TraVIS for Roads – Examples of Road Transport Vulnerability Impact Studies

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About five years and a PhD thesis later...

...and there isn't all that much to say, really. However, knowing me you'd be surprised if I didn't so, here goes. Thanks Mum and Dad, for raising me in the belief that nothing is impossible. And thank you Kennet, for patiently acting as my life-line during the times when that belief didn't seem to help. As for the rest of you, Jerry Seinfeld put it very aptly in his book “Seinlanguage”:

Friends are the DNA of society.
They are the basic building blocks of life...
Your friends help you carry the big weight in life.
That big burden we’ve all got called, “What the hell am I doing?”.

And if I wasn’t confused enough before, research certainly helped...
To all my friends, scattered as you are all around the globe, Thank You for reducing this pressure to a minimum!

Stockholm in November 2002

/ Katja Berdica
Berdica, K. “TraVIS for Roads –
Examples of Road Transport Vulnerability Impact Studies”
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Abstract

Road vulnerability as such has not been in focus for long, despite the fundamental importance of our road networks as being one of our most important lifelines. This thesis consists of five different papers, all relating to the overall subject of vulnerability in the road transport system in different ways. The first paper An Introduction to Road Vulnerability - What Has Been Done, Is Done and Should Be Done brings up definitions and concepts necessary to characterise the topic as such and proposes vulnerability analyses as the comprehensive framework within which various transport studies should be undertaken. Since controlled, real life, field experiments are somewhat difficult to perform, computer models are often used for studying the effects of changing conditions in the road network. The second paper Vulnerability - A Model Based Case Study of the Road Network in Stockholm presents the results of such a study, investigating the effects of interruptions and capacity reductions in the Stockholm Region by means of the traffic analysis package emme/2. Deploying a user equilibrium based model inherently means simulating the effects of a disturbance after a long enough time has passed for travellers to adapt to the new situation. This isn’t suitable for studying incidents of a shorter duration, issues that are investigated further in the third paper Simulating Road Traffic Interruptions - Does It Matter What Model We Use?. The same range of closures were simulated in three different models (TRACKS, SATURN and Paramics) representing macroscopic, mesoscopic, and microscopic modelling, respectively. Micro simulation is found to be a feasible tool for studying effects of short term incidents. It is noted that Paper III is a comparison of different modelling approaches, rather than of particular models. This is then the source of origin for the fourth paper Comparing Traffic Models: Two Case Studies. Revolving around two main questions – namely why and how to compare models/programs – a number of interesting issues regarding the use of different modelling approaches for evaluation of transport network performance are discussed. Instead of the computer intensive models and methods discussed so far, the fifth paper 2+1 Roads with Cable Barriers – Traffic Safety and Transport Quality Effects gives an example of an empirical approach. It presents a conceptual model for practical vulnerability analysis which is then used to characterise vulnerability for two road objects of the new 2+1 design. This new concept has recently been implemented as a standard in Sweden, mainly based on the expected traffic safety effects, which are found to be substantial.
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**LIST OF PAPERS:**

(I) **BERDICA, K:** *AN INTRODUCTION TO ROAD VULNERABILITY – WHAT HAS BEEN DONE, IS DONE AND SHOULD BE DONE. TRANSPORT POLICY* 9 (2002) 117-127

(II) **BERDICA, K:** *VULNERABILITY – A MODEL BASED CASE STUDY OF THE ROAD NETWORK IN STOCKHOLM. SUBMITTED TO TRANSPORTATION*

(III) **BERDICA, K, ANDJIC, Z & NICHOLSON, A:** *SIMULATING ROAD TRAFFIC INTERRUPTIONS – DOES IT MATTER WHAT MODEL WE USE? FORTHCOMING IN BELL, M G H & IIDA, Y “THE NETWORK RELIABILITY OF TRANSPORT”, ELSEVIER SCIENCE*

(IV) **NICHOLSON, A, BERDICA, K & ANDJIC, Z:** *COMPARING TRAFFIC MODELS: TWO CASE STUDIES. TRANSPORT ENGINEERING IN AUSTRALIA* 7 (2001) 65-76

(V) **BERDICA, K, BERGH, T & CARLSSON, A:** *2+1 ROADS WITH CABLE BARRIERS – TRAFFIC SAFETY AND TRANSPORT QUALITY EFFECTS. SUBMITTED TO ACCIDENT ANALYSIS AND PREVENTION*
SETTING OUT...

Vulnerability, exposure, criticality... these are issues that become increasingly important as society displays a more and more complex system of intertwined infrastructures vital for its function. Consequently, these topics have in recent years been more explicitly looked into. Communication is often stressed as being crucial, although the tendency has been to concentrate on the more modern telecom and computer systems – especially their susceptibility to acts of terrorism and/or war. The “traditional” communication system of physical transports is less well investigated despite its fundamental importance in assisting/maintaining/repairing other infrastructures and for evacuation in case of disaster, as well as a direct means for “normal” transport.

This order of prioritisation is maybe founded in the belief that conventional transports are well established and have been accommodating our travel needs (more or less) satisfactory for a long time. In this perspective, road traffic stands out from the other modes of physical transport in three main respects. First, the road transport system is in most countries the most dense and most widely spread. Second, it is generally speaking readily available to a majority of the population. Third, there is limited authoritative control. The private car is also an icon of individuality and freedom and as such it is often the favourite mode choice, seeing to society as a whole. The above can of course be subjected to an extensive debate upon cause and effect, but the fact still remains: compared to the world of train time tables, aviation safety protocols and (relatively speaking) limited number of shipping activities on a vast sea, road transports are in a sense undertaken in a setting of ordered chaos.

Road transports are tightly linked to everyday life, both private and business, and problems in the road network can have wide repercussions on the whole of society. With growing populations and increasing traffic volumes – of both people and merchandise – there is a need for better and more efficient planning, maintenance and operation of the road transport system. Recent events, such as 11 September 2001 and the serious floods in central Europe of late, also bear evidence of circumstances in which the road network’s capability to serve our needs is seriously compromised. All this put together makes vulnerability of the road transport system a highly important subject in terms of public economy and welfare, as well as an interesting research challenge because of its complexity. This is, to put it simply, the underlying motive for this thesis.
THIS THESIS

General outline

The conceptual construct of the research work presented in this thesis can be illustrated by Figure 1. Paper I forms the foundation in terms of an overall theoretical framework, bringing up necessary definitions and concepts as well as reviewing what has been done in this field of research so far. The remaining papers then explore methods and pose examples for studies that can be conducted within this vulnerability analysis framework. Paper II studies the effects of interruptions and capacity reductions in the Stockholm Region by means of the traffic analysis package emme/2. That this model is equilibrium based has certain implications for studying incidents of a shorter duration and these issues are investigated further in Paper III. This in turn resulted in a number of interesting issues regarding the use of different modelling approaches for evaluation of transport network performance, which are discussed in Paper IV. As opposed to these computer based studies, Paper V presents the results from a mainly empirical case study. It proposes a model for practical vulnerability analysis in general, which is then used to characterise vulnerability for two road objects in particular. Finally, this introductory section summarises the research work, presenting the red thread and pulling it all together in the end.

Figure 1. Schematic structure of the present thesis.
Laying the Foundations

Road vulnerability as such has not been in focus for long, despite the fundamental importance of our road networks as being one of our most important lifelines. Its wide spread and lack of supervision makes it difficult to manage, but at the same time lends it a certain robustness. In order to implement e.g. suitable policies to successfully work towards set goals there is a need for an overall characterisation of road networks. This involves gaining insight into their propensity to “malfunction”, the extent of the resulting consequences, the scope for mitigation measures, etc. In transport studies of today, a comprehensive framework to this end is felt to be missing so far. Paper I therefore conceptualises and puts into context a relatively new notion: vulnerability in the road transport system. In the Wheel of Concepts (Figure 2) the abstract concept of vulnerability is concretised by a series of sequential definitions, each depending upon the other. The function of the road transport system is accentuated by introducing the term serviceability, which describes the possibility to use a link/route/road network at a given time. Various incidents can however cause reductions or interruptions in serviceability. The probability for such incidents to occur, and the consequences of them should they occur, are combined in the term risk. Thereby vulnerability is defined as a susceptibility to incidents that may cause considerable reductions in road network serviceability.

![DEFINITIONS](image)

**Figure 2.** Vulnerability in the road transport system: Wheel of Concepts
*(Paper I: Fig 2, p 119)*
The incidents in question that are considered are those that have an injurious effect on the road transport system. An overview of the most important reasons for complete closures in the Swedish road network listed road works, flooding, traffic accidents, snow, storm related incidents, hazardous goods accidents, physical collapses, thaw weakening damage and bridge openings, ranked in that order on a national level (Berdica, 2000). It is hence a question of occasions when the road transport system is injured, not occasions when it is injurious to its surroundings etc. The range of possible threats can also be wide, as illustrated in Figure 3, with an increasing degree of human involvement/malevolent intent and varying predictability. There is also often a time dimension involved, e.g. longer term climatic changes will influence the probabilities for flooding and snow-related problems. This entails that although the risk concept is generally described as a combination of probabilities and consequences, it is sometimes more purposeful to deal with conditional vulnerability, i.e. what are the consequences given that the incident has occurred. The extent of the consequences also varies greatly, both among incident categories and among incidents within categories. This would complicate Figure 3 somewhat, since the consequences would best be represented by an area rather than a line, and they are therefore for the sake of simplicity omitted in this illustration.

