weakness of these studies is that UE assignment approaches make these studies meaningful only in planning applications and not suitable for incident situations.

## 2.4 Summary

The contents reviewed in this chapter can be divided into two parts. The first part is Section 2.1, in which robustness studies on general networks and other types of large networks are reviewed, with an aim of deriving potentially useful experience from them. Such a process has also been carried out by (Dekker & Colbert, 2004) and (Dekker, 2005) in the robustness studies for so-called critical networks that are discussed in Section 2.3.4. However, these studies focus on the static connectivity performance between nodes of networks with the incident scenarios of node removal. This means that they either ignore the travel costs on links/paths, or ignore the possible queues of flows on the network, which are important characteristics and indicators of road networks. Thus, besides the methods of testing different incident scenarios to analyze network robustness, these studies are not much valuable for road network robustness analysis.

The second part of the review is Section 2.3, in which robustness studies on road networks are presented following a detailed description of the characteristics of road networks in Section 2.2. In Table 2.1, all of the 14 selected studies on road network robustness are listed. It is noticeable that most of these studies (9 out of 14) analyze the robustness problem caused by single (or two) link degradation. Besides this, the identification of vulnerable links/sections in a road network (Section 2.3.1) is the most prevalent topic at this moment (7 out of 14). It is an improvement that in these studies links are considered as critical elements for road networks, and network robustness is studied by comparing the network performance in the incident scenarios with a base case. With the exception of the two studies in Section 2.3.3 on the static accessibility problems within an area after the natural disaster like earthquakes, other studies all try to catch the network performance under situations with incidents, and most of them adopt a (stochastic) UE assignment approach to represent travelers' behavior. This makes them suitable only for analyzing the long-term effects of long-term incidents, so that the system has enough time to reach a new equilibrium. For example, the studies on the implementation of robustness into road network design and planning discussed in Section 2.3.5. At the same time, it also means that the methods in these studies are not suitable for the analysis of road network robustness against short-term and unexpected incidents, such as accidents.

## 2.5 Discussion

Network robustness studies in the road network domain are still new and on a primary stage. This fact is demonstrated by the small amount of literatures available for discussion in this chapter. The importance of carrying out road network robustness analysis has become clear because modern society has become more and more dependent on a road network that is robust against unexpected and exceptional incidents, as well as malevolent attacks. In other network domains, such as communication and internet networks, the methodologies and methods for robustness analysis are more comprehensive and systematic. But road network system has its special characteristics (Section 2.2). Road network robustness analysis has several basic requirements as described in Section 1.2.1. The values of the studied literatures to our proposed robustness analysis of road networks then can be discussed with reference to those requirements.

1. Reference status. In some of the research works, a reference status of the road network is acquired through a (stochastic) UE assignment approach, which supplies an option when there is no enough real data over the studied road network.
2. Interaction between network performance and travelers' choice behavior. In most of the studies discussed in this chapter, such interactions have been represented through the DTA models, which is an important improvement in the methodology and methods. However, almost all of them only use the UE assignment approach. For our interests in analyzing the network robustness after the exceptional and short-term events like accidents, UE assignment model is no longer suitable any more. Thus we need other DTA approach(es) to better represent the interactions between network performance and travelers' (route) choice behavior after such events.
3. Queuing model. The queuing model, especially modeling the spillback of queues, are important for the accurate calculation of network performance. Unfortunately, none of the studies gave detailed information about it. Nevertheless, an apparent request of the network loading model (including the queuing model) for different situations without and with disturbances should be consistent so that the results of the network performance can be comparable.

From the review and discussion, we find that in order to carry out a comprehensive and systematic study of road network robustness, suitable traffic assignment models are of primary importance. Thus in the next chapter, an investigation study on the suitability of several traffic assignment models for robustness analysis will be given. Such investigation is also on the basic requirements for analyzing road network robustness, as well as the features of different approaches of the traffic assignment models. After the investigation study, the decisions on choosing and developing appropriate traffic assignment models will be given for the following road network robustness studies.

# 3

# Suitability of Traffic Assignment Models for Robustness Study

In both Chapter 1 and 2, we have emphasized that a better representation of the interaction between road network performance and travelers' (route) choice behavior is very important for the analysis of road network robustness. Thus we need suitable traffic assignment (TA) models. In fact, TA models have been adopted in most of the reviewed studies in Chapter 2. But, as we also briefly discussed, most of the adopted TA models are not suitable for the analysis of network robustness. In this chapter, a more detailed analysis and investigation will be given on several simulation-based TA models that are available for us at this moment. The analysis focuses on the distinctions between two approaches of dynamic TA (DTA) model, which are UE (user equilibrium) assignment approach and en-route assignment approach, particulary on the feasibility and necessity of each approach for analyzing road network robustness. Based on this analysis, a preliminary investigation into these DTA models is presented in this chapter through the simulation of a common road network presented in Appendix B. We found that even for a simple road network, different TA models will give many differences in the assignment results and network performance outcomes when only the default settings are used. The differences emerge from the different methods for path generation, path assignment and network loading in these models. This urges us to choose and/or develop compatible TA models for the analysis of road network robustness.

The structure of this chapter is organized as follows. Section 3.1 introduces the main features and major components of the traffic assignment models, especially the DTA models that are the most suitable for the studies on road network robustness. In Section

3.2, two approaches of DTA models are introduced and compared, including the UE assignment approach and en-route assignment approach. The differences in the assignment results for a simple network with different models are discussed in Section 3.3. Finally, Section 3.4 provides the analysis of the results and summarizes this chapter.

## 3.1 Introduction to DTA Models

### 3.1.1 DTA models

(Cascetta, 2001) pointed out that traffic assignment (TA) models “play a central role in developing a complete model for a transportation system since the results of such models describe the state of the system, or the ‘average’ state and its variation”. TA models represent the interaction between the travel demand for the road network and the supply of the capacity of the network. The DTA models describe this interaction both in time and space. These models allow the calculation of performance measures and flows for each supply element, i.e. every network link, resulting from origin-destination (OD) demand flows, route choice behavior, and the interactions between supply and demand. In fact, the results of route choices and path flows depend on the path level generalized costs, and the demand flows are generally influenced by the path costs. Therefore there is a circular dependence between demand, flows, and costs. A systematic and complete DTA model can represent more than route choice behaviors of travelers. Choices of whether to make trips, mode choice of commuters, as well as departure time choice can also be modeled in a DTA model. In our analysis, route choice is considered to be the most important role influencing network robustness because in case of an unexpected disturbance, the assumption is valid that the departure time and travel mode have already been determined before the disturbance. Thus other choice behaviors are not considered. Figure 3.1 illustrates the structure of a typical DTA model with route choice and departure time choice functions.

TA models can be categorized into static and dynamic models according to whether time variance is included or not. Static models basically assume that the traffic demand and supply are time-independent, hence constant during the considered time period (i.e. stationary). As a consequence, the ‘movement’ of vehicles/flows through the network are ignored in static assignment models, and the assigned traffic for a path is placed over all the links of the path at once. Dynamic models use the more realistic assumption that OD demand and link characteristics vary by time and the ‘movement’ of vehicles/flows through the network are taken into account. More computation demand and extra requirements with respect to the data are needed for dynamic models. It is then clear that static models are not suitable for our robustness studies due to the following reasons:

- Robustness studies deal with the situations associated with incidents on road

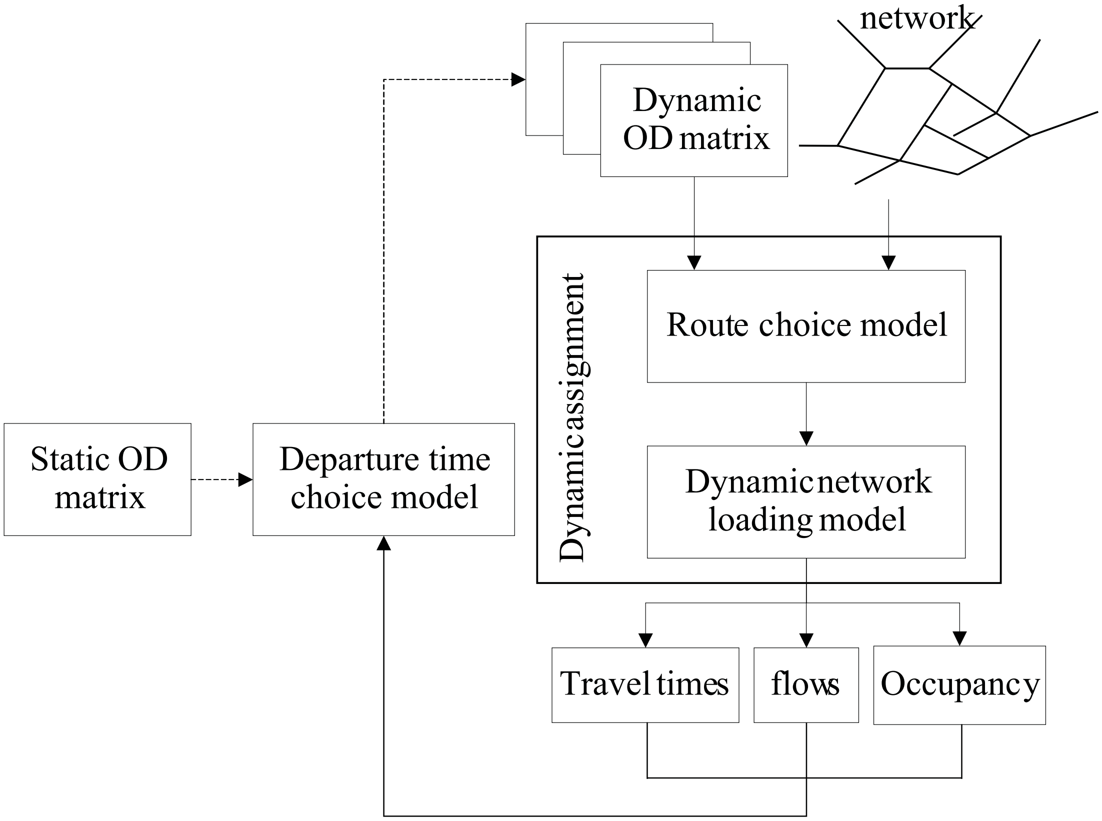

**Figure 3.1: Schematic framework of DTA models including route choice and departure time choice**

networks that inevitably result in the change of demand or capacity. This is beyond the ability of static models;

- The most direct and obvious consequence of an incident on the road network is the appearance of (extra) congestion or queues. The queues can spill back through links and nodes. After the removal of the incident, the queues will also disperse. The process of such phenomenon all needs a network representation in space and time, which cannot be done by static models;
- Travelers' driving/choice behavior is an important factor in road network performance, especially when they face unfamiliar situations. A typical phenomena in the reality is that new bottlenecks and congestion are created far away from where an incident appears on the road because a certain amount of travelers switch to another possible route to avoid the queues caused by the accident (Zuylen & Chen, 2004). Such phenomena cannot be described by static models.

Thus, DTA models, which overcome all the above-mentioned disadvantages of static TA models, have become the only (current) option for road network robustness analysis. A DTA model typically describes travelers' (route) choice behavior and the way in which traffic propagates through a network, i.e. network loading. 'Dynamic' does not only mean that the demand between origins and destinations (OD) varies in different discrete time slices, but also covers the dynamics of the network situation, especially the phenomena of queuing (e.g. forming, spilling back, and dispersing of queues) due to all kinds of objective variabilities in the nature and subjective changes in travelers' behavior. A DTA model is better able than a static model to model 'over-capacity' queuing because it captures the inherent dynamic nature of traffic by following the trajectories in time and space of the vehicles/flows.

### 3.1.2 Components of DTA Models

Any one of the DTA models consists of a route choice model and a dynamic network loading model. The route choice model distributes the trips in a dynamic OD matrix over the generated paths for each departure time or interval and for each OD pair. So in most DTA models a path generation model is also integrated to search for available and suitable paths. After the assignment, i.e. route choice, path flows are transferred to the dynamic network loading (DNL) model that simulates the movement of the path flows over the network and computes the dynamic link travel times and dynamic link flows. After the DNL process, which might be for the whole study period or for just one sub-period depending on the different approaches, network performance information - particularly the path cost information - will be transferred back into the route choice model if the path sets are fixed. Otherwise it will be transferred back into the path generation model to update the path sets. Travelers may then adapt their route choices according to this traffic condition information and their preference. DTA therefore always takes an iterative procedure from day to day, or within a day.

In the following sub-sections path generation, route choice and network loading modules will each be briefly discussed.

**Path generation module**

Path generation is the first process of any integrated DTA model. Generally, three possible path generation approaches exist: exogenous process, iteratively updating process and en-route updating process. The differences among these processes mainly exist in the their operating time and operating frequency in the DTA model. Exogenous process operates before the assignment starts and its generated path sets are fixed for the whole DTA process. Iteratively updating process updates the path sets after each DTA iteration according to the path costs results of the last DTA iteration. En-route updating process then updates the path sets for every interval according to the path costs results of the last DTA interval. Thus the size of the path sets can change in both iterative updating process and en-route updating process. A recent study by (Bliemer et al., 2007) pointed out that the amount of generated paths has a remarkable influence on the network performance outcomes.

**Route choice module**

Route choice (assignment) is the joint module between the path generation process and the network loading process. Using certain algorithms, it assigns all the traffic to paths that have been generated during the path generation process. Most of the assignment models generate flow distribution over paths as a function of the path costs, which are the results of network loading based on the previous assignments. According to whether or not the travelers' perception of path costs is assumed perfect, the route choice model can be either deterministic or stochastic. Deterministic models assume that all travelers have perfect information about the traffic status of the whole network, which is in general an incorrect assumption in most cases. One solution to this problem, i.e. a stochastic model, will be discussed in more detail in Section 3.2.1. (Cascetta, 2001) gave detailed descriptions and comparisons of some of these models in his book.

**Network loading module**

Network loading is the third module in a DTA model. Its function is to determine a self-consistent set of values for link inflows, link travel time, path travel times (costs) and path flows from the assignment results. It is basically a simulation/propagation of path flows over the links of the network, including the generation and spilling back of queues. A basic requirement of a favorable network loading module for a DTA model is the proper description of the queue phenomenon in the network, including the formation, spill back, and dispersal of the queues. The network loading module is the heart of any DTA model since its outcome directly influences the assignment for the next step, while the assignment results also decide the outcome of network loading.

## 3.2 Approaches of DTA Models

Generally, two distinct approaches are used for modelling route choice and network loading in DTA: the user equilibrium (UE) assignment approach and the en-route assignment approach. UE assignment models assume that the network can reach a kind of (approximate) equilibrium status, but en-route assignment models refuse the existence of such an equilibrium status in the network. These two approaches will be discussed individually in the next two sub-sections.

### 3.2.1 User equilibrium (UE) assignment

Depending on whether or not travelers are assumed to havie perfect information about the attributes of the network, UE assignment models can be classified into the deterministic user equilibrium (DUE) assignment models and the stochastic user equilibrium (SUE) assignment models. Together with the classification of static or dynamic, any UE model can be categorized as shown in Table 3.1.

**Table 3.1: Basic classifications of UE assignment models**

| | | Perception Error? | |
|---|---|---|---|
| | | No | Yes |
| Network Uncertainty? | No | DN-DUE | DN-SUE |
| | Yes | SN-DUE | SN-SUE |

where:
DN: Deterministic Network
SN: Stochastic Network

(Wardrop, 1952) was the first to propose the following condition (as *Wardrop's first principle*) for a DUE:

> for each OD pair, the costs of the paths actually used are equal, and less or equal to the costs of each path not used.

DUE assignments necessarily make critical assumptions that each traveler has perfect information, that each traveler chooses a route that minimizes his/her travel time or travel costs, and that therefore all travelers between the same OD have the same travel time or cost. A consequence of the DUE principle is that all used paths for an OD pair have the same minimum cost. Unfortunately, (Slavin, H., 1996) pointed out that this is not a realistic description of the overloaded and congested road networks.

SUE was proposed by (Daganzo & Sheffi, 1977). They defined the equilibrium state of traffic flow on a network as a stochastic user equilibrium when every user $i$ traveling from origin $o$ to destination $d$ chooses his/her path such that his/her *perceived* travel cost is the minimum. So the perceived travel cost function $\hat{c}_i^{rod}(k)$ for traveler $i$ departing during interval $t$ and using route $r$ is the sum of two components - a systematic term $c_i^{rod}(k)$ (the exact travel cost) and an *error* term $\varepsilon_i^{rod}(t)$ (the perceptional deviation):

$$\hat{c}_i^{rod}(t) = c_i^{rod}(t) + \varepsilon_i^{rod}(t) \qquad \forall o,d,r,t,i \tag{3.1}$$

Depending on the distribution types chosen for the error component among all the travelers, different models for SUE can be obtained. The perceived path travel cost can be computed by adding up the perceived link travel times taking into account the flow propagation along that route. The SUE conditions state that the perceived route travel times of any unused route for the OD pair $(o,d)$ is greater than or equal to the minimal perceived route travel time. Therefore, for each OD pair $(o,d)$, if the flow over route $r$ departing during interval $t$ is positive, i.e., $h^{rod}(t) > 0$, then the corresponding perceived route travel cost/time is the minimal, which is $\hat{\pi}^{od}(t)$. However, if no flow occurs on route $r$, i.e., $h^{rod}(k) = 0$, then the corresponding perceived route travel cost/time is at least as high as $\hat{\pi}^{od}(t)$. This equilibrium condition of SUE can be mathematically expressed as follows:

$$\hat{c}^{rod}(t) \begin{cases} = \hat{\pi}^{od}(t) & \text{if } h^{rod}(t) > 0 \\ \geq \hat{\pi}^{od}(t) & \text{if } h^{rod}(t) = 0 \end{cases} \qquad \forall o,d,r,t \tag{3.2}$$

The following constraints exist for SUE problems, including flow conservation and nonnegativity constraints.

$$\text{Flow conservation constraint :}$$

$$\sum_r h^{rod}(t) = q^{od}(t) \qquad \forall o,d,t \tag{3.3}$$

$$\text{Nonnegativity constraint :}$$

$$h^{rod}(t) \geq 0 \qquad \forall o,d,r,t \tag{3.4}$$

where $q^{od}(t)$ is the total traffic demand of OD pair $(o,d)$ during interval $t$.

It is clear that the above-mentioned equilibrium condition and constraints for SUE problems also hold for DUE problems, while in DUE $\hat{c}_i^{rod}(t)$ only includes $c_i^{rod}(t)$.

The stochastic cost/utility perception error term on a link varies randomly across users, which can be assumed following a distribution. If we assume that $\varepsilon^{rod}$ follows a Gumbel distribution, the solution of the assignment of trips over the generated paths for the SUE problem can be solved by the function with the LOGIT type as shown in (3.5).

$$P^{rod}(t) = \frac{exp\left(-c^{rod}(t)\right)}{\sum_l exp\left(-c^{lod}(t)\right)} \tag{3.5}$$

The solution algorithm for solving the SUE problem normally takes the form of an iterative procedure till the (approximate) convergence. It consists of two main components: a method to determine a new set of time-dependent path flows given the experienced path travel times in the previous iteration (i.e. traffic assignment), and a method to determine the actual travel times that result from a given set of path flow rates (i.e. network loading). Furthermore, the algorithm requires a set of initial path flows for the first iteration of network loading, which can be based on the free-flow travel times of all the generated paths as the travel costs.

### 3.2.2 En-route Assignment

In order to capture the phenomenon of the discrete or continuous path switching decisions of travelers in response to real-time traffic information, in particular in case of unexpected disturbances, en-route assignment has been developed in several simulation models, such as INTEGRATION (Aerde, 1995) and DYNASMART-P (Mahmassani et al., 2004a). In en-route assignment models, the routing mechanism consists of successive executions of a set of heuristic behavioral rules, which determine how travelers iteratively react to the information received en-route. Information may be available at discrete points in time and/or space, or be continuously available in both time and space. Some information may only be available to certain classes of travelers. Typically, the information strategy is an exogenous input for en-route assignment models. Drivers' responses to information can be modeled by some heuristic rules that may involve one or more parameters, such as the 'penetration rate' or the 'compliance rate', that is the fraction of drivers who would react to the information.

Another necessary input for an en-route assignment model is a pre-trip or initial assignment, which determines the distribution of the demand for the first (several) interval(s). In many cases only the shortest path (in distance or free-flow travel time) of an OD pair is generated for the first interval. All of the demand of the OD pair departing during the first interval is assigned to this shortest path. Thus the initial assignment for the en-route assignment model is normally an all-or-nothing (AON) assignment. An en-route assignment process only requires running a single dynamic loading of the demand onto the network over each time period of interest - apart from the assignments needed to determine the initial route choice. Because of this feature, en-route assignment is often used to analyze the effects of non-recurrent incidents to the network, such as accidents.

It must be mentioned that some research also studies the so-called optimal routing policy (ORP) problems. A routing policy is defined as a decision rule that specifies which node to take next at each decision node based on realized link travel times and the current time. This is the same as what an en-route assignment model does. (Gao & Shabini, 2006) gave a good review of the literature on the ORP problem, and they also established a framework for it with stochastic time-dependent link travel times in networks. However, since they only work on networks with fixed structure, which does not fit our requirement in representing incidents in the network, we will not consider this method in analyzing network robustness problems.

### 3.2.3 Comparisons between UE and en-route approaches

In addition to the above introductions, the general difference between the structures of UE approaches and en-route approaches are illustrated in Figure 3.2. It is evident that UE assignment approaches use some convergence criteria to control the total number of iterations, while en-route approaches run just one iteration and update path for each time interval. In the flow chart of en-route assignment approach, $t_s$ is the starting interval of an event to the network, and $t_e$ is the ending interval of the whole studying period. When $t < t_s$, the network performance and the choice behavior of travelers are the same as daily normal results, i.e. the UE assignment results.

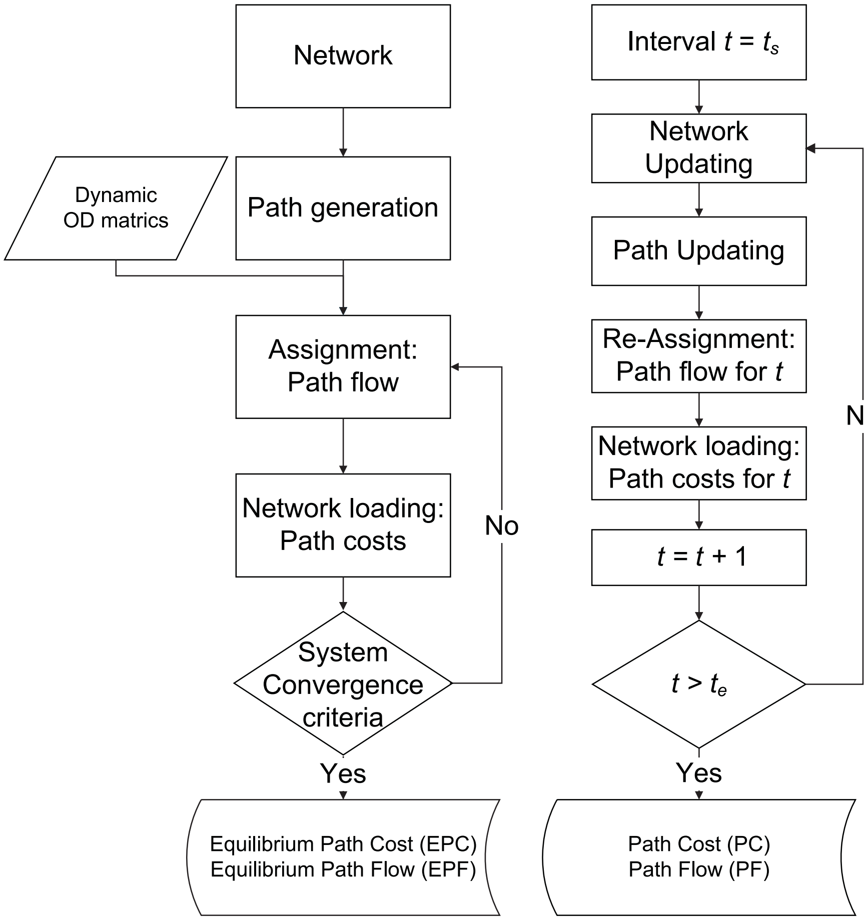

**Figure 3.2: General differences between UE assignment approach (left) and en-route assignment approach (right)**

As discussed in Chapter 2, UE assignment models are widely used in the existing studies on road network robustness. It was also pointed out that because of the ‘equilibrium’ assumption, UE assignment models cannot represent the network situations under unexpected and short-term incidents, such as accidents. From this point of view, UE assignment models are not suited for road network robustness studies. However, they can still be used in the network planning domain to analyze the impact of recurrent and long-term network changes, such as adding a new link to the network or using new control measures.

On the other hand, the en-route assignment approach seeks for one-shot, non-equilibrium situations of transport networks that, in our view, just fits the requirement of representing the interactions between network performance and travelers’ route choice behavior under the situation after the disturbance. Thus it is more appropriate for the robustness analysis. But very few road network robustness studies are based on en-route assignment approaches. In en-route assignment models, reassignment of the traffic demand is realized by carrying out a set of heuristic rules for modeling drivers’ responses to the information about the network performance (e.g. travel time, delay, queue length, etc.) that they can receive and perceive. The accuracy of these rules and the values of the parameters are critical for the accuracy of the results of the network performance. But at this moment the calibration and validation of en-route assignment models are difficult because of the lack of real data, especially when the certainty of the information itself cannot be guaranteed. The study of (Mahmassani et al., 2004b) is a good example with which to illustrate such a problem. In their study, the parameter *response rate* of travelers to the information from Variable Message Signs (VMS) was used. Different values (40% and 50%) were chosen to investigate whether an increase in the response rate would be beneficial or not (should surface streets become jammed). However no conclusions or suggestions were given about which value is more suitable or closer to reality. So there is still long way to go to make the en-route assignment model sophisticated.

The major objective of our research is to find and/or create generic methodology and methods for systematical analysis of road network robustness. Thus intensive calibration studies about the models are not included in our contents but for the future development. In next section, several DTA models with different categories (e.g. UE assignment models and en-route assignment models, macroscopic models and microscopic models) will be investigated on their basic performance in traffic assignment through case studies. The investigation results will be used as the base for the selection or generation of suitable DTA models for our robustness analysis.

## 3.3 Discussion

At this moment, many business software and academic tools exist for transportation research based on or integrated with DTA models. However, the majority of these DTA models only have a single function, i.e. either UE assignment or en-route assignment. Examples for the former approach include VISSIM (PTV, 2004), (TSS, 2005) AIMSUN-NG, (INRO, 2005) Dynameq , (Bliemer et al., 2004) INDY and MARPLE (Taale et al., 2004). Examples for the latter approach include INTEGRATION (Aerde, 1995) and (SIAS2005, 2005) S-PARAMICS. Furthermore, the DYNASMART-P tool contains both DTA approaches.

These software tools are all available for carrying out DTA for road network analysis, but they belong to different categories and each of them has a particular emphasis on certain applications. In order to better understand how the DTA models work in distributing traffic between multiple OD pairs, we tested some of them that are available for use. The tested tools are VISSIM 3.70, INTEGRATION, DYNASMART-P 1.0, MARPLE, and INDY 1.0. Their general information is listed in Table 3.2.

These models were tested using a simplified medium-size road network, that of the city of Delft, in The Netherlands. Detailed information about the models and the tested network, as well as the results of the comparison studies can be found in Appendix A. For all of the chosen models only the default values of the parameters are used, which is mainly due to the following two considerations: i) The default values of the

**Table 3.2: General information about the tested DTA models**

| | **Category** | **Approach** | **Path generation** |
|---|---|---|---|
| VISSIM3.70 | Microscopic | UE | Iteratively updating |
| INTEGRATION | Mesoscopic | En-route | En-route |
| DYNASMART-P | Mesoscopic | UE | Iteratively updating |
| | | En-route | En-route |
| MARPLE | Macroscopic | UE | Exogenous |
| INDY 1.0 | Macroscopic | UE | Exogenous |

parameters supplied in these models are more or less achieved from certain calibration studies, and it is a logical assumption that with such values these models can deal with a simple network with satisfactory results; ii) The tested network is not complex and the tested demand is hypothetical and it only results in a moderate congestion. No real traffic data was available to execute a further calibration. The lack of path-level data in particular makes it difficult for a direct calibration of the assignment models.

Although the lack of calibration of the tested models makes it difficult to cross compare them, some general remarks can still be drawn from the assignment results and from our experience of using these models:

- As the only tested microscopic model with a UE assignment approach, VISSIM is the most difficult of the models with which to achieve equilibrium. This is mainly because of its microscopic feature, which takes long time to simulate every iteration. Another reason might be due to its iterative path updating method, which functions not only within the successive iterations, but also within the successive intervals in each iteration. The UE approach in DYNASMART uses the same method. Large fluctuations exist in the path flows of the successive iterations in both models;

- Irrational paths, such as detours using an off-ramp and an on-ramp in succession, have be found in VISSIM and DYNASMART-P. Such phenomena can be (partially) avoided by using some extra constraints or tricks, such as adjusting the link settings or some parameter values. But it is difficult to be totally eliminated. We feel that iterative path updating method need to be used carefully;

- For the same road network, a microscopic model generally generates much lower network performance (e.g. speed) than other models. The reasons might be complex, but in VISSIM much more traffic are assigned to the second or third fastest paths than other models. Lots of unnecessary congestions are caused by such assignment results. This means that the assignment model used in VISSIM (Kirchhoff model) or its default parameter values are probably unsuited;

- Exogenous path generation methods in MARPLE and INDY generate a reasonable amount of paths for such a simple road network. Combined with Logit-based assignment models, the changes in the assignment results within the successive assignment intervals are smooth. Differences in the results of these two models mainly result from their different network loading models. But they would both have difficulty in analyzing the network with incidents, because new and temporary better alternatives cannot be updated during the simulation. Although this can be partly solved by creating a larger initial path set, it is still difficult to guarantee that all possible useful paths will be generated.

## 3.4 Conclusion

In this chapter, a general introduction is given on DTA models. Two distinct approaches of the DTA models, i.e. UE assignment and en-route assignment, are compared in detail. Several commercial and academic tools for transport applications with DTA functions have been tested on a real but simplified road network. These DTA models cover different categories of models (e.g. microscopic, macroscopic, and mesoscopic) as well as different approaches (i.e. UE and en-route). A comparison study has been carried out to investigate the availability of these DTA models for road network robustness studies. According to the basic requirements for road network robustness analysis proposed in Chapter 1 and 2, we will first summarize the functions of the tested models in relation to the requirements in Table 3.3. Furthermore, some remarks about the performance of the tested DTA models in our common network are also provided.

### 3.4.1 Overview of the functions of tested DTA models

This section contains a summary of several crucial functions of a DTA model for road network robustness analysis. Besides these, the criterion of ‘*coding possibility*’ was also added. It is an important characteristic of a DTA model because road network robustness analysis is such a new topic that we need the potential to be able to realize innovative ideas.

**Table 3.3: Functional overview of tested DTA models**

| | UE | En-route | Queuing spill-back | Coding possibility |
|---|---|---|---|---|
| VISSIM3.70 | + | | + | |
| INTEGRATION | | + | + | |
| DYNASMART-P | + | + | + | |
| MARPLE | + | | + | + |
| INDY 1.0 | + | | | |

### 3.4.2 Remarks on the tested DTA models

In this section, some remarks about the tested DTA models are listed based on the experience obtained from the case study introduced in this chapter and Appendix B. These remarks are made particularly aiming at their possibilities for road network robustness analysis.

1. VISSIM, as a microscopic model, generates much higher traffic delays than other types of models in our simple road network test study. Another feature of VISSIM is that it takes very long time to achieve the (approximate) equilibrium status for a network. According to our analysis, an equilibrium status of the road network is considered a necessary reference for network robustness studies. Although a microscopic model has a natural advantage in accurately representing the queuing phenomenon, we found it difficult to use VISSIM for the dynamic traffic assignment in a road network. For this reason, we did not continue to use it for the next robustness analysis.

2. The iteratively path updating method can grasp changes in path costs, search for new paths, and make a new assignments between successive intervals within each iteration of the UE assignment. As a result, many paths with negligible flows have been generated. Considerable fluctuations also exist in the assignment results. One adverse consequence of the iterative updating method is the appearance of irrational detours, which indicates that to use this method researchers must spend a lot of effort to carefully adjust the parameters or even use some tricks.

3. Path information, including the composition of the paths and assigned flows of the paths, are necessary for analyzing traffic assignment results in robustness studies. INTEGRATION and DYNASMART cannot directly supply such information, but their en-route assignment approaches show us a way of developing a suitable DTA model to represent network performance after a disturbance.

4. Two macroscopic models, INDY and MARPLE, have certain similarities in most of the modulus, such as a macroscopic feature, an exogenous path generation method and a UE assignment approach. From their assignment results, we feel that exogenous path generation method might be the most suitable method for the equilibrium assignment approach, which has also been noted by (Fiorenzo-Catalano, 2007). However, the INDY model version we tested does not have a queue spill-back implemented, which makes it less desirable for our further studies.

5. In these tested models, only MARPLE gives us the possibility to make further developments for robustness analysis, which is quite important for this research work. MARPLE has proved its ability in achieving satisfactory UE assignment results taking into account queuing phenomenon. So we selected MARPLE as

the base from which to make further development for our road network robustness analysis. Detailed information on the MARPLE model and its development are discussed in Appendix A and B.

# 4

# Framework and Methods for Network Robustness Studies

One conclusion from the literature review in Chapter 2 is that till now the study of road network robustness is still in a primary stage, lacking in a generally accepted and well-designed methodology. The analysis on DTA models in Chapter 3 showed the importance and urgency of building up a systematical methodology with suitable DTA models for road network robustness studies. In this chapter, a two-stage framework for road network robustness study will be designed and presented. This framework has been built based on the basic requirements for the valid road network robustness studies and on the characteristics of the two necessary DTA approaches, i.e. the SUE (stochastic user equilibrium) assignment approach and the en-route assignment approach. This framework has the ability to quantitatively evaluate the influences of the incidental disturbances (e.g. road works and accidents, etc.) on the performance of road networks using the combination of an SUE assignment model and an en-route assignment model. Thus network robustness against the disturbances can be calculated with the proposed framework. Furthermore, several other applications of this framework are available to the analysis of road networks, including analyzing the weak or vulnerable link(s) of a given road network, assessing the effectiveness and efficiency of the new traffic management measures or schemes to network robustness. As provided in Chapter 3, the traffic assignment models used in the framework are originally based on the MARPLE model.

The structure of this chapter is organized as follows. Section 4.1 introduces the proposed framework and its working mechanism with different DTA approaches. The adopted en-route assignment model, MARPLE-e, is developed based on the SUE assignment approach of MARPLE and is described in Section 4.2. Section 4.3 introduces other methods that will be used for the study of road network robustness, including the scenario-based approach and the sensitivity analysis. Finally Section 4.4 summarizes this chapter.

## 4.1 The Framework for Network Robustness Study

In this section, a systematic framework for road network robustness studies is proposed in order to fulfill the basic requirements that we have put forward in Chapter 1.

### 4.1.1 The framework

The proposed framework comprises two stages with different tasks for analyzing road network performance as shown in Figure 4.1.

