# A Combined DTA Approach for Road Network Robustness Analysis

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Keywords: Combined DTA, Road Network, Robustness.

Abstract: In this paper a DTA model with two components is described: a user equilibrium (UE) model and an en-route model. The UE model is called MARPLE (Model for Assignment and Regional Policy Evaluation) that uses an iterative process to achieve equilibrium (deterministic or stochastic) (Taale *et al.*, 2004). In each iteration a network loading model is used to determine travel times. MARPLE en-route is developed based on the MARPLE model, which runs one-shot simulation starting with the equilibrium assignment results. It updates the path sets and path costs after each evaluation interval during the simulation. Travellers will update their path choice according to the instantaneous path costs at the end of each interval using some heuristic rules. A systematic framework for the robustness study of road networks is built up by combining both DTA approaches, in which the results of UE approach are used as references and en-route approach is used to simulate the network response for non-recurrent and short-term disturbances. The results for a hypothetical network show that for evaluating the network performance after such disturbances, the en-route assignment approach based on UE assignment results shows its capability and advantages in appropriately representing dynamic drivers' route choice behaviour when facing unfamiliar or unexpected situations on the route.

## 1 INTRODUCTION

Network robustness, defined 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 (Gribble, 2001), has been widely developed in large-scale networks such as electronics and internet. It also became an important topic for transport networks. In that context robustness can be considered as the ability of the system to keep a certain capacity level to handle traffic demand under abnormal situations. Dynamic Traffic Assignment (DTA) models play an important role in almost all the network robustness studies, because they take into account the reaction of drivers concerning route choice. Two approaches of DTA, user equilibrium (UE) assignment and en-route assignment, are separately implemented for different categories of network robustness and/or reliability studies. Basically, UE assignment models are used by many researchers when considering random changes in supply or/and demand of a transportation network. En-route assignment models are normally used to evaluate the effectiveness of certain traffic management schemes or measures for emergency situations or a short-term disturbance in the network. But, so far, little work has been done to develop a combined DTA model, to realize both UE and en-route assignment approaches, with the aim to be able to do a complete network robustness study.

A main task of network robustness studies is to assess whether an existing transport network system is susceptible to random failures (i.e. severe accidents) and destructive events (i.e. earthquake or terrorist attack). More important, we would like to know which parts (so-called *hot* or *weak* spots) of the network are most fragile, or vulnerable to the external disturbances, so that both infrastructure and control schemes could be improved in such a way that the deterioration of the network caused by those disturbances is mitigated.

Network robustness is rather new in the transportation domain and a limited amount of literature references could be found, such as Chiu and Mahmassani (2002) and Kaysi *et al.* (2003). Most of the methods implemented in these studies are borrowed from network reliability studies, which is in fact a quite different concept from robustness. Network reliability is defined as the *probability* of a device or a system performing adequately according

Li M., J. van Zuylen H. and Wen H..
A Combined DTA Approach for Road Network Robustness Analysis.
DOI: 10.5220/0004055803150320
In *Proceedings of the 2nd International Conference on Simulation and Modeling Methodologies, Technologies and Applications* (SIMULTECH-2012), pages 315-320
ISBN: 978-989-8565-20-4

to its purpose for the period of time intended under the operating conditions encountered (Henley and Kumamoto, 1981; Wakabayashi and Iida, 1992). It means that reliability studies are generally concerned with probabilities only. And reliability problems are rooted in the uncertainty of traffic conditions. In most of the existing reliability studies of road networks, stochastic user equilibrium (SUE) assignment models are implemented representing choice behaviour, especially route choice behaviour of travellers, to get the values of some chosen performance measures, such as the work of Bell and Iida (1997), Chen *et al.* (1999), Chen *et al.* (2002) and Du and Nicholson (1997).

However, UE is only an ideal situation that never appears in reality due to many uncertainties in both demand and supply. So, it is mainly meaningful for network planning purposes. But for the network robustness problem that focuses more on the evaluation of network performance and assessment of its ability to handle unpredictable incidents, this equilibrium assumption is no longer suitable for the non-recurrent and short-term congestion. In order to achieve more accurate and realistic values of network performance measures after the occurrence of such disturbances, appropriate dynamic traffic assignment models, such as en-route assignment models, must be developed to realise more accurate description or simulation of the choice behaviour of travellers.