![Diagram showing malevolence and predictability](image_url)

**Figure 3.** Illustration of a possible range of threats to infrastructure

Reducing vulnerability can hence be regarded as reducing the risks involved in various incidents, which can be brought about in two ways. In a fail-safe approach, the probability for e.g. a bridge to fail is reduced, while approaching the problem from a safe-fail perspective implies reducing the resulting consequences should the failure occur. This thesis is mainly
concerned with studies based on the latter, so called conditional vulnerability approach. Also, the focus lies in the lower end of the spectrum, concentrating on everyday conditions (although more toward non-recurrent than recurrent congestion) rather than incidents of a more catastrophic nature. The problem can be approached from two sides, by aiming at establishing a robust base system or by developing various contingency plans. Here, vulnerability is defined in terms of serviceability from the standpoint that if the road transport system does not function satisfactorily under more or less normal circumstances, it very well cannot be expected to do so the in case of a disaster.

Paper I concludes that vulnerability in road transport systems as such has rarely been considered so far. However, well-established reliability theory constitute a feasible tool for addressing such issues, the main measures considered in literature being terminal-, travel time- and capacity reliability. Furthermore, Paper I proposes that road vulnerability analysis could be an all-embracing framework using the different aspects of transport reliability studies and related methods as its foremost tools. It should regard the road transport system as a whole and involve identifying a spectrum of incidents, collecting data on probabilities and consequences to estimate risks, performing various studies and experiments to set values for desirable and/or acceptable serviceability, as well as investigating and assessing the effects of possible mitigation measures and improvement strategies. Examples of such studies are given in the following.

**Vulnerability Studies Using Transport Models**

Rare events like collapsing bridges, as well as every day incidents like traffic accidents or closures due to maintenance activities, can reduce the capacity of the road transport system. Since controlled, real life, field experiments are somewhat difficult to perform, computer models are often used for studying the effects of changing conditions in the road network. Paper II presents the results of such a study, in which a traffic model based on the traffic analysis package emme/2 was used to investigate how closures and capacity variations influence the users’ travel time and trip length in the road network in Stockholm, Sweden.

The study results clearly indicate the Stockholm road transport system’s weaknesses and give a fair idea as to the relative size of the expected consequences. It shows that Stockholm’s central water strait – and the consequent dependency on a limited number of bridges – is a crucial feature from a vulnerability point of view. Also, there is at present little, if any, extra capacity to handle rerouting in case of incidents, let alone to swallow a more permanent increase in traffic volume. It is also discussed to what extent it is
possible to use a link flow based equilibrium model to study vulnerability issues. Since bottleneck effects are not taken into consideration, modelling partial capacity reductions seems to give unrealistically small effects, which is supported by a complementary study using an alternative network equilibrium method. Also, studying effects of drastic capacity reductions may be to push the model over the boundaries for its validity. Then again, it could be a question of calibration of the volume delay functions representing the behavioural responses to capacity changes in the network.

Deploying a user equilibrium based model inherently means that the road users are assumed to have perfect information of the system status. Hence, it simulates the effects of a disturbance after a long enough time has passed for travellers to adapt to the new situation, finding their new “best” routes. However, many of the every day incidents causing reductions in road serviceability are of short duration and a new equilibrium is never reached. Using a network equilibrium approach could therefore underestimate the effect of the disturbance. Dynamic models, where changing conditions like congestion are taken into account by regular “updating” of route choice, may be more promising for studying short-term capacity reductions. In Paper III, the implications of model choice are investigated further, as well as the practicability of studying the effects of short-term incidents using micro-simulation.

The same range of closures in the network around the University of Canterbury Campus (Christchurch, New Zealand) were simulated in three different models. The three programs used were TRACKS, SATURN and Paramics, representing macroscopic, mesoscopic, and microscopic modelling, respectively. Micro simulation is found to be a feasible tool for studying effects of short term incidents, although longer closures rendered the system overly congested and the Paramics simulation broke down. It is likely that the small size of the network contributes to this problem: drivers would in reality use more of the surrounding street network to avoid congestion but these more peripheral routes are not included in the current simulation network. The different types of models are usually used for different sized networks but here all three were used for a rather small one. As network size increases the scope for traffic to find alternative routes will generally increase, but with growing network size, it also becomes less practical to use a microscopic model due to the greater level of detail in network coding and the computer capacity needed for running the program. Paramics is found to be the most sensitive to disturbances of the three models used, but an interesting result is that the incremental assignment procedure available in TRACKS makes this model more sensitive in some respects than SATURN, which is otherwise more detailed in its formulation. It can thus be the case that smart use of a traditional macroscopic
equilibrium model can in fact carry you far. However, it should also be pointed out that the time-slice feature available in SATURN was not used, a choice that to some extent put this model in an unfavourable light. Hence, Paper III is a comparison of different modelling approaches, rather than of particular models.

The issues of model comparisons are discussed further in Paper IV, including not only the Paramics-SATURN-TRACKS comparison of abnormal circumstances, but also an earlier SATURN-TRACKS comparison during normal conditions (Andjic, 2001). The discussion revolves around two main questions, namely why and how to compare models/programs. Paper IV states that a fair comparison requires consistency and the first question is whether it is easier to bridge the differences in one person’s familiarity with two or more models, or the differences between two or more separate experts. Also, in the process of calibrating models to obtain a high level of correspondence between predicted and observed link flows, network attributes may be changed and the objective is achieved by different network adjustments in different models. The question is then: is a comparison of calibrated models fair? Then, when comparing a micro simulation model to so called conventional models, it is virtually impossible to find equivalent coding solutions and a question that deserves to be raised is how to make a meaningful comparison of so fundamentally different models. Nevertheless, vulnerability studies of this kind can be one aspect in assessing strengths and weaknesses of different models. Depending on the problem to be solved and the prevailing circumstances, different models are suitable for different tasks and different situations. A macroscopic strategic model can be used to identify some parts of the network that require traffic management schemes to be applied, while a more detailed model could be used to evaluate such schemes.

A more general conclusion for all three papers is that the transport models and methods of today can be used to conduct vulnerability studies, but none of them seem to be designed with studies of this kind in mind. It is also important to remember that although a model may be well calibrated for normal conditions, there is no guarantee that it will also predict abnormal conditions correctly. It would be good to have empirical data about actual traffic behaviour during a closure, to enable calibration of models for closure conditions as well. The subsequent validation of models is also an essential issue in order to assess the error in the forecasts produced by such a system (Lundqvist & Mattsson, 2002). Further development of modelling tools is clearly needed to increase our knowledge about the status of the road network, the expected effects when incidents do happen, and possible mitigation measures.
Empirical Vulnerability Analysis

Instead of the computer intensive models and methods investigated for studying effects of given incidents in a network discussed above, Paper V presents a conceptual model for practical vulnerability analysis based on an empirical approach. Following the definition of vulnerability in terms of serviceability in Paper I, the aim is to illustrate the traffic performance on a stretch of road in different key situations using a number of suitable indicators. This is done by on the one hand describing the propensity for serviceability reductions, on the other hand describing the reduced serviceability itself. In other words, the first is attributed to probabilities while the other is a measure of consequences, thus moving away from the area of conditional vulnerability studies dealt with before. The model (Figure 4) sets out from the supposition that different events in the transport system give rise to disturbances, which in turn can be detected in traffic measurement data. The basic measure of traffic performance chosen is average speed. The wheel comes full circle via “actions”, although further elaboration on this is outside the scope of this particular study. The model also indicates an interaction with set serviceability goals, although this is wishful thinking at present since no such goals have been introduced as yet.

Figure 4. Schematic of conceptual model for vulnerability analysis
(Paper V: Fig 4, p 14)
The model is then applied to two semi-motorway objects of 2+1-design with a median cable barrier, a new cross section recently introduced on a large scale in Sweden. The decision to implement this new concept as a standard was based mainly on the expected traffic safety effects, which are found to be substantial. The accident analysis in Paper V shows that the number of severe and fatal injuries is significantly reduced. The question of interest is whether the new lane arrangement in combination with a physical barrier has an injurious effect on traffic performance in case of physical obstructions (accidents, break-downs, management operations etc.), extreme weather (mainly snow) and temporary increases in travel demand (peak hour as well as holiday traffic). Apart from other, already established data sources, a special survey was carried out in co-operation with the rescue corps working on each stretch of road. This provided a so far unused opportunity to gain more direct information on frequencies for incidents, reasons for different types of break-downs and the resulting consequences. The results of applying the model are summarised in Result Schedules. The overall conclusions are that negative effects of physical obstructions could not be identified in the present case study but this should be investigated further. Winter road conditions is a major cause of reduced serviceability and there are indications of risk for traffic break down when travel demand is high.