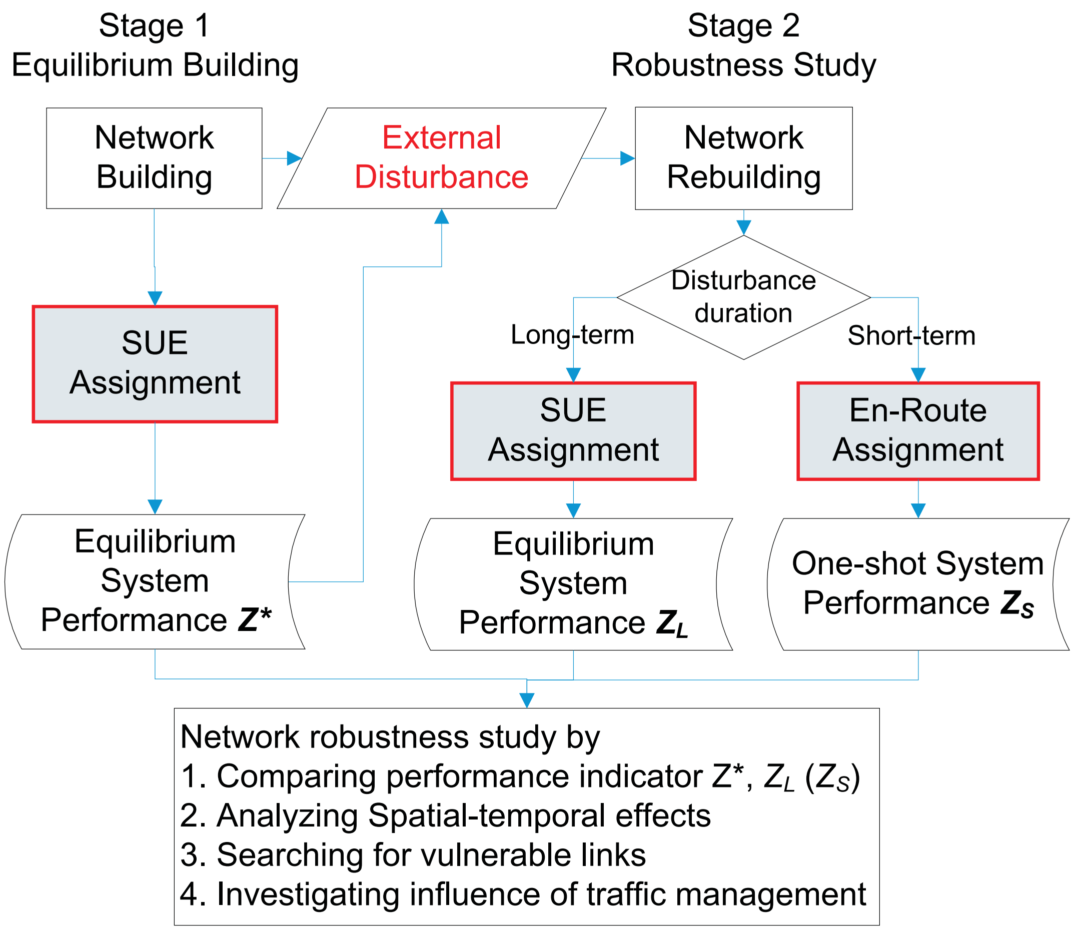

**Figure 4.1: Framework for road network robustness study**

The design of the two-stage framework is based on the requirements for road network robustness studies and the characteristics of the two DTA approaches, i.e. SUE approach and en-route approach. In Stage 1 of the framework, a SUE assignment approach is carried out to achieve an 'equilibrium' status of the studied road network. This satisfies the first requirement, which is a reference status. An external disturbance to the reference status is modeled as the cause of the robustness problem, which satisfies the second requirement. So the performance of the road network with an external disturbance is analyzed in Stage 2 using either an SUE approach or an en-route approach. The choice of the DTA approach is dependent on the characteristics of the disturbance. If the disturbance is unpredictable and only lasts for a short term, such as an accident, the en-route approach is preferable. Alternatively, if the disturbance lasts for a long time or has long-term effects so that a new equilibrium is possibly to be established, then the SUE approach becomes preferable. For instance, road construction or maintenance work lasting for several months or years might create a new equilibrium traffic status within the period and the area that it influences. The feasibility of choosing one of the DTA approaches in Stage 2 fulfills requirements three and four, thus all of the four basic requirements for a systematical road network robustness analysis can be satisfied with this two-stage framework.

An advantage of this framework is that it has an open structure which means that all DTA models that match the basic two requirements for road network robustness analysis can be implemented. The first requirement is that both the (stochastic) UE approach and the en-route approach should be available. The second requirement is that both DTA approaches should be compatible in the network loading module to guarantee the consistency in traffic modeling. The functions and outcomes of the SUE approach and the en-route approaches in this framework are discussed in detail in the following two subsections.

### 4.1.2 The SUE assignment model

The SUE assignment model can be adopted in both stages. In Stage 1, the results of the SUE assignment approach can be classified into two groups according with different applications:

1. Performance results: The performance results represent the normal daily performance of the network, which are used as the reference for road robustness analysis. Such results include the values of some aggregated network-level performance indicators, such as total travel distance ($TTD$), total travel time ($TTT$), and total delay ($TD$);

2. Assignment results: The dynamic traffic assignment results are used as the initial assignment of the traffic before the disturbance appears in the system. Such results include the time-dependent equilibrium path set $EPS(k)$ ($k$ is the index of time intervals), equilibrium path flows $EPF(k)$ and equilibrium path costs $EPC(k)$.

In Stage 2, SUE assignment can also be adopted to model the network performance if the disturbance to the system lasts for a long time or becomes recurrent that are predictable. This is because in such cases the system can achieve a new equilibrium if travelers get used to the disturbance after a learning process. Before implementing the SUE approach, the path set must be updated with the new network topology since some paths might no longer be available after the disturbances. However, in this thesis, such a type of disturbance is not considered because our interest focuses on the robustness of the network against one-shot disturbances.

As discussed in Chapter 3, the MARPLE model is used to realize the SUE assignment, as well as the basic model for development of the compatible en-route assignment model.

### 4.1.3 The en-route assignment model

An en-route assignment model is adopted in Stage 2 to model the non-recurrent and unpredictable disturbance situation. Travelers at this moment would either like to persist on their original paths, or search for alternative paths to avoid the unfamiliar congestions and extra delays that are different from their daily experience. Thus, an en-route assignment model is built based on several heuristic routing rules that are assumed to be followed by travelers on their way to their destinations, or even before their departure from the origins. These rules should at least include the answers to the following questions:

1. How should travelers' daily path sets be decided?
2. What information of the travel costs will be supplied to travelers, including the knowledge of alternative routes?
3. When and how travelers' path sets should be updated when necessary (especially for the travelers who are already on their way)?
4. How should new distributions be calculated when the update of assignment is necessary?

In the next section 4.2 and Appendix B, detailed descriptions of the en-route assignment model developed for the network robustness analysis are described.

## 4.2 En-route Assignment Model

Before building up a suitable new en-route assignment model, we first analyze the weakness of the existing en-route assignment models. Based on this analysis, some improvements will be proposed to overcome these weakness.

### 4.2.1 Weakness in existing en-route assignment models

There exist very few en-route assignment models and we have experience for two of them - DYNASMART and INTEGRATION with a case study. Detailed introduction and analysis to them can be found in Appendix A. In an en-route assignment approach, travelers update their perceived path costs information and update their paths (stick on or change at so-called decision points) at the beginning of each discrete evaluation period (e.g. DYNASMART) or at each decision-making point where they can switch paths (e.g. INTEGRATION). Besides that, initial path sets and initial assignment are also necessary for the start of the modeling. In these two en-route assignment models the initial path sets of any OD pair normally only include the fastest (selected by the free flow travel time) path. Initial path assignment is to distribute 100% of the traffic of each OD pair to the shortest path, i.e. all-or-nothing (AON). The further assignment then either takes the combination of AON and MSA (method of successive average) in DYNASMART, or equally distribute the traffic demand to the generated paths in the path set in INTEGRATION. These methods for determining the initial and follow-up assignment are rough approximations with the following weaknesses:

- In reality, route choice behaviors of travelers are much more complicated than only choosing the shortest or fastest path, especially when travelers have enough knowledge and experience about the road network. For an individual travel, he/she might have one fixed or favorite path. But for all travelers of the same OD, different path choices must be taken into account, even for the initial interval of the simulation. Therefore, the AON method for the initial assignment is not suitable;

- For network robustness studies, we proposed using both the SUE and the en-route assignment approach to model travelers' choice behavior under different situations. Considering the comparisons results and the analysis presented in Chapter 3 and Appendix 1, we found that it is very difficult to compare different DTA models due to the differences in any submodels, such as the path generation model, traffic assignment model, and network loading model etc. This means that a combination of an SUE assignment model and an en-route assignment model could cause inconsistency in their results. So it is essential for the en-route assignment model to be compatible with the SUE assignment model, especially for the network loading model.

According to these two reasons and the decision of using the MARPLE model for the SUE assignment, we decided to build up a new en-route assignment model based on MARPLE, which is named MARPLE-e.

### 4.2.2 Improved en-route assignment model: MARPLE-e

Supposing a non-recurrent and unpredictable incident starts on a road network within the interval $t_s$ ($\geqslant 2$) and finishes within the interval $t_e$ ($> t_s$). Then the deviation of the network performance from its normal situation will occur and be noticed by the travelers, which means that the en-route approach will start to work. Three general concepts, or assumptions of the application of the en-route assignment model are given as follows:

1. Before the incident, the performance of the road network maintains the normal situation and travelers who depart before the incident also follow the equilibrium assignment results until the incident occurs;
2. When the incident occurs within interval $t_s$, the equilibrium status is broken immediately. As the evaluation of the network performance is done at the end of each interval, the effects of the incident then can only be assessed at the end of $t_s$. This means that there exists a certain delay between the appearance of the incident and the feedback of travelers. This treatment for the information delay, in our opinion, is representative in two ways:
    (a) After the incident, the management system needs some time to detect the incident through the changes in the traffic flows, such as the speed and intensity. The system can then supply the information about the incident and network performance to travelers and/or adapt the control schemes to the incident;
    (b) Travelers also need time to feel and respond to both the provided information and their own observations of the changes in road conditions.

    Thus the en-route assignment approach would start from interval $t_s + 1$;
3. Although the ending interval of the disturbance is $t_e$, the en-route assignment approach will continue to the end of the complete studying period because the disturbance will continue to effect the road network due to the fact that queues will exist longer than $t_e$.

An improved en-route assignment model has been developed based on some assumptions about travelers' behavioral. Detailed description of the MARPLE-e model can be found in Appendix B. Here, an important parameter set that might significantly influence the assignment results of the en-route assignment model will be emphasized. This parameter set is called the *compliance rate* or the *response rate*, which is defined as the percentage of travelers who will respond to the real-time traffic conditions and/or the provided information, such as information from the variable message system (VMS). Although the compliance rate is important and has been widely involved in many related research works, very few studies have been done on investigating its real or suitable value. For instance, in the research work of (Mahmassani et al., 2004b) for the evaluation of the measures of the Intelligent Transportation System (ITS), cross comparisons between two compliance rate values (40% and 50%) are given. But the researchers did not give any suggestions or reference values for the compliance rate. This means that several questions still exist, including:

- What value(s) of the compliance rate is the most valid or suitable for the case of the studied road network?
- If it is impossible or difficult to get a '*validated*' value for the studied network case, how will the different adopted values influence the modeling results?

For our road network robustness studies, the former question, i.e. deriving valid value(s) of the compliance rate, is not one of the tasks. However, the latter question is of great interest and importance for the current study because different compliance rate values might significantly change the outcomes of the assignment results, as well as the conclusion of the network robustness against incidents.

In order to carry out the studies of road network robustness against incidents, which can unpredictably occur on any position on the network with different levels of severity, different incident scenarios with different incident characteristics (e.g. position, time, duration etc.) must be taken into account. A scenario-based analysis method is chosen and treated as the most suitable method for our research. In the next section, the method of scenario-based analysis and its application in the road network robustness analysis will be discussed in detail.

## 4.3 Scenario-based Analysis for Network Robustness Studies

For the study of road network considering travelers' choice behavior, there exist two major challenges: firstly, we do not (and maybe never will) understand human behavior with enough detail and accuracy to make the assignment models completely correct in representing human choice behavior; secondly, it is difficult to perfectly model the uncertainties in traffic demand and capacity, especially the impacts of those non-recurrent and unpredictable incidents on the network performance. To solve or avoid facing such problems, a scenario-based approach has been introduced by (Mulvey et al., 1995) to analyze road network performances in different designed scenarios. Each scenario has different values of the uncertain input variables to represent one situation of the network. This method has also been used in the research works done by (Yin et al., 2005), which has been introduced in Section 2.3.5. In the following subsections, the scenario-based analysis method and its applications in the road network robustness studies will be explained in detail.

### 4.3.1 Scenario-based analysis approach

The scenario-based analysis/optimization approach deals with the uncertainties via a limited number of discrete scenarios that can occur in reality. The situation of each scenario with an extreme condition is calculated to investigate the extreme behavior of the system resulting from the extreme condition. The original function of the scenario-based analysis attempts to solve the (optimization) problem across different scenarios for solutions that are near-optimal with respect to the population of all possible realizations of uncertainty.

Although there is no optimization problem in our network robustness analysis, a similar idea can still be borrowed to deal with uncertainties in the values of internal parameters or external variables. A detailed description of the scenario-based approach follows.

### 4.3.2 Scenario-based analysis for road network robustness studies

Consider a road network in the form of a direct graph $G = (N, A, D, CL, \ldots)$ ($N$: node, $A$: link, $D$: demand, $CL$: control) with uncertain capacity of links and/or uncertain demand between OD pairs. For simplicity, all of the uncertain input variables are assumed to be independent from each other. This assumption has the following two implications:

1. The changes in the capacity of links will not influence the values of the traffic demand, and vice versa. For our robustness analysis, we focus on the scenarios with the one-shot and short-term incidents. In such scenarios, the changes in the capacity (or demand) will hardly influence the demand (or capacity). Thus this assumption can be considered to be valid in most cases;
2. The changes of the capacity of one link will not influence the capacity of other links; and the changes of the demand between one OD pair will not influence the demand between other OD pairs.

In the robustness analysis for the two road network cases in Chapter 5 and 6, we focus on the performance of the road network with the short-term and non-recurrent disturbances, such as an accident. Thus each incident scenario will be represented only with the en-route assignment approach based on a basic scenario achieved by an SUE assignment. Moreover, according to the direct effects of the disturbance, incident scenarios for road networks can be classified into capacity-related scenarios and demand-related scenarios. Thus two sets of scenarios associated with (link) capacity $A$ and demand $D$ can be generated respectively as:

- $\Omega_A = \{a_1, a_2, a_3, \ldots\}$: capacity-related scenario set includes all the incident scenarios caused by the capacity changes in link $a_i$ ($i = 1, 2, 3, \ldots$);

- $\Omega_D = \{d_1, d_2, d_3, \ldots\}$: demand-related scenario set includes all the incident scenarios caused by the demand changes in OD pair $d_i$ ($i = 1, 2, 3, \ldots$).

For each scenario set, the number of the scenarios is basically controlled by the network characteristics, such as the number of links and the number of OD pairs of the network. It is also influenced by other factors, such as the size of the network and the proposed status of the link or OD pair. In the following two sections, basic rules for scenario design are introduced for each scenario set.

#### Capacity-related incident scenario set $\Omega_A$

The number of scenarios for $\Omega_A$ is basically controlled by the number of links ($S_A$) in the studied network, and the designed number of the degradation levels of the link capacity. For simplicity, the degradation levels of the link capacity can be set as a list of ten discrete values from -10% to -100% with -10% as the step. Based on this set of degradation levels, the complete number of the capacity-related scenarios is $10 \times S_A$. However, for a large-sized road network with thousands of links, this number implies tremendous computing efforts. A further pre-selection process and a filtering process are then needed to reduce the number of the scenarios without loosing the generality. Such pre-selection and filtering processes for choosing a limited number of possible critical links in a road network are based on the SUE assignment result, which is considered to be a close representation of the normal daily situation and a basic stable status from which the changes occur due to the incidents. A detailed description of those process will be given in Chapter 6.

#### Demand-related incident scenario set $\Omega_D$

In each scenario in $\Omega_D$, the demand between one OD pair will be increased by a certain percentage to its original value or a certain absolute value. There are several ways to choose the OD pairs for the design of the scenarios. One way is to choose the OD pairs with the top demand values because the same percentage changes in the demand of these OD pairs will create more extra demand to the network. The other way is to choose the OD pairs which are related to the results of the links for capacity-related scenarios. For instance, corresponding to a selected link, the OD pair that contributes the most of its flow will be chosen.

### 4.3.3 Sensitivity analysis method

Sensitivity analysis (SA) measures the impact on project outcomes of the change of one or more key input values about which there is uncertainty (Marshall, 1999). In transportation engineering, SA mainly measures the traffic assignment results (e.g., link flows, link travel times, path travel times) resulting from alternative values of uncertain variables that affect the assignment of the network, such as demand and capacity. (Chen et al., 2002) proposed an assessment methodology that combines SA, bi-level programming, and Monte Carlo simulation to evaluate the capacity reliability of a degradable road network. It addresses the question: If $C_a$ (the capacity of arc $a$) had been $C_a + \Delta C$, what would have been the corresponding changes $\Delta M$ of the performance measure $M$. That is, the derived information allows the identification of the arcs that are most sensitive to the performance measure. Of course disturbance can appear not only on arc capacity, but also on other components of the road network, such as $\Delta D$ for OD demand $D_{ij}$ of OD pair (i,j). The existence of analytical derivatives depends on the performance measure of interest. At this moment, there only exists analytical derivatives for the travel time reliability from the *equilibrium* network flow (see (Tobin & Friesz, 1988), (Yang, 1997), and (Bell & Tida, 1997)). However, the equilibrium network status has been proved incorrect for describing network performance with short-term and non-recurrent disturbances. Thus analytical derivatives in these SA method cannot be used directly in our robustness analysis. Hence, we propose a method in the next subsection using a combination of an approximate SA method and the scenario-base analysis to perform the systematic network robustness study.

### 4.3.4 Combination of scenario-based analysis and SA

It is assumed that for the design of incident scenarios, input variables are independent from each other. So we can analyze the influence of each of them separately by changing only one variable for one set of scenarios. For instance, to estimate the influence of the link capacity ($c_a$) on the network performance, a set of scenarios $\Omega_A$ with different link capacity values but the same demand and control will be designed. Assume that in $\Omega_A$ a number of $K_a$ scenarios exists related with link $a$. For each scenario $s_a(k), k = 1, 2, \ldots, K_a$, the capacity of link $a$ is $c_a(k)$ and the network performance measure $M_a(k)$ is obtained by solving the en-route assignment problem with this link capacity. Changes in $M_a(k)$ with respect to the changes in $c_a(k)$ can be used to identify the influence of $c_a(k)$ as follows:

$$\frac{\partial M(a_k)}{\partial c_a(k)} \approx \frac{M(a_k + \Delta c_a(k)) - M(a_k)}{\Delta c_a(k)} \tag{4.1}$$

For a real-sized road network, it is difficult to imagine that a very small change in any component (such as $\Delta c_a \to 0$ for $c_a$) will result in obvious changes in the network performance $M$. Also in the scenario-based analysis method, only a limited amount of discrete values of the network component are used for the study. Thus, in this thesis, we only compare the differences in the network performance derived from different scenarios for the same element, e.g. differences in $M(a_{k+1})$ and $M(a_k)$ achieved with $c_a(k+1)$ and $c_a(k)$ respectively. With such comparisons, which are normally illustrated through figures, we can conclude which elements have more impact on the road network when they are disturbed. We name these elements *critical elements* in the network.

## 4.4 Summary

In this chapter, a framework and several methods that will be applied in our road network robustness study have been described. The most important part is that the framework consists of both a SUE assignment approach and an en-route assignment approach. Depending on the characteristics of the disturbances to the network, either the SUE approach or the en-route approach is implemented in order to represent the travelers' behavior and network performance.

For road network robustness studies, the method of the scenario-based analysis, together with the simplified sensitivity analysis will be adopted to represent uncertainties in the basic elements of the road network via a limited number of discrete uncertainty scenarios. Such methods have been proved to be quite suitable to solve the complex problems, for which no complete and precise analytical expression exists.

All these methodology and methods are tested through two network cases in Chapter 5 and Chapter 6 respectively. In Chapter 5, a simple hypothetical network is designed to examine the models in the framework, and to validate the values of the parameters in the models. In Chapter 6, a real-sized road network in The Netherlands is used for an advanced assessment of the model, as well as network robustness.

# 5

# Case Study with a Small Network

Chapter 4 introduced a framework for the systematical analysis of road network robustness. This framework proposed a new idea of combining two approaches of DTA models (UE approach and en-route approach) to model different (route) choice behavior of travelers in both familiar and unfamiliar situations. Such an innovative traffic assignment model has been built based on the basic requirements for the robustness analysis of road networks and the characteristics of each DTA approach. From a methodological point of view, this proposed framework should be capable of analyzing road network performance in the face of different types of disturbances because of the flexibility in choosing appropriate DTA approaches.

This new framework, including the adopted DTA models at this moment, needs to be tested and validated through case studies. In this chapter, two sets of complete designed incident scenarios of a small hypothetical road network with hierarchical structure will be studies in order to demonstrate the feasibility of the framework for road network robustness analysis. The first aim of this case study is to give a kind of *face validation* of the framework and the currently adopted DTA models (i.e. MARPLE and MARPLE-e) in simulating network performance and route choice behavior of the travelers with and without disturbances. The face validation work focuses on two points:

1. Can the assignment model represent travelers' (route) choice behavior when they meet unexpected disturbances on their trip in a logical way?
2. Are the chosen network performance indicators suitable for robustness analysis?

Furthermore, this chapter also aims at gaining knowledge about the robustness of the tested road network against disruptions to link capacity or OD demand. More specifically, so-called *critical elements* in this network can be identified.

The structure of this chapter is designed as follows. A description of the tested small network is given in Section 5.1. Section 5.2 presents the criteria for incident scenario design and final lists of the scenarios. Some indicators, including several conventional aggregated network-level indicators and newly developed time-dependent indicators are introduced in Section 5.3. In Section 5.4 we analyze the influences of different values of an important parameter set (response rate) to the simulation results and deliver the parameter sets in the subsequent studies. Sections 5.5 and 5.6 illustrate the analysis of the network performance in the incident scenarios rooted from link capacity degradation or OD demand increase. Finally Section 5.7 summarizes this chapter.

## 5.1 Description of the Tested Network

As introduced before, the aim of the case study in this chapter is mainly for the face validation and demonstration purpose. Thus a small, simple and hypothetical road network will be tested, but still with a hierarchical structure. In this section, this network will be described in detail.

### 5.1.1 Network outline and link characteristics

The outline of the road network is illustrated in Figure 5.1.

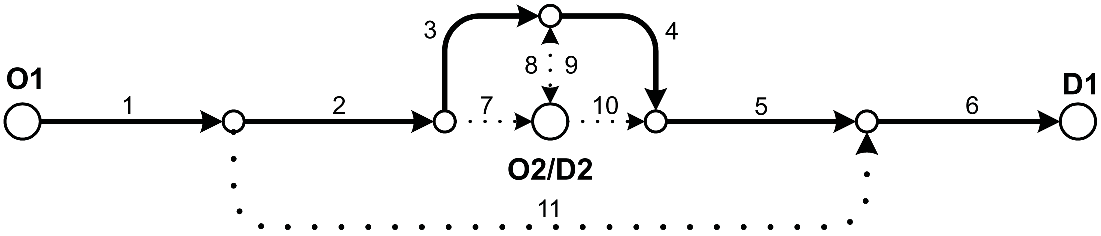

**Figure 5.1: Simple and hypothetical network**

The network has 11 single directional links, including 6 motorway links (solid line) with higher desired speed $(120\,km/h)$ and higher unit capacity $(2150\,veh/hour/lane)$, and 5 urban links (dashed line) with lower desired speed $(50\,km/h)$ and lower unit capacity $(1800\,veh/hour/lane)$. The important characteristics of all the links are listed in Table 5.1.

### 5.1.2 OD Demand

Three zones (O1, D1, and O2/D2) are displayed as large circles in Figure 5.1. Zone O1 is an origin only and zone D1 a destination only. Zone O2/D2 is both an origin

**Table 5.1: Link Characteristics**

| Link ID | Length $(km)$ | Desired Capacity $(veh/h)$ | Desired Speed $(km/h)$ | Type |
|---|---|---|---|---|
| 1, 2, 5, 6 | 4.0 | 8600 | 120 | Motorway |
| 3, 4 | 4.0 | 6450 | 120 | Motorway |
| 7, 8, 9, 10 | 2.0 | 1800 | 50 | Urban |
| 11 | 16.0 | 1800 | 50 | Urban |

and a destination (that represents a town/city center). Since all the links are single directional, only three OD pairs exist. These are (O1,D1), (O1,D2) and (O2,D1).

Demand for these OD pairs is designed with a triangular temporal loading profile as depicted in Figure 5.2. It includes four periods as ‘warming’, ‘peak’, ‘cooling’ and ‘clearing’. The basic time unit is so-called *demand interval* and the length of each demand interval is 10 minutes. Each period of ‘warming’, ‘peak’, and ‘cooling’ is composed of 6 intervals, i.e. 60 minutes, with traffic demand; while ‘clearing’ period has zero demand and only 3 intervals, i.e. 30 minutes, in order to clear the road network. Thus in total there are 21 demand intervals (three and half hours) simulation time. In Figure 5.2, the ratios of the demand in each interval to the peak demand are also shown.

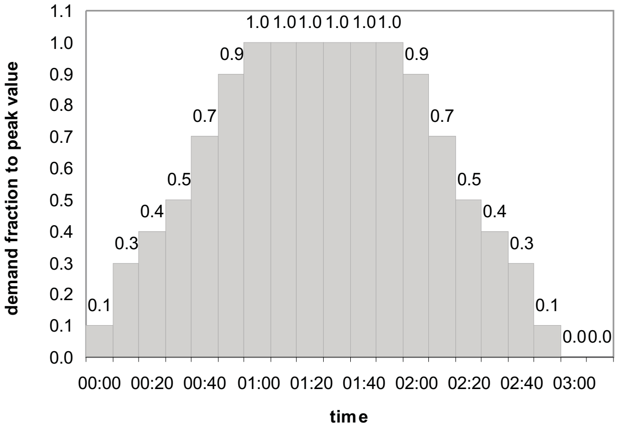

**Figure 5.2: Profile of OD demand with ratios to peak-hour value**

### 5.1.3 Path information

Due to the simplicity of this tested network, nine possible paths for all of the three OD pairs can be found easily as listed in Table 5.2. Among them, the three italic paths (3, 4, and 5) will not be used by travelers between (O1,D1) for normal daily trips. It is either because of their extremely high free flow travel time (*FFTT*) than others, such as Path 3; or because of the irrationality of containing unrealistic detours, which we call ‘off-and-on-ramp’ detour, such as Paths 4 and 5. However, these paths are of great interest in network robustness analysis. In some circumstances, they might become acceptable alternatives for travelers to avoid heavy congestion on the other paths when the motorway is degraded. Such phenomena might mitigate congestion in the network so that the total delays of the network can be reduced. Specifically, Link 11 (only used in Path 3) is denominated as the *passive redundancy* in the network by (Immers & Jansen, 2005) because it is seldom used in normal situations. The design of this link and Path 3 is for testing the function of the en-route assignment model because a valid en-route assignment model should be able to find and use Path 3 when the motorway is seriously congested. It can also illustrate the relationship between redundancy and robustness proposed by the researchers, which is that redundancy makes the system robust.

**Table 5.2: Path and OD demand information**

| (O,D) | Path ID | Link Sequence | Length (km) | *FFTT** (sec) | Peak demand (veh/h) |
|---|---|---|---|---|---|
| (O1,D1) | 1 | 1-2-3-4-5-6 | 24 | 720 | 6000 |
| | 2 | 1-2-7-10-5-6 | 20 | 768 | |
| | *3* | *1-11-6* | *24* | *1392* | |
| | *4* | *1-2-3-8-10-5-6* | *24* | *888* | |
| | *5* | *1-2-7-9-4-5-6* | *24* | *888* | |
| (O1,D2) | 6 | 1-2-7 | 10 | 384 | 1500 |
| | 7 | 1-2-3-8 | 14 | 504 | |
| (O2,D1) | 8 | 10-5-6 | 10 | 384 | 1500/3000** |
| | 9 | 9-4-5-6 | 14 | 504 | |

**FFTT*: free flow travel time

**: Two levels of demand value resulting in uncongested and congested reference states

As described in Chapter 4, network performance under the daily normal situation is used as a reference for robustness analysis. In the following section of scenario designs, this daily normal situation is defined as scenario $\omega_0$ for both uncongested and congested demand levels.

## 5.2 Scenario Design

Incident scenarios are designed in this section for both model testing and the study of network robustness. The designed scenarios should on one hand cover as many incidents as possible, and on the other hand not lose their generality. In view of these two basic requirements, the following criteria are adhered to in designing scenarios.

### 5.2.1 Designing criteria

The effects of disturbances on road networks can be classified into two basic categories: capacity degradation and demand increase. So the design of incident scenarios for the road network also focuses on these two basic situations. Furthermore, the following guidelines are applied in the design procedure:

1. The capacity of the selected links will be degraded, but the selected links should not lose their generality in the network. For instance, those entrance links from an origin zone are special because their degradation will impede the traffic entering the network as they are assigned. Since the entrance delay of the traffic is not included in the travel delay that we want to calculate, these entrance links, as well as other links that have the same effects, should be excluded from the incident scenario design;
2. Degradation of the physical capacity of a link is designed with different levels for the sensitivity analysis;
3. Demand for the selected OD pairs will be increased, but the total demand from an origin should not exceed the capacity of the entrance link; otherwise its effects cannot be correctly represented;
4. Increase of the OD demand also have different levels for the sensitivity analysis.

### 5.2.2 Designed Scenarios

For simplicity we assume that in each scenario only one element of the network will be disturbed. For instance, only one link's capacity is degraded or only one OD pair's demand is increased. So there exist two major scenario categories: $\Omega_A$ for link capacity degradation and $\Omega_D$ for OD demand increase. According to guideline 1, link 1, 2, 9, and 10 are excluded from the design of $\Omega_A$. Furthermore, link 6 is the only exit for Zone D1 and link 11 is never used under normal conditions. So they will also be excluded from the scenario design. The remaining five links together with three OD pairs will be used for the incident scenario design as eight scenario sets denominated from $\omega_0$ to $\omega_8$ in Table 5.3. For each scenario set, different levels of changes (degradation of link capacity and increase of OD demand) are designed for each scenario. As well as these two major categories, a reference scenario category $\Omega_0$ is also needed for robustness analysis, which represents network performance under the normal daily situation.

The following is the detailed explanation of the designed scenario categories:

- $\Omega_0$: This is derived from the SUE process with full link capacities and normal daily traffic demand without any disturbance. Thus there is only one scenario for each demand level, which is $\omega_0$;

**Table 5.3: Scenario information**

| Scenario set | Description | Degree of change | Category |
|---|---|---|---|
| $\omega_0$ | Daily condition | none | $\Omega_0$ |
| $\omega_1$ | Capacity reduction on Link 3 | [-10%:-10%:-100%]* | $\Omega_A$ |
| $\omega_2$ | Capacity reduction on Link 4 | | |
| $\omega_3$ | Capacity reduction on Link 5 | | |
| $\omega_4$ | Capacity reduction on Link 7 | | |
| $\omega_5$ | Capacity reduction on Link 8 | | |
| $\omega_6$ | Demand increase for (O1,D1) | [+300:+300:+1200]** | $\Omega_D$ |
| $\omega_7$ | Demand increase for (O1,D2) | | |
| $\omega_8$ | Demand increase for (O2,D1) | | |

*: [-10%:-10%:-100%] means capacity reduction from 10% to 100% with a step of 10%

**: [+300:+300:+1200] means demand increase from 300 *veh/h* to 1200 *veh/h* with a step of 300

- $\Omega_A$: This is the scenario category related to the reduction of link capacity only. In each scenario in $\Omega_A$, the capacity of a link is degraded during the peak period so that travelers will confront unexpected congestion caused by the drop in the link capacity. The degradation level of the capacity is from -10% to -100%, which means the link is blocked partly or completely;

- $\Omega_D$: This is the scenario category related to the increase of OD demand only. The maximum value of the extra demand is calculated according to the spare capacity of the entrance link in $\Omega_0$. Link 1 (entrance link for Zone O1) has spare capacity of 1050 (=8600-6000-1500) *veh/h* during the peak hour, and link 9 and 10 (entrance links for Zone O2) have spare capacity of 1100 (=1800+1800-1500) *veh/h* during the peak hour. So the maximum value of the extra demand for all three OD pairs is designed as 900 *veh/h*.

### 5.2.3 Two demand levels

There are two levels of peak demand between OD pair (O2,D1) as given in Table 5.2. With the lower demand value (1500 *veh/h*), the reference scenario $\omega_0$ is almost uncongested with very little delay. With the higher demand value (3000 *veh/h*), a bottleneck is generated on link 5 and some congestion appears in the corresponding reference scenario $\omega_0$. The major aim of designing these two reference states of the road network (denoted as ‘uncongested’ and ‘congested’ in the following) is to gain more knowledge about the impacts of the reference state of a road network on its robustness. This study has practical meaning because on one hand different road networks have different congestion levels; and on the other hand even the same road network also has different congestion levels in different periods of a day and in different days. Similar incidents appearing in different traffic situations may have different influence on the network performance, and it is important for us to better understand this relationship so that more suitable measures can be designed to handle different situations.

### 5.2.4 Multiple user types

In our road network robustness analysis, multiple user types have been introduced to represent different types of travelers with different route choice behavior. This is due to the fact that in reality travelers can rarely be treated as one uniform group with the same behavior that have the same reaction to one message. So differences always exist within travelers in their perception of the information and their preference. In the MARPLE model and its en-route extension MARPLE-e, such different types of travelers are distinguished through different values of $\theta$ parameter in the *C-Logit* model. In this thesis, a basic combination of three types of travelers will be adopted as shown in Table 5.4. The study on the reason to choose such combination is described in Appendix C.

**Table 5.4: Combination of multiple user types in this thesis research**

| User Type 1 ($\theta = 0$) | User Type 2 ($\theta = 1$) | User Type 3 ($\theta = 3$) |
|---|---|---|
| 30% | 50% | 20% |

## 5.3 Performance Indicators

Before choosing or designing indicators to display road network performance, we make an assumption that the paths generated in $\Omega_0$ are the most preferable paths for travelers due to their lower costs (travel time in our studies) than those that have not been generated. If an incident occurs on the network, an en-route choice behavior is taken into account. Travelers might take some new paths that were originally not used because the original ones become worse caused by the incident. So the preferred indicators with witch to identify this phenomenon are the total time and total distance traveled by all the travelers within the given period. But for the calculation of these indicators, the amount of the traffic involved is also important and it must be the same value for all scenarios. This is also the reason for designing an period of 30 minutes at the end of the simulation with zero demand in order to clear up the network and get the same amount of traffic for the statistics. Furthermore, capturing the changes in network performance and the changes in the assignment results is necessary for the assessment of the en-route assignment model. They are also valuable for road managers to better evaluate the effectiveness of the traffic management measures. Thus two types of indicators - aggregated indicators and time-dependent indicators - are chosen or designed in our studies to comprehensively describe the network performance.

### 5.3.1 Aggregated indicators

Four aggregated indicators are used to calculate network-wide performance over the whole simulation period, which respectively pays particular attention to travel time, travel distance, travel delay and arrivals. They are also popularly used in existing studies (e.g., (Mahmassani et al., 2004b), (Taale et al., 2004), (Knoop, V.L. and Hoogendoorn, S.P. and van Zuylen, H.J, 2007)).

1. *TTD*: total travel distance of all the vehicles for the given statistical period [$veh \cdot km$], calculated by

   $$TTD = \sum_t \sum_a v_a(t)\, l_a \tag{5.1}$$

   in which $v_a(t)$ is the outflow of link $a$ during interval $t$ and $l_a$ is the length of link $a$.

2. *TTT*: total travel time of all the vehicles for the given statistical period [$veh \cdot hour$], calculated by

   $$TTT = \sum_t \sum_a v_a(t)\, \frac{l_a}{\vartheta_a(t)} \tag{5.2}$$

   in which $\vartheta_a(t)$ is the average outgoing speed of $v_a$ during interval $t$ if $v_a > 0$. In particular, $TTT_0$ is the total travel time of scenario $\omega_0$.

3. *ETD*: extra total delay of all the vehicles for the given statistical period [$veh \cdot hour$], calculated by

   $$ETD = TTT - TTT_0 \tag{5.3}$$

   Robustness analysis is to compare road network performance between the scenarios with and without incident(s). $TTT_0$ is for the reference state without incidents. So *ETD* indicator is used to demonstrate the extra traffic delay caused by the incident.

4. *TNA*: total number of arrivals for the given statistical period [*veh*]. Rather than the other three indicators above, where the number of vehicles queueing in the origin zones and in the network are big trouble for the statistics, *TNA* is a more absolute measure for a fixed-time simulation (Hegyi, 2004).

Although these indicators are often calculated for the whole simulation period, it is also possible to aggregate them for a given statistical period that is interesting. For instance, the aggregation value over the incident period can show the direct impact of the incident, while the aggregation value over the post-incident period can show the recovery ability of the road system from the incident.