The objective of this paper is to develop a method based on a systematic framework for the comprehensive evaluation of robustness of a road network. The paper is organised as follows. Section 2 briefly describes the features and differences of UE assignment approach and en-route assignment approach, highlights the importance of en-route assignment approach in network robustness studies. Section 3 provides a simulation-based systematic framework for network reliability and robustness studies, founded on the combination of above-mentioned two DTA approaches. In Section 4, the framework proposed in this paper is illustrated with a simple network. Section 5 summarises and analyses the results.

# 2 DTA MODELS

A traffic assignment model, especially a dynamic traffic assignment (DTA) model, is the core of any model based reliability and robustness study of transportation networks. A DTA model typically describes route choice by an assignment sub-model, and the way in which traffic propagates through a network by a network loading sub-model. A realistic DTA model should be able to capture "over-capacity" queuing, because it follows the trajectories in time and space of the vehicles. Basically, two distinct approaches exist to model route choice and network loading in DTA: equilibrium assignment and en-route assignment.

## 2.1 Equilibrium Assignment

Wardrop (1952) was the first to propose the following condition for a deterministic user equilibrium (DUE): for each OD pair, the costs of the paths actually used are equal, and they are less than or equal to the costs of each unused path (known as *Wardrop's first principle*). It assumes that each traveller has perfect information and chooses a route that minimises his/her travel time or travel costs, such that all travellers between the same OD have the same travel time or cost. A consequence of the DUE principle is that all used paths for each OD pair have the same minimum costs. Unfortunately, this is not a realistic description of loaded and congested traffic networks (Slavin, 1996).

The stochastic user equilibrium (SUE) was (amongst others) detailedly illustrated by Daganzo and Sheffi (1997). They defined the equilibrium state of traffic flow on a network as a SUE when every user chooses his/her path such that his/her perceived travel time or cost between origin and destination is minimal. But perceived travel time or cost on a link varies randomly across users.

In the equilibrium assignment problem, only pre-trip path choice and iterative process are considered. 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, and a method to determine the actual travel times that result from a given set of path flow rates.

## 2.2 En-route Assignment

In the en-route assignment problem, the routing mechanism consists of successive executions of a set of behavioural rules, which determine how drivers iteratively react to information received en-route. Information may be available at discrete points in time, discrete points in space, or continuously in both space and time. Some information may only be available to a certain class of vehicles. Typically, the information strategy is an exogenous input. Drivers' responses to information can be modelled by some heuristic rules that may involve one or more parameters, such as the 'penetration rate' or the 'compliance rate'. Another input to this problem is a suitable pre-trip assignment. An en-route assignment thus only requires running a single dynamic loading of the demand onto the network over the time period of interest – apart from the assignments need to determine the initial route choice.

## 2.3 Roles of Two Assignment Approaches in Robustness Study

If an equilibrium assignment model is available, it is possible to find the equilibrium traffic pattern in a transportation network, taking into account all kinds of uncertainties. Network robustness studies use these patterns, as well as certain aggregated network performance measures, to perform comparisons and analyses. But equilibrium assignment approach is not possible to represent the network situation under irregular and non-recurrent incidents, such as accidents. Thus it can be used in the network planning domain to analyse the impact of repeatable and long-term network changes, like introducing new measures of intelligent transportation system (ITS) or adding a new link to the network.

On the other hand, according to the features of the en-route assignment approach, it can be used for the analysis of unrepeatable and short-term incidents, such as accidents or a natural disaster. But if a DTA model is only capable of en-route assignment, it is necessary to find the exogenous input, especially the pre-trip assignment, from other simulation tools or by other means. It is logical that the results of a (dynamic) equilibrium assignment can be used as the basic scenario, i.e. reference, for the en-route assignment because it achieves an 'ideal' long-term equilibrium status for a chosen transportation network.

# 3 FRAMEWORK FOR ROBUSTNESS STUDIES

Based on the features of both assignment approaches and the requirements of robustness studies of road networks, a simulation-based two-stage systematic framework is designed by integrating both an equilibrium assignment model and en-route assignment model (Figure 1). In this framework, the equilibrium assignment model is a macroscopic model named MARPLE (Taale et al., 2004). The en-route assignment model, MARPLE-e, is developed based on MARPLE, by using successively the network loading model and the route choice model for every pre-defined discrete interval.