Regarding the proposed vulnerability analysis model itself, it can be stated that it is based on data that is relatively easy to obtain and a comparison between speed distributions, average speeds, rescue frequencies/rates etc. are easily performed as well as simple to comprehend. It gives an overview of the serviceability on chosen road objects and points to areas where further studies may be needed. The method is flexible in that criterion levels, the so called "normal situation" etc. are simple to adjust depending on the prerequisites and purpose for the study at hand. It also supports a more strictly quantitative consequence analysis in comparison with set goals with subsequent proposals of remedial measures and a follow-up of the results. In this particular case, the focus was on roads but it is evident that this general construct can be used for other infrastructures as well, although the data sources and performance measures will have to be modified and adapted of course.

**Introducing TraVIS**

Vulnerability studies in the road transport system encompass both theory and practice, both cause and effect, both producers and consumers of road services. A general description would be comprehensive analysis of road networks, their susceptibility to traffic disturbances, evaluation of the effects of resulting road closures/blockages and possible mitigation measures. Vulnerability analysis of road networks could hence be regarded as an all-
embracing framework – a hub for the whole battery of transport studies needed to gain the insights necessary to describe how well our transport systems work in different vulnerability respects, what steps to take and what policies to implement in order to reach desired serviceability goals. This is a rather large subject area, the different parts of which are impossible to tackle simultaneously. The general idea, however, can be expressed in one generic term: \textit{TraVIS} – \textit{Transport Vulnerability Impact Studies}. The exact composition of a set of \textit{TraVIS} then depends on which questions are sought to be answered in each specific case. By modifying the previously presented thesis structure, a general vulnerability analysis framework may be illustrated as in Figure 5.

![Figure 5. Schematic structure of a vulnerability analysis framework](image)

Just as the general construct of the conceptual model for vulnerability analysis is transferable, there is nothing to hinder the introduction of this general framework for other transport infrastructures. Current work on vulnerability in the Swedish rail transport system (Wiklund, 2002) is clearly in the lines of \textit{TraVIS} for rail and ongoing research in the field of electricity supply could also be collected under a similar umbrella: Electricity Vulnerability Impact Studies, or \textit{EIVIS}.

The work presented in this thesis touches on just some examples of issues and methods relevant for vulnerability analyses on roads. There are numerous other possibilities, many from the domain of reliability studies (Bell & Cassir, 2000). A game-theoretical approach has been used to obtain worst-case link failure probabilities in a network, which can then be used to calculate other reliability measures (Bell, 2000). Bell et al. (2002) present an absorbing Markov chain model for assessing the reliability of a transit
network, investigating the effect of network topology and line capacity constraint on trip reliability. Lo & Tung (2002) adopt a chance-constrained programming approach to study trip time variability caused by minor incidents in degradable road networks, while Chen et al. (2002) extend capacity reliability analysis into a comprehensive Monte Carlo simulation based methodology for assessing the performance of a degradable road network. Taylor (2000) develops network reliability concepts for traffic calming purposes. Studies of a more empirical approach can be exemplified by the historical data analyses of incident frequencies and durations in Golob et al. (1987) and Giuliano (1989), while Cohen and Southworth (1999) go on to formulate and estimate a model of traffic incident-based delays. The main point of the matter is an overall approach that is felt to be missing so far, that developing theoretical models in combination with various empirical studies is vital for a comprehensive vulnerability analysis. This in turn could prove to be an important tool for e.g. governments in their work toward providing good quality transports. In the Swedish national transport policy (Prop 2001/02:20), reliability was part of the transport quality goal for goods and merchandise only, but has now been extended to the transport of people as well. Focus has also been moved toward providing a high level of service during a trip in its entirety, rather than just minimising travel time. In this context, vulnerability in the road transportation system becomes crucial in the overall assessment of transport quality.

...TOWARD THE FUTURE

Vulnerability analysis as described here is not meant to result in a downright measure. It is proposed more as a tool for characterising various aspects of a road transport system. As such it should be integrated in all the different stages of the infrastructure process, adding a valuable dimension to investment planning, optimisation of road maintenance, and daily operations management. A new road may be built in a different corridor when taking overall vulnerability aspects into account; identifying critical links in the road transport system could indicate a different order of maintenance prioritisation in order to minimise the risk for traffic disruptions; vulnerability analysis would aid in recommending optional routes in case of road works or real time incident management, as well as for constructing contingency plans in case of emergencies etc. We suggest that TraVIS should be brought out and recognised as an integral part of the infrastructure sector, and that this over-all notion be the meeting point for all the different strands of e.g. transport reliability research and other related issues. A main point is to identify possible vulnerability related problems at the right (which often means the earliest possible) level, since proactive measures are often preferable to reactive ones from an economic point of view.
However, there are still a lot of blanks to be filled in before reaching the structure for systematic implementation of such a comprehensive network analysis package. In short there is a need for:

- continued development of e.g. micro simulation tools, suitable for detailed modelling of traffic under extraordinary conditions such as road closures etc.
- data on actual redistribution of traffic during disturbances, in order to calibrate and validate these models.
- data on frequencies of incidents and the resulting consequences for an operational valuation of risks.
- inventories on possible mitigation measures and their cost/benefits, both for producers and consumers of road services.
- increased knowledge of how users react to and evaluate unreliability, both for developing theoretical models and for incorporating these impacts into overall cost-benefit analyses.

Transport reliability, or rather unreliability, has received increasing attention in recent years, especially in terms of how users perceive and respond to travel time variability (Noland & Polak, 2002). Time values are also high on the research agenda and a comprehensive meta-analysis of various valuations of time and a wide range of service attributes can be found in Wardman (2001). Another important aspect, discussed in Schneider et al. (2002), is just how to view and evaluate congestion. The research necessary for making progress in this area hence seems to be well under way. It is essential to avoid the possible catch 22 situation that if no one expresses a demand for this kind of analysis tools, further research and development is eventually pointless – and if a sound theoretical and methodological base is not established, no one will find any use for this kind of analysis tools. This thesis gives the notion of vulnerability a more coherent structure, developing it not so much as a quantitative measure in itself, but rather as a way of thinking. It is an attempt to fence in the general idea of vulnerability analysis of the road transport system through five different papers, ranging from theory to practice, each dealing with the issue at hand at a different level and in a different context. To put it simply – it gives examples of TraVIS for roads.

ACKNOWLEDGEMENTS

I would like to express my gratitude to my main supervisor Lars-Göran Mattsson, for his ability to combine splendid supervision with great camaraderie, as well as my assistant supervisors Hans Cedermark and Torbjörn Thedéen for their sometimes stubborn but always invaluable
contributions. My reference group consisting of Staffan Bergström, Anki Ingelström, Helena Nurmiiranta, Jacki Palmér, Per-Erik Westman and Mats Wiklund have been a never-ceasing source of help and inspiration as well. Thank you also to all my co-authors – Alan Nicholson, Zarko Andjic, Torsten Bergh and Arne Carlsson – without whom the papers in question wouldn’t be what they are today. I am also grateful to Erik Anders Eriksson for his valuable suggestions and comments on an early thesis prototype. Furthermore, Alan deserves extra thanks for a warm welcome and making the necessary arrangements for my stay at the University of Canterbury in Christchurch, New Zealand. This will no doubt be one of the highlights when looking back at my time as a PhD candidate!

Last, but not least, the Swedish Agency for Innovation Systems (former Swedish Transport and Communications Research Board), the Swedish Emergency Management Agency (former Swedish Agency for Civil Emergency Planning), the Swedish National Road Administration and the Swedish Research Council for Environment, Agricultural Sciences and Spatial Planning are gratefully acknowledged for supplying the necessary financial funds.

REFERENCES


LIST OF RESEARCH REPORTS

This thesis has been preceded by a number of working papers/reports that may be of interest, produced within the research project Vulnerability in the Swedish Road Transportation System. These are listed in the following, and can be obtained from the author or the Department of Infrastructure, Royal Institute of Technology, 100 44 Stockholm, Sweden.


Berdica, K (2000) Vulnerability – A Model Based Case Study of the Road Network in the City of Stockholm. TRITA-IP AR 00-83


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PAPER I
An introduction to road vulnerability: what has been done, is done and should be done

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Abstract

Vulnerability in the road transportation system, studied not only from a safety point of view but also as a problem of an insufficient level of service, is proposed as a setting for future transport studies. This relatively new notion is conceptualised by discussing a number of definitions and related concepts, reviewing especially the concept of reliability as a feasible theoretical approach. The paper relates how vulnerability related problems have been addressed so far, current developments and finally what the future should hold in order to provide us with the comprehensive network analysis tool that our complex society calls for. © 2002 Elsevier Science Ltd. All rights reserved.