### 5.3.2 Time-dependent indicators

Besides these aggregated indicators over time and space, more detailed indicators that can reflect the spatio-temporal impacts of the incident to the network performance are also important for road authorities and managers to better understand the consequences of an incident. Such indicators are also very valuable for testing the en-route assignment model, as well as for analyzing network robustness against incidents, taking into account the en-route choice behaviors of the travelers. Furthermore, they can supply full information on the effectiveness of the management measures and control schemes in a great detail. So they are useful for road managers to assess these management measures and control schemes.

1. $NL(t)$: network load within simulation interval $t$ [veh/h] as the sum of all the link outgoing flows over $t$, calculated by

$$NL(t) = \sum_a v_a(t) \tag{5.4}$$

   Since the values of $NL(t)$ are small when the road network is either almost empty or very congested, it is necessary to have another indicator that can represent the speed condition of the network in order to distinguish between these two situations. Thus another time-dependent indicator, $NAS(t)$, is designed for this aim.

2. $NAS(k)$: an approximation of the network average speed within simulation interval $t$ [km/h], calculated as the division of the sum of the products of link outgoing flows and link average speeds and $NL(t)$, i.e.

$$NAS(t) = \frac{\sum_a \vartheta_a(t) v_a(t)}{NL(t)} \tag{5.5}$$

$NAS(t)$ follows the changes of the network average speed that will be influenced by the incident. Similarly, $NL(t)$ follows the changes of the network loading (i.e. its transport ability) situation, which is designed to identify the effectiveness of the road network. Generally, for a given road network (i.e. its geological structure is fixed), if it can handle (or maintain) more traffic flows in most of the incident scenarios, it can be considered robust. For instance, when the road network has some redundant capacity under normal situations, in the case of incidents, network performance will gracefully degrade if this redundant capacity can be used by a certain amount of traffic as an alternative. The direct expression of such phenomena is that the falls of $NAS(t)$ and $NL(t)$ after the incident are slow. Thus we can remark that a robust road network is supposed to be able to transport more traffic after incidents and discharge them quickly, i.e. $NL(t)$ and $NAS(t)$ both remain at certain high levels.

After introducing the designed scenarios and indicators for the robustness studies, in the following sections detailed analysis of the results of these scenarios will be presented.

## 5.4 Link Capacity Degradation Scenarios

In this section, we will focus on analyzing the impact of single link degradation on the network performance, i.e. incident scenarios in $\Omega_A$. As described in Table 5.3, for each selected link there exist 10 levels of capacity degradation. Furthermore, we have also designed two reference state with different demand levels resulting in the uncongested situation and congested situation respectively. Thus all the simulation results will be presented based on these two reference state.

### 5.4.1 Uncongested reference state

In the uncongested reference situation, the network has little congestion with basic $TTT_0$ value of 3447 $veh \cdot hour$.

**Aggregated indicators**

In Table 5.5, results of two capacity reduction levels (-50% and -70% degradation respectively) are listed together with the UE assignment results of the scenario $\omega_0$.

**Table 5.5: Aggregated network performance measures in scenario sets $\Omega_A$**

| Scenario | $TTD$ | | $TTT$ | | $ETD$ | | $TNA$ | |
|---|---|---|---|---|---|---|---|---|
| | -50% | -70% | -50% | -70% | -50% | -70% | -50% | -70% |
| $\omega_0$ | 343004 | | 3447 | | 0 | | 17700 | |
| $\omega_1$ | 337074 | 334711 | 7342 | 8477 | 3895 | 5030 | 17700 | 17700 |
| $\omega_2$ | 336158 | 331154 | 4988 | 6969 | 1541 | 3522 | 17700 | 17699 |
| $\omega_3$ | 341511 | 338349 | 5943 | 7493 | 2496 | 4046 | 17699 | 17697 |
| $\omega_4$ | 345012 | 346031 | 3488 | 4241 | 41 | 794 | 17700 | 17700 |
| $\omega_5$ | 345390 | 346661 | 3770 | 4026 | 323 | 579 | 17700 | 17700 |

Firstly, the values of *TNA* in all listed incident scenarios are almost the same, which means the comparisons are unbiased due to the same amount of throughput for the statistics. Secondly, values of *TTD* in all the scenarios are close because of the similar lengths of the paths, especially for the paths of OD (O1,D1) with the most traffic. Incidents on motorway links result in less values of *TTD* because some traffic shifts to the shorter path (*Path 2*) through the town center from *Path 1*. Thirdly, the *TTT* value demonstrates the congestion level of the network. Degradation of motorway links, such as link 3 ($\omega_1$), link 4 ($\omega_2$), and link 5 ($\omega_3$) lead to very high travel times (delays) which means the network performance is remarkably deteriorated. Moreover, the impact of capacity reductions on urban links link 7 ($\omega_4$) and link 8 ($\omega_5$) cannot be neglected. These two links function as off-ramps, which means that their degradation will directly and immediately influence their upstream motorway links. From this point of view, degradation of off-ramps in a road network should also be avoided.

### Time-dependent indicators

In Figure 5.3, changes in *NAS* and *NL* in each evaluation interval (100 seconds per interval) are illustrated for two capacity degradation levels (-70% and -50%). It is obvious that curves of $\omega_1$, $\omega_2$ and $\omega_3$ for both *NAS* and *NL* descend rapidly and remarkably after the incident starts (interval 37), and their *NAS* values still retain a lower value after the incident is removed from the network past interval 73.

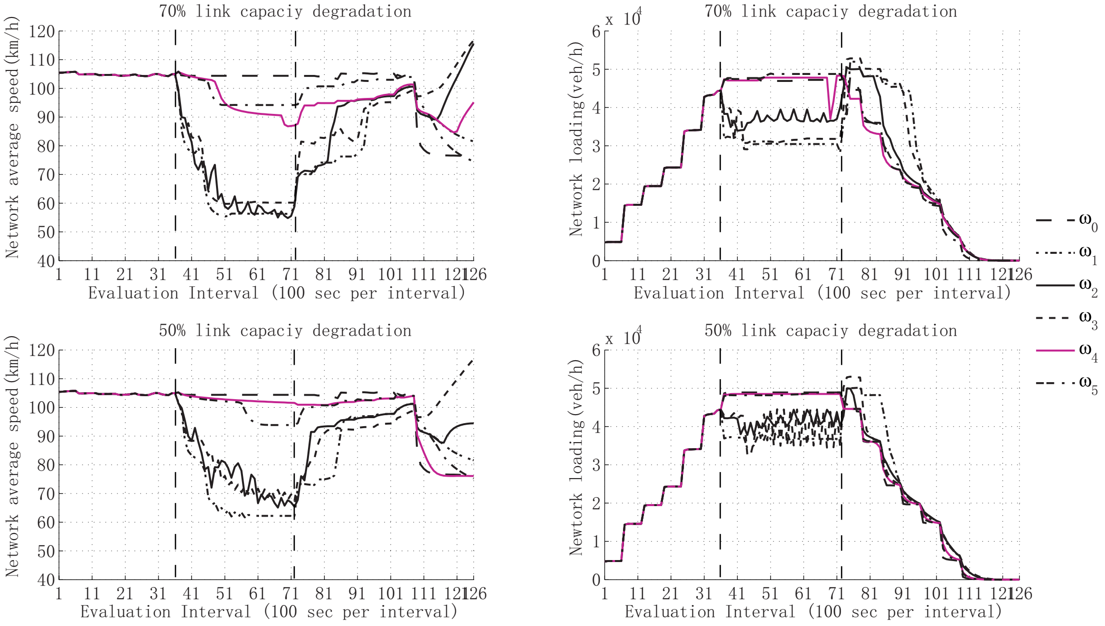

**Figure 5.3: Comparisons of *NAS* (left) and *NL* (right) between two levels of link capacity degradation: 70% degradation (up) and 50% degradation (down)**

Figure 5.4 shows the changes in the splitting rates among the generated paths of OD pair (O1,D1) for the cases with 70% and 50% capacity degradation in scenario set $\omega_1$ and $\omega_3$.. *Path 3* in Table 5.2, which is the unused alternative in $\omega_0$, has been generated and loaded in some scenarios, especially in $\omega_1$, $\omega_2$ and $\omega_3$ with motorway links degradation. It is important to discover that in $\omega_4$ and $\omega_7$, *Path 3* is also used. This means that the influence of the incidents on *Link 7* and *Link 10* is also remarkable in comparison with degradations on other urban links. The commonality between these two links is that they are both used in *Path 2* so that their degradation will become significant for motorway links due to spillback of the queues.

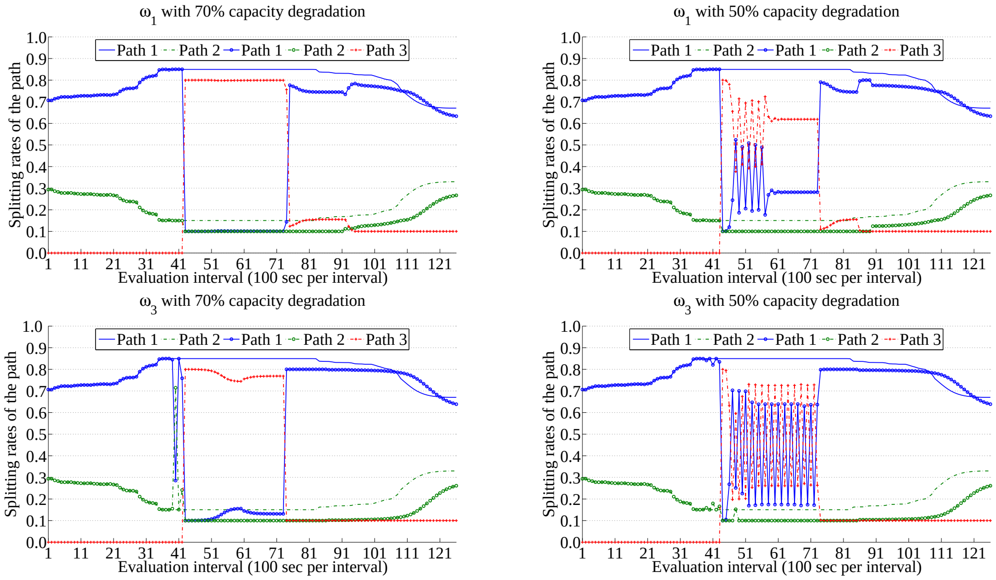

**Figure 5.4: Splitting rates among paths of (O1,D1) with 70% (left) and 50% (right) capacity reduction in scenario set $\omega_1$ (up) and $\omega_3$ (down)**

## 5.4.2 Congested reference state

For the congested reference situation, the network has a considerable amount of congestion with a high value of $TD_0$ (1311 $veh \cdot hour$). High demand between (O2,D1) makes link 5 the bottleneck in the network, with a capacity (8600 veh/h) less than the peak demand to Zone D1 (9000 veh/h). Therefore, due to the spillback, congestion mainly appears on its upstream links, including link 10, link 4, and link 7.

### Aggregated indicators

In Table 5.6, the values of the aggregated network performance indicators with two capacity reduction levels (-50% and -70%) are listed together with the results of the reference scenario $\omega_0$.

Comparable to the results in Table 5.5, this congested network also shows its ability to carry out the traffic demand after the incidents by giving close *TNA* values. Motorway links also prove their importance for the network performance with higher values of *ETD* in the scenarios where they are degraded. Besides these similarities, two different phenomena in the incident scenarios of urban links (i.e., $\omega_4$ and $\omega_5$) can be found as follows:

1. The value of *ETD* in $\omega_5$ is much smaller in the congested scenario. This is because in the equilibrium results of the normal situation, *Path 1* shares less

**Table 5.6: Indicators of aggregated network performance in scenario sets $\Omega_A$ with congested network**

| Scenario | *TTD* | | *TTT* | | *ETD* | | *TNA* | |
|---|---|---|---|---|---|---|---|---|
| | -50% | -70% | -50% | -70% | -50% | -70% | -50% | -70% |
| $\omega_0$ | 375381 | | 4765 | | 0 | | 20650 | |
| $\omega_1$ | 371260 | 368073 | 7369 | 8622 | 2604 | 3857 | 20650 | 20649 |
| $\omega_2$ | 368782 | 362537 | 6421 | 7482 | 1656 | 2717 | 20649 | 20649 |
| $\omega_3$ | 369297 | 366831 | 8732 | 9988 | 3977 | 5223 | 20645 | 20635 |
| $\omega_4$ | 378851 | 380727 | 6450 | 8006 | 1685 | 3241 | 20639 | 20636 |
| $\omega_5$ | 375437 | 375642 | 4894 | 4932 | 129 | 167 | 20649 | 20649 |

traffic from (O1,D1) when link 4 becomes congested, due to the spillback effects from the bottleneck link 5. Thus the degradation of *Link 8* has less effect on the major traffic in the road system;

2. The value of *ETD* in $\omega_4$, in which the off-ramp link 7 is degraded, is comparable with that of $\omega_1$, $\omega_2$ and $\omega_3$ with degraded motorway links. This means that for a congested road network, some off-ramps becomes as critical as the motorway links for maintaining the service level of the network.

In order to explain this phenomena, changes in the assignment results and corresponding time-dependent performance must be analyzed. This can be given in the following sections.

### Time-dependent indicators

The changes of *NAS* and *NL* for all capacity-related scenario set with two capacity degradation levels (-70% and -50%) are illustrated in Figure 5.5.

As shown in Figure 5.5, it is clear that because of the higher demand, the curve of *NAS* for the reference scenario $\omega_0$ drops already within the peak and cooling period. Thus, in most of the incident scenarios, the decrease of *NAS* is stronger and longer than that from the uncongested reference situation because of the superpose of both effects from the incident and high demand. The exception appears for the curve of the scenario set $\omega_1$, in which link 3 was degraded. This is an interesting phenomenon that might be caused by the following reasons:

- Link 3 is the upstream link of the bottleneck (link 5). When it is degraded, its outflow, which is the inflow of the bottleneck, will be restricted. In fact, the bottleneck ‘shifted’ towards upstream, so that the traffic that departs from other zones (Zone O2) and uses link 5 will face no congestion;

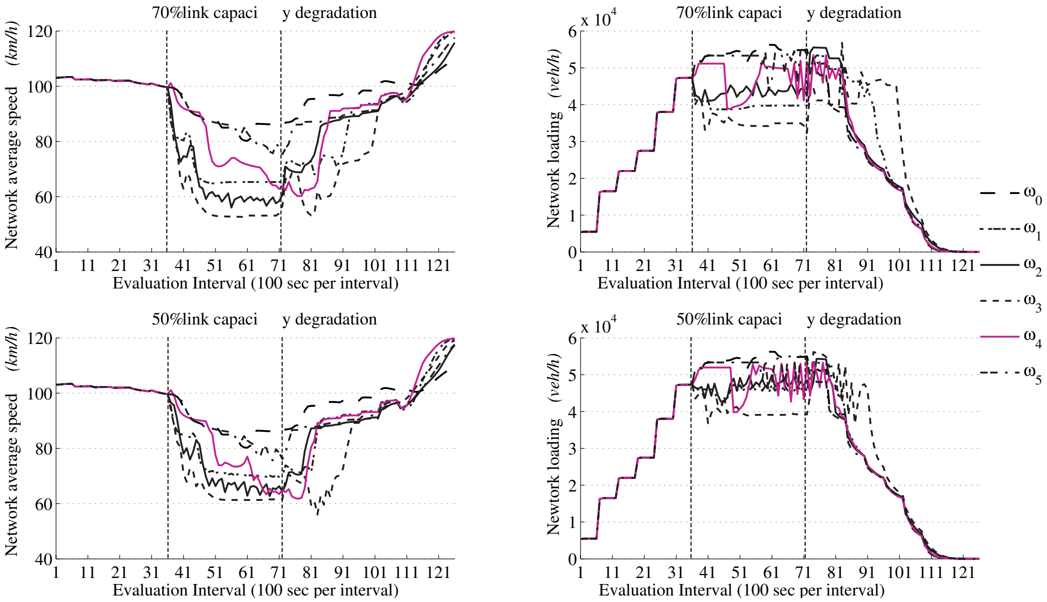

**Figure 5.5: Comparisons of *NAS* (left) and *NL* (right) between two levels of link capacity degradation: 70% degradation (up) and 50% degradation (down)**

- Although a large amount of the traffic that uses link 3 was delayed due to the capacity degradation, the amount of the traffic whose condition was improved is also remarkable in this congested case. Then a better performance of the whole road network can emerge.

In Figure 5.6, the assignment results in scenario sets $\omega_1$ and $\omega_3$ with -50% and -70% capacity degradation will be shown for the comparisons with Figure 5.4.

Figure 5.6 shows that *Path 3* has been generated and loaded earlier and for a longer period than what was illustrated in Figure 5.4. But its generation time and lasting length in all the scenarios are quite different. Generally, the earlier *Path 3* is generated and the longer *Path 3* is used in an incident scenario, the more negative impacts the incident makes. In $\omega_3$ with link 5 being degraded, network performance was damaged the most, and it took the longest time for the network to recover after the incident. This is a reasonable result because link 5 is originally a bottleneck of the system for its normal daily situation. Besides, it is also interesting to notice that sometimes the route assignment results display a sort of ‘oscillation’, and this ‘unstable’ phenomenon becomes more visible in the scenarios of a moderate capacity degradation, for example when the capacity degraded 50%. Such oscillation in the assignment results is caused by the discretization process for the evaluation and reassigning in the en-route assignment models.

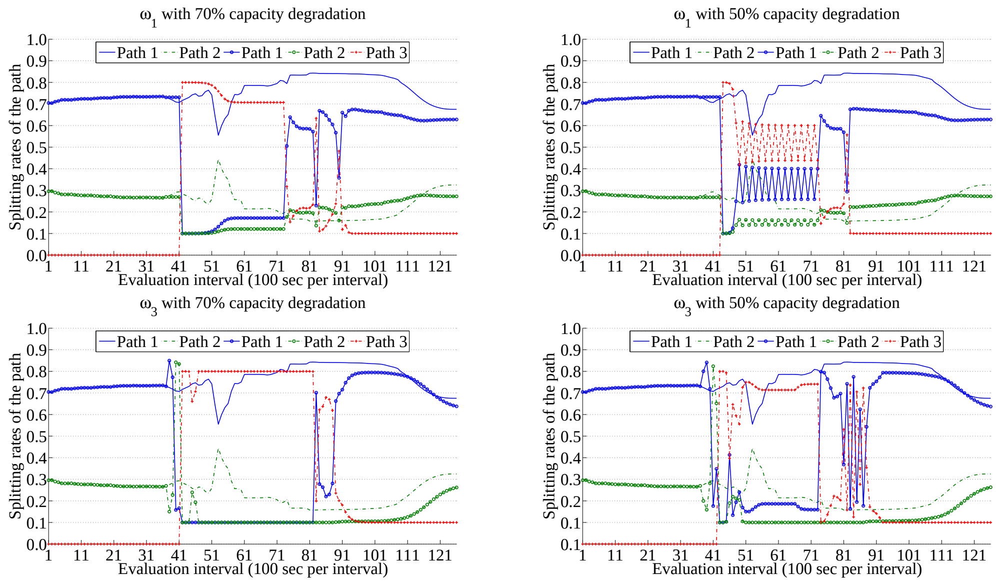

**Figure 5.6:** **Splitting rates among paths of (O1,D1) with 70% (left) and 50% (right) capacity reduction in scenario set $\omega_1$ (up) and $\omega_3$ (down)**

## 5.5 Demand Increasing Scenarios

Besides link capacity reduction, a short-term demand increase between a specific OD pair is another major disturbance road networks. This can often be seen during large social events, which temporarily create and/or attract extra demand. The results presented in this section are from scenario set $\Omega_D$ rooted from demand increase listed in Table 5.3, including three scenarios $\omega_6$, $\omega_7$ and $\omega_8$, each for one of the three OD pairs. Three demand increase levels are tested, which are identified as 300, 600 and 900. These values are also the absolute number of extra trips for the OD pair during the peak period between interval 37 and 72.

### 5.5.1 Uncongested reference state

It has already been established that, in the uncongested reference scenario, most of the links in the network are unsaturated because that very little congestion exists.

#### Aggregated indicators

Since demand are different in each scenarios, the absolute values of the aggregated performance indicators are then less important than their relative changes. Thus, in Figure 5.7, only the results of the incident scenarios are presented.

Theoretically, demand increase in the road network should always result in the increase of the values of the aggregated indicators for network performance. But in Figure 5.7,

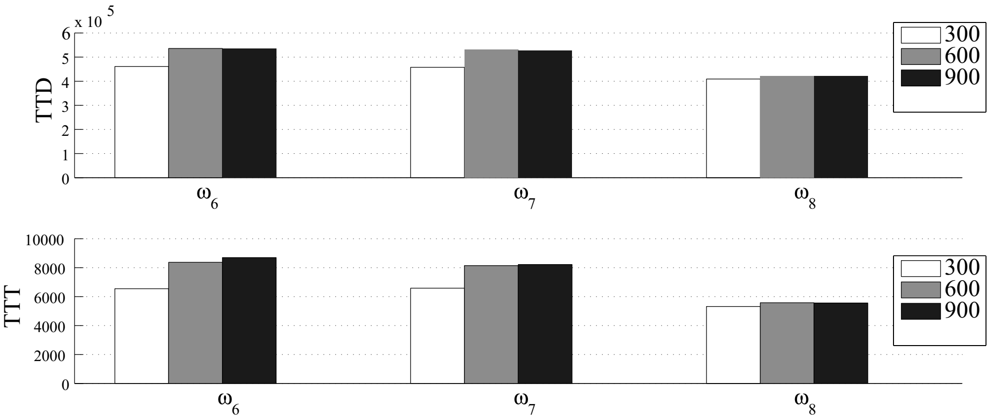

**Figure 5.7: Indicators for aggregated performance in the scenarios of $\Omega_D$ based on uncongested reference status**

after the increase of demand reached a certain amount, values of the aggregated indicators did not increase. This means that the whole system reached its maximum performance level for the simulation period. Extra demand for (O1,D1) ($\omega_6$) and (O1,D2) ($\omega_7$) directly influence the motorway links, so they have stronger impacts on the network performance than the same extra demand for (O2,D1) ($\omega_{10}$). This can be proved by the results of the following time-dependent performance indicators.

## Time-dependent indicators

In Figure 5.8, changes in *NAS* and *NL* in all demand increase scenarios are illustrated.

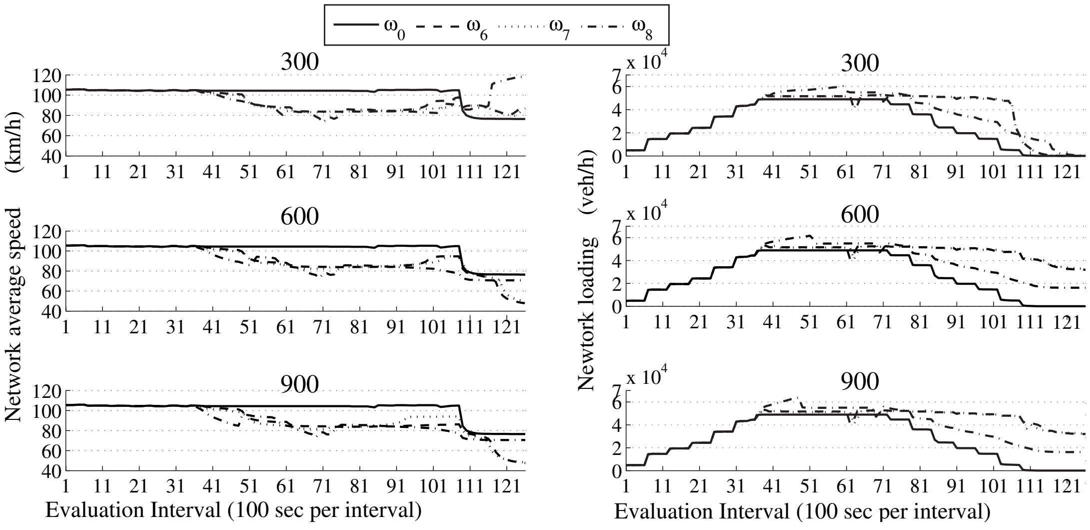

**Figure 5.8: Changes in *NAS* and *NL* of $\Omega_D$**

The values of *NAS* do not change obviously during the incident for different cases, except for their continued lower values during the clearing period of the simulation in the scenarios with higher extra demand. *NL* curves for $\omega_8$ and $\omega_9$ remain at high values for a long period after the incident. Both phenomena elaborate that the extra demand for (O1,D1) and (O1,D2) made the network very congested from the diverging point at the end of link 2. So the queues in the road network are mainly on the common link(s) of all the paths for OD pair (O1,D1), such as link 1 and 2. In such scenarios, the alternative path (*Path 3*) will not be attractive, which can be proved by the assignment results shown in Figure 5.9.

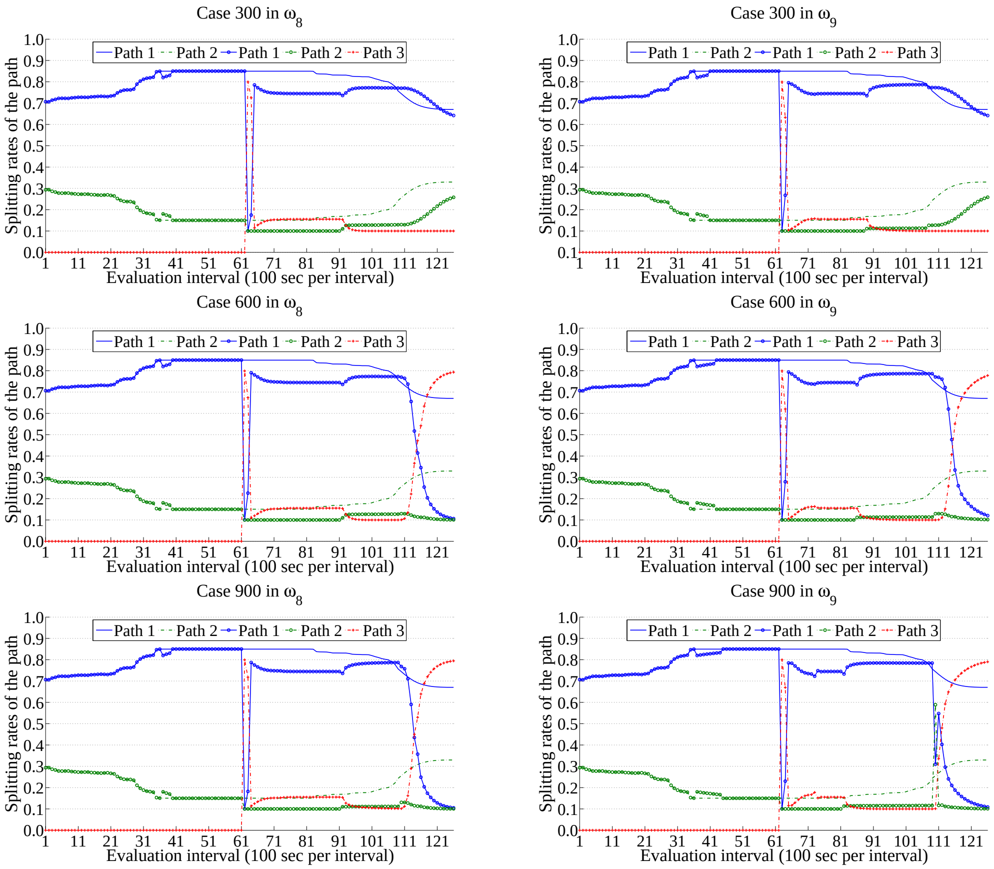

**Figure 5.9: Changes of splitting rates among the paths for (O1,D1) in scenarios $\omega_6$(left) and $\omega_7$(right)**

This result gives us an impression that the extra traffic to leave the motorway makes big trouble to the whole network because it directly blocks the traffic on the major motorway link of its upstream due to the spillback effects.

### 5.5.2 Congested reference state

In the congested reference scenario, congestion is found mainly on *Link 10*, *Link 4*, *Link 7*, and even *Link 2* due to the spill back of queues. In the incident scenarios based on the congested reference state, the same extra demand values are used as those based on the uncongested reference state.

### Aggregated indicators

The results of three indicators for the aggregated network performance are illustrated In Figure 5.10. Again, the results of $\omega_0$ are excluded.

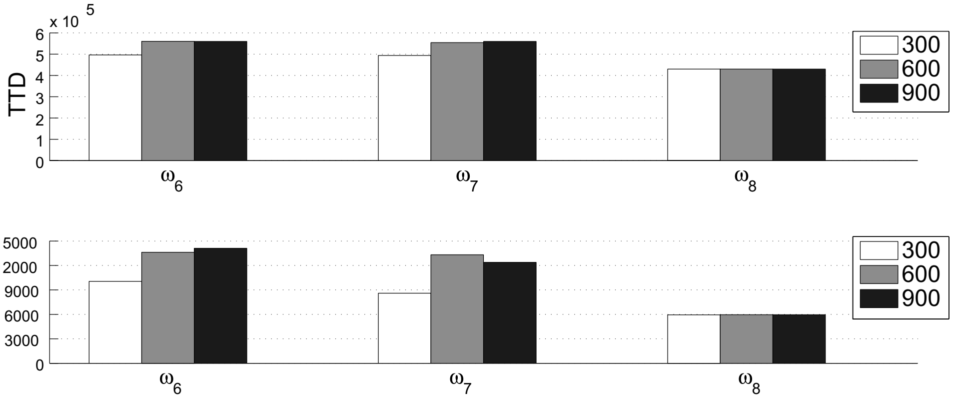

**Figure 5.10: Indicators for aggregated performance in the scenarios of $\Omega_D$ based on congested reference state**

Similar relationship in the results of all the incident scenarios can be found here as for the scenarios based on the uncongested reference state. But obviously, the values of these indicators are much higher because of the more traffic demand in these scenarios. This means that the more congested a network originally is, the more serious impact the extra demand causes. From the following figures of the time-dependent performance indicators, this phenomenon will be better understood.

### Time-dependent indicators

Changes in *NAS* and *NL* in all demand increase scenarios are illustrated In Figure 5.11.

In all scenarios with different extra demand, the reduction values of *NL* are almost the same, but the duration of the reduction period becomes extremely long when the amount of extra demand is equal to or larger than 600. This value is generally determined by the spare capacity of the entrance link(s) for the origin zones. If the total demand exceeds the total entrance capacity for the origin, traffic cannot be dispersed fluently as the predetermined schedule, and they will be detained in the origin zones. It is also possible that extra demand might cause severe congestion in the network and the queues spill back to the origin zones to block the traffic entering the network.

When the splitting rates of the paths for OD pair (O1,D1) were analyzed in Figure 5.12, we found that in scenario $\omega_8$, *Path 4* (Table 5.2) has been generated for the first time in our studies. This is due to the fact that extra demand from O2 to D1 caused serious congestion on both *Link 7* and *Link 4*. Thus for a short period *Path 4* that uses *Link 3* and *Link 10* becomes preferable. When the usage of *Path 4* creates new congestion on *Link 3* and continuously deteriorates the network performance, *Path 3* is then used.

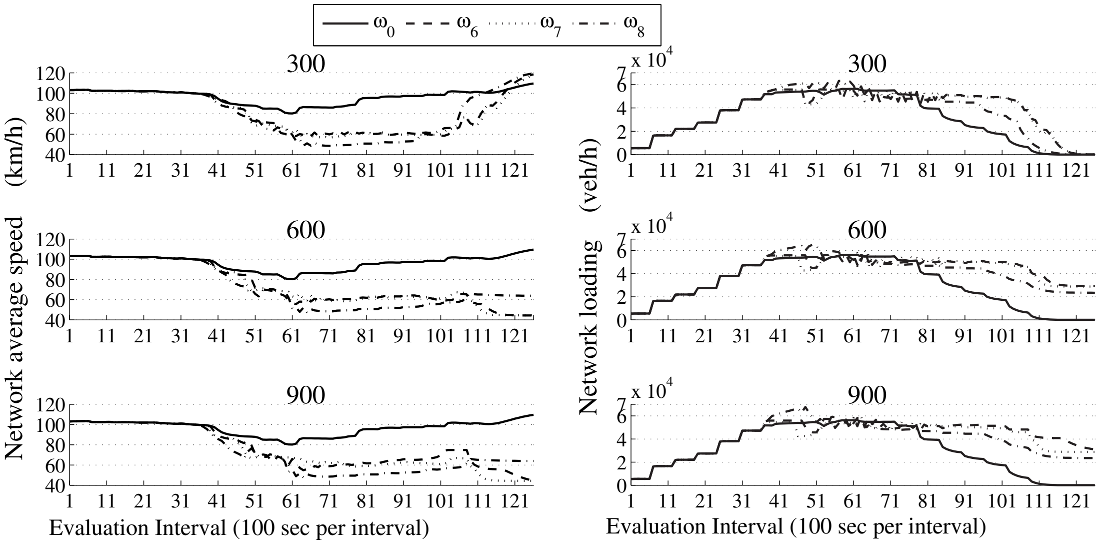

**Figure 5.11: Changes in *NAS* and *NL* of $\Omega_D$**

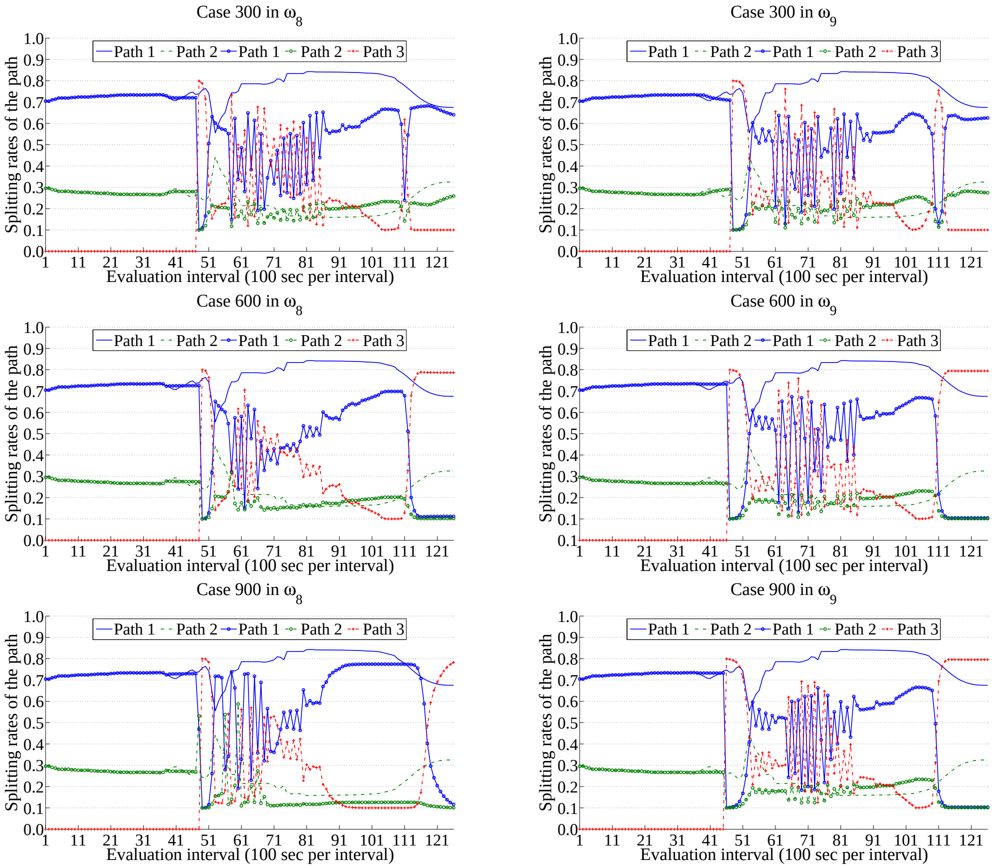

**Figure 5.12: Changes of splitting rates among the paths for (O1,D1) in scenario set $\omega_8$(left) and $\omega_9$(right)**

## 5.6 Discussion and Conclusion

In this chapter, the framework proposed in Chapter 4 is implemented for the robustness analysis of a small-sized road network with a hierarchical structure as shown in Figure

5.1. The main objective of this case study is to test the methodology and method based on this framework for the road network robustness studies. To do this, different types and different levels of disturbances to the network are designed as incident scenarios. Changes in the network performance and changes in the traffic assignment results in these scenarios are compared with the normal situation for the robustness studies. The network is designed with two levels of basic demand for the sake of studying the influence of the initial status (congested or not) of a road network to its robustness against disturbances. Two basic types of disturbances (link capacity degradation and demand increase) are introduced to the network. Besides a reference scenario created by a user equilibrium model, eight incident scenarios are designed, in which five are with one link capacity degradation and three are with one OD pair demand increase. For each incident scenario, different levels of the disturbances are tested. After carrying out those thorough studies, some conclusions of the quality of the proposed framework for road network robustness analysis can be drawn as follows:

- The framework proves its ability for the systematic and comprehensive analysis of road network robustness against disturbances by implementing two DTA approaches. An (dynamic) equilibrium status is more persuasive and reliable in describing the daily traffic situation for the period of interest for the studied road network, and an en-route traffic assignment model is logically more suitable in representing (route) choice behavior of travelers when they face unfamiliar or unexpected situations in the network;

- In all the incident scenarios, the assignment results after the incident are different from that of the reference state. In some scenarios, new paths are found and used by certain percentage of the demand, which means that our newly developed en-route assignment model (MARPLE-e) basically function as we expected, and our proposed framework for the analysis of the road network robustness is feasible. Analyzing the assignment results after the incidents, we can draw the conclusion that MARPLE-e model with the parameter settings from the reference literature can get logical and rational assignment results. But still, the calibration and validation process with the real network-level traffic data for the incident scenarios is necessary in the future;

- Aggregated performance indicator *TTD* did not give clear information in the analysis of this small network because it depends highly on the differences in the lengths of the paths. If the differences are not obvious, *TTD* loses its meaning. It might be useful for large networks because the lengths of alternative paths for abnormal situations are normally much longer than those of the paths for the normal situation. *TTT* is a good indicator for reflecting the congestion levels of the network if the amount of traffic for the statistics are equal in all the scenarios;

- In order to better understand how the road network performs after the incidents, time-dependent indicators such as *NAS* and *NL* are more essential and important.