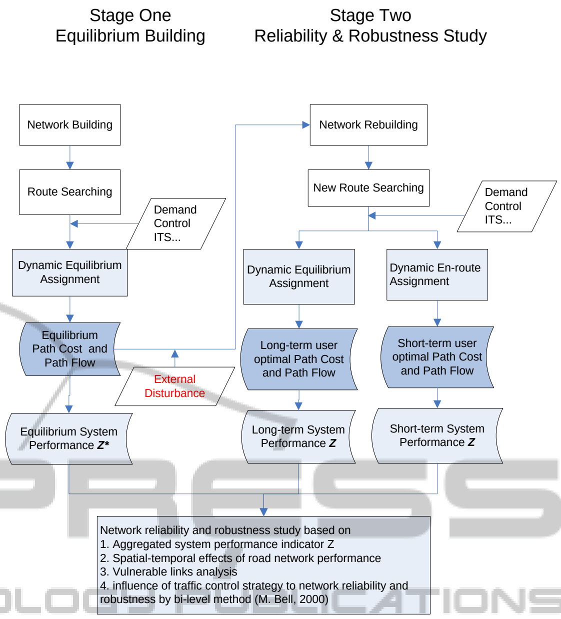


Figure 1: Systematic framework for robustness studies of road network.

In Stage One shown in the left part of the framework, only the equilibrium assignment for the basic situation is carried out. The results are used as the reference of network performance for the following robustness studies, as well as the initial assignment input for the en-route assignment in Stage Two. Several indicators are derived for network performance comparisons as follows.

*TTT*: total travel time for the whole simulation period [*veh•h*];

*TTD*: total travel distance for the whole simulation period [*veh•km*];

*TD*: total delay for the whole simulation period [*veh•h*];

*NAS(t)*: equilibrium dynamic network average speed within period *t* [*km/h*], defined as

$$NAS(t) = \frac{\sum_a v_a(t) f_a(t)}{\sum_a f_a(t)} \quad (1)$$

Where $v_a$(t) is the average link speed and $f_a$(t) is the link flow of link a during period t in the equilibrium situation;

*NL(t)*: network load within period *t* [*veh•h*], defined as

$$NL(t) = \sum_a f_a(t) \quad (2)$$

In robustness studies, random disturbances on individual links will be introduced to the network in Stage Two. Depending on the duration (long-term or short-term) of the disturbance, either the equilibrium assignment approach or the en-route assignment approach could be used for the simulation respectively. Besides the above-mentioned five indicators, the loading multiplier *NLM* in equation (3) is also used as a robustness indicator. The so-called hot spots in the network are those arcs with the smallest loading multiplier.

$$NLM = \sum_t NL(t) \Big/ \sum_t NL^{equ}(t) \qquad (3)$$

in which $NL^{equ}(t)$ is the result of equilibrium assignment.

# 4 CASE STUDY

To demonstrate how the framework and related assignment models works for robustness studies, a simple, hypothetical network as shown in Figure 2 is tested. The network consists of 10 nodes, 11 one-directional links, and three OD pairs, in which origin 2 (O2) and destination 2 (D2) represent a town centre.

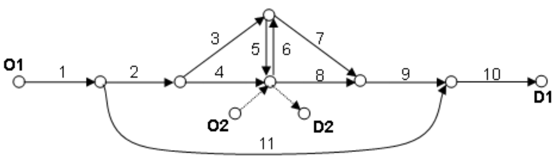


Figure 2: Test network.

In Table 1, link characteristics are listed. Link 3 and 7 form a faster, but longer motorway, and link 11 is a parallel, slower arterial. Links 4, 5, 6, and 8 are urban links with lower speed and capacity, which are the connectors between the motorway and the town centre. There are in total 7 routes available for all the OD pairs as listed in Table 2. Route 3 including Link 11 is not used under normal conditions.