Keywords: Vulnerability; Reliability; Road network; Literature review

1. Introduction

To provide all citizens, trade and industry nationwide, with an economically and in the long-term sustainable transport function is more or less the overall objective of most national traffic policies of today—the Swedish one being no exception. In Sweden, six subsidiary goals have been formulated to obtain: (1) an accessible transportation system, (2) high transport quality, (3) safety, (4) a good environment, (5) a positive regional development and 6) equality (Prop 2001/02:20). The focus of this paper is on the road transportation system, for which the fulfilment of all of these points requires not only that physical links exist between different destinations, but also that these links are open to traffic. However, extreme weather conditions or other natural phenomena can make large parts of the road network impassable. More rare events like collapsing bridges, as well as every day incidents such as traffic accidents or closures due to maintenance activities, can reduce the capacity of the traffic system. The resulting congestion effects and delays cause serious losses in terms of travel time as well as other costs e.g. in case of disrupted ‘just in time’ deliveries. In order to implement suitable policies to attain various goals there is a need for an overall characterisation of road networks, to gain insight into their propensity to ‘malfunction’, the extent of the resulting consequences, the scope for mitigation measures, etc. So far, this is felt to be missing in transport studies of today. The purpose of this paper is therefore to conceptualise and put into context a relatively new notion, proposed to constitute a framework for such analyses: vulnerability in the road transportation system.

The starting point is the fact that road networks from time to time display a reduced level of service due to various reasons. A number of definitions and related concepts are used to fence in the general idea, going on to suggest a basis from which vulnerability issues can be addressed, as well as pointing out the possibilities and problems involved in practical implementation. The final discussion argues for a more systematic consideration of these issues throughout the road infrastructure planning process, all the way from investment planning, through operations management, to optimisation of maintenance activities.

2. How to define vulnerability

2.1. Serviceability versus accessibility

Vulnerability of the road transportation system is here regarded not from a safety point of view, but rather as a problem of reduced accessibility that occurs because of various reasons. Also, emphasis is put on the function of the system rather than the physical network itself, although some of the reasons for discontinuities in the road network are indeed caused by physical failures. Accessibility is however a term of widely varying meaning depending on the context in which it is used. Generally, accessibility is understood as ‘ease of reaching’ and concerns the
opportunity provided by the transport system for people to take part in a particular activity/set of activities from a given location (Jones, 1981). In this sense accessibility can be increased either by increasing the number of routes to a certain service or by increasing the amount of services reachable on a certain route or within a certain time budget. Accessibility is, according to Jones, a function of mobility, meaning the ability of an individual to move about (i.e. a potential to move, not the completed movement that Ross (2000) uses in his arguments for the relationship being one of reciprocity) by means of private and/or public transport. Mobility in its turn consists of: (1) the performance/effectiveness of the transport system in connecting spatially separated locations, and (2) individual characteristics influencing the extent to which people are able to make use of the transport system.

This implies that even though accessibility depends on the degree to which the transportation system is functioning, it is actually approaching the issue from the demand side. This is of course important when dealing with the quantification of consequences, i.e. evaluating the total delays caused by various events. At this stage it is however more interesting to regard the road network from the supply side, meaning the actual existence of a functioning route from one location to another. Therefore, it is in this case better to describe the performance of the road transportation system in terms of serviceability. Definition: The serviceability of a link/route/road network describes the possibility to use that link/route/road network during a given time period. Another approach can be to talk about quality in transport, which is a multi-dimensional concept with many different attributes, all of which exist in the context of (quote): “the basic ability of a system to deliver you from where you are, to where you want to be, at the time you want to travel, at a cost...that makes the journey worthwhile” (Goodwin, 1992, p. 661). This is in fact, another more detailed way of describing the previously defined term serviceability.

2.2. Incidents

The events of interest in the case of vulnerability in the road transportation system are the ones causing disturbances in traffic. These events can be of a more or less sudden and/or unpredictable nature, ranging from extremely adverse weather through physical failures and traffic accidents, to planned road works, as well as intentional harm in the shape of conflicts in labour relations or terrorist actions—all of which have bearing on the performance of the road network. The frequency, predictability, geographical extent, etc. vary greatly both among event categories and among events within categories. What these events have in common though, is that they could have a negative influence on the serviceability of the road network, either on their own or by starting a chain of events resulting in a disturbance. They are therefore referred to as incidents. Definition: An incident is an event, which directly or indirectly can result in considerable reductions or interruptions in the serviceability of a link/route/road network.

According to this, an incident is hence an event causing reduced capacity and/or increased demand. This is a somewhat more specific usage of the term, since in most dictionaries ‘incident’ is simply a synonym for ‘event’. To distinguish between the two, it is suitable to note that studying vulnerability in the road transportation system is not primarily a question of network optimisation regarding the function during ordinary traffic flow variations or minor changes in weather. Therefore the specification ‘considerable reductions or interruptions’ is used in the definition earlier. The actual quantification of this level is an important task for future studies and is elaborated later.

2.3. Risk is probabilities and consequences

Risk is generally associated with something that entails negative consequences for life, health and/or the environment. The definitions of the term vary, but mostly involve a combination of two parts: (1) the probability for an event of negative impact to occur, and (2) the extent of the resulting consequences once this event has taken place. The evaluation of different influencing factors and the consequent rating of risk depend on the point of view taken—the decision maker, the affected user or other interested parties see things differently, i.e. they have different perceptions of risk. Subjects using a definition of risk in terms of consequences tend to give higher ratings than those that focus on probabilities, and the same tendency can be seen when comparing the perspectives ‘risks to others/people in general’ and ‘personal risk’ (Drott-Sjöberg, 1991). There is also the aspect of time and space, in which risks ‘here today’ tend to be perceived as greater than risks ‘there yesterday/tomorrow’ (Westin and Jansson, 1994). Hence, measuring risk involves considerable uncertainty. Even if both probabilities and consequences are theoretically measurable in scientific terms, they in practice involve assessments impaired with various degrees of subjectivity that makes it more difficult to obtain an objective composite of the two.

The earlier mentioned incident categories, causing the road transportation system to malfunction, cover a wide range of combinations where probabilities and consequences are concerned: from minor accidents that happen every now and then, to highly improbable failures (e.g. of a bridge) resulting in serious injuries. This stresses the importance of a risk definition that takes both these aspects into account. Definition: Risk is a composite of (1) the probability for an incident to occur and (2) the resulting consequences, should the incident occur. One way to explain this is to construct a risk matrix, the principle of which is exemplified in Fig. 1. Of our earlier mentioned examples, the ‘everyday minor accident’ would be placed in the lower right-hand corner, while a bridge failure would fall into the
2.4. Vulnerability

As is often the case when discussing terminology, there are many alternative ways of understanding the term vulnerability. In one paper the following definition is used (quote): “Vulnerability is a susceptibility for rare, though big, risks, while the victims can hardly change the course of events and contribute little or nothing to recovery.” (Laurentius, 1994, p. 278). From the road network point of view, this is a rather narrow definition, concentrating on events of catastrophic nature. A better approach is to start by stating that, a vulnerable system is a system susceptible to extreme strains. In a government bill (prop 1996/97:11), handling extreme strains on society is described as the ability to deal with situations characterised by: a deviation from the situation which is considered as ‘normal’; sudden occurrence, more or less unpredicted and without warning; basic values being threatened; demand of quick decisions and coordinated/concentrated actions by several authorities. Here the low level of probability and high level of consequence, implied by ‘rare, though big, risks’ in the previous citation, is omitted. There is, however, an improper emphasis upon the unexpected, considering that in the case of road transports planned actions such as road works can cause serious disturbances in traffic (Berdica, 1998). Therefore, in the specific case of the road network, a definition of vulnerability that is of a more general nature is suggested here. Definition: Vulnerability in the road transportation system is a susceptibility to incidents that can result in considerable reductions in road network serviceability. These incidents may then be more or less predictable, caused voluntarily or involuntarily, by man or nature. A similar definition, in principle, is found in Nicholson and Du (1994).

By addressing these terms in that order one can see a system of back tracking the issue at hand through a series of sequential definitions, illustrated by the Wheel of Concepts in Fig. 2. Reducing vulnerability can hence be regarded as reducing the risks involved in various incidents, which can be brought about in two ways: (1) by a fail-safe approach, meaning that the probability for e.g. a bridge to fail is reduced, or (2) by adopting a safe-fail perspective, implying a reduction of the resulting consequences should the failure occur (Holling, 1981). In this example the latter could be achieved by an emergency terry service. Consequence minimisation is in fact a very important aspect of vulnerability studies, since it is not always suitable to talk about the probabilities of certain incidents, e.g. terrorist actions. In those cases it is necessary to investigate expected effects and possible remedial actions under the assumption that the incident has already taken place.

2.5. ‘Neighbouring’ terms

There are several other terms that can be regarded as related to the general subject of vulnerability in technical systems that may or may not be relevant in the specific case of vulnerability in the road transportation system. The most common of these are discussed shortly here, mainly in relation to the earlier stated definitions. However, reliability—the term that probably first comes to mind—is found to be of special importance and is therefore elaborated later.

In dictionaries, robustness is often exemplified in the area of computer technology, i.e. it is the ability of a computer system to cope with errors during execution. In other words,
it is the ability of a system to withstand strain. It is easy to
draw a parallel and talk about robustness in the road trans-
portation system, as opposed to vulnerability that is defined
as a susceptibility to disturbing incidents. Hence the terms
can be used as oppositely interchangeable in the present
case, i.e. a less vulnerable system can be regarded as
more robust and vice versa.