But still, analyzing the en-route assignment results, i.e. splitting rates among the paths for OD pairs is the most fundamental way to explain the outcome of all the scenarios.

Besides the knowledge about the proposed framework and the DTA models currently used, through the studies of the tested network, some general understandings about the robustness of road networks with the hierarchical structure can be concluded as follows:

1. Degradations of the motorway links have severe negative effects on the network performance. This is because of the fact that the motorway carries a great part of the traffic in the network and it is often heavily loaded. Furthermore, degradations of off-ramp links also have significant impacts on network performance, especially for an off-ramp that is the first off-ramp and also carries most of the traffic leaving the motorway, such as *Link 7*. For other types of urban links, their capacity degradations either have little influences on the motorway flows, or it takes a long time for the motorway traffic to be influenced by the spillback. This gives us a concept that the capacity of the important off-ramps is also critical for the whole network;

2. Compared with link capacity degradations, demand increasing incidents show complex sequences to the network performance. For a network which normally has little congestion, the increase of the demand has mild influence. But for a network that is originally quite congested, introducing extra demand during the peak period has significant negative impact on the whole network, such as the very low average speed. Generally speaking, extra demand, no matter leaving or entering the motorway, causes visible reductions in the network speed;

3. Redundant capacities, such as *Link 11* in the network, play an important roles in mitigating the congestion in the network, so as to reduce the total delay.

Thus, through such a thorough scenario-based study, road network robustness has been for the first time systematically analyzed by combining both SUE and en-route assignment approaches. From theoretical point of view, this combination of different DTA approaches together with other traffic models is suitable for studying transportation systems on the network level. From practical point of view, the results presented in this chapter clearly demonstrate the different impact on the network performance of the same level incidents on different locations (links) in the road network. So it is easy for road authorities and managers to find critical positions (links) in the road network. It is also valuable for them to make suited network-level management schemes (e.g. route guidance, speed limit, etc.) for the corresponding incident scenarios based on the simulation results.

In reality, road networks are more complex than the small network tested in this chapter, which means that more possible paths are available for travelers to choose en-route.

So some findings in the simple network might be not obvious any more, and some new phenomena might be found in large and complex networks. In the next chapter, studies of a real-sized hybrid network will be presented.

# 6

# Case Study with a Large Network

Chapter 5 presented the robustness analysis of a small and simple hypothetical road network. The results from this case study reveal the applicability of the framework and the face validity of the adopted DTA models (MARPLE and MARPLE-e) for network robustness analysis. Furthermore, some general remarks on the robustness of the tested small road network are also drawn following the studies of all the incident scenarios. However, all the conclusions in Chapter 5 are derived from the analysis of the small and simple network, which only contains very few numbers of OD pairs and possible paths. For real-sized and complex road networks, more complicated interactions might exist among the traffic from many more OD pairs. More redundant capacities on lower level roads and more congestion on higher level roads might exist in the daily traffic situation of real road networks. Therefore the conclusions from Chapter 5 might not be generic or no longer applicable, and some new and more important phenomena might also appear for real road networks. For instance, the affected period and area of an incident might be longer and wider because the traffic from more OD pairs would be influenced by the incidents. In this chapter, a much bigger and more complex network is chosen to test its robustness against the exceptional disturbances.

Similar to the structure of Chapter 5, this chapter is also arranged according to the analysis of different incident scenarios. The description of the network is given in Section 6.1. Section 6.2 describes a pre-selection and a filtering process for picking out possible critical links and OD pairs for the design of incident scenarios. Such processes are based on the UE assignment results of the tested road network. In Section 6.3 the details of the incident scenarios are described, which are also categorized as capacity-based incidents and demand-based incidents. In Section 6.4, two new indicators are introduced that are proved more suitable for the robustness analysis of large road networks. The results of capacity degradation scenarios are presented and analyzed in Section 6.5, and the results of OD demand increase scenarios are presented in Section 6.6. Finally Section 6.7 summarizes this chapter.

## 6.1 A10-West Network

The A10 motorway is the ring road around Amsterdam, the capital city of The Netherlands. The selected part for the case study is the A10-west region in the year 2000 as shown in Figure 6.1. It is the map in the year 2006 including several important surrounding destinations. This network is a typical example with hierarchical structure, which consists of motorway (A4 and A10), major city road (S101, S102, S103, S106 . . . ), and large numbers of urban links. This makes the network much more complex than the road network tested in Chapter 5.

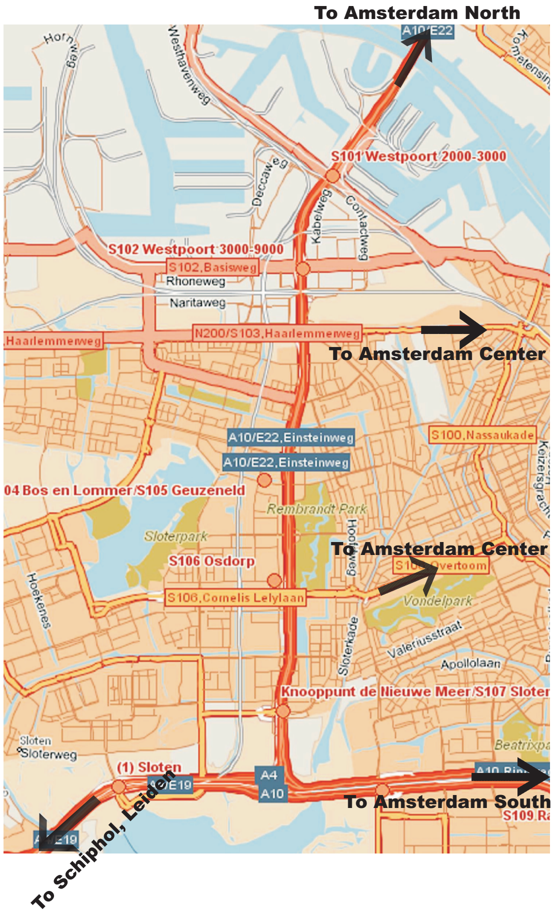

**Figure 6.1: Map of A10-West road network in 2006 (Source: www.map24.com)**

This road network and OD demand for the analysis have been calibrated with the MARPLE model by (Taale et al., 2004) with the SUE assignment approach. Thus, for consistency, all the values and configuration settings will be used in our robustness analysis of the incident scenarios. Detailed information is given in the following sections.

### 6.1.1 Link Characteristics

The modeled road network in MARPLE (Figure 6.2) is in great detail, which contains 1439 one-way links with the total length of 288.16 *km*. The general characteristics and the total lengths of each type of links are summarized in Table 6.1.

**Table 6.1: Link allocations of A10-West network**

| Link Type | Amount | Total Length (*km*) | Desired Speed (*km/h*) |
|---|---|---|---|
| Motorway Link | 62 | 33.84 | 100 |
| Urban Arterial | 91 | 14.85 | 80 |
| Urban Link | 1286 | 239.47 | 30 or 50 |

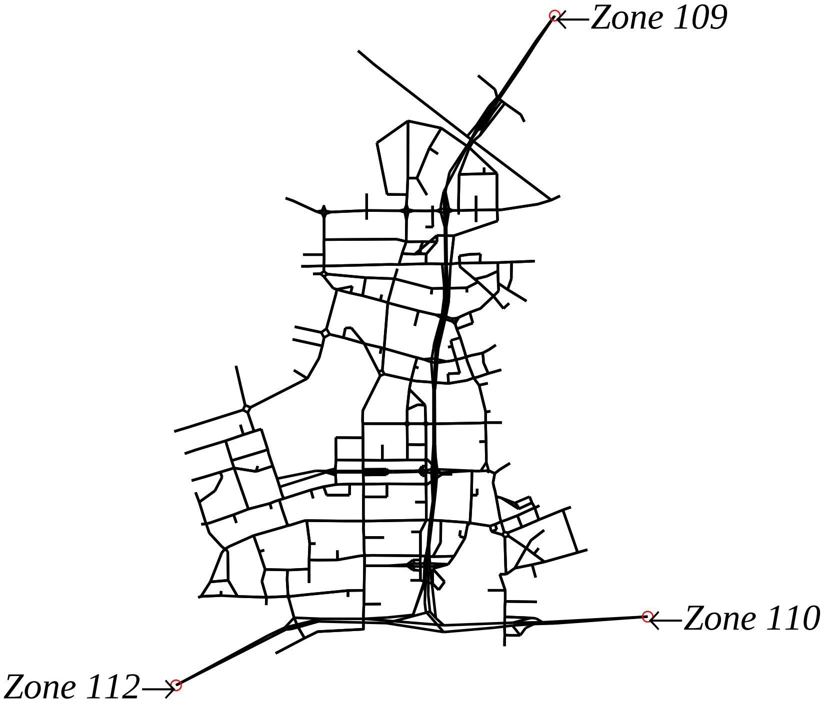

**Figure 6.2: Modeled A10-West road network in MARPLE**

In this road network, the amount and the total length of urban links dominate. This is seldom found in other road network research. Thus, compared with the small and simple network tested in Chapter 5, or road networks mainly composed of motorways modeled in most other research, travelers could have many more alternatives for their route choice if they feel that the original or/and the preferable paths become ‘unacceptable’ or ‘inconvenient’ with unexpected exceptional congestion. However, such changes in the path choice only happen when travelers have a good insight into the available alternatives according to their experience or/and according to the available information. Such information is normally supplied by the traffic management system or by the third party, such as a navigation system.

### 6.1.2 Information of OD demand and paths

This network has 112 zones including 100 origins and 100 destinations. 4618 OD pairs have the non-zero traffic demand for the morning peak of the year 2000. For the whole period, the total amount of traffic demand is about 124,670 vehicles. In the original study on this network, this peak period has 9 demand intervals with 15 minutes each. The original demand profile for these 9 demand intervals is shown in Figure 6.3.

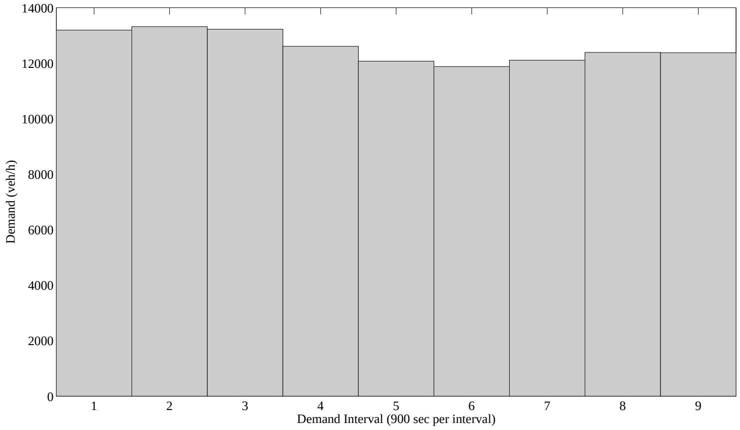

**Figure 6.3: Demand Profile of A10-West Network**

Several characteristics of the demand for this network should be stressed as follows:

- First, since the network has been studied and calibrated in other studies, we try to keep the original data as much as possible. This is the reason for no extra ‘warming-up’ period in the demand profile. But we added a ‘clearing’ period of 15 minutes without traffic demand at the end of the simulation, so the length of the whole simulation period is 2.5 hours. Furthermore, we treat the first 15 minutes as the ‘warming-up’ period for the network to be loaded. The network loading results in Figure 6.9 show that such treatment is logical because the total number of the traffic in the whole network become stable after about 5 minutes.
- Second, demand interval with the length of 15 minutes is considered too long for the travelers to re-estimate the network performance and update their route choice. For instance, the online traffic information service supplied by ANWB

(www.anwb.nl) refresh the information about every 5 minutes. So in the DTA models for the robustness studies, the new interval with the length of 5 minutes each is adopted as the frequency for the path updating and assignment updating procedure. Such interval is named as the *evaluation interval*. Thus, for each demand interval of 15 minutes long, there will be three evaluation intervals. For simplicity, each evaluation interval shares 1/3 demand of the demand interval that it belongs to. Therefore, in the following case studies of this network, totally 30 evaluation intervals are used for the periodical performance evaluation and traffic assignment. In the following context, 'interval' will only stand for evaluation interval.

- In this network, three zones are located on the motorway, which are marked as *Zone 109*, *Zone 110* and *Zone 112* in Figure 6.2. These three zones represent all the external origins and destinations that generate or attract traffic demand occupying space within the studied area of the network. Besides them, the remaining 99 zones are all located inside the urban area. For the whole simulation period, about 13% of the total demand (around 16,230 vehicles) travel between the motorway zones. Normally this traffic only uses the motorway. The other 22% of the traffic demand has either its origin or destination as one of the three motorway zones, which means that it must use an on-ramp or an off-ramp to enter or leave the motorway. The rest and the majority of the traffic (about 65%) travels between two zones that are both located in the urban area to form the so-called *intracity traffic*. However, intracity traffic does not always use urban roads only. As a matter of fact, much intracity traffic uses the motorway system as part of its path(s), which means that transition of the traffic between motorway and urban roads is popular in this road network. Thus, the motorway takes a role as traffic 'sewer' and the ramps play a very important role in deciding the performance of the network.

As the result of the SUE assignment approach of MARPLE, 12,272 paths for all the OD pairs have been generated after 100 random generation iterations with the constraint of maximum 4 paths for each OD pair. So the average number of paths for each OD pair is about 2.66.

## 6.2 Pre-selecting and filtering the possible critical links and OD pairs

In this big road network with the hierarchical structure, most of the links are urban links with low capacity and a small amount of flows. If all the links are tested for incident scenarios as what has been done in Chapter 5, the computational time will be enormous. In fact, incident scenarios for some links are unnecessary because of the little impact according to the general knowledge of the traffic. For instance, the capacity degradation of short links with little traffic flow or the demand increase of trivial OD pairs with little traffic demand can be definitely neglected. So it is unnecessary to study all the possible incident scenarios for each link and for each OD pair. In this case study, a pre-selection process will first be carried out to search for the most likely critical links and OD pairs, which means that the capacity degradation on these links or the demand increase of these OD pairs should result in the most serious negative consequences to the network. Such negative consequences mainly present very long queues in the network in both length and time, sometimes even gridlock. After the pre-selection process, a filtering process will also be applied to check whether the selected links and OD pairs are reasonable. As discussed in Chapter 5, one of the criteria for designing the incident scenarios is that traffic should be able to enter the network as scheduled. So the filtering process is implemented mainly to guarantee this requirement. In the following contents of this section, the pre-selection process and the filtering process will be described in detail.

### 6.2.1 Pre-selection process

Several criteria can be used for pre-selecting latent critical links, which are often implemented in the studies of designing improvement schemes for road networks, such as (Zhang & Levinson, 2004a). They used volume dependent and capacity dependent criteria to determine network failure scenarios. Volume dependent criteria assumes that a link carrying more traffic is more likely to breakdown than its low-volume peers and the failure rate is proportional to traffic volume. Capacity dependent criteria assumes that links with the highest capacity are the most important links and they can easily be destroyed by deliberate attacks. But according to what we found through the case study in Chapter 5, not only the links with high volume and high capacity (which are mainly motorway links) are critical, but also some connection links between different types of links with less capacity (i.e. off-ramps) are critical for the network. These links normally carry the traffic from high-volume links to low-volume links so that their degradation will immediately influence the high-volumes links by spillback. Thus, using one single criterion to determine the critical links might not be sufficient for a large road network with hierarchical structure. In this research work, we propose using the following steps and criteria to search for possible critical links candidates.

Step 1: A stochastic user equilibrium (SUE) assignment for the whole network under normal situations is firstly carried out with MARPLE. Through this SUE approach, network performance is simulated and some detailed statistics are calculated, including path information and time-dependent link volumes;

Step 2: All the links are ranked from high to low according to their maximum volume-capacity ratio (*V/C*) values. The higher *V/C* ratio a link has, the busier this link is, and its capacity degradation should have more serious impact. The top 100 busiest links are selected and they are prime candidates for the selection of the critical links. An important remark about the maximum *V/C* values of urban links and off-ramps is that we can only use their designed capacity as *C*. The influences of the traffic controls on the real throughput capacity of a link is not considered because the information about the control schemes is lacking. So the *V/C* values of the links with control at the end are underestimated. But as what we find in the results of the incident scenarios, this simplification didn't influence the selection of the critical links too much because basically the importance of the urban links cannot be mentioned in the same breath as motorway links and off-ramps;

Step 3: All the links are ranked from high to low according to their *commonality*, which is calculated by counting the frequency of a link being used in the total 12,272 paths generated in the SUE approach. The higher commonality a link has, the larger the number of OD pairs that will be influenced when the link is degraded, so that more changes in en-route path choices might be made;

Step 4: In order to reduce the influence of using the underestimated *V/C* values for off-ramps in Step 2, we use this final step specially for off-ramps. From the results of Chapter 5, we know that off-ramps also play critical roles in maintaining network performance, due mainly to the spillback effects. So in the A10-West network, all 16 off-ramps are identified and they are also selected as candidates.

In Appendix D, three lists of candidates derived from three steps (Step 2 to Step 4) and figures showing their positions in the network can be found.

Furthermore, important OD pairs that might have a large influence on the network performance due to their demand increase are selected based on the results of critical links. Basically, for each critical link, several possible critical OD pairs are chosen for the design of demand increase scenarios.

### 6.2.2 Filtering process

After the pre-selection process, three lists of candidates for possible critical links are generated, those are based respectively on the maximum link *V/C* ratio, link commonality and link type. It is interesting to notice that within the top 100 most frequently used links, 29 are also in the top 100 busiest links; and 5 out of 16 off-ramps are also within the top 100 busiest links. Besides the possible repetitions among these three lists of links, some other filtering criteria are also necessary to avoid that some unnecessary incident scenarios will be designed. Such unnecessary incident scenarios include incidents on the entrance link(s) of original zones that can only block the entering of traffic, and also the incidents on some unimportant links that can only influence a small amount of traffic. In this section, three criteria are used to filter the candidate links in order to make the final list of links for designing capacity degradation scenarios, as well as some OD pairs for designing demand increase scenarios.

- The value of *V/C* ratio must be larger than or equal to 0.70 so that the capacity degradation of the chosen links will make observable changes to the network. But this value is just an assumed value, and it needs to be calibrated through this study to find a suitable value as the threshold for preliminarily searching for the critical links of a network;
- If a link is the entrance link or the only and inevitable downstream link of an entrance link, it will not be considered for designing an incident scenario because its degradation will only influence the input of the traffic. Moreover, attention must be give to the links that are the only exiting links for destination zones. Generally, degradation of such links would generate more delays than other links because traffic that wants to exit through them cannot be rerouted;
- When possible critical links are selected, we will choose several busy and frequently used links for the bases of demand increase scenarios. For each link, two or three OD pairs with highest contributions to the link flow are selected. For these OD pairs, the same amount of extra demand will be introduced for the comparisons of their impact on the network.

In the next two sections, the results of the pre-selection and filtering processes will be introduced for links and OD pairs separately.

### 6.2.3 Selected links for capacity degradation scenarios

44 links for the design of capacity degradation scenarios are finally selected. A list of these links can be found in Appendix D. Positions of these links are illustrated in Figure 6.4. Within these 44 links, there are 26 motorway links, 3 off-ramps, 4 on-ramps, and 11 urban links. Some more detailed information about these links are given as follows.

- More than half of the busiest links are motorway links because motorway are mostly saturated during peak period in reality. Most of the 26 motorway links are the exit links to those three motorway zones (*Zone 109*, *Zone 110*, and *Zone 112*) because all the traffic that aim to enter these zones must use these links;
- 1/4 of the selected links are urban links, and 8 of them are from two roundabouts in the network. This is also reasonable because roundabouts, as well as other types of junctions, are basically the busiest in the urban area and most of the time are the sources of the congestion;
- On-ramps and off-ramps are considered as transition links between motorway and urban roads. From the predominant amount of motorway links and the ramps in the final selected links, a primary conclusion can be drawn that most of the possibly critical links of a hybrid road network are motorway or motorway-related links.

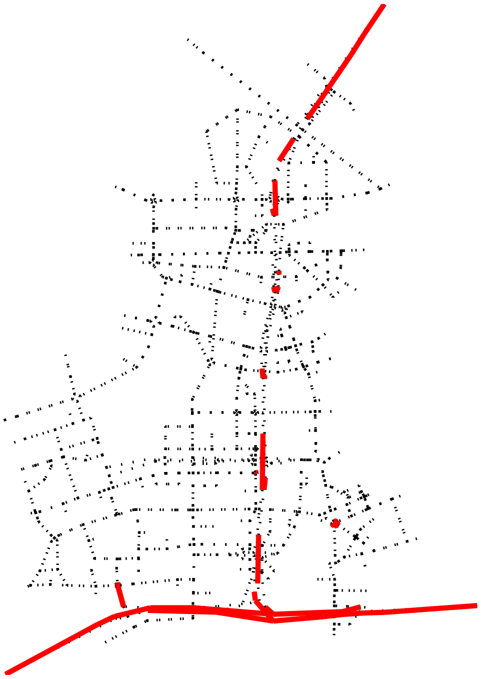

**Figure 6.4: Positions of the selected links in A10-West network for capacity degradation scenarios**

### 6.2.4 Selected OD pairs for demand increasing scenarios

After obtaining the list of the possibly critical links, several of them will be chosen to search for the OD pairs for the demand increasing scenarios. Four different types of links from Table D.4 in Appendix D are selected. For each link, its flow composition is analyzed by sorting the source OD pairs. Two OD pairs that have the highest contributions to the link flow and have different origin zones are then chosen. Information on the chosen links and OD pairs are listed and illustrated in Table 6.2 and Figure 6.5.

**Table 6.2: Selected links and related OD pairs for demand increase scenarios in A10-West network**

| Link ID | Type | *V/C* | Frequency | OD pair 1 | OD pair 2 |
|---|---|---|---|---|---|
| 34 | motorway | 0.76 | 527 | (110,112) | (106,112) |
| 19 | off-ramp | 0.95 | 811 | (110,1737) | (112,1741) |
| 12 | on-ramp | 0.95 | 713 | (89,112) | (85,110) |
| 22 | urban | 0.87 | 507 | (112,1743) | (110,1743) |

It is important to discover that the chosen OD pairs in Table 6.2 have either their origins or destinations on the motorway zones, no matter what type of link it is. Although

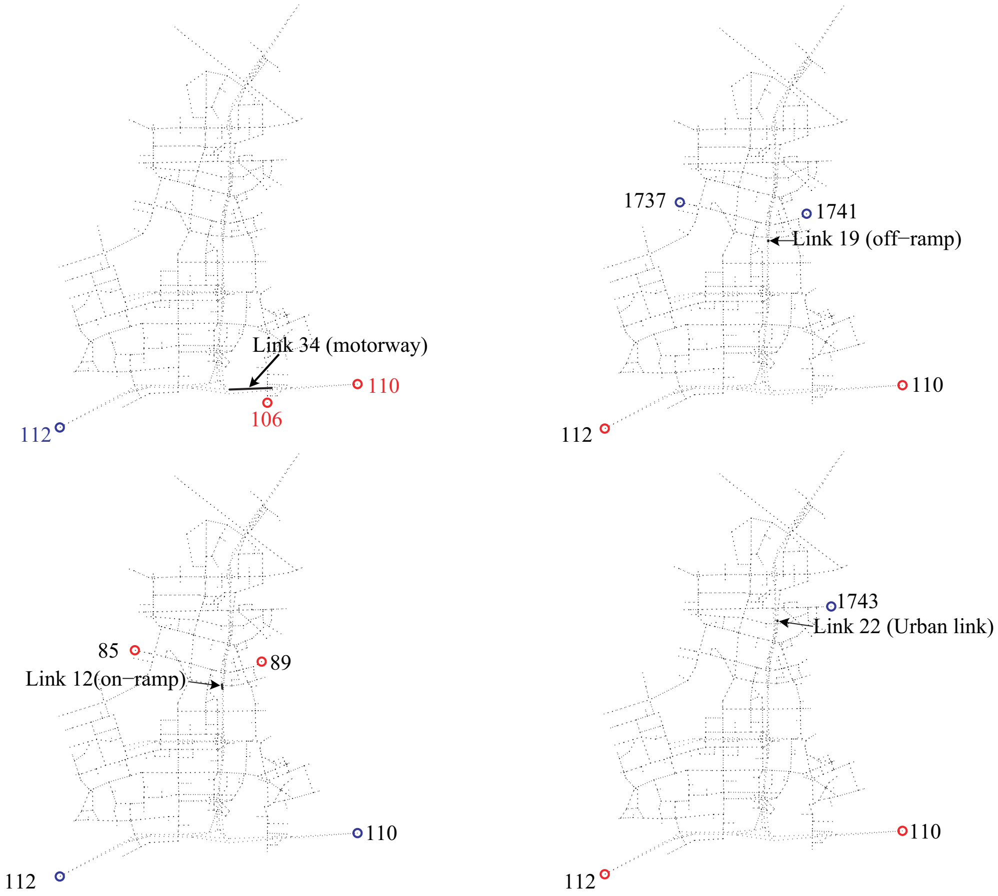

**Figure 6.5: Position of the selected links and OD pairs for demand increasing scenarios**

traffic between urban zones makes up the majority of the total demand (about 65%), critical OD pairs, whose demand increase will probably cause big congestion problems, are still related to those motorway zones because such OD pairs have a much larger amount of demand than others.

## 6.3 Scenario design

### 6.3.1 Capacity degradation scenarios

Design of a capacity degradation scenario on one link involves three attributes: degradation level, starting time and duration. For the sake of comparability, the starting time and the duration in all of our incident scenarios are the same. These three attributes are designed as follows:

1. Starting time: As introduced in Section 6.1, the 'warming-up' period of this road network is about 3 intervals, i.e. 15 minutes. Thus the starting time of all

the incidents is designed from the 7th interval, i.e., from the 30th minute of the simulation;

2. Duration: The duration of each incident is designed as 6 intervals (i.e. 30 minutes) from interval 7 to 12;

3. Degradation levels: The lower bound of the capacity degradation level is refered to the Highway Capacity Manual (Board, 2000). HCM supplies the information that one lane blockage makes 65% capacity reduction for a two-lane link, and 51% capacity reduction for a 3-lane link. This means that the minimum degradation level of a link with maximum 3 lanes is about 50%. So in the designed capacity degradation scenarios for the A10-West network, in which most of the links have 3 lanes or less, 50% degradation of the link capacity is set as the low bound. Furthermore, we would also like to discover the relationship between the network performance and the degradation level of a single link for the sensitivity analysis. Therefore, 6 capacity degradation levels (coded from A to F) are designed from -100% to -50% with -10% step value as shown in Table 6.3.

**Table 6.3: Capacity degradation scenarios for A10-West**

| Scenario set | A | B | C | D | E | F |
|---|---|---|---|---|---|---|
| Degradation level | -100% | -90% | -80% | -70% | -60% | -50% |

### 6.3.2 Demand increase scenarios

Design of a demand increase scenario between an OD pair also involves three attributes: the increased demand value, the starting time, and the duration. The same starting time and duration are used for the demand increase scenarios as for the capacity degradation, which is within intervals [7, 12] (i.e., [30, 60 min]). Since we also want to discover the relationship between the network performance and the amount of the extra demand, six levels of the extra demand amount are designed for the demand increase scenarios as shown in Table 6.4.

**Table 6.4: Demand increase scenarios for A10-West**

| Scenario | I | II | III | IV | V | VI |
|---|---|---|---|---|---|---|
| Extra demand (*veh/h*) | 500 | 1000 | 1500 | 2000 | 2500 | 3000 |

## 6.4 New indicators: Influenced Length (*IL*) and Influenced Flow (*IF*)

From the case study in Chapter 5, it is evident that those conventional aggregated network performance indicators, e.g. *TTT* and *TTD* are dependent on the effective volume of traffic for the statistics. This means that a fair comparison can only be guaranteed when the considered traffic volumes are equal in all the incident scenarios. To do this, extra care is required in the network design and scenario design. Thus in this section two new time-dependent indicators are proposed to avoid such extra effort: influenced length (*IL*) and influenced flow (*IF*). They are designed to assess the exact influence of an incident in size and duration by considering the performance of the so-called *influenced links*, whose concept is defined as follows:

> Influenced links are the links in the network whose performance (such as speed) is lower than a given expected value caused by an incident. For instance, the reference speed of a link in an interval is the link speed in that interval obtained from the SUE assignment approach. In this case study, we define the links whose speed is lower than 50% of their reference speed after the incident as influenced links of the incident. Since the number and location of the influenced links could be different among different intervals, it is also a time-dependent variable that can represent the changes in the network performance in an incident scenario.

Thus, the definitions of *IL* and *IF* are clear:

- *IL(t)* of an incident is the total length of the influenced links in interval *t*.
- *IF(t)* of an incident is the total number of vehicles on the influenced links in interval *t*.

## 6.5 Scenarios of capacity decreasing

The contents presented in this section are selected from the results of a total of 264 (44×6) link capacity degradation scenarios. Since scenario A (with 100% capacity degradation) for all the selected links is supposed to have the most serious consequence, *ETD* values for all 44 links from scenario A are sorted from high to low as shown in Figure 6.6.

Figure 6.6 shows that the first 23 links with high *ETD* values are all motorway links. This again proves the remark given in Chapter 5 about the criticalness of the motorway links for road networks with a hierarchical structure. However, it is also interesting

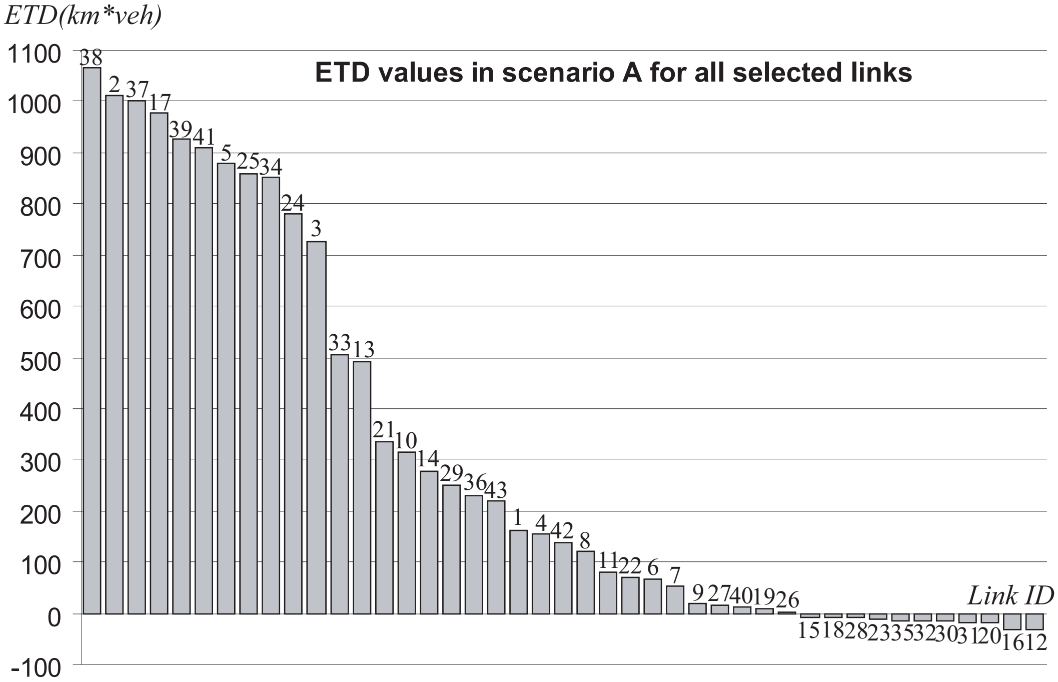

**Figure 6.6: *ETD* values of Scenario A for all selected links**

to find that critical links do not necessary have very high *V/C* values. For instance, Link 38 and Link 37 rank *No.* 1 and *No.* 3 in the figure, but both of them only have *V/C* values of 0.73. Thus only using *V/C* ratio to rank possible critical links in a road network should be approached with caution.

Another interesting phenomenon can be found from Figure 6.6. In general, the degradation of a single link in such a large road network has relatively small effects on the whole network performance. The ratio of $ETD$ to $TTT_0$ is used to describe this finding, in which $TTT_0$ is the total travel time (12772 $veh \cdot hour$) in the reference state for this network. First, the maximum value of $ETD/TTT_0$ is only 8.3%, and only 11 values are larger than 5%. Second, 11 scenarios have minus values of $ETD$. Explanations for these phenomena might be follows:

- Relatively small impact of an incident on a single link for such a large road network is basically caused by many possible alternatives and a certain amount of redundant capacity in the network that can handle the traffic to mitigate congestion;
- Blocking one link in the network means less traffic can go through this link to the downstream network. This will also mitigate congestion in the downstream traffic. In some cases, this effect gives remarkable compensation to the delay that is caused by the blockage;

- Blocking some links might prevent some traffic from entering the network at their scheduled time because of the spillback. In our model this entrance delay is not calculated, so the total travel time is underestimated. What we can do here is to use the filtering rule 2 to avoid such situations as much as possible.

To illustrate the impacts of link capacity degradation on the network performance and route choice behavior of travelers in detail, 8 links are chosen as representatives of the 4 different link types, which are motorway links Link 38(1) and Link 34(9), off-ramp Link 11(24) and Link 7(27), on-ramp Link 19(31) and Link 20(41), and urban links 22(25) and Link 9(28). The number in the parentheses following the link ID is its position in Figure 6.6. These 8 links are marked in Figure 6.7. They are chosen according to the impact levels of their degradations, and also by avoiding the loss of generality of the incidents, e.g. alternative paths are available when incidents occur on these links. So most of the selected links are located in the center of the network.

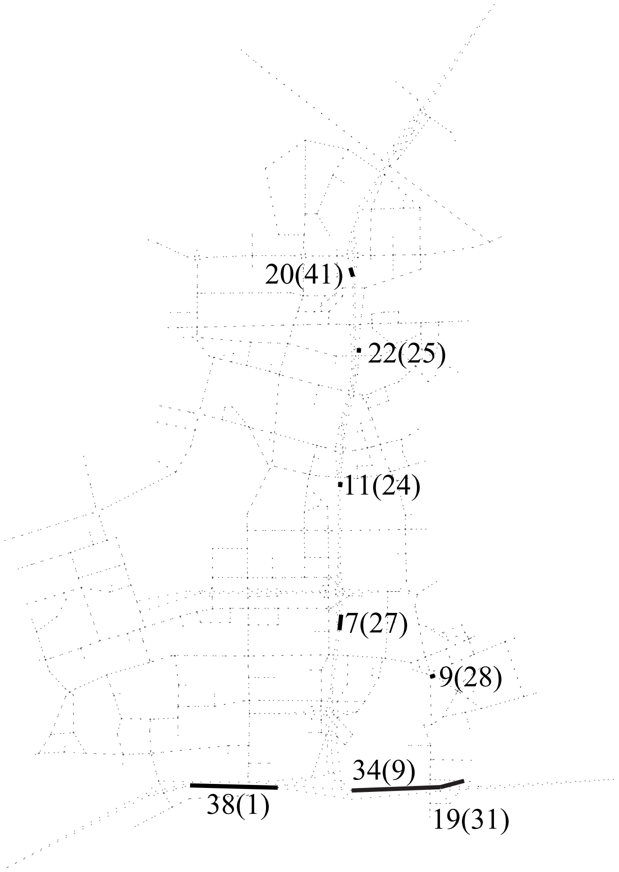

**Figure 6.7: Positions of the chosen links in A10-West network for analyzing capacity degradation**

### 6.5.1 Aggregated performance indicators

In this section, results of the aggregated network performance indicators for 8 selected links from all scenarios are presented. First, in Figure 6.8, changes of *TTD*, *TTT*, and

*TNA* values with different link degradation levels are shown.