Table1: Link characteristics.

| Link No. | No. of lanes | Length (km) | Capacity (veh/h) | Desired speed (km/h) |
|---|---|---|---|---|
| 1,2,9,10 | 4 | 4 | 8600 | 120 |
| 3,7 | 3 | 4 | 6450 | 120 |
| 4,5,6,8 | 1 | 2 | 1800 | 50 |
| 11 | 1 | 16 | 1800 | 50 |

Table 2: Route information for the OD pairs.

| (O,D) | Route No. | Link Sequence | Length (*km*) | Free flow travel time (*sec*) | Peak-hour demand (*veh/h*) |
|---|---|---|---|---|---|
| (O1,D1) | 1 | 1-2-3-7-9-10 | 24 | 720 | 6000 |
| | 2 | 1-2-4-8-9-10 | 20 | 768 | |
| | 3 | 1-11-10 | 24 | 1392 | |
| (O1,D2) | 4 | 1-2-4 | 10 | 384 | 1500 |
| | 5 | 1-2-3-5 | 14 | 504 | |
| (O2,D1) | 7 | 8-9-10 | 10 | 384 | 1500 |

In case studies, simple incident scenarios are designed. In each scenario, one and only one link, except for link 1 and 10, is deteriorated during the peak hour. In this hour, the capacity of the chosen link is set as the certain ratio (from 0.0 to 1.0) to the designed capacity. Before and after the peak hour, the network works properly. In all scenarios, 70% of the travellers are assumed to get instant and perfect knowledge about the network conditions and to update their paths accordingly. The rest 30% stay on their pre-defined paths.

For each scenario, a 3.5-hour demand profile as shown in Figure 3 is used, representing a 'warming-peak-cooling' loading procedure. The last half an hour is designed with zero demand to 'clear up' the network

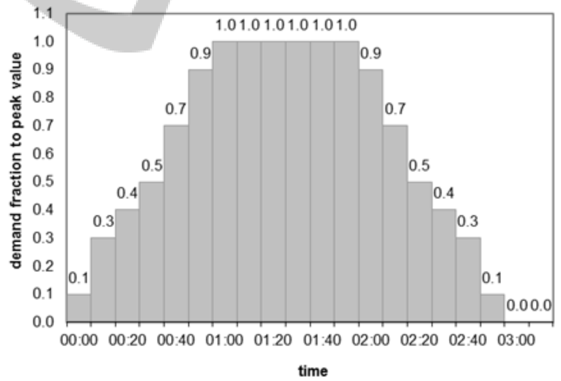


Figure 3: Profile of the demand ratio (related to peak-hour value).

## 4.1 Aggregated Indicators

In table 3, the values of *TTT, TTD and TD* for the scenarios that the link is 100% blocked are listed. The values in the parenthesis are the ratios to the equilibrium ones (when link 11 is blocked). The highest *TD* values appear when motorway links (link 2, 3, 7 and 9) are blocked. For the arterial links, the influence of off-ramps (link 4 and 5) is much higher than on-ramps (link 6 and 8).

Table 3: Aggregated network performance indicators when links are blocked

| Blocked link | *TTT* (*veh•h*) | *TTD* (*veh•km*) | *TD* (*veh•h*) |
|---|---|---|---|
| 2* | 10256.83 (1.59) | 349208.02 (1.01) | 4119.47 (13.23) |
| 3* | 11771.86 (1.82) | 330207.10 (0.96) | 5634.50 (18.09) |
| 4 | 8785.83 (1.36) | 349700.57 (1.01) | 2648.47 (8.50) |
| 5 | 6712.87 (1.04) | 346888.87 (1.01) | 575.51 (1.85) |
| 6 | 6474.63 (1.00) | 343449.95 (1.00) | 337.27 (1.08) |
| 7* | 12091.59 (1.88) | 320616.49 (0.93) | 5954.23 (19.12) |
| 8 | 7253.05 (1.12) | 349336.07 (1.01) | 1115.69 (3.59) |
| 9* | 11666.83 (1.81) | 334251.18 (0.97) | 5529.47 (17.76) |
| 11 (equ) | 6448.78 (1.00) | 344757.57 (1.00) | 311.42 (1.00) |

* means route 3 is used in that case

## 4.2 Dynamic Indicators

Since en-route assignment is just a one-shot procedure, using indicators *NAS(t)* (Figure 4) and *NL(t)* (Figure 5) can describe the dynamics of the network performances more clearly. In two figures, the equilibrium scenario and the scenarios with link 3, 4 and 9 completely blocked are presented. In Figure 4, it is obvious that after blocking link 3 and 9, network speed drops much more and longer than other scenarios. In Figure 5, the curve for the scenario when link 3 is blocked shows that although the blockage is removed after the peak hour (interval 72) and the link capacity returns to its desired value, it takes about one hour (till interval 100) for the total network load to recover to the normal value. This indicates the remarkable after effect level of the incident.