Resilience is often an issue in ecology and expresses the
capability of an ecosystem to `return to normal` after having
been disturbed. It is hence a question of stability, involving
the factors (1) maximum disturbance from which the
system can recover and (2) speed of recovery (Goldberg,
1975). It is clearly possible to transfer this concept to the
road transportation system, with, e.g. `time to restored
serviceability` being a factor of interest. Resilience could
also be described as the capability of reaching a new state of
equilibrium. However, many of the incidents causing reduc-
tions in serviceability have a relatively short duration, never
reaching a new equilibrium. This so called transient state
still remains to be studied/modelled more thoroughly and
recent research shows that microsimulation can be a feasible
tool for such analyses (Berdica et al., 2001).

In electronics/mechanics there is often redundancy in
the system, meaning a duplication of components so that
operations can continue even though part of the equipment
fails. The parallel to the road transportation system is
obvious: the existence of numerous optional routes/means
of transport between origins and destinations can result
in less serious consequences in case of a disturbance in
some part of the system. This is an important factor in the
evaluation of vulnerability in a road transportation system.

If traffic is routinely divided between possible routes in
everyday use, the redundancy is active. A ferry service
that is activated only in case of a bridge failure (i.e. a
`reserve`) is an example of passive redundancy. It is
however necessary to remember that the redundancy of the
system is dependent upon the nature of the `threat`. In
the electronics case, putting duplicate cables in the same canal
is not enough if the canal itself is destroyed e.g. by a bomb assault.
In the road transportation system, a serious snow-
storm may well disable all alternative routes in a larger area.

3. How to approach vulnerability

3.1. Introducing reliability

So far, there has not been much research on road trans-
portation vulnerability as an explicit subject, although the
need for more comprehensive vulnerability analyses
obviously grows concurrently with the increasing complex-
ity of modern infrastructures. One fundamental reason could
be a want of a well-tried theoretical basis to build on. Let us
therefore at this point turn to the concept of reliability, in an
attempt to close in on the topic of vulnerability. To start

with, consider the following, widely accepted definition:
`Reliability is the probability of a device performing its
purpose adequately for the period of time intended under
the operating conditions encountered.` (Billington and
This leads to the conclusion that reliability studies are
generally concerned with probabilities only, which in fact
often is the case. D’Este and Taylor (2001) choose to regard
vulnerability as completely separated from reliability due to
the main probabilistic base of the latter and (quote): “the
concept of vulnerability is related to the consequences of
link failure, irrespective of the probability of failure”. If so,
vulnerability would be just a measure of consequences
instead of the comprehensive framework for analysis that
will be argued here, and in which the composite risk
concept is a central idea. However, the formulation of reli-
ability in terms of probabilities is not the only approach
possible: ‘performing its purpose adequately’ and ‘operating condi-
tions encountered’ can well pertain to this aspect. The
consequences can hence be included in terms of a level of
performance. The performance of engineering systems can
be expressed by a number of various indices, e.g. expected
number of failures within a certain time, average time
between failures, expected loss of revenue and/or output,
etc. These are more and more commonly referred to simply
as ‘reliability indices’ even though they are not associated
with probabilities only, as in the classic case of reliability
studies (Billington and Allan, 1992). Reliability theory can
well be used for the evaluation of these indices, provided
that levels for the unacceptable/inadequate are set first.
By choosing this wider interpretation, reliability can be
regarded as a complement of vulnerability, expressed in
the following. Definition: vulnerability in the road transpo-
sation system is reliability, meaning adequate serviceability
under the operating conditions encountered during a given
time period.

The conclusion is that vulnerability in transportation
systems has not yet been considered directly but well-
established reliability theory can constitute a tool for
addressing such issues, provided that consequences as
well as probabilities are taken into consideration. In trans-
portation systems, reliability describes the possibility of
successfully travelling from one place to another. So far
in the literature, it has been considered in three main
aspects: (1) reliability of connectivity (also referred to as
terminal reliability), meaning the probability of at all reaching
a chosen destination, (2) reliability of travel time, meaning the
probability of reaching a chosen destination within a given
time, and (3) capacity reliability, meaning the probability of
the network being able to ‘swallow’ a certain amount of
traffic. The main difference from traditional systems reliability
analysis is the need to identify an acceptable level of service,
exchanging the dichotomous states ‘functioning—not function-
ing’ with ‘serviceability acceptable—not acceptable’. Further-
more, changes in road network reliability can be observed as a
result of either fluctuation in traffic flow (‘normal’ conditions;
often referred to as recurrent congestion), or fluctuation in capacity (‘abnormal’ conditions; often referred to as non-recurrent congestion).

In the following, what has been done in terms of research conducted so far is reviewed, giving account of essential lines of thought pertaining to these matters (see also Berdica, 2000; Schmöcker and Nicholson, 2001).

3.2. Network reliability is general

Wakabayashi and Iida (1992) and Bell and Iida (1997) focus on terminal reliability. The stochastic variable $x_i$ represents the state of, e.g. congestion on link $i$, with the value of 1 if link $i$ functions and 0 otherwise. The system reliability value is found through the structure function $\phi(x)$, where $x$ is the system state vector containing the link state variables. Accordingly, the structure function has the value 1 if the system functions and 0 otherwise. For systems that have—or easily can be broken down into—a series and/or parallel configuration, the structure function is simply $\phi(x) = \Pi_i x_i$ for a series system and $\phi(x) = 1 - \Pi_i (1 - x_i)$ for a parallel system, or a combination of these. For more complicated systems the structure function is derived by different methods, of which ‘path-and-cut’ is the most practical. The system reliability is calculated directly from either: (1) the minimal routes, which is the minimum number of successive links needed to connect a pair of nodes, regarded as series systems in parallel—as long as any one of the routes functions, the system functions; or (2) the minimal cut sets, which is the minimum number of links needed to disconnect a pair of nodes, regarded as parallel systems in series—if any one of the cut sets fails, the system fails.

Link reliability $r_{ij}$ is the expected value of the (assumed) random binary variable $z_{ij}$ and system reliability $R$ is the expected value of the structure function. However, the evaluation of $R$ involves complicated calculations since links can appear in more than one set. Furthermore, large or very complicated networks result in a great amount of calculation. Therefore various heuristic methods for obtaining estimated values of reliability, for instance upper and lower bounds (some using partial route/cut sets), are most interesting. Some other ‘problem areas’ are identified, e.g. that connectivity reliability studies overlook mutual relationships or dependencies among links, as well as the fact that connectivity reliability does not take flow on links into account.

3.3. Reliability and fluctuation of traffic flow

The main issue in Asakura and Kashiwadani (1991) is a modified traffic assignment model for simulating day-to-day fluctuations of traffic flow during ‘ordinary’ traffic conditions, that is when capacity is not reduced by road works, accidents, natural disaster etc. The basic assumption is that travel demand in origin–destination (OD) relations fluctuates stochastically from day-to-day around its (observed/estimated) mean value and that this random variation can be described by two mutually independent, normally distributed random variables. One represents OD-specific variation (e.g. special offer at a certain mall) while the other represents variation that affects the network as a whole (e.g. adverse weather). A correlation parameter of fluctuation ($\lambda$) decides how much of each type is included in the total variation. It is easy to show that the correlation coefficient ($\rho$) for two different OD-demand (on the same day) is determined by this correlation parameter, with the special cases of (1) demand fluctuation being the same for every OD-pair when ($\lambda = 0 \Rightarrow \rho = 1$); and (2) completely independent fluctuating OD-demand when ($\lambda = 1 \Rightarrow \rho = 0$).

The results of the simulation model are used to define and estimate two reliability measures. The first is a connection measure (i.e. connectivity), i.e. the probability of travel in an OD-relation without encountering congestion beyond a certain level. If this level of congestion (which can be measured in terms of traffic volume, travel time, generalised travel cost or the like) is exceeded, the link in question is regarded as disconnected. Link congestion fluctuates in proportion to link traffic volume, which has been determined by the simulation model. If the different routes can be regarded as parallel, the probability of an OD-pair being connected is calculated in accordance with the theory presented earlier (Wakabayashi and Iida, 1992; Bell and Iida, 1997). By defining connectivity in terms of congestion level, this connection measure describes the probability of finding at least one route without unacceptable congestion between $i$ and $j$. The second is a time reliability measure, as either (a) the probability of travel time in an OD-relation not exceeding the prescribed travel time, or (b) the travel time bound in an OD-relation for which the probability of not being exceeded is at a prescribed level. Because of the assumed stochastic variation in traffic volume, travel time between OD-pairs fluctuates randomly. This randomness is assumed to follow a normal distribution for which the parameters can be calibrated using the results of the simulations.

It is interesting to note that Asakura (1996) makes a connection between the two reliability measures discussed earlier. In the case of deterioration in a road network with variable flows, travel time reliability is expressed as a function of the ratios between travel times at reduced capacity and those during ‘normal’ conditions. When the level of degradation is so great that the destination in question cannot be reached, the ratio move towards infinity. This extreme case of travel time reliability is then consistent with the reliability of connectivity concept.