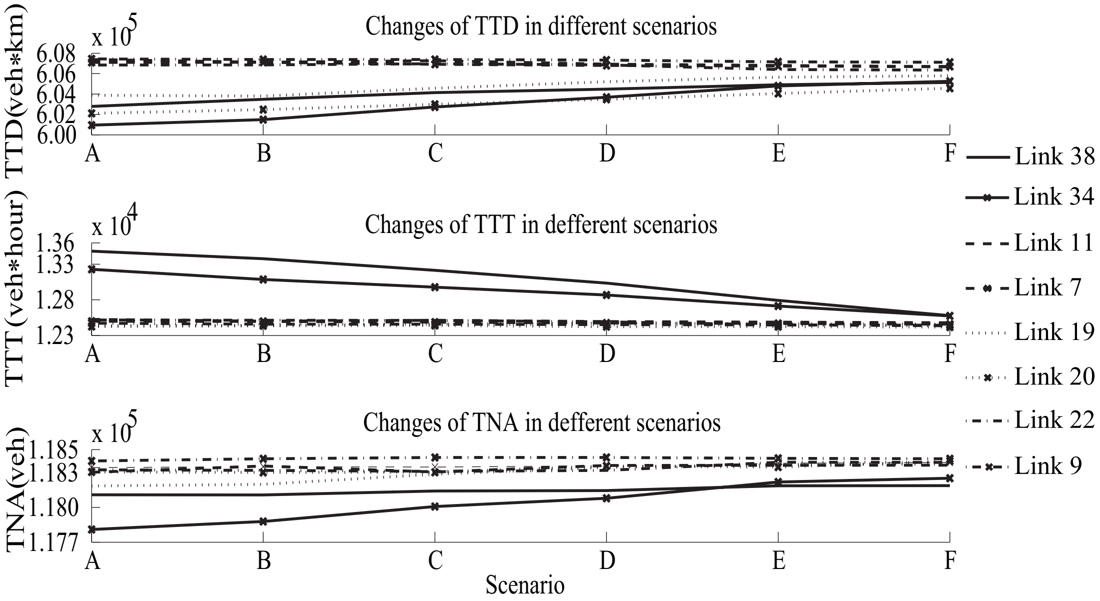

**Figure 6.8: Values of *TTD*, *TTT*, and *TNA* for selected links in all capacity degradation scenarios**

From the values of those aggregated network performance measures, it is evident that the influences of single link degradation to such a large and hierarchical network are insignificant compared to the small tested network in Chapter 5. The reference status of the network is already quite congested with a high delay value of 4191 $veh \cdot hour$. But what we found is that most of the delays are caused by the over-saturated flows and congestion on the motorway. So there are several urban links parallel with the motorway containing unused spaces, i.e. redundancy. This might be the main reason for the insignificant impact which those results reflect. Besides this, several other phenomena can be discovered by analyzing these figures:

- Degradation of motorway links (Link 38 and 34) has a much more negative impact on the network performance than other types of links. This is demonstrated by the following facts:
    1. Smaller values of *TTD* and *TNA* in the incident scenarios are mainly due to the fact that a large amount of traffic still queues in the network when the simulation finishes, which means that the throughput of the network is reduced by these incidents;
    2. Higher *TTT* values mean that the speed of large amounts of traffic decreases after the incidents, as compared with their daily trips.
- Degradation of off-ramps (Link 11 and 7) can also create a certain level of congestion in the road network, which can be demonstrated with the low values of $TTD$ and $TNA$. But its significance is not as high as what we found in Chapter

5. This might be due to the fact that off-ramps are densely distributed in the A10-West network (about 1.5 km average distance), which means that travelers who want to leave the motorway can easily find a close alternative exit if their preferred off-ramp disfunctions;

- Degradation of on-ramps (Link 19 and 20) also has little impact on the outcomes. This might be due to the fact that after the incident, less traffic can enter the motorway through these on-ramps. Congestion at its downstream links will the be mitigated, so that the values of all three indicators are slightly influenced;
- Degradation of urban links (Link 22 and 9) has almost no influence on the outcomes of these aggregated indicators over the whole network, although their *V/C* values are high;
- To calculate the conventional aggregated network performance indicators, i.e. *TTD* and *TTT*, one important input is the total number of the traffic for the statistics. This variable might be different in different incident scenarios if some vehicles are detained in the original zones. From this point of view, the indicator *TNA* is more appropriate in describing the aggregated road network performance.

### 6.5.2 Time-dependent performance indicators

***NAS* and *NL***

For the sake of grasping the dynamics of traffic and network performance under incident conditions, time-dependent network performance indicators *NAS* and *NL* have shown their advantages in representing the dynamics in the network. In Figure 6.9, changes in *NAS* and *NL* for the selected links in scenario A (100% link capacity degradation) are illustrated.

Within and after the incident period (interval [7, 12]), values of *NAS* of most links are lower than the reference. The values of *NL* also decrease during the incident period, but they quickly retrieve to higher values after the incidents than the reference. This illuminates two things. On one hand, because of the incidents, a large number of traffic is blocked in the network so that the average speed decreased. On the other hand, the network has enough capacity to sustain the delayed traffic with a certain service level. For instance, the maximum fall of the network average speed is only 15% in all the scenarios. This means that a local incident has some impact to the road network, but this impact is restricted in a small scale area.

It is also interesting to notice that for several links, such as the on-ramp Link 20 and the urban link Link 9, after their degradation, the *NAS* values become higher than the reference. This is because after these links are blocked, some motorway links that carry high traffic volumes get less flow from these on-ramps and their performance are improved. From this phenomenon we can draw the conclusion that the degradation of some links might bring benefit to the whole network.

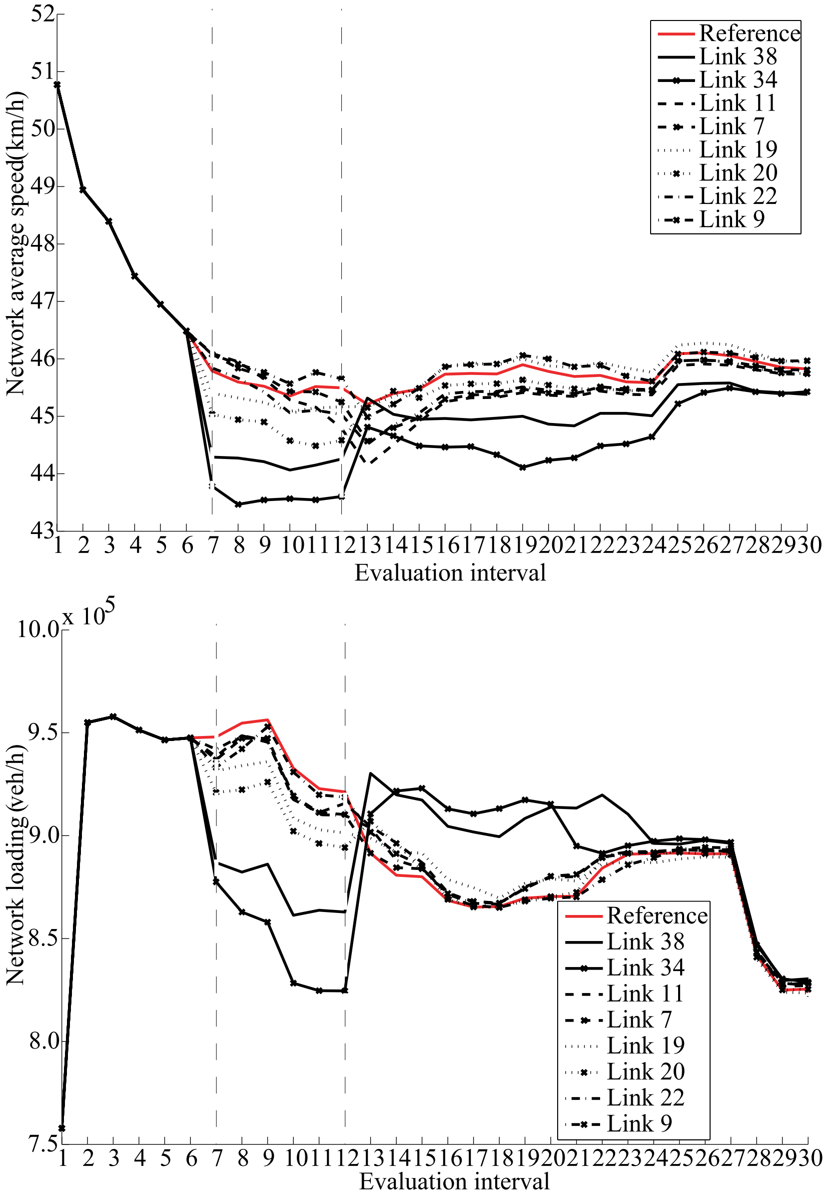

**Figure 6.9: Changes of *NAS*(t) (up) *NL*(t) (down) in scenario A when link capacity is reduced by 100% during interval 7-12**

### *IL* and *IF*

From the changes of *NAS* in Figure 6.9, it seems that drop of the average speed of maximum 15% after the incident does not influence the travelers and the network performance seriously. But as what we also mentioned above, calculating the average speed over the whole road network may not accurately represent the exact impact of an local incident on its surroundings. Thus, two new indicators *IL* and *IF* have been introduced in this case study for a better description of network performance after the incidents. In Figures 6.10 and 6.11, changes in *IL* and *IF* for the selected links are illustrated respectively. Two capacity degradation scenarios *F* (100% capacity degradation) and *A* (50% capacity degradation) are selected for the illustration.

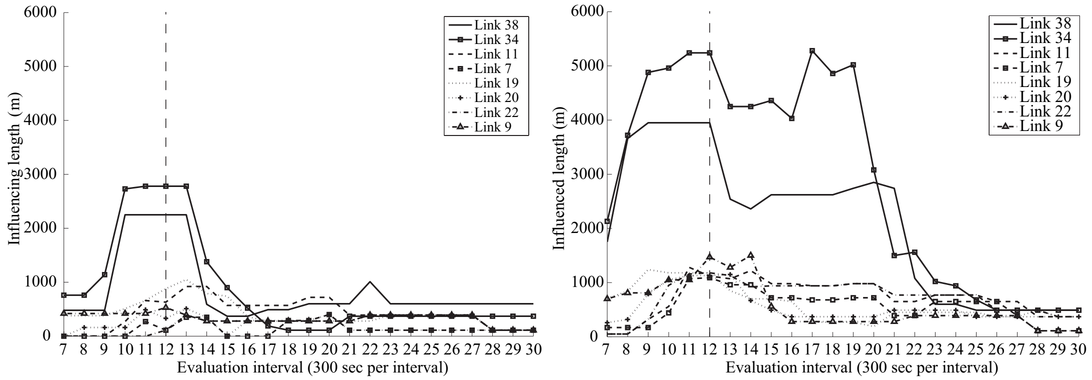

Figure 6.10: Changes in *IL* of scenarios *F* (left) and *A* (right)

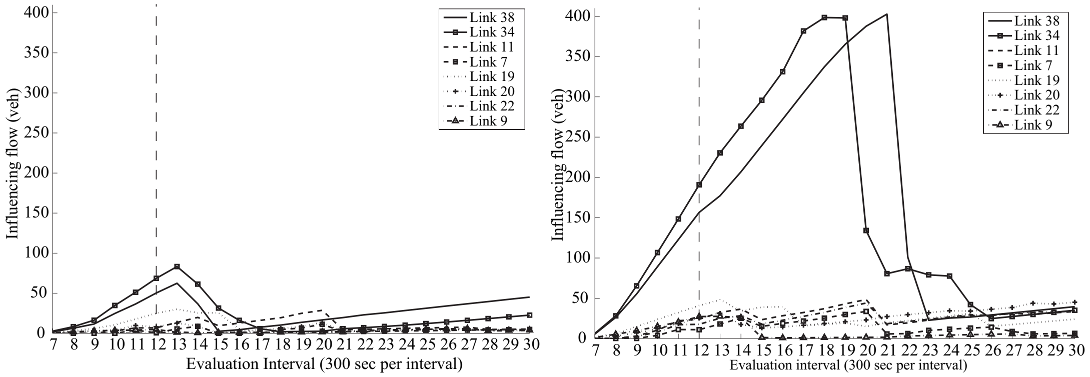

Figure 6.11: Changes in *IF* of scenarios *F* (left) and *A* (right)

From two small figures on the right side for scenario *A*, it is evident that the complete capacity degradation of a single link might have big influence to the network, such as over 5km links and 400 vehicles being influenced. This cannot be found by only analyzing the network-level indicators. Furthermore, by comparing the figures from different incident scenarios, it is easy to grasp the effects on the road network of different link capacity degradation levels. When the degradation level increases, *IL* and *IF* increase to higher values and last for a longer period. In each figure one curve illustrates the changes in *IL* (or *IF*) in the analyzed incident scenario of one link. Differences within these curves clearly distinguish the ‘importance’ of each link to the network. Generally speaking, the values of *IL* and *IF* after the degradation of a motorway are much higher than those of other types of links, and such high values last for a longer period.

## 6.6 Scenarios of demand increasing

In this section, results of demand increase scenarios are introduced. The 8 selected OD pairs and the related links are listed in Table 6.2 and identified in Figure 6.5.

### 6.6.1 Aggregated performance measures

In this section, the changes in the increased values of *TTD*, *TTT* and *TD* with the increase of the demand are illustrated in Figure 6.12 and analyzed afterwards.

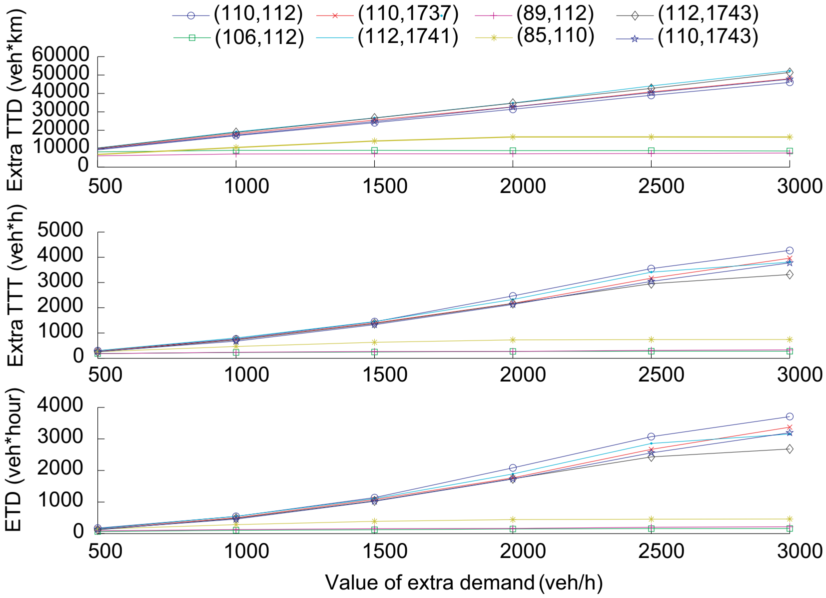

**Figure 6.12: Values of the extra *TTD* (top), *TTT* (middle) and *ETD* (bottom) in the demand increase scenarios**

The figure clearly shows that the increase of the extra *TTD*, *TTT* and *ETD* follows an approximately linear relationship with the increase of the demand of a single OD pair. This probably means that under the daily status of the road network, there still exists enough residual capacity to handle the extra demand tested in our scenarios. Furthermore, we ca also find that the eight curves in each small figure can be clearly classified into two groups according to their slopes. The curves in the group with higher slope have the origins on the motorway (e.g., zone 110 and 112); and the other curves for the OD pairs with urban zone origins (e.g. zone 106, 89 and 85) have much lower slope. The most logical explanation for this phenomenon is that urban network in this road network has more capacity to accommodate and assign the extra traffic so that the whole network is much less influenced.

### 6.6.2 Time-dependent performance measures

In Figure 6.13, changes in the time-dependent network performance indicators *NAS* and *NL* for the selected OD pairs are illustrated. Two demand increase scenarios I and VI are compared to demonstrate the impact of different extra demand values to the network performance.

Following the changes of $NAS(t)$ and $NL(t)$, we found that demand increase for different OD pairs generally have the same impacts on the network performance, which

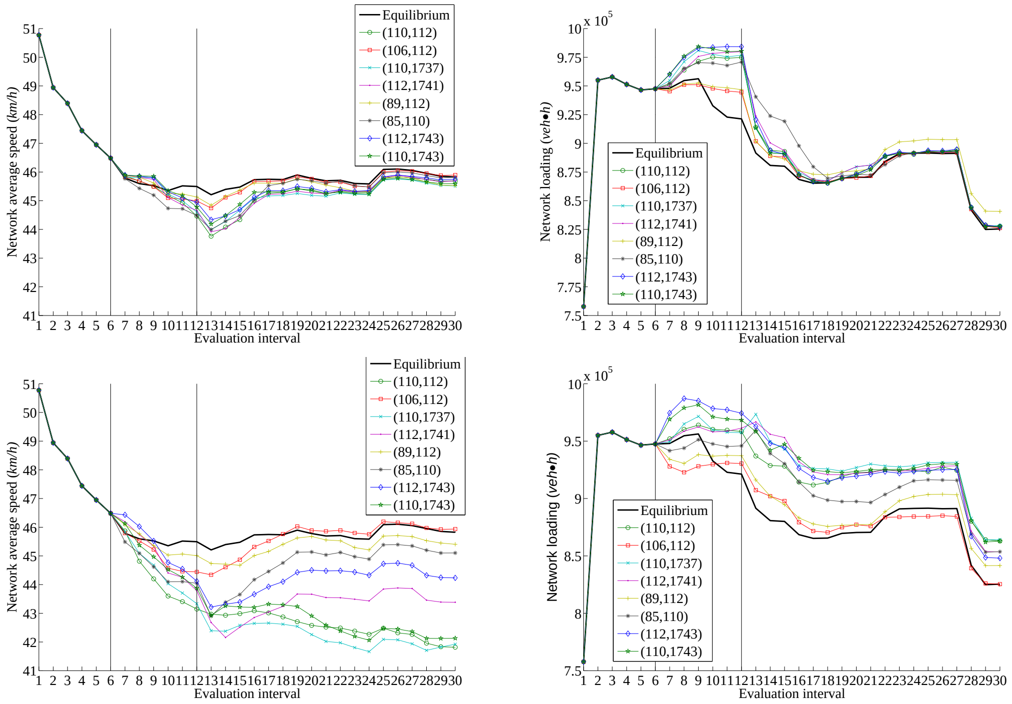

**Figure 6.13: Changes of *NAS*(t) (left) and *NL*(t) (right) in scenario sets I (above) and VI (down)**

are decreasing the network speed and increasing the network loading. But depending on the types of the original zone, the performance of the road network has some differences. If the extra demand is from the motorway zone, *NAS* values firstly become higher than the reference value for a short period because the extra demand is with a higher speed. After the extra demand causes congestion in the network, *NAS* values then decrease to the lower level. If the extra demand is from an urban zone with a lower speed than the average value, *NAS* values normally decrease immediately and remain lower than the reference.

## 6.7 Summary and Conclusion

In this chapter, the framework introduced in Chapter 4 have been applied to analyze the robustness of a real road network against local incidents. The results first show the capability of the proposed methodology for the systematical analysis on the robustness of large road networks, which is seldom found in the exiting case studies. Furthermore, a better understanding of the robustness of large road networks with hierarchical structure can be obtained through the analysis of different sets of incident scenarios, especially the findings about the critical elements (e.g. links and OD pairs) in a road network. They can be summarized as follows:

- Motorway links are the most critical elements for a road network with the hierarchical structure. Incidents on the motorway links have the most negative impact on the whole network performance, which can be proved by all of the aggregated and time-dependent indicators;

- For other types of links, their capacity degradation has very little influence on the whole network. It is because that the original flows on these links are low, and there exist numerous alternatives for the traffic that use these links to be re-assigned;
- Demand increase for an OD pair has the impact on the network performance for a much longer period than the degradation of a single link. But their influencing degree to the road network is generally low because the extra demand is always restricted by the link capacity. This means its influencing area is probably limited by one bottleneck in the network, so that the rest part of the road network and traffic are less influenced.

Comparing the results presented in this chapter and in Chapter 5, the differences in the impact of a local incident on the whole network performance are distinct. All the performance indicators that are aggregated on the network level (e.g. *NAS* and *NL*) show that a local incident does not have noticeable influence on a big network. These results might give us the impression that in a real road network, a local incident is not very harmful. But after analyzing the influencing length (*IL*) and the influencing flow (*IF*) of an incident, it is clear that its impact can also be remarkable depending on its location and degree. So on one hand, we might say that the robustness problem is a ‘local’ problem because of the large size of the road network. On the other hand, some time-dependent performance indicators are needed to describe the influence of an incident in more detail. Thus through the studies presented in this chapter, several contributions to the knowledge about road network robustness can be drawn:

1. The robustness of a road network against local incidents can be better evaluated through the time-dependent indicators than the aggregated performance indicators;
2. Critical links of a road network can be scanned and selected by combining several criteria, including analyzing link $V/C$ values, analyzing the commonness of links, and searching for special types of links;
3. Basically motorway links and the ramps for the motorway are more crucial for a road network. Thus the incidents on these links should be dealt with in a higher priority.

# 7

# Information Service and Network Robustness

In Chapters 5 and 6, network robustness against unexpected and exceptional incidents has been studied through several incident scenarios in one simple hypothetical network (Chapter 5) and one complex real-sized network (Chapter 6). The analysis of these scenarios demonstrates that network robustness against incidents can be well evaluated with several indicators that are derived from dynamic traffic assignment models. Furthermore, by comparing the results from various scenarios, the importance of a link or an OD pair to network performance can be quantitatively identified.

From those aforementioned studies, it is found that the (route) choice behavior of travelers with respect to the traffic situation is a key factor in the robustness analysis of a road network. After the occurrence of an incident, if travelers have the opportunity and the will to use the redundant capacity in the network by re-routing according to the real traffic conditions, the negative influence of the incident will be reduced. In order to realize this, there should first exist redundant capacity in the network in the normal traffic condition. Secondly, accurate and timely traffic information is also necessary and important to support and guide travelers to use the redundant capacity. Thirdly, travelers, or at least some travelers, must be willing to re-route when they are en-route. To increase the robustness of a road network, these three conditions are naturally considered as three basic options. But due to economic, environmental and ecological reasons, it is now almost impossible for governments to build more redundant capacity than necessary. Thus, for road authorities and managers, two other ways are more feasible and easier to be realized. These are guiding traffic flows by supplying accurate real-time or estimated traffic information, and trying to influence the route choice behavior of travelers if possible.

It is known that in reality, when travelers face unexpected congestion during their daily travel, they behave differently from their normal behavior. Such changes in the (route) choice behavior partially influence the network robustness as described above. Another fact is that travelers are different from each other, which means they will not behave in the same way. Appendix C indicates that the combination of travelers with various responses to the information has significant impacts on the network performance outcome. But in the studies presented in Chapters 5 and 6, we use the same combination of the different types of travelers for both daily circumstances (represented by the SUE assignment approach) and incident situations (represented by the en-route assignment approach). This means that travelers are assumed to behave in the same way in response to the traffic information under both situations. This is due to the fact that only a very limited number of studies have been published on travelers' behavior under incident situations, so we could not use a calibrated model for our analysis. In order to study the possibilities of increasing network robustness through information services, first of all it is necessary to better understand the (routing) behavior of travelers under incident situations with supplied information. Based on this knowledge, the impact of information services on network robustness against incidents can then be systematically analyzed. Although no references about travelers' (routing) behavior under incident situations could be found, a primary study can still be carried out to analyze the impact of information services on road network robustness. It can be done by designing and analyzing scenarios with different travelers' behavior in respond to the real-time traffic information. The result of such a study can be useful references for the future research and practices, which is the main content and target of this chapter.

This chapter includes the following content. A short introduction to the information services and brief discussion of the relationship between the information services and network robustness are given in Section 7.1. Section 7.2 describes the methods and the incident scenarios designed for the analysis. In Section 7.3, results of the scenarios are presented and analyzed. Finally Section 7.4 summarizes this chapter.

## 7.1 Information Service and Network Robustness

### 7.1.1 Information service

Information services in a transportation system provide the travelers with pre-trip and en-route travel information. They are mostly supplied by road authorities and managers. Pre-trip planning assistance provides travelers with roadway information, including the condition of the road, traffic information and travel times, and transit information which can be used to select route, mode, and departure time. En-route traveler assistance provides the traveler with roadway and transit information while traveling, including traffic information, roadway conditions, transit information, route guidance information, and other information such as adverse travel conditions, special events, and parking. Through information services, traffic managers can influence or guide travelers in order to significantly increase the productivity and utilization of the existing capacity of the road infrastructure. Other goals are also expected to achieve through information services, such as enhancing the intermodality, system integration, safety and environmental quality. For instance, under incident conditions when congestion is serious, the Dynamic Route Information Panels (DRIP) or Variable Message System (VMS) shown in Figure 7.1 are used to inform drivers about the traffic conditions and probably the solutions. So the traffic can be guided to alternative paths in order to avoid time loss. Such information services are examples of ITS (Intelligent Transport Systems). ITS is the name given to all application of ICT (Information and Communication Technology) to transport systems, i.e. infrastructure, vehicles and services.

**Figure 7.1: Example of VMS for incident management**

ITS can be categorized into management services and traveler services. The quality of many ITS traveler services, such as DRIP and VMS, are heavily dependent on the availability of timely and accurate estimates of prevailing and emerging traffic conditions in the various components of the area's transportation network. This means that information services for travelers can play crucial roles in the realization of the intended objectives of these advanced systems. Although some research has pointed out that a rather low percentage (about 5%) of the travelers will follow the suggestions when only queuing information is given (Gouda, 1997), it is rational to consider that much higher proportions of travelers would follow the route guidance under incident situations, which has a close relationship with our interests of road network robustness. It has also been formed that a stronger influence over route choice behavior might be expected if the information is provided as an instruction rather than a description of the road status.

### 7.1.2 Relationship between information services and network robustness

Information services implemented in most of the ITS components are aiming to improve the convenience, safety and efficiency of travel by providing real-time or estimated traffic information to travelers. But on one hand their actual effects are decided by their quality, while on the other hand they also depend on the response of travelers, i.e. the percentage of travelers who could receive the information and the reaction of these travelers to the information. This is still an unknown or unclear phenomenon for researchers and practitioners. The only thing we are sure of is that different responses exist among travelers and their reactions influence the road network performance remarkably, so as to influence its robustness. Another factor in the impact of information services on network robustness is the quality of the information, such as the time-lag (i.e. reaction time) and the accuracy of the information. So new questions now need to be addressed: Can information services improve network robustness by influencing (route choice) behavior of travelers? What is the influence of the quality of the information on road network robustness?

A simple way of understanding the relationship between information services and road network robustness is to theoretically compare their main objectives. One major objective of information services is to reduce overall system travel time and delay. Road network robustness concerns about the performance of the whole road system being least degraded by the incidents, which can be described as a small value of extra delay under incident conditions. From this point of view, a prime conclusion can be drawn that the implementation of information services will increase road network robustness. However, what we learn from the studies carried out in Appendix C is that if all the travelers receive the real-time traffic information and choose the ‘best’ path with the lowest cost (mainly in time), the system will present an unstable state caused by the ‘flip-flop’ phenomena in travelers’ route choice behavior. No doubt, this would have a negative impact on the network robustness. Furthermore, from the start of the incident until the start of the information services, a certain time-lag inevitably exists. It is also unclear how this time-lag influences network robustness. Thus, before the implementation of information services in any ITS measures, it is very important for road planners and managers to correctly understand and predict the effects on the road network of such information services. This is the main topic in this chapter.

## 7.2 Methodology and Scenario

### 7.2.1 Methodology

In the traffic assignment model implemented in MARPLE and its en-route extension, a *C-Logit* model as shown in (7.1) is used for the assignment of travelers among different paths for each evaluation interval.

$$p_k^{rod} = \frac{exp\left(-\theta c_k^{rod} - CF_k^{rod}\right)}{\sum\limits_{s \in R^{od}} exp\left(-\theta c_k^{sod} - CF_k^{sod}\right)} \tag{7.1}$$

The *C-Logit* model for the single mode network has the following specification: $R^{od}$ is the path set for OD pair (o,d); $p_k^{rod}$ is the probability of choosing path $r$ of $R^{od}$ during the time interval $k$; and the term $CF_k^{rod}$ is the commonality factor for path $r$ by reducing the systematic utility of a path proportionally to its level of overlapping with other alternative paths in $R^{od}$. The parameter θ identifies the perception level of the travelers of the real traffic situation (or information). It relates not only to the information quality, but also to the measure of how far travelers choose the route recommended by the information. More discussions about the function of θ in the *C-Logit* model can be found in Appendix C. $c_k^r$ stands for the cost of path $r$ in interval $k$. In the UE assignment approach path costs are real experienced costs derived from the previous iteration of the assignment and simulation. However, in the en-route assignment approach, for each path, travelers only have the knowledge of the costs for the normal situation. They cannot predict the path cost because what they face en-route after an incident has never happened before in their daily experience. Thus, in our en-route assignment model MARPLE-e, path costs are simply calculated by summing up all the instantaneous costs of the links in the path at the end of each evaluation interval as most of the other en-route assignment models, such as INTEGRATION, DYNASMART, etc.

In the previous case studies, the same classification of travelers. i.e. the same value set of θ are assumed for both UE and en-route assignment approaches. The adopted value set of θ for multiple user types has been calibrated by (Taale et al., 2004) in their studies of the A10-West network in the Netherlands. They distinguished three types of travelers with θ values of 0, 1 and 3, with proportions of 30%, 50% and 20% of the travelers respectively. UE assignment are carried out with this value set and we get $u^*(k)$ for the dynamic distributed path flows for interval $k$. But under incident circumstances, travelers can be simply classified into two groups: one group of travelers will not change their daily paths and the other group of travelers will change to the paths with lowest costs. So for the periods during and after the incidents, we also have the instantaneous user optimal path flows $\overline{u}(k)$ based on the real-time traffic status and calculated with θ value of 3. Such information of path costs as well as the path with the lowest cost will be calculated and supplied to travelers by road authorities and managers through ITS/ATIS measures for each evaluation interval. If the compliance rate of travelers to such information is $\alpha$ ($0 \leq \alpha \leq 1$), then the final assigned path flows $\hat{u}(k)$ for interval $k$ will take the values calculated by (7.2).

$$\hat{u}(k) = (1-\alpha)u^*(k) + \alpha\overline{u}(k) \tag{7.2}$$

By using different values of α for the en-route assignment approach in a number of scenarios, the impacts of the proportion of responding travelers to network performance can be analyzed through the comparisons among these scenarios. So that changes of network robustness against incidents with different compliance rates can also be studied.

### 7.2.2 Scenario

The network to be used for the analysis here follows the small network in Chapter 5 as shown in Figure 7.2. The demand chooses the lower one with an uncongested reference state; and the chosen incident scenarios are from the scenario set $\omega_2$ in Table 5.3, in which Link 4 is degraded with two degradation levels: -50% and -70%. For each capacity reduction level, values of the compliance rate $\alpha$ are designed from 0% to 100%. The related scenarios are marked from s1 to s11 respectively as shown in Table 7.1.

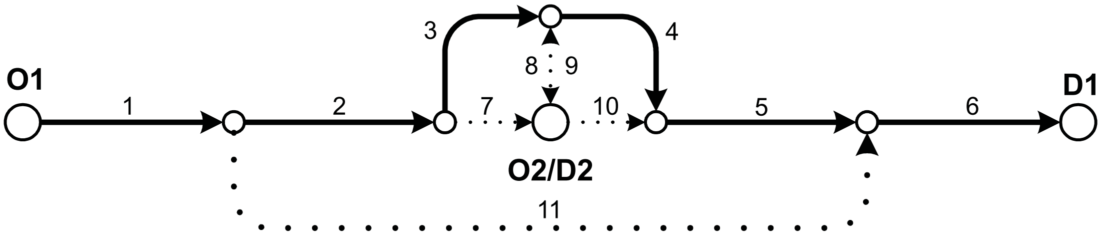

**Figure 7.2: Simple and hypothetical network**

**Table 7.1: Scenarios with different percentages of responding travelers**

| Scenario | s1 | s2 | s3 | s4 | s5 | s6 | s7 | s8 | s9 | s10 | s11 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| $\alpha$ | 0% | 10% | 20% | 30% | 40% | 50% | 60% | 70% | 80% | 90% | 100% |

Moreover, three time delay situations for the information supply are considered for the scenario design, which are 0 delay, 5 minutes delay and 10 minutes delay. Within the delay period after the incidents, all of the travelers still follow their daily paths, i.e. the equilibrium path assignment results $u^*$. When the information services start working, a certain proportion of travelers will receive and respond to the information according to the value of $\alpha$.

## 7.3 Results of All Scenarios

### 7.3.1 Aggregated indicators for network performance

In this section we use the value of extra total delay (*ETD*) to identify network robustness. In Figures 7.3 and 7.4, values of *ETD* in all the scenarios are shown. Each line in the figure represent one type of information delay with different compliance rates.