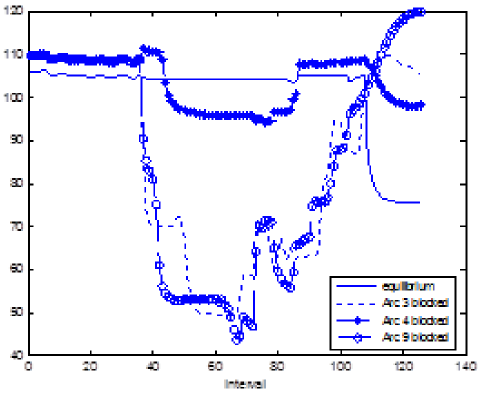


Figure 4: Changes of *NAS* for some scenarios.

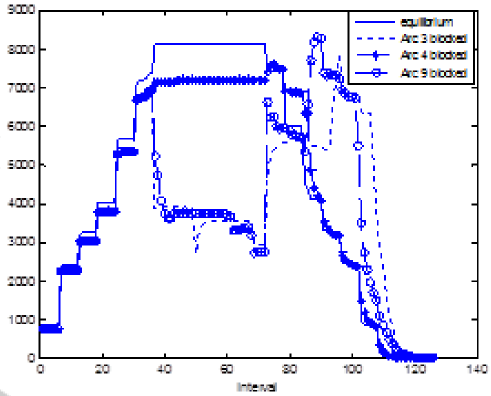


Figure 5: Changes of *NL* for some scenarios.

## 4.3 Sensitivity Analysis

Sensitivity information provides the change of the network loading multiplier calculated by equation (3) with respect to the changes of service level of each link capacity. Level of service is defined as the remaining capacity of the link after the incident on the link. Figure 6 shows the values of *NLM* of the scenarios with different level of services when the capacity on links 3, 7, 8 and 9 drops respectively. The curve of link 9 drops first and also the fastest if the service level decreases in those curves, because link 9 is a common link for both OD pairs (O1, D1) and (O2, D1). So to a certain extent, link 9 is one hot spot in this network.

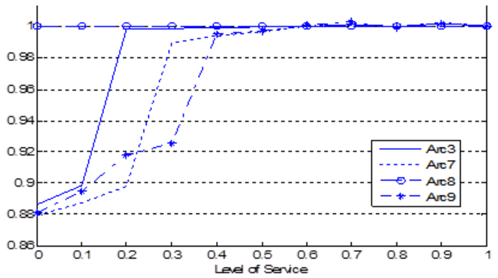


Figure 7: Changes of Network Loading Multiplier (NLM) in relation with different level of service.

# 5 CONCLUSIONS AND DISCUSSION

In this paper, we presented a new simulation-based systematic framework for the study of robustness in road networks and tested its feasibility by evaluating several network performance indicators. It is the first time that both equilibrium assignment and en-route assignment approaches are integrated in the study of robustness of road networks. This framework can be considered as a complete structure. The reason is simple: the equilibrium assignment model can represent normal daily situations and describe the effects of long-term disturbances, while the en-route assignment model can represent network performance after non-recurrent and short-term disturbances. Neither model shall be neglected due to the different functionality for different conditions. In addition, several time-dependent network performance indicators, next to some common aggregated indicators, have been derived for both DTA approaches. A simple hypothetical network, which represents a typical city network with a motorway and parallel low-level path bypass, has been used for testing. After introducing incidents on different links, numerical results demonstrated the feasibility of the robustness evaluation procedure. Some general remarks on the robustness of such kind of network can be made:

1. Common links that are used by multiple OD pairs have more influence on the network performance;
2. Disturbances on off-ramps have more deterioration effects to the network, because they will immediately influence the motorway traffic and cause high delay;
3. Time-dependent indicators *NAS(t)* and *NL(t)*, and *NLM* derived from *NL(t)*, can clearly describe the changes of the network performance, as well as the robustness of the network.

A potential research topic of road network robustness is to incorporate robustness constraints to the network design problem. Some researchers, such as Yin et al. (2004) and Zhang and Levinson (2004), have introduced the concept of robustness to network design and upgrade. But due to the simplicity of their static assignment models, the understanding of the disturbances and their impact on the robustness performance of a road network is not suitable for describing the dynamics. Thus, our framework can improve the quality of related studies for network design and planning purpose.

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