3.4. Improvement of reliability under traffic management

Wakabayashi and Iida (1993) take more or less the same approach as Asakura and Kashiwadani (1991). They propose new indicators of road network performance level, instead of the conventional quantitative (e.g. total length of road per unit area) or static (e.g. average travel time)
indicators of road network quality: (1) terminal reliability is the probability that two given nodes are connected with a certain service level for a given time period, and (2) travel time reliability is the probability that travel time between two given nodes will not exceed a given travel time, alternatively treated as the maximum travel time to arrive at a destination with given probability. Traffic variation is assumed to be the main factor influencing both of the above. The difference, however, is the 'abnormal conditions' approach, described in the statement that (quote): "A highly reliable road network provides sure and unfluctuating traffic service by offering drivers alternative routes even when some part of the network is unavailable due to traffic accidents, maintenance or natural disaster." (Wakabayashi and Iida, 1993, p. 29).

Terminal reliability is addressed at link level, and link reliability of connectivity is the probability that demand flow does not exceed reference capacity on a certain link for given time periods. The variation in link flow originates from the variation in OD-flow, following the two assumptions that these are normally distributed and that OD-portsions using a certain link are constant. This is explained in a functional model, expressing the coefficients of variation. Link reliability of travel time can then be converted from that of connectivity by derivation of the probability density function for demand traffic volume and using for instance the BPR function as link performance function. Estimations can then be made in two ways, by assuming either independent or correlated link flow variations. By considering traffic flows explicitly, the method proposed can be used to assess the effects of a change in traffic flow on reliability.

3.5. Degradable transportation systems

Nicholson and Du introduce the term 'degradable transportation system' (DTS), since (quote): "transportation systems are subject to degradation as a result of a wide variety of events (e.g. earthquakes, floods, traffic accidents, adverse weather, industrial action, and inadequate maintenance)" (Nicholson and Du, 1997, p. 209). Existing network reliability models are lacking on a number of accounts when considering transportation networks. Most importantly they assume fixed traffic demand, statistically independent component states, and they do not allow for components to have degradation levels between full and zero capacity.

The proposed integrated equilibrium model (Nicholson and Du, 1997), on the other hand, allows for elastic demand, varying levels of degradation, and interdependent component states. Also, it focuses on long duration capacity variations, since there is more scope for traffic to move towards a new equilibrium situation. The network configuration chosen for the DTS is multi-modal, as different transport modes are not necessarily affected equally by an incident. Each link pertains to a single mode, hence there is no modelling of interactions between different types of vehicles. Moreover, this means that route choice also implies mode choice. Both links and nodes are system components of the DTS, although all component degradation is considered to occur within links.

The relationship between a given component state (i.e. link capacity) vector and its corresponding system state vector is defined using a combined model which solves the problems of traffic generation, distribution, modal split and assignment simultaneously within a framework based on the assumption of demand-supply equilibrium. It is assumed that demand in each OD-pair can be formulated explicitly as a function of the generalised travel cost. Various forms of demand function, including the logit, power, exponential, and elastic exponential functions, satisfy these assumptions. The supply function is a multi-variable function and is therefore represented implicitly through the following. Route flows are determined from OD-flows by assuming that individuals choose routes in order to minimise their generalised costs under the usual Wardrop condition on user equilibrium. The travel time on a link is a function of the vehicle flow and the component state, which in turn influences the generalised travel cost on that link. System surplus is then chosen as the performance measure to assess the socio-economic impacts of system degradation. The authors refer to previous work that has shown that the equilibrium OD-flow and link flow vectors, and system surplus, are unique—although the equilibrium route flow vector generally is not (which is also the case in the standard traffic assignment problem). This uniqueness is important when analysing how the system state and thereby its performance is affected by changes in component state, i.e. component degradation. The sensitivity and reliability analysis based on the integrated equilibrium model (Du and Nicholson, 1997)—and hence the model itself—are for a steady-state condition. A future task is to include differences in degradation duration (which as well as degradation occurrence can be regarded as a stochastic variable), since the socio-economic impact of component degradation clearly grows with increasing time for repair/replacement.

3.6. Capacity related reliability

Allowing for varying demand and fluctuating capacity, initiated with the concept of Degradable Transportation Systems, has since been taken up and developed further. Recently the measure of capacity reliability, meaning the probability that a certain traffic demand can be accommodated at an acceptable level of service, has been introduced. It starts with the concept of network reserve capacity, defined as (quote) "the largest multiplier applied to an existing OD-demand matrix that can be allocated to a transportation network without violating the link capacities or exceeding a preassigned volume to capacity ratio (level of service)" (Chen et al., 1999, p. 186). Roadway capacity is modelled as a random variable with defined distributions.
The issue of interest is then to estimate the probability of network reserve capacity being greater than, or equal to, required demand for different levels of degradation. However, a common multiplier is used for all OD-pairs to increase travel demand, which is a restriction of this approach. It is also necessary to consider link dependencies when generating capacity degradation for each link.

Chen et al. (1999) state that travel time reliability is obtained as a ‘side product’ when solving the traffic equilibrium problem to obtain the maximum network reserve capacity. In later work they investigate how the estimation of capacity reliability and travel time reliability is affected by the degree of stochasticity in the route choice model (Chen et al., 2000). Yang et al. (2000) then proposed the combination of travel time and capacity reliability as a comprehensive performance measure of a road network, instead of modelling them separately as has been the case so far. They show that the two reliabilities are closely linked by two reference parameters, namely a traffic time threshold and a traffic demand threshold. For a certain demand, the only way to obtain higher capacity reliability is through a higher travel time threshold—i.e. reducing the level of service—while for a given travel time threshold, travel demand needs to be lowered in order to increase capacity reliability.

4. How to study vulnerability

4.1. What has been done

Vulnerability problems have so far mostly been addressed in terms of isolated in-depth-studies of effects of either individual emergency situations or of separate vulnerability related issues. Disturbances in city traffic have often been in focus—their occurrence, type, and consequences in terms of delay. Studies may vary from pure field studies (Kronborg, 1993; Svensson, 1994) to historical data analyses (Golob et al., 1987; Giuliano, 1989). An example of a theoretical extension is found in Ardekani et al. (1997), in which a PC-based tool for identifying diversion routes (based on changes in traffic volume) around roadway disruptions is calibrated against actual observations in the field. Another frequent type of vulnerability related study is ‘after-the-emergency’ analyses (Savas, 1973; Wolfiram, 1981; Romero and Adams, 1995; Swedish National Road Administration, 1999), often going on to more organizational aspects, issues of information and co-ordination of involved parties, etc. Answering these questions is a good beginning, but the piecing together into an overall consideration of vulnerability in the road transportation system is missing.

One factor contributing to this tendency for a piecemeal approach could simply be the difficulty of defining system type—an important issue in starting any systems analysis. Using the terminology in Billington and Allan (1992), mission oriented systems accept failure of some components as long as the system as a whole continues to function for the duration of the mission. Reliability can be said to measure to which extent this system is staying in the operating state. In systems of the continuously operating type, failure is acceptable provided that it is not too frequent or lasts too long. In this case availability is a better measure, describing the possibility of finding the system operating. However, when working with the road transportation system determining system type is not a straightforward task—it varies with the level of focus. At the level of individual travel demand, the system is mission oriented in that some links/routes may fail but alternative links/routes ensure the successful completion of a trip e.g. to work. At the aggregate level, on the other hand, the system is continuously operating. That is, interruptions in some parts of the network are accepted temporarily (e.g. during a heavy snow storm) if the ‘emergency network’ provides adequate serviceability at the given time. The road transportation system can hence be described as a continuously operating system consisting of a number of mission oriented subsystems, and functionality is in a way expected at both levels simultaneously.