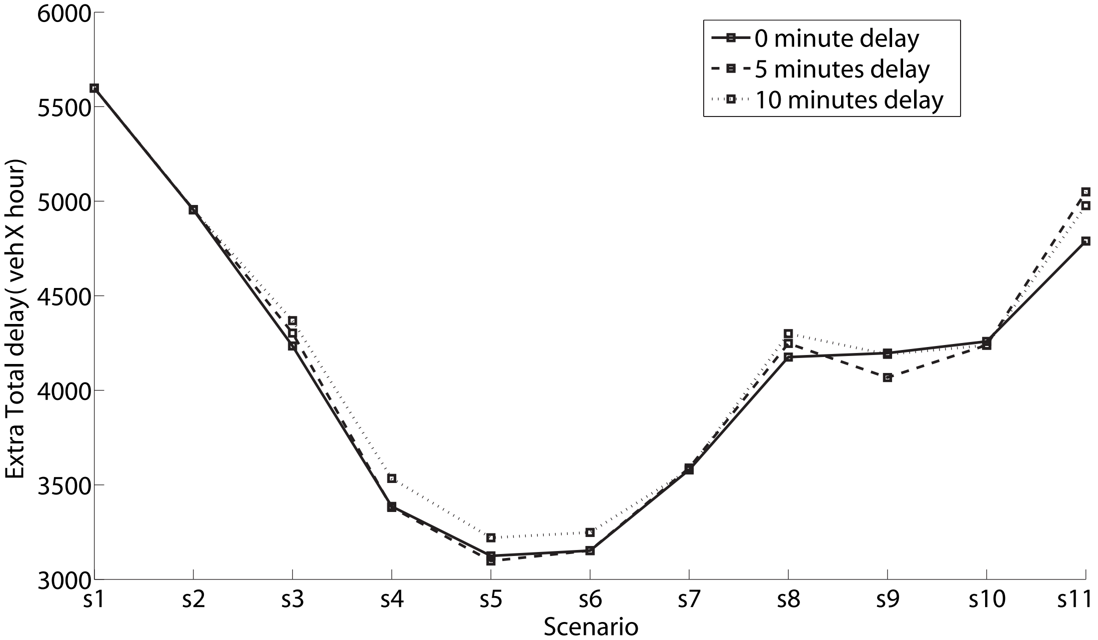

**Figure 7.3: Changes of *ETD* with different compliance rates when 70% link capacity degraded**

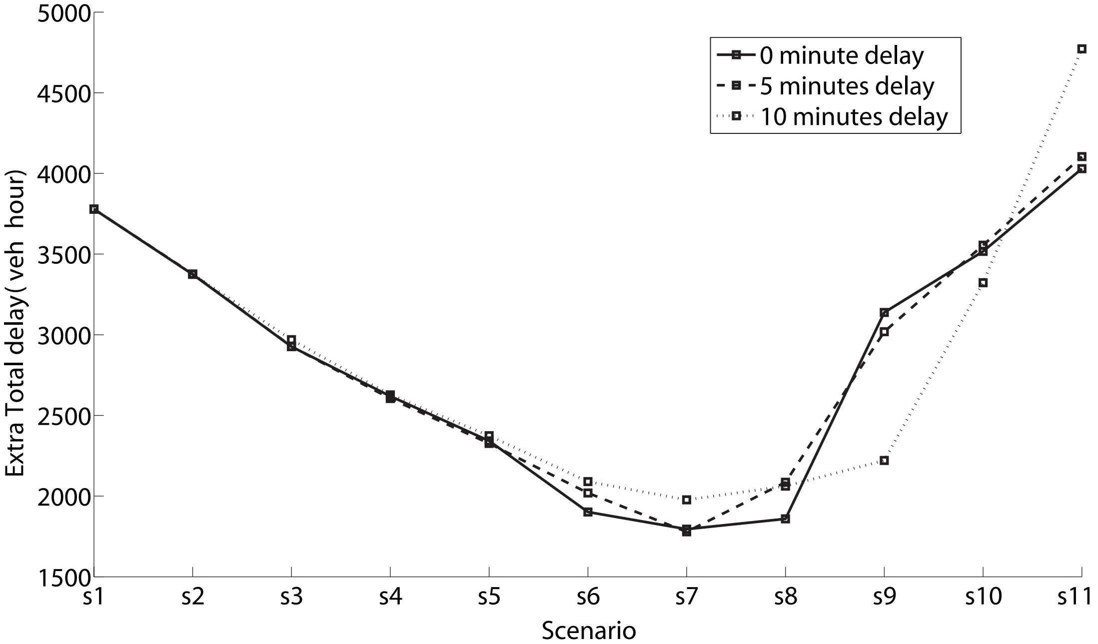

**Figure 7.4: Changes of *ETD* with different compliance rates when 50% link capacity degraded**

An interesting and important phenomenon is that there exist optimal compliance rates for the system with the minimal delay for all the incident scenarios. This means that when the compliance rate of travelers to the real-time traffic information exceeds a certain percentage, the system performance would get worse. When the capacity reduction degree is moderate (e.g. 50%), if 100% of the travelers choose the paths with the real-time lowest cost, the system would behave even worse than if no travelers respond. This occurs also when there is delay in the information supply. In most of the cases, information delay induces higher delays, but the differences are not so obvious for the whole network. This might be due to the fact that it takes some time for the impact of the incident to become noticeable, especially when the location of the incident is far from the closest decision point upstream. In some cases, information delay induces less network delay, which only appears with high proportions (e.g. 80% in scenario s9) of travelers reacting to the information. From these two incident scenarios, we found that the length of the information delay does not change the optimal value of the compliance rate.

Furthermore, the values of the optimal compliance rate vary in different incident scenarios, which means it is difficult to determine a general value for traffic managers to choose for system optimization. Nevertheless, even if a small percentage (e.g. 10%) of travelers would receive and react to the information, the total delay on the network will be reduced more than if travelers could not get any information. This indicates that information services can make the network more robust against incidents.

### 7.3.2 Time-dependent performance indicators

**Network average speed (NAS)**

In this subsection, changes in *NAS* in scenarios s1, s4, s6, s8 and s11 in all types of information delay are analyzed as a function of the time.

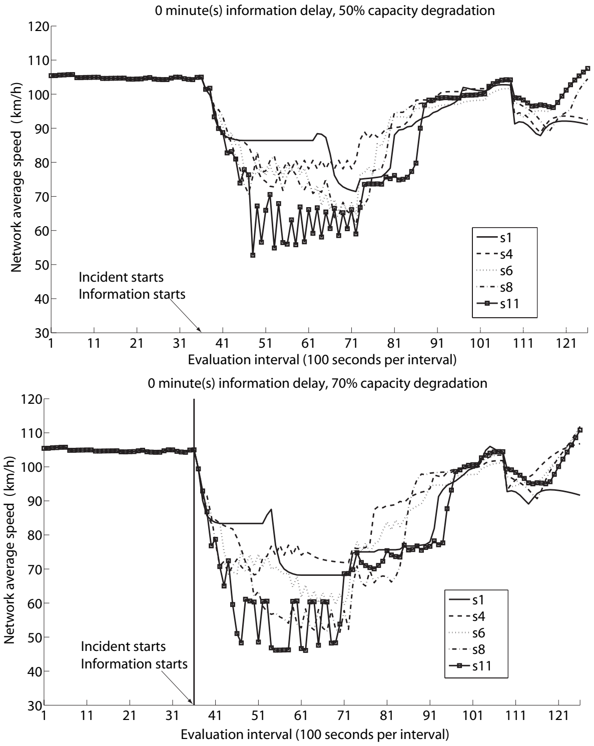

Figure 7.5: Changes in *NAS* without information delay when 50% (upper) and 70% (lower) capacity degraded

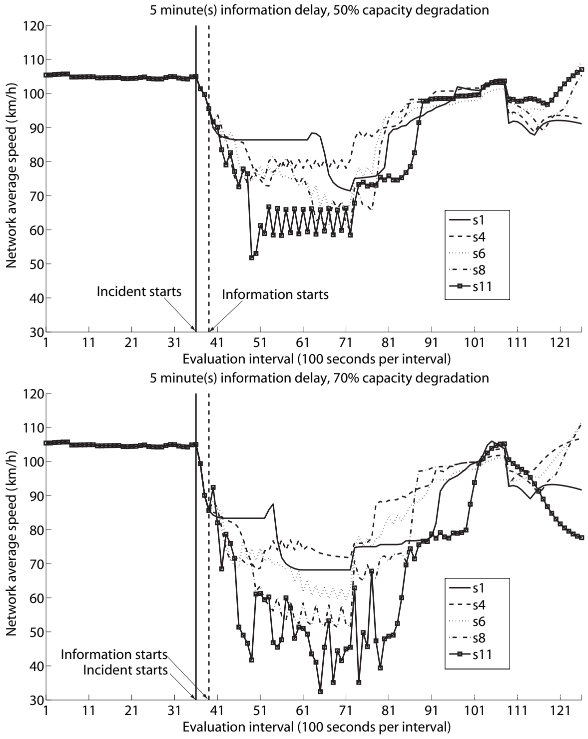

Figure 7.6: Changes in *NAS* with 5 minutes information delay when 50% (upper) and 70% (lower) capacity degraded

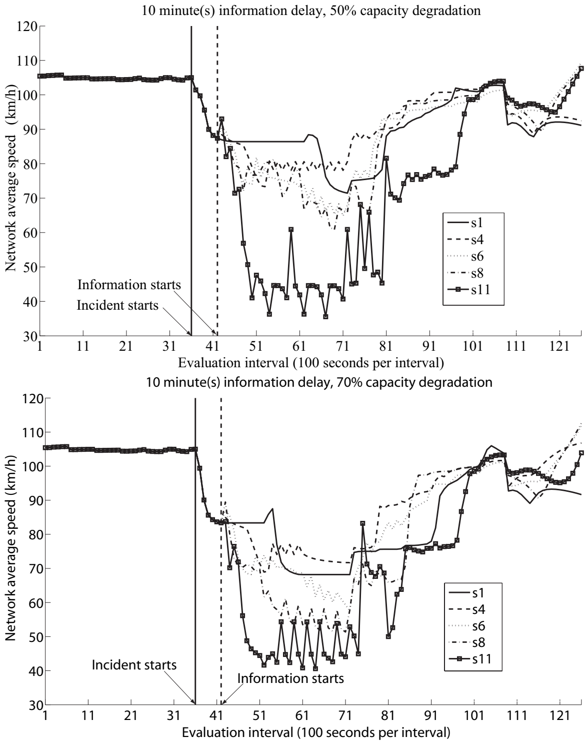

**Figure 7.7: Changes in *NAS* with 10 minutes information delay when degraded 50% (upper) and 70% (lower) capacity degraded**

It is very clear that with the increase of the information delay time, network performance (*NAS*) decreases. This means that delayed information service results in negative effects to the network performance.

### Network loading (NL)

In this subsection, changes of *NL* in scenarios s1, s4, s6, s8 and s11 in three information delay situations are illustrated respectively in Figure 7.8, 7.9, and 7.10.

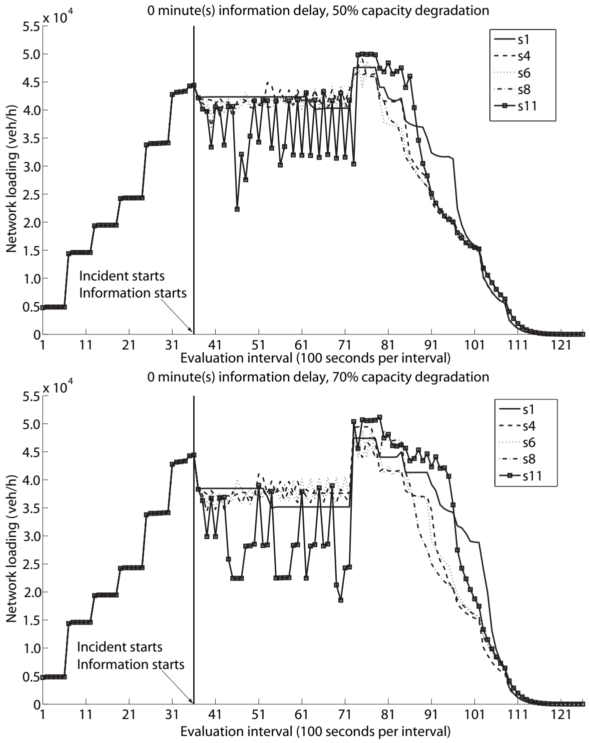

**Figure 7.8: Changes of *NL* without information delay for Link 4 being degraded 50% (upper) and 70% (lower)**

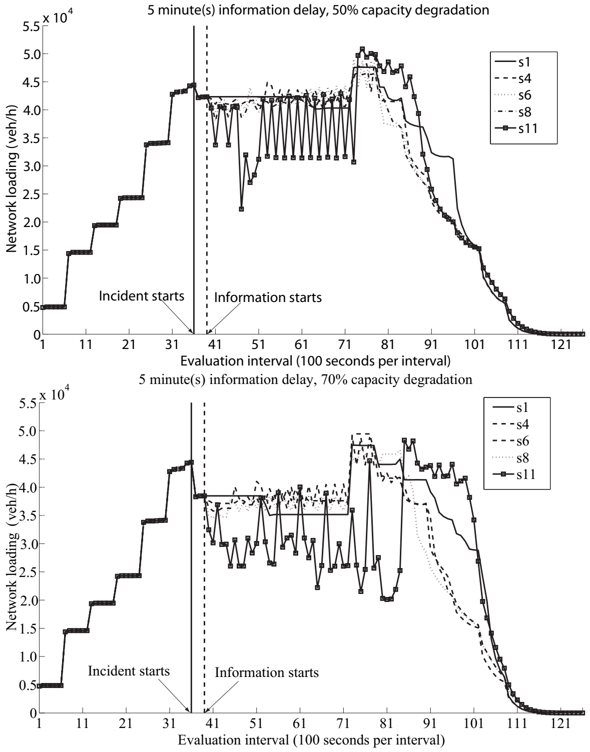

**Figure 7.9: Changes of *NL* with 5 minutes information delay for Link 4 being degraded 50% (upper) and 70% (lower)**

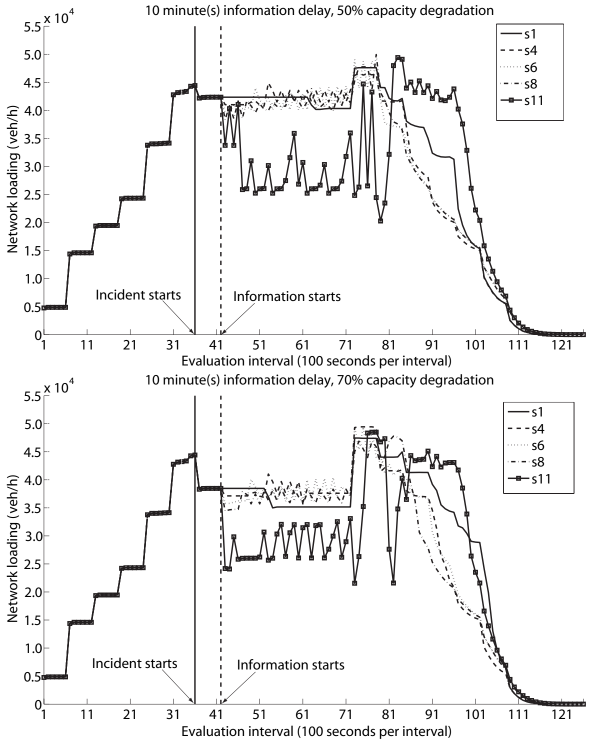

**Figure 7.10: Changes of *NL* with 10 minutes information delay for Link 4 being degraded 50% (upper) and 70% (lower)**

Similar results can be found for *NL* as for *NAS*. Curves of scenario s11, in which all travelers update their paths to the ones with the real-time lowest costs, present the most fluctuant changes and the worst performance. This is the reason for the large value of delay of scenario s11. The curves of scenario s1, in which all travelers persist on their original paths, keeps a higher and stable value after the incident for a certain period before it becomes lower but still stable. This is because when the assignment did not change, the network performance is simply controlled by the bottleneck caused by the incidents. Thus no large fluctuations would appear until a new link being congested and the network performance degrades to a lower level. Moreover, a general knowledge got from these figures is that information delay reduces *NAS* and *NL* values and also delays the system from recovering, especially in the scenarios with higher compliance rate. To better explain this, the analysis of the assignment results of the (major) demand in the network are necessary.

### Route assignment results

In the following Figures 7.11, 7.12, and 7.13, changes in the splitting rates among the generated paths of OD pair (O1,D1) in the scenario with 70% capacity degradation and all three information delay time are presented for illustration and comparison.

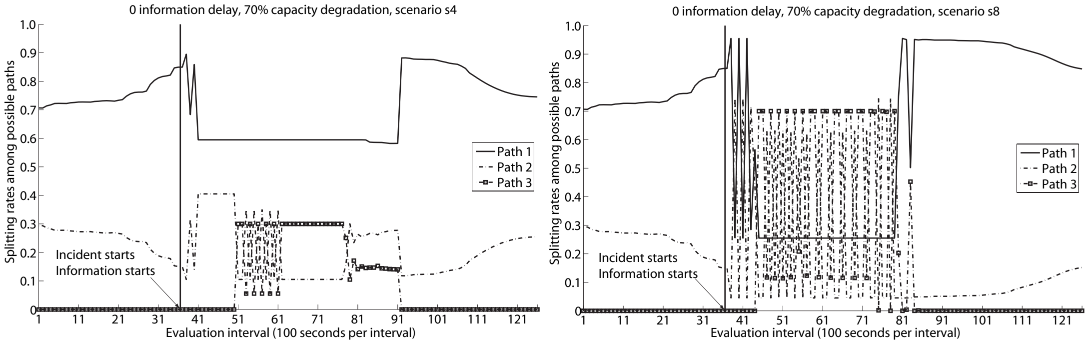

**Figure 7.11:** **Changes of route assignment for (O1,D1) in scenarios s4 (left) and s8 (right) without information delay**

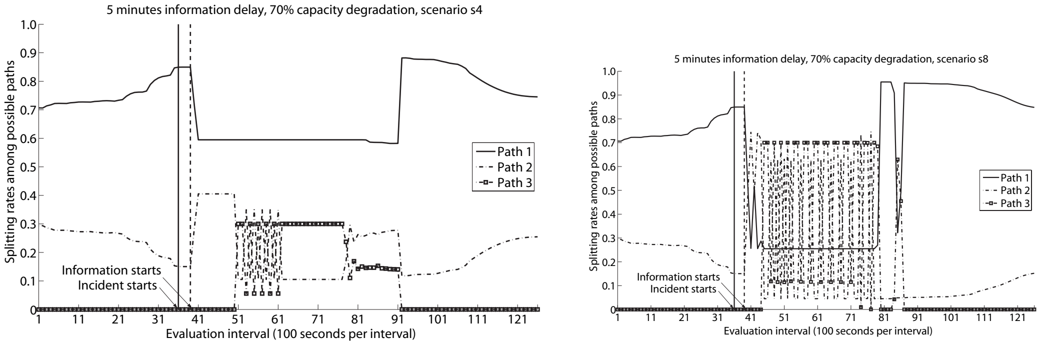

**Figure 7.12:** **Changes of route assignment for (O1,D1) in scenarios s4 (left) and s8 (right) with 5 minutes information delay**

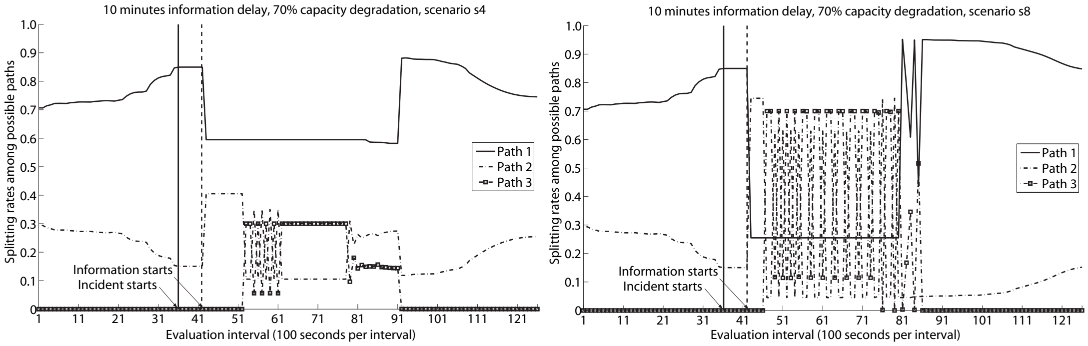

**Figure 7.13:** **Changes of route assignment for (O1,D1) in scenarios s4 (left) and s8 (right) with 10 minutes information delay**

For all the scenarios, re-assignment between *Path 1* and *Path 2* immediately took place after the information services started. After the usage of *Path 3*, re-assignment were done among these three paths. The higher percentage of travelers who responded to the information, the earlier *Path 3* was used, and the higher the fluctuations in the assignment results are. We believe that this is the main reason for the system performance becoming worse after the compliance rate of travelers grew higher than a certain value.

## 7.4 Conclusions

Information services, as part of the ITS, supply real-time traffic or travel information to travelers pre-trip or en-route. The main objective of the information services is to improve the convenience, safety and efficiency of travel by supplying information and guidance. The study of the influence to the network performance of the travel time information has attracted much interest among researchers and practitioners in the past decade. But we also know that the response of travelers to the information in fact decides the effects of the services. So travelers' response influences the network robustness against incidents.

In this chapter, the impact on road network performance of the following two factors - compliance rates of travelers to the real-time traffic information; and delay time of the information service - have been studied with some designed incident scenarios. These incident scenarios consist of eleven values of travelers' compliance rates to real-time information and three levels of delay time of the information service. The results of the network performance and path assignment have been presented and analyzed to illustrate the the network robustness in these scenarios. Several important achievements about the information services and network robustness can be drawn as follows:

1. By supplying real-time information to travelers en-route, road network robustness against incidents can be improved by reducing the total network delay. But such improvement can be realized only when a 'certain' proportion of travelers follow the information and update their paths;

2. There exists one optimal compliance rate for an incident scenario with which the total (extra) system delay caused by the incident can be minimized. The situation in which all travelers respond to the information is not ideal for the efficiency of the whole network due to the large fluctuations in the assignment results. Thus, it is important for the road managers to get better understanding about the compliance rate of travelers, especially its influencing factors, such as the type and format of the supplied information;

3. Delay in the information generally causes extra travel costs to the network because some redundant capacity could not be fully used due to the growth of congestion. Thus a fast incident detection can bring benefit to the road network with less congestion. The concrete effects of the information delay are controlled by the compliance rate of the travelers.

Furthermore, the value of optimal compliance rate is not only controlled by the severity level of the incident as tested in this chapter. It would also be influenced by other characteristics of the incident, such as its type, location and its duration. To thoroughly understand the compliance rate of travelers, more studies in psychology and human behavior should be made. This is beyond our research domain.

# 8

# Conclusions and Further Research

The motivation for the research presented in this thesis is to clarify the concept of road network robustness as compared with network reliability, and find a suitable way to analyze the robustness of road networks. To do this, we proposed a framework in Chapter 4 for systematical and comprehensive studies on road network robustness.

In Section 8.1 of this concluding chapter is a brief summary of the research outlined in this thesis. Conclusions following from this research are drawn in Section 8.2, where some main results concerning modeling approaches and implications for traffic management will be presented. Several questions that remain unanswered will be proposed for further research in Section 8.3.

## 8.1 Brief summary

In this thesis, the concept of robustness for road networks has been clearly brought forward and distinguished from the topic of reliability for the first time. Based on the knowledge of the characteristics of a road network and its robustness, a framework for analyzing the robustness of road networks has been designed. It integrates two dynamic traffic assignment (DTA) models to represent road network performance under different traffic situations: a stochastic user equilibrium (SUE) assignment model for a daily normal situation, and an en-route assignment model for a situation with accidents. Combined with the method of scenario-based analysis, this framework provides the opportunity to analyze changes in network performance after the incidents in designed scenarios. The methodology and related methods constructed in this framework have been tested in two case studies. One tested network is a small road network (Chapter 5), and the other one is a real-sized road network in the west of the city of Amsterdam (Chapter 6). Both networks have a hierarchical structure, which means that parts of the network are superior in performance than other parts, such as city ringroads and urban arterial. This type of road network is prevalent in real life, especially in large modern cities. The robustness of these two networks has been analyzed through many incident scenarios, with disturbances on either link capacity or traffic demand. The results show the feasibility and capability of the proposed framework and the adopted DTA models for robustness studies of road networks. Dynamics in network performance and travelers' route choices have been well represented, which is the advantage of our framework and the combined DTA models. Furthermore, several preliminary conclusions about the robustness of road networks with hierarchical structure can be derived from the results. Generally speaking, motorway links and offramps in a road network are more critical than other types of links. Further studies on analyzing the impact on road network robustness of information services and travelers' perception level of the information show that real-time traffic information does not always bring positive effects to the road network. The influence of the real-time information on network robustness highly depends on the percentage of travelers who can receive and would like to respond. There exists an 'optimal' percentage value of the reacting travelers for the whole network performance. The study also shows that delay in the information services will worsen the traffic situation caused by the incidents.

## 8.2 Conclusions

Here we will summarize the main results established in the previous chapters. Each contribution is related to one of the questions arisen in Chapter 1 about road network robustness. We will distinguish between advances in the field of traffic modeling and advances in the field of network robustness analysis.

### Advances in Traffic Modeling

a. The stochastic user equilibrium (SUE) model can well represent the daily normal situation of a given road network, which can be used as a reference status of the network for the robustness analysis;

b. The en-route assignment model shows its advantages for road network robustness analysis in representing the choice behavior of travelers when they face unfamiliar and exceptional situations on their way;

c. Building up an en-route assignment model based on a SUE assignment model guarantees consistency in the assignment results and network performance before the incidents take place, which is necessary for fair comparisons;

d. The designed framework that combines both DTA models, i.e. SUE assignment model and en-route assignment model, satisfies the basic requirements of the systematical road network robustness analysis. Its capability has been proved through the case studies of two road networks with incident scenarios;

### Advances in Road Network Robustness Studies

e. Combining several criteria can give a preliminary but complete scan for the critical links in a road network. The criteria include the link $V/C$ value, link commonness, and special types of links;

f. For a road network with hierarchical structure, degradations of motorway links have more remarkable negative effects on the network performance than those of urban links;

g. Capacity degradation of off-ramp links also has a significant impact on the network performance, and sometimes the effects become comparable with the degradation of motorway links;

h. Increase in traffic demand shows complex sequences in network performance. When a network is originally very congested, extra demand has a significant negative impact on the whole network, and such impact lasts for a very long time. Furthermore, if extra demand must leave or enter the motorway, visible reductions in the network speed will appear;

i. A combination of several time-dependent performance indicators, such as average speed and network loading, can better describe the changes in network performance;

j. For assessing the importance of links on network robustness, comparing the influencing length ($IL$) and the influencing flow ($IF$) of different incident scenarios can give a direct and clear view;

k. Information services for real-time traffic status have a complex impact on road network robustness. Basically the effects of the information service depends on the compliance rate of travelers, and the delay in the information service will aggravate congestion in the network.

## 8.3 Further research

In this section we present topics for further research. The topics are grouped into the categories *DTA model* and *incident scenario*.

## DTA model

As we emphasized several times before, the accuracy of the DTA model(s) controls the validity of the analysis. In our studies, the MARPLE model and its en-route extension MARPLE-e are adopted mainly because it is the only model that has been calibrated and it is also the only one with which we could further develop. However, these models still can be improved with more advanced and accurate network loading algorithms. As mentioned in Chapter 4, our framework for road network robustness analysis has a open structure, which means that all suitable DTA models can be integrated. If other DTA models can realize both assignment methods with compatible sub-modules, they can also be integrated into the framework.

## Incident scenario

In the studies of this thesis, only the most basic and simple incident scenarios for a single link or single OD pair are analyzed. Such scenarios represent the typical accident situations that occur at one location in the network. However, a more serious situation might appear with more than one element of the road network being affected at the same time. For instance, an accident may also block the opposing traffic, which is more likely to occur on urban roads. So more complex incident scenarios need to be designed and analyzed for a more sophisticated analysis about road robustness.

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# A

# Tests of DTA Models

## A.1 Objective and Criteria of the Tests

In this appendix, five available DTA (dynamic traffic assignment) models are tested with a common road network. The outcomes of the network performance as well as the assignment results of these DTA models are compared. According to the discussions in Chapters 1 and 2, one one hand, DTA models are crucial for the calculation of road network performance; on the other hand, studies of road network robustness basically focus on the changes of network performance with and without incidents. This means that DTA models are also critical for road network robustness studies. It is known that one DTA model consists of several sub-models and for each of the sub-models, there exist different algorithms so as to different categories. This results in a great diversity of the existing DTA models, which also brings difficulties for us in choosing suitable DTA models for road network robustness analysis. Based on this fact, there are several reasons for us to carry out the comparison study presented in this appendix.

- A preliminary assessment of the ability of these DTA models for simulating real-size road networks is the main aim. In particular, the function and performance of the two different approaches of DTA models - SUE (stochastic user equilibrium) assignment approach and en-route assignment approach - in the case study need to be investigated;
- There is lack of knowledge about the influence of using different algorithms for each sub-model on the assignment results. For instance, several methods are available for path generation module as introduced in Chapter 3. For the same

testing road network, how many paths will different methods (with their default parameter settings) generate? How will the number of the generated paths influence the assignment results as well as the outcome of network performance? The answer to such questions can improve our understanding about DTA models;

- According to the framework proposed in Chapter 4, both SUE and en-route assignment approaches are necessary for network robustness studies. Through this test, we want to select the most suitable DTA model(s) for the analysis of road network robustness.

Since this is just a preliminary investigation on different DTA models without further calibration and validation process, and our main goal is to search for the most suitable DTA model(s) for the study of network robustness, we cannot make a rank of the tested DTA models based on current results. Thus the following criteria are used for our test and comparison:

- Time to achieve (approximate) equilibrium for SUE models;
- Path flows of a given OD pair;
- Several aggregated indicators for network performance.

This appendix is organized as follows. The first part is the introduction of the tested models. The second part is the description of the tested road network. The third part is the results of different models. Discussions are given in the last part.

## A.2 Introduction of the tested DTA models

In this study, five transportation models listed in Table 3.2 are tested with a common simple road network. These models are selected because first of all they are available of DTA function, including SUE assignment and en-route assignment functions. Secondly, they were available for us when this study was carried out. Thirdly, these models cover different categories of models, such as microscopic, macroscopic, and mesoscopic. Also various methods for each of the sub-models in DTA models are used in these tools. Thus through the comparisons of the assignment results and network performance outcomes within these models, at least some basic knowledge about the effects of these methods and models can be obtained.

In the following paragraphs, brief introductions of the tested DTA models are presented.

## VISSIM 3.70

VISSIM is a microscopic, time step and behavior based simulation model developed to model urban traffic and public transit operations by PTV Company, Germany. So in VISSIM simulation, every vehicle runs over the network by obeying a set of rules in several models, including route choice model, lane changing model, and car following model. It's DTA procedure is based on the idea of the iterated simulation, in which a modeled network is simulated with the traffic demand repetitively and the drivers update and choose their paths based on the path costs they have experienced during the preceding simulations. For the first iteration, shortest path in *length* of each OD pair is chosen for the assignment. In the following iterations, new paths are searched and generated (if necessary) for each demand interval based on the path costs calculated in the previous iteration. Thus the path generation in VISSIM takes the method of iteratively updating. The Kirchhoff distribution function shown in (A.1) is used for the discrete path choice of the traffic demand of each OD pair. The basic idea of the Kirchhoff model is that the traffic between an OD pair will be assigned to all the generated paths based on the relative utility differences among those paths, instead of using Logit function that considers the absolute utility differences among the paths.

$$\Pr(R_j) = \frac{U_j^k}{\sum\limits_i U_i^k} = \frac{1}{\sum\limits_i \left(\frac{U_i}{U_j}\right)^k} \tag{A.1}$$

in which:

| | |
|---|---|
| $\Pr(R_j)$ | probability of route $j$ to be chosen |
| $U_j$ | utility of path $j$, calculated as the reciprocal of the path cost $C_j$, i.e. $U_j = 1/C_j$ |
| $k$ | sensitivity of the model |

An important parameter for the Kirchhoff distribution is the sensitivity $k$ in the exponent. It determines how much influence to the assignment results the differences in utility have. A very low sensitivity would lead to a rather equal distribution with nearly no regard of the utility, and a very high sensitivity would force all drivers to choose the best route with the highest utility, i.e. the path with the lowest cost.

For determining the network equilibrium status, the maximum value of the path travel time differences being less than 5% between two consecutive simulations was selected as the criteria for convergence control. But practically, simulations were stopped after 100 iterations, in which only few paths (less than 3%) exceed the criteria, which could be considered as approx equilibrium.

## DYNASMART-P 1.0

DYNASMART-P is a dynamic network analysis and evaluation tool originally conceived and developed at the University of Texas at Austin. It is a tool for transportation network designing, planning, evaluation, and traffic simulation. DYNASMART-P models the evolution of traffic flows in a traffic network that results from the travel decisions of individual travelers. Packets of vehicles (the vehicles departure in a same period with same destination) compose the traffic flow and follow the pre-specified macroscopic traffic flow relationships. So it is a combination of micro assignment model and macro traffic flow model, which could be called a mesoscopic model.

DYNASMART-P can be deployed to operate in two distinct modes. These modes differ mainly in the assignment component applied. In the first mode, the vehicles are assigned to the best current path, random path or any pre-determined paths (e.g. historical paths). So it represents a one-run en-route simulation assignment approach with a recurrent all-or-nothing (AON) model for every user-defined time interval for the path choice. In the second mode, a consistent iterative assignment procedure is applied with the combination of the AON model and Method of Successive Average (MSA) over two successive iterations for the path choice. A predefined convergence criterion of the maximum value of the path volume differences in all the departure time intervals between two successive iterations is used to control the number of iterations.

## INTEGRATION

The INTEGRATION model was conceived during the mid 1980's as an integrated simulation and traffic assignment model. It uses the same logic to represent both freeway and signalized links, and both the simulation and the traffic assignment components are microscopic, integrated and dynamic. In order to achieve these attributes, traffic flow is represented as a series of individual vehicles that each follows pre-specified macroscopic traffic flow relationships, especially the speed-headway relationship that is considered to be monotone (i.e. the higher speed a vehicle has, the larger headway it needs). From this point, it is also a mesoscopic model.

INTEGRATION only has the en-route assignment approach. Each vehicle of a certain vehicle class chooses one downstream link when it is close to the completion of the current link. To determine the paths, all of the paths are eventually conveyed to the simulated vehicle using a look-up table format. This routing look-up table format provides, for each vehicle class, an indication of the next link to be taken towards a particular destination. In INTEGRATION, the default assignment mechanism was tested, In which the shortest path (in cost) is calculated for every scheduled vehicle departure interval, in view of the link travel times anticipated in the network at the time the vehicle will reach these specific links. The anticipated travel time for each link is estimated based on anticipated link traffic volumes and queue sizes.

## MARPLE

MARPLE (Model for Assignment and Regional PoLicy Evaluation) is the prototype of an integrated simulation and evaluation tool, and it is still under development. It is a fully macroscopic simulation model, in which traffic flow is represented by the prespecified macroscopic traffic flow relationships. MARPLE generates the path choice sets by an exogenous approach, in which a Monte Carlo method is implemented for finding multiple paths (if existing) for all the OD pairs. The number of paths for each OD pair is decided by several parameters, including the maximum number of paths, number of iterations of Monte Carlo method, and the upper limit of common links in different paths. The assignment model basically applied in MARPLE is C-logit model, which has been proved effectively in solving the problem of overlap in different paths of one OD pair. MARPLE uses the maximum ratio of the path flow differences of an OD pair between two successive iterations to the corresponding OD demand as the indicator to control the convergence. If the indicator values of all the OD pairs become smaller than a pre-defined threshold, the convergence is thought to be reached. Network loading in MARPLE is based on travel time functions, which are different for various link types.

### INDY 1.0

INDY (INterative DYnamic) traffic assignment model is developed by Delft University of Technology and TNO. It is one of the few truly multiclass analytical dynamic traffic assignment models that can include not only different driver classes, but also different vehicle classes. INDY and MARPLE have many similarities in their structures, algorithms and application domains. A Monte Carlo approach is used as an exogenous path generation method before the assignment and simulation. The route choice model is formulated as a variational inequality (VI) problem using a dynamic extension of Wardrop's equilibrium conditions developed by Chabini (1999) and Bliemer (2001). The VI problem is iteratively solved by using the method of successive averages (MSA) on the route flows. To assess the convergence, INDY uses the dynamic duality gap (summation of the differences between the shortest and average path travel costs) as a measure. According to our experience, the duality gap after 5 iterations for a small network would be less than 0.1%, which can be treated as the equilibrium. Thus in our study, the DTA execution is simply stopped after a given number (5 to 10) of iterations. It must be noticed that in INDY 1.0 version that we tested, the spill-back of queue was not available yet, which means that the queues are vertically cumulated in each congested link.

## A.3 Road Network Case

The main content of this case study is to test the DTA models in the above-mentioned five simulation tools with the same road network and the same demands. Such test study is based on the idea that for a simple road network, these DTA models are all able to give reasonable and close assignment results. Thus we want to give the comparisons on the following aspects:

- How much difference can be found in the results of the aggregated network performance within these DTA models? And what is the main reason for the differences?
- How much difference exists in the number of the generated paths within these DTA models? And what is the influence on the assignment results of the number of the generated paths?
- How much difference can be found in the assigned path flows within these DTA models?

The selected network is the simplified road network of Delft city in The Netherlands as shown in Figure A.1.

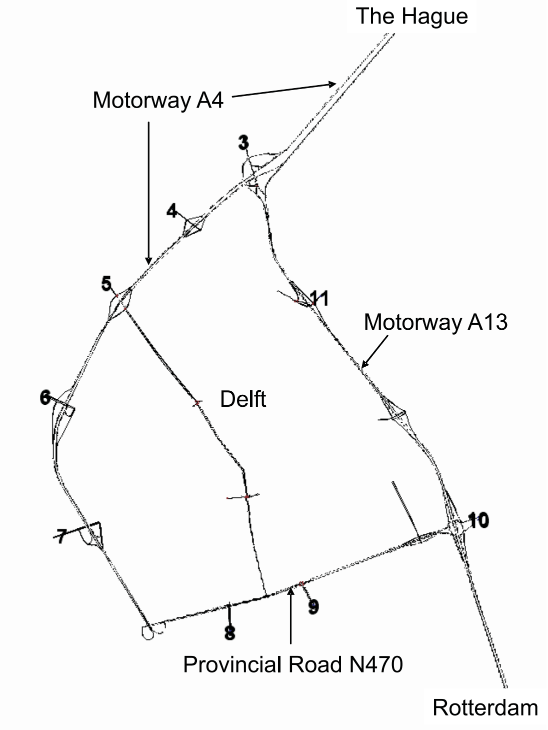


**Figure A.1: Layout of Delft network**

The chosen network locates between two important cities (The Hague and Rotterdam) in The Netherlands, which is an important corridor with large amount of traffic demand. Two motorway (A13 and A4) pass by Delft, which diverge at the north of Delft. A4 at this moment ends at the south-west corner of Delft and is connected to A13 with an urban arterial N470. In order to focus on the major traffic in the network, the minor arterial roads inside Delft city were ignored. There are 12 zones as origins and destinations, in which zone 1 and zone 2 represent The Hague and Rotterdam respectively and the trajectory length between them is about 11 km. The whole network consists of 93 nodes and 153 links in MARPLE model. But due to the different network representation methods in different models, these two values might have some variance in different models. For instance, in INDY model, between zones and links, there exists another type of link: *connection*. They are used for the traffic to enter the network strictly according to the schedule to avoid so-called *entrance delay* caused by the spillback of the queue to the zone. Thus INDY has several more links than MARPLE.