This brings up the question of how to determine whether the system is operating or not—a question that can have a range of answers, partly because of the duality discussed earlier but also due to geographical setting, objectives of the study in question and/or parties involved, etc. Table 1 presents a selection of performance measures for multi-modal transportation systems (Pratt and Lomax, 1996) often used for describing base conditions, identifying problems, aiding in the selection between alternative improvements, evaluating the outcome of various implementations, system monitoring, etc. Travel time is identified as a common thread, in that it exists not only as a direct measure but also as an element of other indicators. In the Highway Capacity Manual, speed is chosen as a simple indicator for the level of service. Speed is directly influenced by traffic flow in that low volumes permit high, steady speed while high volumes cause low, varying speed. In other words, traffic volume should be kept at a lower level than the capacity of the street in order to retain high transport quality. The difference between the two (preferably expressed in terms of actual traffic volume as a proportion of theoretical capacity) is a measure of quality denoted by Goodwin (1992) as the ‘quality margin’. In theory, the larger the quality margin the less sensitive the system is to disturbing incidents (although a large quality margin seems to be a rather unrealistic way of reducing system vulnerability since in practice the traffic system is often operated close to capacity). These indicators can measure transport system performance, but vulnerability analysis demands that a level for the acceptable/unacceptable is set first. Also, these measures are static mean values but used to describe a highly dynamic process—traffic. Thus, there is clearly a dimension missing when it comes to discussing what adequate serviceability is and if it is maintained.
Table 1
A selection of performance measures for transportation systems (Source: Pratt and Lomax (1996); author’s adaptation)

<table>
<thead>
<tr>
<th>Measure</th>
<th>Calculated by</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Travel time, tt</td>
<td>t/segment length = (speed $^{-1}$) - 1</td>
<td>$at = actual travel time, dt = desired travel time$</td>
</tr>
<tr>
<td>Travel rate, tr</td>
<td>(at - dt) - at - dt/length</td>
<td>$ar = actual travel rate, dtr = desired travel rate$</td>
</tr>
<tr>
<td>Delay rate = dr</td>
<td></td>
<td>Easier to use than speed in statistical analyses</td>
</tr>
<tr>
<td>Total delay</td>
<td>$dr \times$ people vol. $\times$ length = (at - dt) $\times$ people vol.</td>
<td>Illustrates the intensity of the congestion problem to travellers</td>
</tr>
<tr>
<td>Relative delay rate</td>
<td>$dr/dtt = ar/tt - 1$</td>
<td>Dimensionless measure for comparing systems</td>
</tr>
<tr>
<td>Delay ratio</td>
<td>$dr/tt - 1 = dr/ttt$</td>
<td>Dimensionless measure to illustrate the magnitude of the mobility problem in relation to actual conditions</td>
</tr>
<tr>
<td>Speed of person movement</td>
<td>Passenger vol. $\times$ average travel speed</td>
<td>Measure of travel efficiency</td>
</tr>
<tr>
<td>Corridor mobility index</td>
<td>$spn/standard value$</td>
<td>Standard value = e.g., one freeway lane operating at capacity with a typical urban vehicle occupancy rate</td>
</tr>
<tr>
<td>Accessibility</td>
<td>Average it to objectives or percentage of objectives reachable within a specified time</td>
<td>Specialty for joint performance of transportation and land-use</td>
</tr>
</tbody>
</table>
| Congested travel         | $\sum$ (congested segment length $\times$ people vol.) | of not encountering any degraded links on the least expected cost path between origin and destination. Since users will probably try to avoid using degraded links, the level of information and the users’ reaction to this information are important considerations. Apparently, the more ‘risk averse’ users are, the closer encountered reliability is to terminal reliability — given that link degradation probabilities are known to, and followed by, the users. Another way to model this is the game theory approach proposed by Bell (2000), in which the user seeks a minimum expected trip cost path while an ‘evil entity’ tries to maximise the expected trip cost by degrading a critical link in the network. The Nash-equilibrium point (at which neither user nor assailant can ‘improve’ their situation) provides worst-case link failure probabilities that can then be used to calculate other reliability measures. Fluxuation of flow and fluctuation of capacity are generally identified as important factors when it comes to maintaining an acceptable level of performance, since reduced supply (capacity) on one link often results in increased demand (flow) on another. The interaction between demand and supply depends very much or individual road users’ perceptions, e.g., of congestion levels and expected travel times, and also what aspects of travel time they regard as important. In order to correctly assess road network performance and decide what should be regarded as adequate levels of service — as well as to estimate the effects of possible mitigation measures — increased knowledge of these behaviour aspects of transport modelling is needed. Noland et al. (1998) present a simulation model that determines congestion effects of travel time uncertainties resulting from capacity reducing incidents such as traffic accidents, etc. They found that the extra travel costs...
resulting from increased travel times were in fact not as great as those connected to an increasing probability of arriving at the ‘wrong’ time, so called scheduling costs. Noland (1997) suggests that instead of increasing capacity (an often very capital-intensive solution) it may be more effective to reduce expected costs of travel by reducing travel time uncertainty e.g. by providing information on travel time variance and changing congestion conditions.

How users perceive and respond to travel time variability (generally in terms of departure time choice) has been the subject for both theoretical model development and empirical analysis in the past several years, a comprehensive overview of which was published recently (Noland and Polak, 2002). Other research deals more directly with how drivers react to information of varying detail and accuracy, given to them at various stages of their journey—Mahmassani (1990), Mahmassani and Jayakrishnan (1991) and Mahmassani and Chen (1993) are only some examples. This is all the more important considering recent developments in information technology and that advanced traveller’s information systems (ATIS) are often exemplified as possible alleviators of congestion problems. While spatial and environmental constraints often make it impossible to solve capacity shortages by increasing capacity, ATIS could allow us to use existing capacity more efficiently. Also, real-time information systems should enable quicker and more effective rerouting of traffic e.g. in case of blockages. However, it is important to recognise and further look into the fact that information will not automatically lead to improved traffic conditions (Mahmassani and Jayakrishnan, 1991) and if all drivers are given and also act on this information, conditions could actually worsen (Mahmassani and Chen, 1993). Another important issue in the development of behavioural models is the lack of actual observations of behaviour and corresponding measurements of traffic conditions. One solution that has been tried is conducting interactive laboratory-like experiments (Mahmassani, 1990).

4.3. What should be done

It is plain that road network reliability is on the rise as an important issue in society today. Three main areas of research are identified in Iida (1999): the development of a modelling framework capable of reliability investigations, the establishment of a traffic management system capable of providing high road performance, and new procedures for evaluation and optimisation of road network planning, construction and management which take reliability issues into account. Now, this seems to be comprehensive enough, so why not just leave the notion of vulnerability and concentrate on reliability instead?

It is clear that road vulnerability encompasses all of the above, but we also feel that vulnerability in road transport concerns more than this. Bearing the previous definitions and discussions in mind, road vulnerability analysis regards the road network as a whole and involves identifying a spectrum of incidents, collecting data on probabilities and consequences to estimate risks, performing various studies and experiments to set values for desirable/acceptable serviceability, as well as investigating and assessing the effects of possible mitigation measures and improvement strategies. We admit that the reliability concept could probably be stretched and modified to include these steps as well but it is always hazardous to fill old words with new meanings. Vulnerability as such is of course not completely new to our vocabulary either, but at least of such novelty in the area of transport that we feel comfortable with suggesting vulnerability analysis of road networks as an all-embracing framework using the different aspects of transport reliability studies as its foremost tools.

Vulnerability analysis is not introduced as a downtight measure but more as a way of characterising a road network, basically as a means for being ‘wise after the event in advance’. As such it should be integrated in all the different stages of the infrastructure process, adding a valuable dimension in investment planning, optimisation of road maintenance, and daily operations management. A new road may be built in a different corridor when taking overall vulnerability aspects into account; including risks and consequences of different incidents in a network could indicate a different order of maintenance prioritisation; vulnerability analysis would aid in recommending optional routes in case of road works or real time incident management, as well as for constructing contingency plans or for other emergency related issues. It can also be of help in assessing possible outcomes and overall effects of various strategic policies to avoid so-called problem migration (Hass-Klau et al., 1998). A main point is to identify possible vulnerability related problems at the right (which often means the earliest possible) level, since proactive measures are often preferable to reactive ones from an economic point of view.

Many question marks still need to be straightened out before reaching the structure for implementation of this comprehensive network analysis method. One main issue is that common transport modelling tools are often based on equilibrium assumptions on a macroscopic level. This is not suitable for detailed modelling of traffic under extraordinary conditions such as road closures, and continued development of tools e.g. microsimulation with these issues in mind is important (Goodwin, 1999; Berdica et al., 2001; Nicholson et al., 2001). Data on actual redistribution of traffic during disturbances is needed for the calibration and validation of these models, but such information is scarce today. An increased knowledge of how users—both private and business—react to and evaluate unreliability is of utmost importance, both for developing theoretical models and for incorporating these impacts into cost-benefit analyses (Small et al., 1995; Kooray and Miticjell, 2000).

Different aspects of these issues are already being addressed in different research projects and will undoubtedly continue to be of interest in the near future. Still, there is
always a risk of running into a catch 22 situation: if no one expresses a demand for this kind of analysis tools, further research and development in this area is eventually pointless—and if a sound theoretical and methodological base is not established, no one will find any use for this kind of analysis tools. We suggest that vulnerability in the road transportation system should be brought out and recognised as a crucial part in the infrastructure sector, and that this over-all notion be the meeting point for all the different strands of transport reliability research and other related issues. A first step has already been taken by the Swedish government in their statement that reliable transports are an important aspect in the national policy goal of providing good quality transports (Prop 2001/02:20). Similar ideas are detectable in the British Government’s transport strategy (Goodwin, 1999).