A time-dependent OD demand profile is used in this study to represent traffic conditions during the morning peak hour, including one hour increasing and one hour decreasing period respectively. The demand of three-hour duration is loaded to the network with 10-minute interval. After this three-hour non-zero demand, an extra period of half an hour with zero demand has been designed for the sake of clearing up the network. The peak hour demand for the whole network is about 24,000 vehicles/hour, in which about 13,000 vehicles travel between zone 1 and zone 2.

## A.4 Results

The results of this comparison study can be divided into two parts: network performance part and traffic assignment part. They will be illustrated separately in the following two sections.

### Network performance

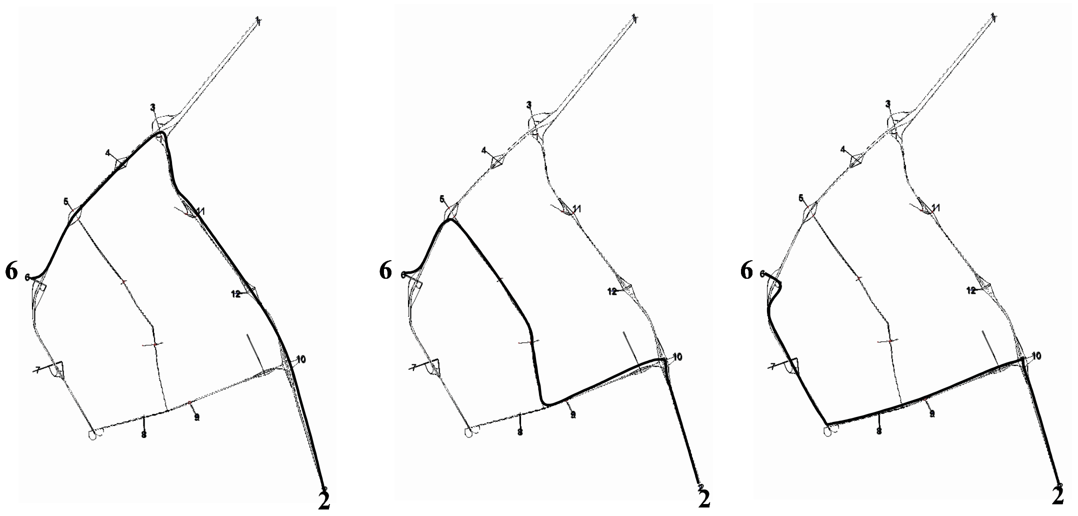
Three performance indicators, including the number of paths (NP), average travel distance (ATD) and average network speed (ANS) are listed in Table A.1. NP is used to reflect the path generation results. ATD is normally used to reflect the path assignment results. Higher values of ATD means that more traffic has been assigned to the *longer* paths in distance. ANS, which is defined as the ratio of the total travel distance and total travel time for the whole network, is used to indicate the performance of the whole road network by loading the traffic according to the assignment results. Furthermore, for SUE assignment models, the simulation time needed to achieve the (approximate) equilibrium are also listed in the table.

**Table A.1: Network performance indicators**

| | | NP | ATD (km) | ANS (km/h) | Time for Equilibrium |
|---|---|---|---|---|---|
| VISSIM 3.70 | | 126 | 8.72 | 36.7 | $>$ 8 hours |
| INTEGRATION | | 159 | 8.26 | 30.6 | – |
| DYNASMART-P 1.0 | UE | 304 | 7.93 | 37.7 | $\approx$ 3.5 min |
| | en-route | 533 | 8.43 | 35.5 | – |
| MARPLE | | 168 | 8.18 | 76.6 | $\approx$ 2 min |
| INDY 1.0 | | 170 | 8.18 | 56.0 | $\approx$ 4 min |

### Path assignment

To analyze time-dependent path flows (TPF), the traffic between zone 2 and zone 6 was selected, because for this OD pair same three paths (Figure 3) were generated in most tools.



Path 1 (13.53km, 8.16min) Path 2 (11.55km, 9.40min) Path 3 (12.05km, 9.28min)

**Figure A.2: Generated paths between zone 2 and zone 6**

Basically, the assignment results in path flows are presented for each so-called *departure interval* because the assignment is normally done at the beginning of each interval and be effective for all the vehicles that are assigned to depart within the interval. Unfortunately, INTEGRATION couldn't give the information of paths, and VISSIM 3.70 can only supply the path flow information for the vehicles arriving at the destination. So only the results of the other three models are shown in Figure A.3.

## A.5 Discussion

The discussions of the assignment results from these tested DTA models will be mainly on two aspects. One is the path generation, and the other is the path assignment. Both of them have significant influences on the outcomes of the network performance.

### Time for equilibrium

From Table A.1, it is clear that much longer time needed to achieve the equilibrium is a great disadvantage for a microscopic model. Compared with other macroscopic and mesoscopic models, VISSIM seems to lack of a good converging algorithm that can average the path flows in two consecutive iterations to make a faster convergence.

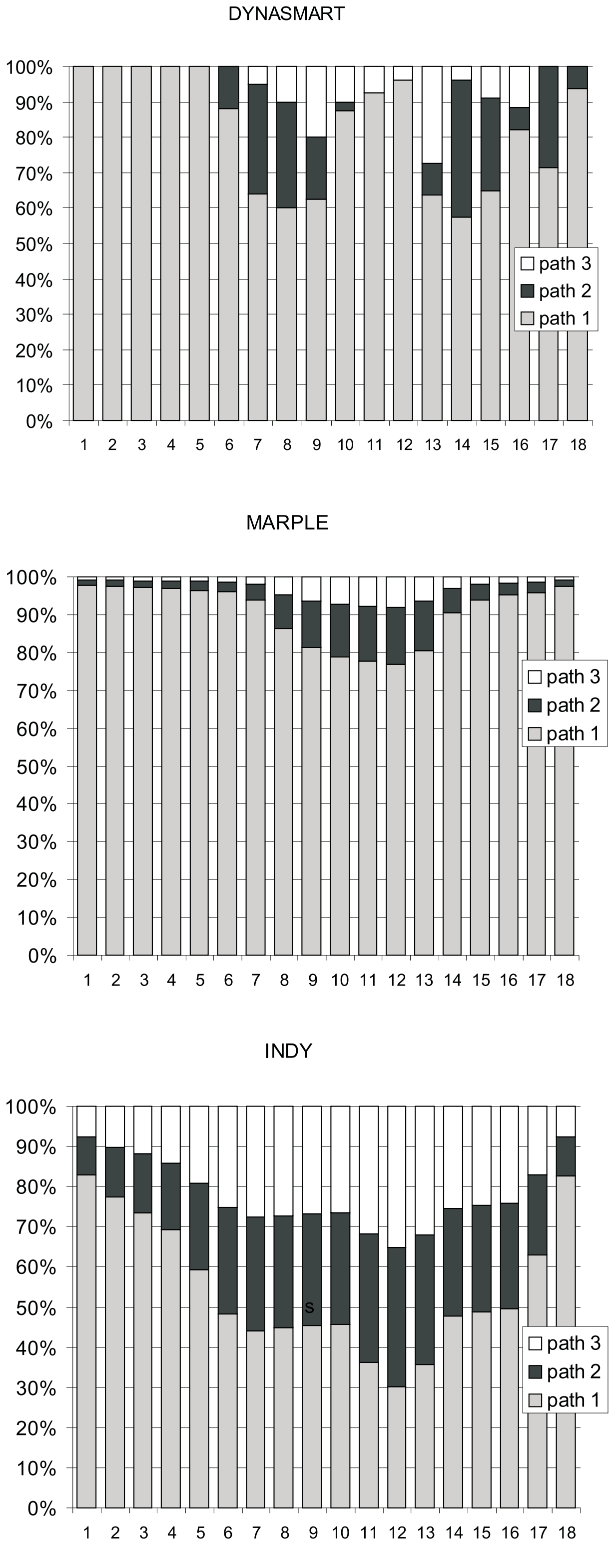


**Figure A.3: Assignment results within the paths between zone 2 and zone 6**

It is probably caused by its microscopic and random features, which result in great variations of the travel costs within vehicles that are from the same OD pair and arrive at the destination zone during a given interval. The average value of these travel costs is used for the path assignment of next interval, so that it is more difficult to control the convergency of a microscopic model than other types of models.

## Path generation

As listed in Table A.1, DYNASMART-P generated many more paths than other models, especially for its en-route assignment function. This might be due to the default value of the threshold setting for the new path generation in the iteratively updating approach used in DYNASMART-P. When this threshold value is low, new paths are easily generated even if they only have very little advantages over the existing paths for a very short period. This remarkably increases the total number of the paths. As a result, these new paths are valid very shortly and only a small amount of traffic is assigned to them. By checking the path flows, we found that over 50% of the paths generated by DYNASMART can be ignored since less than 5 vehicles used them during the whole simulation period. From this point of view, we may say that with the default setting values, the path generation model in DYNASMART is sensitive to the small changes in the road network.

Little differences exist between the number of paths in MARPLE and INDY because they adopt similar exogenous path generation approach. It has been pointed out by Fiorenzo-Catalano (2007) that this approach is the most preferable method to generate an adequate choice set for prediction purposes and for groups of travelers. An obvious effect of such method is that the number of paths is fixed during the whole simulation period so that new paths cannot be added when they are needed in case of urgency. For instance, during the accidents or natural catastrophe, traffic must use some paths that have never been used under the normal situation, which is very important for the network robustness analysis. Then DTA models with the exogenous path generation approach have difficulties in dealing with such problems.

From the NP values, these six DTA tools can be classified into three groups. DYNASMART created the largest amount of paths, while VISSIM and INTEGRATION created the least amount of paths, and the number of paths from MARPLE and INDY is in between. It is interesting to notice that for both situations with larger and less numbers of paths, the network performance outcomes are ‘*worse*’ (with very low average network speed) than that of MARPLE and INDY. On one hand, it is probably due to the fact that both MARPLE and INDY are macroscopic models. They have less details in the movement of traffic flow than the other tested models, which might result in less delay. On the other hand, the importance of the NP values to the network performance outcomes cannot be ignored. For this phenomenon, (Bliemer et al., 2007) made a more in-depth analysis about the impact of the amount of generated paths in the outcomes of the multinomial logit (MNL) model and the path-size logit (PSL) model.

### Path assignment

By comparing the path flows in Figure A.3, distinct differences can be found within the tested DTA models. Such differences are resulted not only from different path generation methods (e.g. exogenous path generation method used in MARPLE and INDY, and iterative updating method used in DYNASMART), but also from different assignment and network loading models (i.e. MARPLE and INDY). The equilibrium assignment approach of DYNASMART-P gave out discontinuous changes in the path flow distributions. As we discussed before, the iteratively path updating method in DYNASMART-P generated or delete large numbers of new paths for very short period (e.g. one or several intervals). Thus the assignment results within different amount of paths presents fluctuant even in consecutive intervals. On the contrary, more continuous changes in the path flow distributions appear in the results of both MARPLE and INDY. But their differences are also remarkable mainly because of different assignment model and network loading model used in them.

## A.6 Conclusion

The study presented in this appendix was carried out as the preliminary step of our road network robustness analysis in order to get more knowledge about how a DTA model functions in a road network and which sub-model(s) is most crucial for the outcomes. Due to the lack of real traffic data, especially the data of the OD traffic demand and data of the route choice of travelers, we could not make further calibration and validation work for any model. So it is difficult to give even a brief conclusion on which model gave the best assignment results. However this is not a trivial study because some valuable gains about DTA models, especially the applicability of different DTA approaches for road network robustness studies can be achieved from it:

- Microscopic DTA model (VISSIM) needs much longer processing time to reach (approximate) equilibrium status of a road network than other types of models. Its results of the network performance also have lower values than other models. One of the reasons might be its microscopic feature in describing vehicles behavior in more detail;

- Exogenous path generation method (used in MARPLE and INDY) seems to generate reasonable path assignment results for a UE assignment approach;

- The assignment results of an en-route assignment approach (including en-route path generation method) show a kind of '*discontinuity*' (sometimes even fluctuating) because of the periodical updating of the paths and assignment. This seems to be an inevitable phenomenon of an en-route assignment model. However, in the analysis given in Chapter 5 and 6, we found that such phenomenon does not result in large fluctuations on the network performance.

# B

# MARPLE and MARPLE-e

In this appendix, a detailed introduction is given about two DTA models, i.e. MARPLE for SUE (stochastic user equilibrium) assignment and MARPLE-e for en-route assignment. Those models are currently implemented in our framework for the analysis of road network robustness proposed in Chapter 4. As shown in Figure 3.2, the essential difference between the SUE assignment model and the en-route assignment model exists in the assumption of whether the network reaches an equilibrium assignment results or not. According to the requirements of the assignment results for each step of the framework, MARPLE and MARPLE-e (MARPLE en-route) are used in different steps. In the following content, MARPLE and MARPLE-e will be compared from two points: path generation and traffic assignment. After the comparisons, the detailed process of MARPLE-e is described in a separate section.

## B.1 Path Generation

### MARPLE

MARPLE adopts an exogenous path generation method to build up the predefined set of paths for each OD pair of the road network before the iterative assignment process. This means that all the paths for the assignment are generated independently from the network performance, which is the outcome of the assignment and loading of the traffic demand over these paths. The strength of this method is that the paths can be computed and checked in advance firstly to avoid the appearance of the '*irrational*' paths; and secondly to reduce the computation time from generating the paths sets for every iteration. There also exist several weakness of such method. The first is that it is difficult to guarantee that all the generated paths are used in reality and all the used paths in reality are generated. The second is are that the generated paths cannot be updated and complemented during the subsequent assignment.

The method used in MARPLE for the enumeration of paths is a combination of several methods: the *K-shortest paths method*, the *essentially least cost paths method*, and the *most probable paths method*.

- *K-shortest paths method*: This method gives the shortest $k$ paths of each OD pair. The shortest path is found for every searching iteration till $k$ paths, if available, are found;
- *Essentially least cost paths method*: This method is similar to the *k-shortest paths method*, but restricts the paths to a certain predefined bandwidth. Only paths that have the length within a certain bandwidth are included in the set of paths;
- *Most probable paths method*: This is another method to restrict the set of paths, using Monte Carlo simulation. A number of times the link costs are randomly varied according to a certain distribution and the shortest path is calculated and added to the path set.

In MARPLE, with the Monte Carlo simulation method the link costs are varied randomly within a certain bandwidth by using a scale factor. With the randomly adjusted link costs the shortest path can be calculated and added to the set of paths if it is shorter than the k-th shortest path and doesn't have too much overlap with the existing paths in the path set. The overlap control is calculated by the length of the common links between the new path and all the existing paths. The generated paths set of MARPLE for the equilibrium assignment is labeled as $EPS$ (equilibrium paths set), and the corresponding results for evaluation interval $t$ are $EPF(t)$ for the equilibrium paths' flows and $EPC(t)$ for the equilibrium paths' costs.

## MARPLE-e

The essential characteristic of an en-route traffic assignment model different from a UE assignment model is that it updates path sets and assigns traffic for every evaluation interval. In the developing process of MARPLE-e from MARPLE, such characteristic is realized based on several assumptions about travelers' behavior on path updating and path assignment en-route. These assumptions are listed in the following texts. For simplicity and generality, all the variables with subscript $od$ indicate that they are related to the traffic demand from origin $o$ to destination $d$.

*General path updating assumptions*

1. For each evaluation interval, the path sets and assignment results for all the OD pairs are calculated before the interval. Such results are fixed for each interval, but might be different between different intervals;

2. Travelers are willing to stay on their experienced paths for the coming evaluation interval $t$, i.e., the original equilibrium path sets $EPS^{od}$ or the old path set $PS^{od}(t-1)$ for the previous interval $t-1$, unless the differences between the perceived instantaneous path costs of the old paths and the new path exceed a certain threshold;

3. For each interval $t$, each OD pair can add at most one new path $\hat{r}^{od}(t)$. In detail, following conditions must be satisfied if the new path $\hat{r}^{od}(t)$ can be added for $(o,d)$:

    - $\hat{r}^{od}(t)$ must not be in the existing path sets $PS^{od}(t-1)$, i.e.

    $$\hat{r}^{od}(t) \notin PS^{od}(t-1) \tag{B.1}$$

    - The cost $C_r^{od}(t-1)$ of any path $r^{od}(t-1) \in PS^{od}(t-1)$ must be larger than $\alpha$ times the cost of $\hat{r}^{od}(t)$, i.e.

    $$C_r^{od}(t-1) > \alpha C_{\hat{r}}^{od}(t), \forall r^{od}(t-1) \in PS^{od}(t-1) \tag{B.2}$$

    where the parameter $\alpha$ is used to illustrate travelers' willingness to use the new paths. The higher value of $\alpha$ is, the higher probability of the travelers to continue using the known paths, i.e. $PS^{od}(t-1)$. So the new assignment for interval $t$ will be done within the old paths.

## B.2 Traffic Assignment

### MARPLE

In our application of MARPLE model for the analysis of road network robustness, stochastic user equilibrium (SUE) method with the C-Logit method is adopted.

The definition of dynamic SUE can be defined as:

**Definition 1** *For a road network, the perceived path travel costs for all users traveling between a specific OD pair and departing during a specific time interval are equal, and less than (or equal to) the perceived path travel costs of any unused feasible path.*

The perceived path cost $\overline{c}_i^{rod}(t)$ for traveler $i$ using path $r$ of OD pair $od$ and time period $t$ can be represented by

$$\bar{c}_i^{rod}(t) = c^{rod}(t) + \varepsilon_i^{rod}(t) \tag{B.3}$$

where $c^{rod}(t)$ is the real travel cost of path $r$ and $\varepsilon_i^{rod}(t)$ is the random component for the traveler $i$. When $\varepsilon_i^{rod}(t)$ is assumed an independently and identically distributed Gumbel variate over all the travelers, the choice probability for path $r$ can then be described by

$$P^{rod}(t) = \frac{exp\left(-\theta c^{rod}(t)\right)}{\sum\limits_{s\in R^{od}} exp\left(-\theta c^{sod}(t)\right)} \tag{B.4}$$

where $\theta$ is a parameter that reflects the degree of uncertainty in the travel time knowledge of the road users. When $\theta$ approaches infinity, perfect knowledge is assumed and the deterministic user equilibrium solution is obtained. To overcome the problem of paths overlapping, the C-Logit model (Cascetta et al., 1996) is used here by taking into account the overlaps in paths with the so-called commonality factor *CF*. The most common specification of *CF* for path $r$ is given by

$$CF^{rod}(t) = \beta ln \sum_{s\in R^{od}} \left[\frac{L_{rs}(t)}{\sqrt{L_r(t) L_s(t)}}\right]^{\gamma}, \forall o, d, r \in R^{od}, t \tag{B.5}$$

where $L_r$ and $L_s$ are the 'lengths' of paths $r$ and $s$ belong to OD pair $od$, and $L_{rs}$ is the 'length' of the common links shared by paths $r$ and $s$. $\beta$ and $\gamma$ are positive parameters. 'Length' can be physical length or the 'length' determined by travel costs. In MARPLE and our applications, travel times are used, so they can be different in different intervals $t$. With this commonality factor and the known travel costs, the probability $P^{rod}(t)$ of choosing path $r$ of OD pair $od$ for the time period $t$, and the corresponding flow $f^{rod}(t)$ are given by

$$P^{rod}(t) = \frac{exp\left(-\theta c^{rod}(t) - CF^{rod}(t)\right)}{\sum\limits_{s\in R^{od}} exp\left(-\theta c^{sod}(t) - CF^{sod}(t)\right)} \tag{B.6}$$

$$f^{rod}(t) = P^{rod}(t)\, q^{od}(t), \forall o, d, r \in R^{od}, t \tag{B.7}$$

## MARPLE-e

MARPLE-e uses the same path level assignment model, but two important changes have been made as follows:

1. Instead of using real path travel time as the travel cost in MARPLE, MARPLE-e uses instantaneous path cost as the travel cost. It is due to the fact that in the en-route assignment approach, it is difficult to predict the future traffic situation and get the real path travel time. Thus in most of the en-route traffic assignment models, instantaneous path cost is used for the update of path set and assignment;

2. MARPLE-e can take into account the willingness of travelers to make the changes in their path choice. This is not only done through introducing multiple types of travelers with different $\theta$ values in (B.4), but also controlled by an external parameter $\alpha$ that is introduced in Chapter 7.

## B.3 MARPLE-e

Based on the assumptions for the en-route path updating algorithm and the assignment model (C-Logit model), the flowchart shown in Figure B.1 has been built up for the complete en-route assignment process in MARPLE-e.

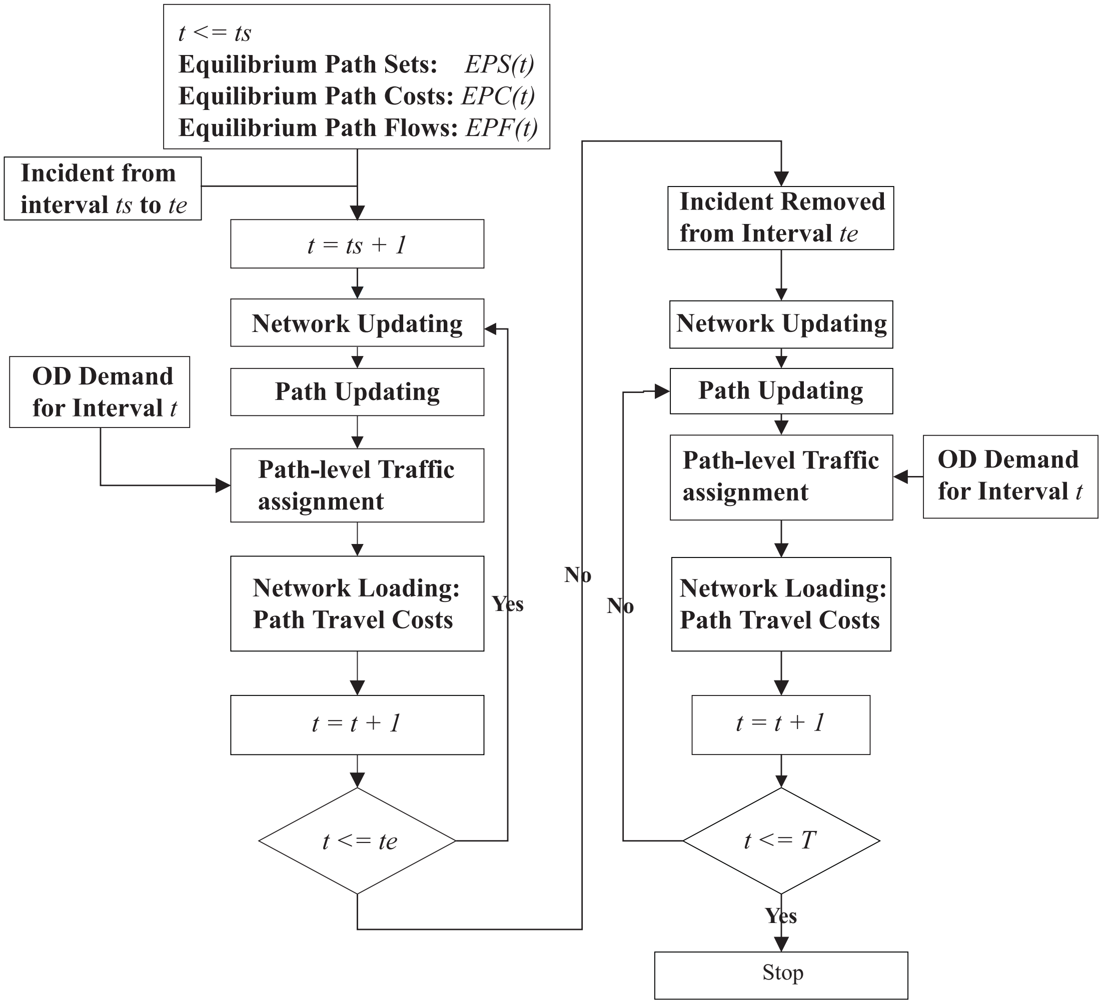


**Figure B.1: MARPLE-e (One-shot simulation-assignment procedure)**

The flowchart clearly illustrates that the whole en-route assignment process starts from the interval when the incident starts, and ends till the end of the whole studying period. Although the incident might be removed from the network after certain time, its influence on the network performance and travelers' route choice will last longer.

# C

# Influence of Multiple User Types on Traffic Assignment Results

In this appendix, the influences of the introduction of multiple user types into the analysis of traffic assignment and network performance are studied. This is because in reality travelers can rarely be treated as one uniform group with the same behavior (e.g., all travelers have the same reaction to one traffic condition or one information about the traffic condition). Thus there always exist differences in the perception of information and preference within travelers. In Chapter 4, we mentioned that in the MARPLE model and its en-route extension MARPLE-e model, such different types of travelers are distinguished by using different values of $\theta$ parameter in the *C-Logit* model. In this model, the smaller value $\theta$ is, the less accurate information travelers can perceive, so that travelers will more randomly choose their path within the generated paths or, in other words, they will insist more on using their original path(s). By following the research work of MARPLE by (Taale et al., 2004), three types of travelers are categorized by using three $\theta$ values, i.e. 0, 1, and 3. Travelers with $\theta = 3$ are supposed to receive complete and accurate real-time traffic information and update their path choices en-route based on these information. On the contrary, travelers with $\theta = 0$ cannot perceive (accurate) traffic information at all so that they can only randomly choose one of the available paths. Travelers with $\theta = 1$ then can receive partly accurate information and part of them are willing to update their paths from their original paths. Each of the travelers is assumed to be one type of these three.

The combination with these three types of travelers from the literature will also be tested and compared with three other combinations in which each combination only has one type of travelers as listed in Table C.1. Three value sets with single user type is denoted as *VS1*, *VS2*, and *VS3*, and the value set with the combination of those three types of travelers is denoted as *VS4*.

**Table C.1: Value sets of combinations among multiple user types**

| Value Set | User Type 1 ($\theta = 0$) | User Type 2 ($\theta = 1$) | User Type 3 ($\theta = 3$) |
|---|---|---|---|
| *VS1* | 100% | 0 | 0 |
| *VS2* | 0 | 100% | 0 |
| *VS3* | 0 | 0 | 100% |
| *VS4* | 30% | 50% | 20% |

In order to thoroughly illustrate the influence of different value sets to the results of road network performance, both the equilibrium assignment (i.e. $\omega_0$) and en-route assignment for a common road network with the lower demand pattern are analyzed in this section. For incident scenario, we choose the scenario of *Link 4* having -50% capacity degradation, i.e. one sub-scenario of $\omega_2$ as an example. The results are presented for aggregated indicators and time-dependent indicators separately.

## C.1 Aggregated indicators for network performance

In Table C.2, values of the aggregated indicators that include $TTD_0$, $TTT_0$, $TD_0$ together with the numbers of iterations for the system to achieve stochastic user equilibrium (SUE) in $\omega_0$ are listed.

**Table C.2: Values of aggregated indicator and No. of iterations to achieve SUE in $\omega_0$**

| Case | $TTD_0$ | $TTT_0$ | *TNA* | No. iterations |
|---|---|---|---|---|
| VS1 | 340291 | 7620 | 17700 | 13 |
| VS2 | 342659 | 3204 | 17700 | 23 |
| VS3 | 341562 | 3099 | 17700 | 15 |
| VS4 | 343004 | 3447 | 17700 | 17 |

In Table C.3, values of the aggregated indicators and *ETD* in $\omega_2$ can be found.

In the C-Logit model, $\theta$ is a measure of the accuracy level of travelers' perceived information. For travelers with $\theta = 0$, they cannot get any (correct) information so that their route choice behavior is totally random. Thus the assignment results for these travelers display an equally distribution among the generated paths, which neglects the differences of the path costs. This causes the extremely high value of $TTT_0$ for VS1

**Table C.3: Values of aggregated indicators in $\omega_2$ with 50% capacity degradation**

| Case | $TTD$ | $TTT$ | $ETD$ | $TNA$ |
|---|---|---|---|---|
| VS1 | 335734 | 5208 | -2412 | 17700 |
| VS2 | 335466 | 7489 | 4285 | 17700 |
| VS3 | 332970 | 7823 | 4724 | 17700 |
| VS4 | 336158 | 4988 | 1541 | 17700 |

because 50% of the traffic between (O1,D1) will use *Path 2*, which makes link 7 a big bottleneck. But much less delay appears for VS1 in $\omega_2$, i.e. $ETD < 0$ because one new paths (*Path 3* has been added for OD pair (O1,D1) from about 800 seconds after the incident started, which was assigned 1/3 of the traffic. Contrary phenomena appears for cases VS2 and VS3, which are also composed of single type of travelers. *TTT* values are small in $\omega_0$, while increase remarkably in $\omega_2$. In case VS4 with multiple types of travelers, although *TTT* values in $\omega_0$ are higher than that of VS2 and VS3, much less $ETD$ is generated in $\omega_2$, resulting in a smaller value of $TTT$. It is evident from such phenomena to derive the following remarks:

- A network only with ‘blind’ travelers (i.e. $\theta = 0$) performs irrational because of the random assignment within all the generated paths.
- If all the travelers get the same accurate information and act the same (i.e. uniform $\theta > 0$), the network performs better for daily normal situation. But when the network is disturbed by some exceptional incidents, the performance of the network decreases tremendously. This is because all the travelers dynamically choose the path with the lowest cost, which results in new bottlenecks and new delay in the network. Thus the network becomes sensitive to the changes of the traffic states and becomes unstable.
- The results of case VS4 show that the combination of multiple user types successfully achieves the balance of the above two cases and avoids the shortcomings of them. On one hand, it represents daily normal traffic situation with satisfactory low delay. On the other hand, it also represents road network performance under incident situations by avoiding the irrational changes appeared in other cases.

To better understand and explain these aggregated indicators of the network performance, the analysis of the changes in the time-dependent performance indicators and OD flow assignment are presented in the next section.

## C.2 Time-dependent performance indicators

In Figure C.1, changes in *NAS* and *NL* are illustrated by comparing the results between scenarios $\omega_0$ (with full capacity) and $\omega_2$ (with 50% capacity decreasing on Link 4).

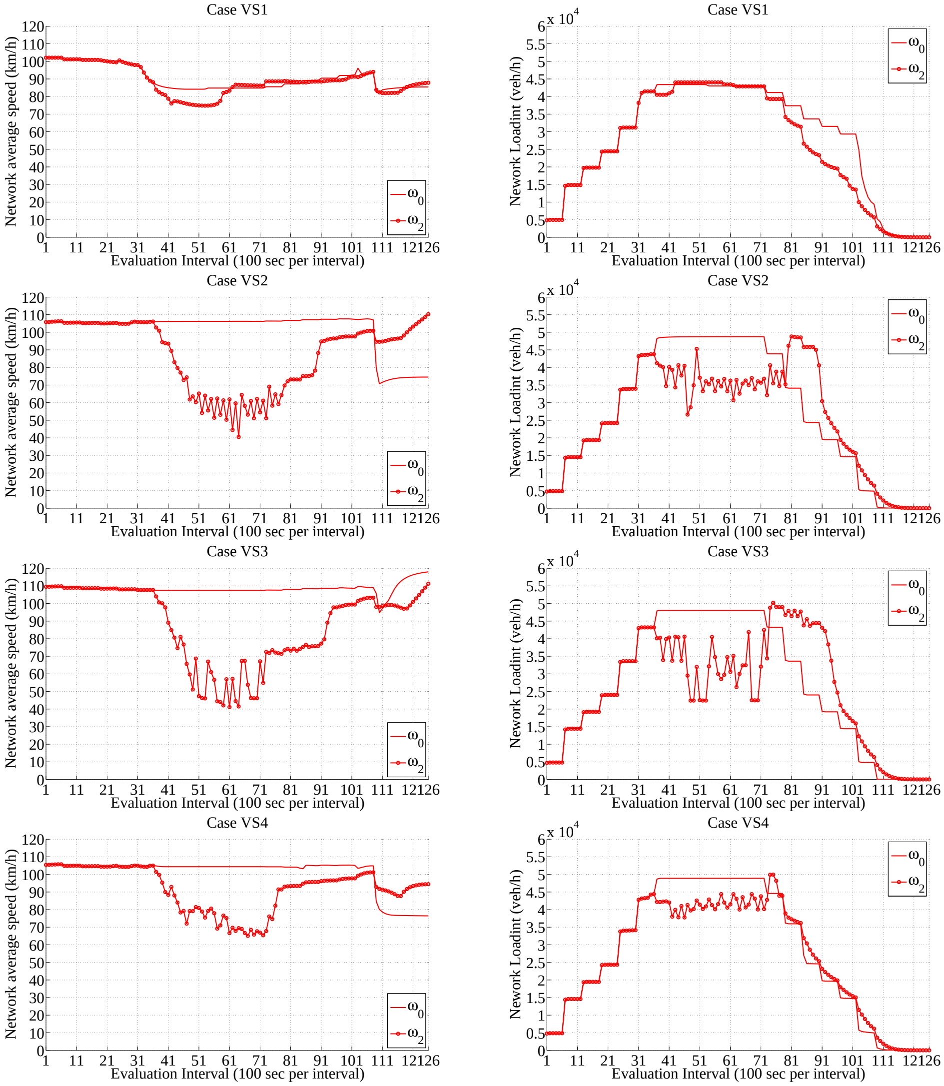


**Figure C.1: Comparisons of time-dependent performance indicators for $\omega_0$ and $\omega_2$ with *NAS* (left) and *NL* (right)**

It is clear that in case *VS1*, values of *NAS* and *NL* are the lowest for $\omega_0$, but their reduction in $\omega_2$ are also the least, or even increase sometimes. In other three cases, values of *NAS* and *NL* are similarly higher, but their reductions during and after the incident are quite different, for which case *VS4* performs the most stable. By analyzing the route assignment results in these cases, we can better understand the basic reasons for these outcomes. Besides case *VS1*, in which travelers are always equally distributed among the generated paths, the assignment results for (O1,D1) in cases *VS2*, *VS3*, and *VS4* are illustrated in Figure C.2.

It is clear that the introduction of multiple user types are of great importance in achiev-

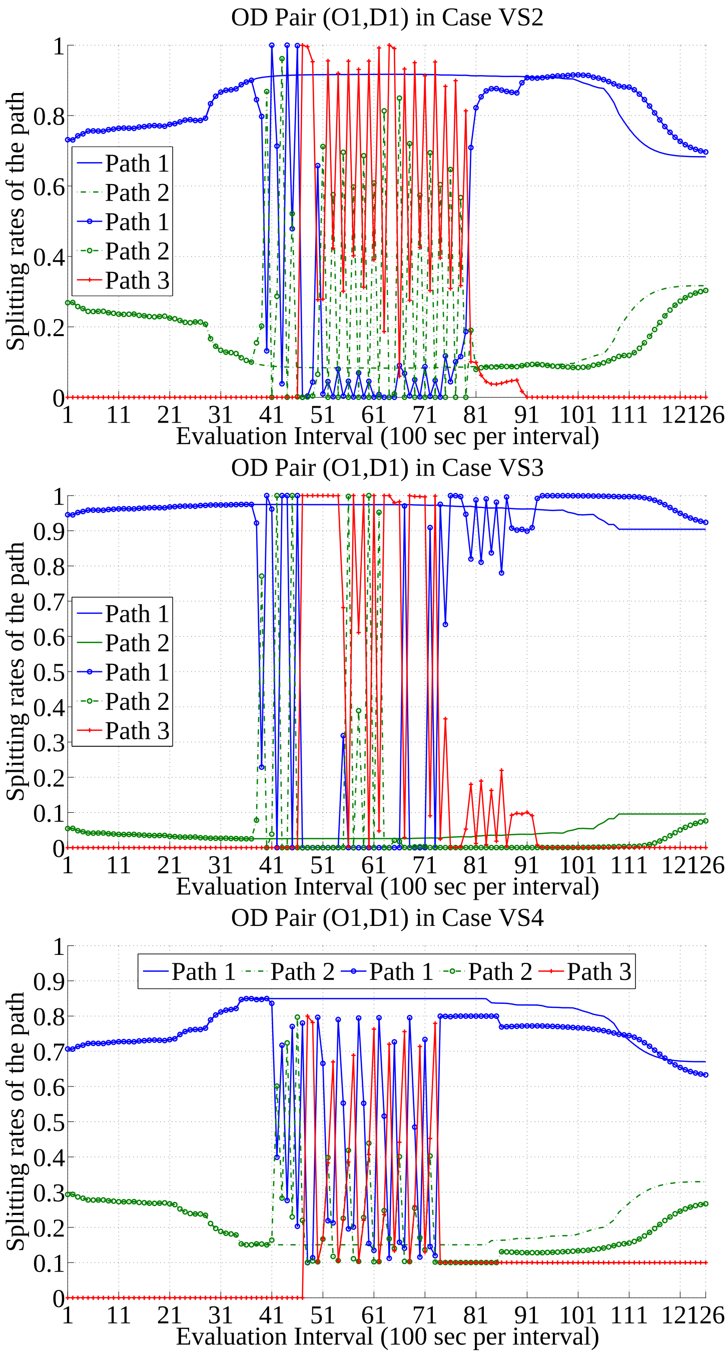


**Figure C.2: Comparisons of time-dependent splitting rates among the paths of OD pair (O1,D1) in cases VS2, VS3, and VS4**

ing rational (probably valid) assignment results, so as to the results of the whole network performance. Cases with single user type either gives out unrealistic results, such as VS1; or make the travelers more sensitive and the path choice results more fluctuant, such as VS2 and VS3. Case with multiple user types (VS4) produced more gradual changes in route assignment results and rational deteriorations of network performance in the incident scenario. So in this thesis, values in VS4 will be chosen for network robustness studies in Chapter 5 and 6. It must be pointed out that the oscillation in the assignment results of VS4 (also in VS2 and VS3) is the artefact of the en-route assignment model in which the network performance is evaluated and the assignment is recalculated for every intervals. Although such oscillation is remarkable, the time-dependent aggregated network performance indicators, such as *NAS* and *NL*, are much more stable, which means that the frequent changes in the assignment don’t influence the network performance so much. Therefore, there is no reason to worry about the remarkable oscillations in the network performance.

# D

# Pre-selection results of A10-West network

In this appendix, results of the pre-selecting and filtering process for searching for the possible critical links in A10-West network in Section 6.3 are listed. These results are classified according to the different selection criteria.

## D.1 Top 100 Busiest Links in A10-West Network

In this section, top 100 busiest links, i.e. links with the highest values of their maximum flow/capacity *V/C* ratios are listed in Table D.1 with their *V/C* ratio values. Their positions in the road network are demonstrated in Figure D.1. It must be mentioned that the capacity value *C* used here is the desired link capacity, which is not the real throughout capacity for a link with controlled end junction.

**Table D.1: Top 100 busiest links**

| Rank | Link ID | V/C | Rank | Link ID | V/C | Rank | Link ID | V/C |
|---|---|---|---|---|---|---|---|---|
| 1 | 818 | 1.000 | 35 | 856 | 0.772 | 68 | 1921 | 0.648 |
| 2 | 822 | 1.000 | 36 | 802 | 0.770 | 69 | 2389 | 0.648 |
| 3 | 864 | 1.000 | 37 | 2040 | 0.762 | 70 | **889** | 0.644 |
| 4 | *2277* | 1.000 | 38 | **728** | 0.761 | 71 | 726 | 0.642 |
| 5 | 854 | 1.000 | 39 | 897 | 0.754 | 72 | **810** | 0.640 |
| 6 | 725 | 1.000 | 40 | 1123 | 0.742 | 73 | 806 | 0.637 |
| 7 | 823 | 1.000 | 41 | 808 | 0.739 | 74 | 831 | 0.633 |
| 8 | **2307** | 0.985 | 42 | 1926 | 0.739 | 75 | ***2221*** | 0.629 |
| 9 | 820 | 0.983 | 43 | 863 | 0.732 | 76 | **2362** | 0.626 |
| 10 | 849 | 0.961 | 44 | 870 | 0.732 | 77 | **732** | 0.622 |
| 11 | ***2228*** | 0.954 | 45 | 853 | 0.729 | 78 | 601 | 0.622 |
| 12 | **2346** | 0.948 | 46 | 859 | 0.706 | 79 | *2245* | 0.612 |
| 13 | 872 | 0.947 | 47 | 842 | 0.703 | 80 | 891 | 0.612 |
| 14 | 824 | 0.930 | 48 | 2319 | 0.702 | 81 | **1200** | 0.599 |
| 15 | **2305** | 0.930 | 49 | 821 | 0.701 | 82 | **2236** | 0.598 |
| 16 | 851 | 0.911 | 50 | **1197** | 0.699 | 83 | **2229** | 0.598 |
| 17 | **2304** | 0.911 | 51 | 2364 | 0.689 | 84 | 1280 | 0.597 |
| 18 | 2288 | 0.901 | 52 | 235 | 0.687 | 85 | 847 | 0.596 |
| 19 | 2318 | 0.900 | 53 | 708 | 0.687 | 86 | **888** | 0.594 |
| 20 | 848 | 0.894 | 54 | **15** | 0.678 | 87 | 729 | 0.594 |
| 21 | **1250** | 0.891 | 55 | 894 | 0.676 | 88 | 1872 | 0.593 |
| 22 | 868 | 0.871 | 56 | **108** | 0.673 | 89 | 1289 | 0.593 |
| 23 | **2233** | 0.866 | 57 | **1810** | 0.673 | 90 | 1840 | 0.592 |
| 24 | 855 | 0.858 | 58 | 2296 | 0.667 | 91 | 1249 | 0.592 |
| 25 | 861 | 0.852 | 59 | **1195** | 0.667 | 92 | 1045 | 0.589 |
| 26 | 2317 | 0.836 | 60 | 819 | 0.667 | 93 | **2173** | 0.585 |
| 27 | *2227* | 0.826 | 61 | **735** | 0.663 | 94 | **2084** | 0.585 |
| 28 | 1308 | 0.816 | 62 | 1353 | 0.659 | 95 | 1282 | 0.578 |
| 29 | 893 | 0.810 | 63 | **843** | 0.658 | 96 | 1128 | 0.570 |
| 30 | 2264 | 0.806 | 64 | **2330** | 0.658 | 97 | 2251 | 0.569 |
| 31 | 2234 | 0.784 | 65 | 846 | 0.656 | 98 | 1835 | 0.566 |
| 32 | 1116 | 0.782 | 66 | **815** | 0.655 | 99 | 2303 | 0.564 |
| 33 | 2321 | 0.782 | 67 | **1660** | 0.653 | 100 | 874 | 0.563 |
| 34 | 2302 | 0.777 |  |  |  |  |  |  |

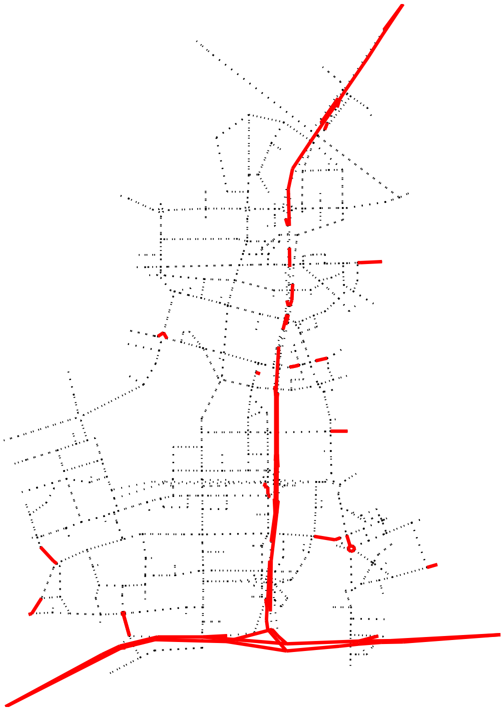


Figure D.1: Top 100 busiest links in A10-West Network

## D.2 Top 100 Common Links in A10-West Network

In this section, top 100 common links, i.e. links used by different paths most frequently are listed in Table D.2 with the number of paths that include the link. Their positions in the road network are demonstrated in Figure D.1.

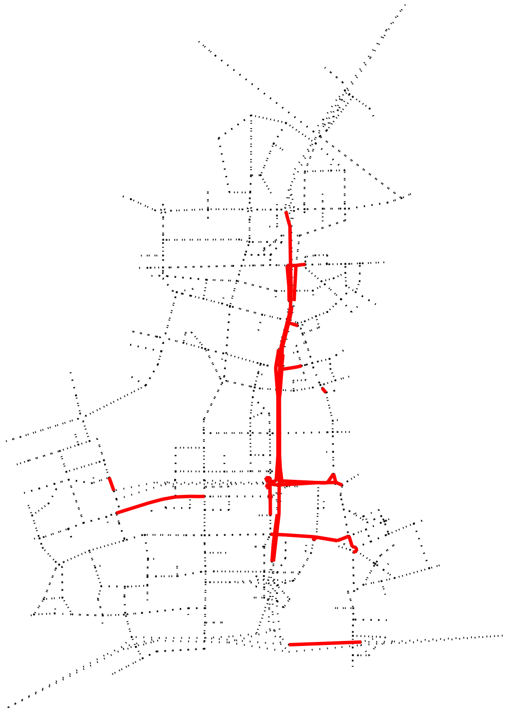


**Figure D.2: Top 100 common links in A10-West network**

**Table D.2: Top 100 common links**

| Rank | Link ID | Frequency |
|---|---|---|
| 1 | **889** | 1447 |
| 2 | **2229** | 1411 |
| 3 | 112 | 1076 |
| 4 | **735** | 1034 |
| 5 | 885 | 1034 |
| 6 | 886 | 1034 |
| 7 | 115 | 982 |
| 8 | **2221** | 982 |
| 9 | 2411 | 982 |
| 10 | 2083 | 956 |
| 11 | 2268 | 938 |
| 12 | 2266 | 888 |
| 13 | **2362** | 888 |
| 14 | 737 | 854 |
| 15 | 836 | 854 |
| 16 | **2084** | 849 |
| 17 | **2173** | 849 |
| 18 | **810** | 822 |
| 19 | 813 | 812 |
| 20 | **815** | 812 |
| 21 | 816 | 812 |
| 22 | **2228** | 811 |
| 23 | 2400 | 811 |
| 24 | **1197** | 807 |
| 25 | 1888 | 805 |
| 26 | 1665 | 800 |
| 27 | 2332 | 799 |
| 28 | 2231 | 791 |
| 29 | 2089 | 773 |
| 30 | 2371 | 751 |
| 31 | **1195** | 750 |
| 32 | 69 | 738 |
| 33 | 2276 | 738 |
| 34 | 1199 | 736 |
| 35 | 1299 | 735 |
| 36 | 1764 | 735 |
| 37 | **888** | 734 |
| 38 | 2241 | 713 |
| 39 | **2346** | 713 |
| 40 | 2081 | 704 |
| 41 | 1666 | 702 |
| 42 | 1885 | 700 |
| 43 | 244 | 698 |
| 44 | 2080 | 698 |
| 45 | 1695 | 688 |
| 46 | **843** | 681 |
| 47 | 844 | 681 |
| 48 | 1717 | 680 |
| 49 | 98 | 664 |
| 50 | 2372 | 658 |
| 51 | 102 | 650 |
| 52 | 1193 | 644 |
| 53 | 110 | 637 |
| 54 | 67 | 624 |
| 55 | 1166 | 624 |
| 56 | 1667 | 624 |
| 57 | 1246 | 622 |
| 58 | 1781 | 622 |
| 59 | **2236** | 610 |
| 60 | **2304** | 603 |
| 61 | 1958 | 602 |
| 62 | 734 | 600 |
| 63 | **1250** | 598 |
| 64 | 1304 | 598 |
| 65 | 1890 | 598 |
| 66 | 30 | 594 |
| 67 | 1565 | 594 |
| 68 | 1566 | 591 |
| 69 | 104 | 590 |
| 70 | 1818 | 590 |
| 71 | 839 | 587 |
| 72 | 2334 | 586 |
| 73 | 1751 | 584 |
| 74 | **1200** | 582 |
| 75 | **2305** | 577 |
| 76 | **15** | 574 |
| 77 | **2330** | 566 |
| 78 | 2240 | 561 |
| 79 | **1660** | 553 |
| 80 | 119 | 551 |
| 81 | 2244 | 551 |
| 82 | **2307** | 544 |
| 83 | 2408 | 538 |
| 84 | 2248 | 533 |
| 85 | 2410 | 533 |
| 86 | **108** | 532 |
| 87 | **1810** | 532 |
| 88 | 2033 | 532 |
| 89 | 2242 | 532 |
| 90 | 142 | 527 |
| 91 | **728** | 527 |
| 92 | 62 | 526 |
| 93 | 1284 | 526 |
| 94 | 1884 | 526 |
| 95 | 1371 | 524 |
| 96 | **732** | 523 |
| 97 | 2050 | 519 |
| 98 | 1658 | 511 |
| 99 | **2233** | 507 |
| 100 | 1245 | 496 |

In Table D.2, 29 links whose ID numbers are in bold also appear in the top 100 busiest links. Positions of these links are shown in Figure D.3.

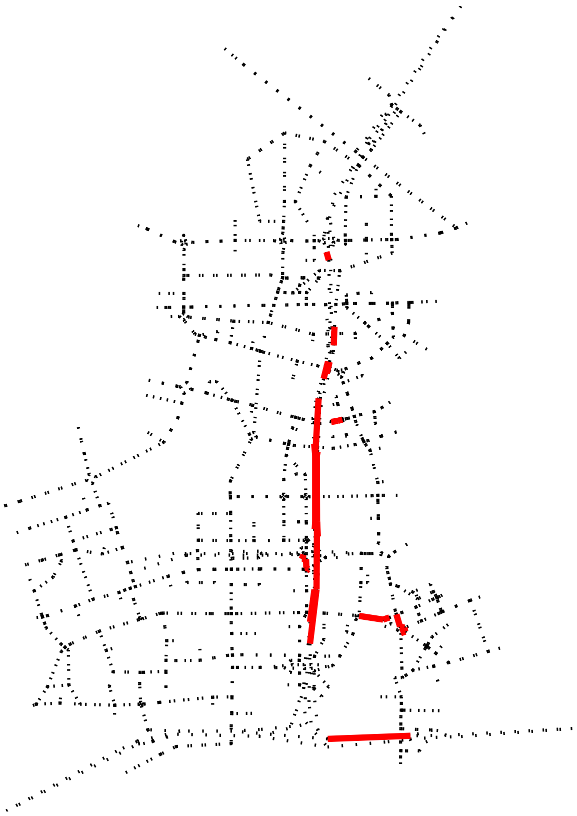


**Figure D.3: Position of links both within top 100 busiest and top 100 common list**

## D.3 Off-ramps in A10-West Network

In Table D.3, all the off-ramps in the A10-West road network are listed. They are ranked according to their V/C values.

**Table D.3: 16 off-ramp links in A10-West network ranked according to their V/C values**

| Link ID | V/C | Frequency | Link ID | V/C | Frequency |
|---|---|---|---|---|---|
| 2277 | 1.000 | 299 | 2246 | 0.382 | 254 |
| 2228 | 0.954 | 811 | 2230 | 0.375 | 25 |
| 2227 | 0.826 | 471 | 2255 | 0.306 | 336 |
| 2221 | 0.629 | 982 | 2220 | 0.285 | 267 |
| 2245 | 0.612 | 85 | 2254 | 0.277 | 300 |
| 2219 | 0.480 | 78 | 2215 | 0.260 | 36 |
| 2293 | 0.399 | 160 | 2225 | 0.236 | 267 |
| 2295 | 0.393 | 163 | 2223 | 0.046 | 50 |

The positions of all these off-ramps are illustrated in Figure D.4 below.

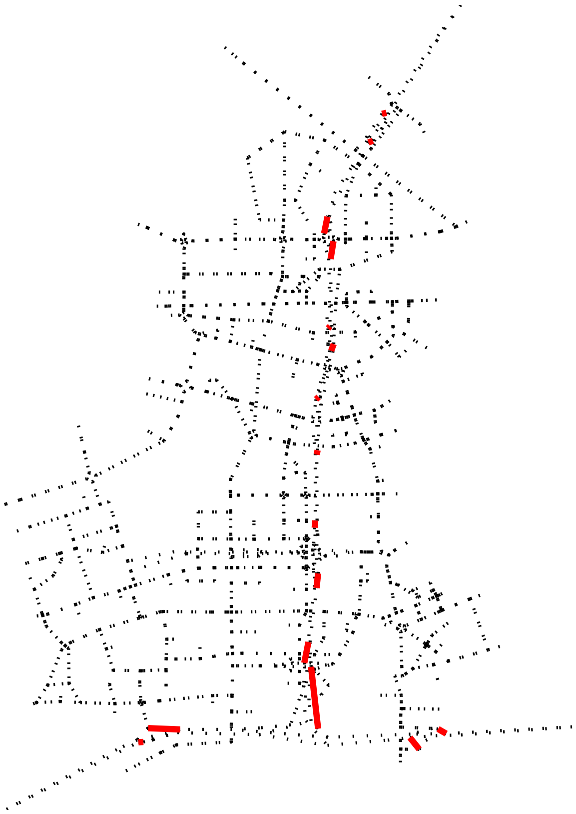


**Figure D.4: Off-ramps in A10-West network**

## D.4 Final list of the selected links

44 links for capacity degradation scenarios are listed in Table D.4 in the sequence of their maximum *V/C* values from high to low. Their new ID are also given according to their positions in the table. Other information of these links, such as the type, desired capacity and maximum *V/C* values can also be found in the table.

**Table D.4: Selected links for incident scenarios in A10-West network**

| Rank | ID | Type | Capacity | *V/C* | Rank | ID | Type | Capacity | *V/C* |
|---|---|---|---|---|---|---|---|---|---|
| 1 | 882 | motorway | 4300 | 1.00 | 23 | 2302 | urban | 1800 | 0.78 |
| 2 | 864 | motorway | 6100 | 1.00 | 24 | 855 | motorway | 8600 | 0.86 |
| 3 | 854 | motorway | 6450 | 1.00 | 25 | 861 | motorway | 6450 | 0.85 |
| 4 | 823 | motorway | 4000 | 1.00 | 26 | 2317 | urban | 1800 | 0.84 |
| 5 | 725 | motorway | 6700 | 1.00 | 27 | 2227 | off-ramp | 1800 | 0.83 |
| 6 | 818 | motorway | 4300 | 1.00 | 28 | 1308 | urban | 1800 | 0.82 |
| 7 | 2277 | off-ramp | 1800 | 1.00 | 29 | 2264 | motorway | 4000 | 0.81 |
| 8 | 820 | motorway | 4300 | 0.98 | 30 | 893 | motorway | 4300 | 0.81 |
| 9 | 2307 | urban | 1800 | 0.98 | 31 | 2234 | on-ramp | 1800 | 0.78 |
| 10 | 849 | motorway | 4000 | 0.96 | 32 | 2321 | motorway | 1800 | 0.78 |
| 11 | 2228 | off-ramp | 1800 | 0.95 | 33 | 856 | motorway | 4300 | 0.77 |
| 12 | 2346 | on-ramp | 1800 | 0.95 | 34 | 728 | motorway | 8600 | 0.76 |
| 13 | 872 | motorway | 4300 | 0.95 | 35 | 2040 | urban | 2000 | 0.76 |
| 14 | 824 | motorway | 4300 | 0.93 | 36 | 808 | motorway | 6450 | 0.74 |
| 15 | 2305 | urban | 1800 | 0.93 | 37 | 863 | motorway | 8600 | 0.73 |
| 16 | 2304 | urban | 1800 | 0.91 | 38 | 870 | motorway | 8600 | 0.73 |
| 17 | 851 | motorway | 8600 | 0.91 | 39 | 853 | motorway | 10750 | 0.73 |
| 18 | 2318 | urban | 1800 | 0.90 | 40 | 2319 | urban | 2000 | 0.71 |
| 19 | 2288 | on-ramp | 1800 | 0.90 | 41 | 859 | motorway | 8600 | 0.71 |
| 20 | 1250 | on-ramp | 1800 | 0.89 | 42 | 821 | motorway | 6450 | 0.70 |
| 21 | 848 | motorway | 4300 | 0.89 | 43 | 842 | motorway | 6450 | 0.70 |
| 22 | 2233 | urban | 1800 | 0.87 | 44 | 1197 | urban | 1800 | 0.70 |

# About the author

Minwei Li was born in China in 1976. In 1993, he started his study in civil engineering at Tsinghua University in Beijing. After his graduation in 1998, he continued his master study in material science in the School of Civil Engineering at Tsinghua University.

In 2001, he was affiliated with the Transport & Planning Department of the Faculty of Civil Engineering and Geoscience of Delft University of Technology and started his Ph.D research in The Netherlands. His Ph.D research is on the robustness analysis of road networks considering travelers' (en-route) route choice behavior. He also participated in several researches concerning, among others, the microscopic traffic simulation models in traffic control and traffic flow analysis. During these researches he has presented various papers in international conferences. Next to the research Minwei has also been involved in several teaching activities. he assisted, for instance, the teaching of microscopic simulation model VISSIM for the course of Dynamic Traffic Management.

Since 2007 he is working at the Mobility and Logistic Business Unit of the Netherlands Organization for Applied Scientific Research (TNO) in Delft, in the area of traffic simulation and ITS models.

# Summary

Network robustness is an important topic for road networks, but there has not been paid much attention to it. Compared with the concept of *reliability*, which focuses on analyzing the *probability* of a road network performing its proposed service level adequately taking into account the uncertainties of the circumstances, network robustness problems emphasize particularly on the *ability* of a road network functioning properly facing unpredictable and exceptional incidents. The robustness studies in other network domain and traditional robustness studies for road networks only deal with the basic connecting features of the network with graph theory, which are basically defined as the *connectivity robustness*. However, the performance of a road network, such as the speed and throughput that can be felt and observed by travelers and road authorities are also essential aspects for the evaluation of the service level of road systems. This thesis deals with the design and development of a systematic framework that enables the complete network robustness analysis comparing the network performance between daily traffic conditions and incident conditions.

In order to accurately achieve the network performance and its changes along with time and space, interactions between the travelers (choice) behaviors and the network performance are important factors to be taken into account. To correctly model this phenomenon as well as the performance of road networks, dynamic traffic assignment (DTA) models play core roles in representing the (path) choice behaviors of travelers and simulating the propagation of traffic flows over the network. Basically, DTA models can be distinguished into two categories: user equilibrium (UE) assignment models and en-route assignment models, according to their basic assumptions about the network status and travelers behavior. In the existing robustness studies for road networks that involve the analysis of the network performance, UE assignment models are implemented in the majority. However, according to the definition and requirements of robustness analysis, the straightforward UE approach is insufficient to analyze the network performance when unpredictable and exceptional incidents occur.

Thus, in our proposed framework, both DTA approaches are integrated with the aim to represent the road network performance of daily normal condition and incident conditions. To represent the daily normal condition, (stochastic) UE assignment models are considered as the most suitable and valid tools. For incident conditions, if the occurrence of the incident is unpredicted and exceptional, such as the traffic accidents on the road, en-route assignment models are believed more appropriate than the UE approach to represent them because such approaches are able to model travelers' path updating behavior on their way. Furthermore, by testing different DTA models with a common network, remarkable differences among the results demonstrate that different models have their own specifications and specialities so that it is difficult to compare them. It also means that it is also impossible to combine different models in our framework due to the compatibility problems.

This led to the development of MARPLE-e (MARPLE en-route). MARPLE-e is the en-route extension of the DTA model MARPLE (Model for Assignment and Regional PoLicy Evaluation). In our testings of different DTA models, MARPLE shows its advantages in the reasonable results of path generation, path assignment and fast computation. Furthermore, it is also available for us to make the relative en-route extension by using the same network loading model, which guarantees the compatibility within the simulation results. MARPLE-e adopts new path generation algorithm by calculating the instantaneous travel cost of all used paths and the one with the lowest cost. If the path with the lowest cost is not used before and satisfy certain criteria, it will be added into the path sets and new assignment will be generated. Otherwise new assignment will only be generated within the existing paths.

In order to analyze road network robustness against the incidents, we must admit that for a big network, there exist too many possibilities of the incidents varying in position, time, duration, and severity level. Scenario-based analysis/optimization approach, which is often used to solve the (optimization) problem across a limited number of scenarios, searching for solutions that are near-optimal, is also adopted in our studies. Although there is no optimization problem in our robustness analysis, designing and analyzing limited number of incident scenarios with respect to the population of all possible realizations of uncertainties can remarkably reduce the calculation efforts. Incident scenarios for road networks can be classified into capacity-related scenarios and demand-related scenarios, in which only link capacity or OD demand are considered influenced by the incidents respectively. The method of sensitivity analysis is also adopted to measure the impacts on network robustness of changing one or more input values about which there is uncertainty.

The framework and related methods are thoroughly tested with a small hypothetical road network with hierarchical structure, i.e. the network includes both motorway and urban links with different characteristics. Due to the limited amount of links and OD pairs for the small network, all possible scenarios of the incidents on a single link or a single OD pair are tested. The results first clearly demonstrate the effectiveness of the framework and the adopted DTA models in representing travelers' routing behavior and dynamics of the network performance. Furthermore, some preliminary ideas about the robustness of road networks in different incident scenarios can be drawn:

- Redundant capacity in the network can increase the network robustness;
- Motorway links are the most critical elements of a road network;

- Off-ramp links are also critical for a road network;
- Demand increase generates more negative impacts to the congested road network;

For a large real-size road network, such as the A10-West road network in Amsterdam analyzed in Chapter 6, it is necessary and important to carry out the process of preselecting and filtering to generate a limited amount of incident scenarios without losing the the most possible critical elements (e.g. links). Three criteria, including flow-capacity ratio criterion, commonness criterion, and off-ramp criterion are used based on the link performance in the SUE assignment results. Within the finally selected 44 links for the design of incident scenarios, over half (26) are motorway links and 7 are ramps that connect motorway and urban roads. Besides this fact, the results of the network performance from the incident scenarios again confirmed that motorway links are the most critical elements for a road network with hierarchical structure. However, in such a large and complex network, the impacts of a local incident also become ‘local’ because if the travelers are well informed, there exist many alternatives for them to avoid the exceptional congestions so that the whole system maintains a high service level. Furthermore, for a large network, incidents on one location would probably reduce the burden of its downstream network, which can also mitigate the total loss of the system.

We have proven that our framework in connection with suitable DTA models and scenario-based analysis approach is able to realize complete road network robustness studies in different incident situations. Another interesting topic is how to improve the robustness of a road network against incidents. We analyze the impacts on network robustness of the information services and compliance rate of travelers to the information. It showed that there exists an optimal value of the compliance rate for minimizing the extra delay caused by the incidents, which means that information services can improve the network robustness in a certain extent, but its effects are highly influenced by the response of travelers to the information. So for road authorities and managers who aim at increasing road network robustness through information services and controls, a better understanding of travelers behavior is the prime task. Such a research topic is also important for making better DTA models, so as to all the problems involving transportation networks.

# Samenvatting

Robuustheid is voor het wegennetwerk van groot belang. Dit onderwerp heeft echter nog niet veel aandacht gekregen. Robuustheid is gerelateerd aan het begrip betrouwbaarheid. Betrouwbaarheid richt zich op de kans dat een wegennetwerk op een bepaald serviceniveau blijft functioneren onder wisselende omstandigheden en robuustheid richt zich op de mate waarin een wegennetwerk kan blijven functioneren bij onvoorspelbare en uitzonderlijke gebeurtenissen. De robuustheidsstudies in andere toepassingsgebieden en de traditionele robuustheidsstudies voor het wegennetwerk richten zich voornamelijk op de connectiviteit van het netwerk op basis van de grafentheorie. Prestatie-indicatoren zoals de snelheid en de doorstroming zijn echter ook belangrijke indicatoren voor de evaluatie van het serviceniveau van het wegennetwerk. Deze indicatoren kunnen door reizigers en wegbeheerders waargenomen worden. Deze dissertatie beschrijft een systematische methode waarmee de robuustheid van een netwerk bepaald kan worden door de gemiddelde dagelijkse verkeerstoestand te vergelijken met incidentsituaties.

Om de netwerkprestatie en de verandering van de netwerkprestatie over de tijd in plaats voldoende nauwkeurig te kunnen bepalen moet rekening gehouden worden met het routekeuzegedrag van reizigers. Dit keuzegedrag is afhankelijk van de netwerkprestatie. Om hier rekening mee te houden zijn dynamische verkeersmodellen nodig. Met deze modellen kan het routekeuzegedrag van reizigers gemodelleerd worden en kan de afwikkeling van het verkeer op het netwerk gemodelleerd worden. Dynamische verkeersmodellen kunnen aan de hand van hun veronderstellingen over de netwerkcondities en het gedrag van reizigers in twee categorieën onderverdeel worden: evenwichtsmodellen en en-routetoedelingsmodellen. In de meeste studies over robuustheid worden evenwichtstoedelingsmodellen gebruikt. Volgens de definitie en de eisen van robuustheidsanalyses is een traditionele evenwichtstoedeling echter niet voldoende geschikt om de verkeersafwikkeling bij onvoorspelbare en grote incidenten te kunnen analyseren.

In het voorgestelde raamwerk zijn beide vormen van dynamische toedeling daarom geïntegreerd met als doel de netwerkprestatie bij reguliere omstandigheden en bij incidentsituaties te voorspellen. (Stochastische) evenwichtstoedelingsmodellen worden over het algemeen als meest geschikt en meest valide beschouwd voor het modelleren van de normale dagelijkse verkeerscondities. Bij incidentsituaties zoals verkeersongelukken worden en-routetoedelingsmodellen over het algemeen als meer valide beschouwd, omdat deze modellen het mogelijk maken om tijdens de rit alternatieve routes kiezen zodra informatie over het incident beschikbaar komt. Beiden type toedelingsmodellen zijn vergeleken op hetzelfde netwerk. Hieruit is gebleken dat beide modelleringstechnieken opvallend verschillende resultaten opleveren. Een verklaring hiervoor is dat ze verschillende specificaties en toepassingsgebieden hebben. Dit betekent echter ook dat beide vormen van modellering niet in één raamwerk gecombineerd kunnen worden.

Om deze rede is MARPLE-e (MARPLE en-route) ontwikkeld. MARPLE-e is de en-routeuitbreiding van het dynamische verkeersmodel MARPLE (Model for Assignment and Regional PoLicy Evaluation). Vergeleken bij andere dynamische toedelingsmodellen genereert MARPLE aannemelijke paden en resultaten en heeft MARPLE een korte rekentijd. Bovendien was MARPLE bij ons beschikbaar waardoor de uitbreiding met en-routeroutekeuze in dezelfde omgeving geïmplementeerd kon worden als het originele toedelingsmodel. Compatibiliteit is hierdoor gegarandeerd. In MARPLE-e is een nieuw padgeneratiealgoritme geïmplementeerd waarmee instantane reiskosten van alle gebruikte paden en van het pad met de laagste kosten berekend kunnen worden. Als het pad met de laagste kosten nog niet gebruikt wordt en dit pad wel aan bepaalde criteria voldoet kan het toegevoegd worden aan de padenset. Volgens wordt een nieuwe toedeling uitgevoerd.

In praktijk vinden veel verschillende incidenten/verstoringen plaats. Deze variëren in locatie, tijd, duur en ernst. Bij de analyse van de robuustheid van het netwerk voor verstoringen is het onmogelijk om alle combinaties door te rekenen, omdat in een groot netwerk te veel combinaties voorkomen. Om deze reden is een scenarioaanpak gevolgd. Bij optimalisatieproblemen is dit een veel gebruikte methode om een benadering van de optimale oplossing van een probleem te vinden. Hoewel bij robuustheidsanalyse geen optimalisatie plaatsvindt, wordt door ook hier een scenarioaanpak te kiezen de rekentijd aanzienlijk verkort. Incidentscenario’s kunnen geclassificeerd worden in aanbods- en vraaggerelateerde scenario’s waarbij alleen de capaciteit of alleen de vervoervraag beïnvloed wordt. Met behulp van gevoeligheidsanalyses is bepaald wat het effect is van het variëren van meerdere inputvariabelen op de robuustheid van het netwerk.

Het raamwerk en de daaraan gerelateerde methodes zijn uitgebreid getest op een klein hypothetisch netwerk met een hiërarchische structuur. Een hiërarchische structuur wil zeggen dat het netwerk zowel snelwegen als lokale wegen bevat met verschillende eigenschappen. Door het beperkte aantal schakels en zones in het netwerk was het mogelijk om alle incidentscenario’s op één schakel of voor één herkomst-bestemmingspaar te testen. De resultaten geven duidelijk aan dat het raamwerk en de toegepaste dynamische verkeersmodellen goed het routekeuzegedrag en effecten op de weg weergegeven. Bovendien heeft deze analyse een eerste inzicht geboden in de robuustheid van het netwerk bij verschillende incidentscenario’s:

- Reservecapaciteit in het netwerk kan de robuustheid vergroten;

- Snelwegen zijn cruciale elementen van een netwerk;
- Afritten zijn ook cruciaal;
- Als de vervoervraag toeneemt, is de impact van incidenten op het netwerk groter omdat er al congestie bestaat.

In een groter realistisch netwerk, zoals de A10-West bij Amsterdam, is het noodzakelijk om eerst een voorselectie te maken van incidentscenario's waarbij de netwerkelementen die naar verwachting het meest kwetsbaar zijn, geselecteerd worden. Hierbij worden drie selectiecriteria gebruikt, die op basis van een stochastische evenwichtstoedeling bepaald kunnen worden. Schakels met een hoge intensiteit-capaciteitverhouding en/of een hoog aantal paden dat over de schakel gaat, worden geselecteerd. Daarnaast worden alle afritten geselecteerd. Uiteindelijk zijn 44 schakels geselecteerd waaronder 26 snelwegschakels en 7 afritten. De incidentscenario's hebben bevestigd dat snelwegen inderdaad de meest cruciale schakels zijn in een hiërarchisch netwerk. In tegenstelling tot de situatie in het kleine testnetwerk blijven op het netwerk van de A10 de effecten van lokale incidenten relatief lokaal. Dat wil zeggen dat slechts een gedeelte van het netwerk vast komt te staan en dat de door het incident veroorzaakte extra reistijd beperkter is. Als reizigers goed geïnformeerd worden hebben zij veel alternatieve routes waardoor zij de congestie kunnen vermijden. Hierdoor blijft het serviceniveau in het hele netwerk hoger. Daarnaast verbetert bij incidenten de doorstroming stroomafwaarts van het incident waarschijnlijk, waardoor het serviceniveau in het totale systeem minder snel achteruit gaat. In grote netwerk is dit effect duidelijker zichtbaar dan in kleine netwerken.

We hebben bewezen dat met ons raamwerk in combinatie met toepassing van geschikte dynamische toedelingsmodellen en scenarioanalyse de robuustheid van grote netwerken getest kan worden. Een interessante vervolgvraag is welke maatregelen genomen kunnen worden om het wegennetwerk robuuster te maken tegen incidenten. Om deze vraag te beantwoorden hebben we getest wat de invloed van verkeersinformatie en de mate waarin bestuurders deze informatie opvolgen (de opvolgingsgraad) is op de robuustheid van het wegennetwerk. Hieruit is gebleken dat een optimale opvolgingsgraad van informatie bestaat waarbij de vertraging door incidenten minimaal is. Dit betekent dat verkeersinformatiediensten de robuustheid van het netwerk tot op zekere hoogte kunnen verbeteren. Het effect van deze diensten is echter wel sterk afhankelijk van de reactie van reizigers op de informatie. Dit betekent dat het voor wegbeheerders die, door informatie te bieden, de robuustheid van het wegennetwerk willen vergroten noodzakelijk is om het gedrag van reizigers beter te begrijpen. Beter begrip van het gedrag van reizigers is bovendien essentieel voor het verbeteren van de dynamische toedelingsmodellen en is in het algemeen van belang voor alle transportproblemen.

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