5. Conclusion

Road vulnerability as such has not been in focus for long, despite the fundamental importance of our road networks—not only as a direct means of ’normal’ transport but also in assisting/maintaining/repairing other infrastructures and for evacuation in case of disaster. The road transportation system is hence one of our most important lifelines. Its wide spread and lack of supervision makes it difficult to manage, but at the same time lends it a certain robustness. Vulnerability analysis of road networks is regarded as a framework using the different aspects of transport reliability studies as its foremost tools. Road vulnerability analysis could thereby be regarded as a hub for the whole battery of transport studies needed to gain the insights necessary to describe how well our transport systems work in different respects, what steps to take and what policies to implement in order to reach desired goals. This paper gives the notion of vulnerability a more coherent structure, developing it not so much as a quantitative measure in itself, but rather as a way of thinking. We believe that adopting this perspective all through the planning, construction and management stages of the road infrastructure process will contribute to the public economy and welfare in society as a whole. The achievement of this, however, calls for cooperation on all levels, between all parties involved. This paper is an attempt to form a starting point that introduces concepts and views necessary to facilitate such a dialogue.

Acknowledgements

We would like to thank the Swedish Agency for Innovation Systems (former Swedish Transport and Communications Research Board) and the Swedish Agency for Civil Emergency Planning for their financial support.

References


Berdica, K., 2000. Analyzing Vulnerability in the Road Transportation System—Putting Theory into Practice Using Sweden as an Example. TRITA-IP-PR 00-76, Department of Infrastructure and Planning, Royal Institute of Technology, Stockholm.


NCFG, Canadian infrastructures and their dependencies, National Contingency Planning Group, March 2000.


Erratum

Errata to: “An introduction to road vulnerability: What has been done, is done and should be done” by Katja Berdica

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The author would like to draw your attention to the following errors:

In Table 1 on page 124, the second line in column 2 should read:

\[(\text{atr} - \text{dtr}) = (\text{att} - \text{dtt})/\text{length}\]

In the right hand column of page 120, the final sentence of the first paragraph should read: “Definition: the complement of vulnerability in the road transportation system is reliability, meaning adequate serviceability under the operation conditions encountered during a given time period”.
VULNERABILITY: 
A MODEL-BASED CASE STUDY OF THE ROAD NETWORK IN STOCKHOLM

Katja Berdica

Submitted to: Transportation

Abstract
This paper presents the results from a case study in which a traffic equilibrium model is used to study vulnerabilities in the Stockholm road network. A total of twelve scenarios illustrate the effects of 1) interruptions of critical links, 2) general capacity reductions/sub-network prioritisation and 3) traffic demand variations. The study considers adaptations in route choice under equilibrium conditions and the effect that this has on travel times and distances for the road users at a regional level. Due to the constraints implied by the model choice, a secondary objective of the study is how well the traffic equilibrium model is suited for this purpose. To further clarify this, a slightly different model was also applied and compared. The results clearly indicate the Stockholm road transport system’s weaknesses and give a fair idea as to the relative size of the expected consequences. The dependency on a number of bridges is a crucial feature from a vulnerability point of view; there is at present little extra capacity for rerouting traffic in case of incidents; prioritising the main road network for e.g. snow clearing results in considerable reductions of delay at a regional level. Our conclusion is that it is possible, although not ideal, to use the transport models and methods of today to conduct vulnerability studies. However, the volume-delay functions fundamental for the representation of the behavioural responses to the disturbances may need to be revised. In the longer perspective there is a need for developing better tools in general.

Keywords:
capacity reduction, case study, EMME/2, road closure, vulnerability
1. THE WHY AND HOW

1.1 Background and Scope of the Study

Vulnerability, exposure and criticality in various infrastructures are issues that have been more explicitly looked into in recent years. However, road vulnerability as such has not been in focus for long, despite the fundamental importance of our road networks – in every day life as well as in crisis evacuation situations. Consequently, network reliability in transport modelling is an important and growing field of research (Lam, 1999). The connection between reliability, vulnerability and other related concepts are discussed in Berdica (2002), with the main proposition that vulnerability analysis of road networks should be regarded as an overall framework within which different transport studies can be performed to describe how well our transport systems function when exposed to different kinds of disturbances. Following that approach, this paper presents the results from a model-based case study performed with the overall objective to study how vulnerable the Stockholm road network is in different respects. More specifically it is built up around three main questions:

1) How do interruptions of different critical links affect the system and how important are they in relation to one another?
2) How is the network performance affected by general capacity reductions and possible prioritisation of a sub-network?
3) How is the system affected by traffic demand variations, i.e. how close to its capacity limit does the system operate?

The network subjected to the present analysis is that of the entire Stockholm Region (Fig.1). The area has a total of about 1.8 million inhabitants and stretches over 6500 km². The focus is on disturbances of such duration that it is reasonable to assume that the road users are informed of the network status and have changed their behaviour accordingly. There are a number of behavioural mechanisms through which travellers adapt to new network conditions. For the disturbance duration of say a couple of days assumed here, changing trip frequency, travelling at another time of day, choosing another route or another mode of transport would be considered, while changing ones destination would be less plausible although it could come into question for certain types of errands. Longer-term changes such as car-ownership and localisation of home and/or place of work would hence not be considered in the present context. In order to simplify the analysis and highlight the results in a more distinct way, the present study considers adaptations in route choice only under equilibrium conditions and the effect that this has on travel times and distances for the road users at a regional
level. It hence concerns a fixed car travel demand, not allowing for changes in time period, trip frequency and/or transfers to other modes. This may seem inappropriate, since not allowing for possible reductions in car traffic could lead to an overestimation of the congestion problems after an incident. However, a recent study (Transek, 1999) shows that people in general do not abandon their private car so easily. Very long delays must be the case for most people to consider choosing to go by public transport even when information on the disturbance is available beforehand. Therefore, excluding by assumption e.g. transfers to public transport is deemed acceptable for the case study at hand.

1.2 Model System Used

The model system available for such a large-scale application at a regional level as this study is an example of, is an implementation of the network equilibrium based traffic analysis package emme/2 (INRO, 1998). It was at the time the standard traffic forecasting tool at the Swedish National Road Administration (SNRA) and henceforward EMME/2 is used to refer specifically to this Stockholm model. The EMME/2 network consists of 10841 directed links, defined by origin-destination (OD) nodes, which in turn are defined by coordinates. Each link is assigned a number of attributes: available mode of travel, link length, number of lanes, and one of seven volume delay (vd) functions that describes the travel time/speed on the link as a function of its traffic volume. Car travel demand in the form of a fixed OD-matrix of 1246 zones is assigned to the road network, under the usual Wardrop conditions for user equilibrium. These state that individuals choose routes in order to minimise their travel time and in an equilibrium situation all used routes between any OD-pair have equal travel time, not greater than those on unused routes. This kind of equilibrium solution hence involves assuming that the road-user has perfect information of the system status, i.e. it simulates the effects of disturbances after such a long time that the travellers have adapted to the new situation by finding their new “best” routes.

The vd-functions are hence fundamental for the representation of the behavioural responses to the disturbances in the network. They express travel time on links as a function of traffic volume V (vehicles per hour and lane) and link length (kilometres). Their general construction (as presented below) is a polynomial curve combined with a linear function at the reference capacity, such that the function but not its derivative is continuous.
\[ t(V, l) = \left[ \frac{V}{k_1} + k_2 \left( 1 + \left( \frac{V}{k_3} \right)^\alpha \right) \right] \times l + k_4 \quad \text{if } V \leq \bar{V} \]

\[ t(V, l) = t(\bar{V}, l) + k_5 (V - \bar{V}) \quad \text{if } V \geq \bar{V} \]

where 
- \( V \) = traffic volume, vehicles per hour and lane
- \( \bar{V} \) = reference capacity, vehicles per hour and lane
- \( k_i \) = speed limit and traffic condition dependent constants
- \( l \) = link length, kilometres

The functions are different for different links depending on their respective speed limit and traffic conditions, e.g. traffic is deemed more “disturbed” in the city centre than on peripheral links. Because of the link length dependency, the exact form of the corresponding graphs will vary accordingly. The three vdfunctions used on 50 km/h links for unit length of 1 km are shown in Figure 2, while an explicit listing of all vdfunctions can be found in Berdica (2000). As traffic volume approaches the reference capacity, link travel time should increase drastically. For final equilibrium solutions on the left hand side of this point, the form of the curve to the right does not matter. It simply ensures the convergence of the algorithm by which the equilibrium solution is found. For solutions to the right, the linear function is designed to impose an extra travel time (independent of link length, as opposed to the polynomial part that is length dependent) to take into account that exceeding the reference capacity will result in queues\(^1\). To represent this queuing time in a realistic way is very tricky, however, since it is very much dependent on for how long a period this “overloading” lasts.

The most important implication of choosing EMME/2 for this case study comes from the construction of the vdfunctions: the modelled situation is that of a steady-state but the linear part of the vdfunction beyond reference capacity means that there is no actual capacity limit – all traffic being let through is just a question of time. The resulting traffic volumes during e.g. the morning peak hour are hence to be regarded as manifested demand for travel on a link, rather than actual traffic flows during that hour. Also, the presently used algorithm is based on link flows only and the feature of queues spilling over backwards on adjacent links is not captured. At the

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\(^1\) The basis is the theoretical “clearing time” for a queue built up during one hour. In theory, the average queuing time is half of this value. The extra time added (i.e. “real” queuing time) is then again half of the theoretical queuing time, based on an assumption that the average bottleneck consists of two consecutive links.
same time links downstream an overloaded link are experiencing the same “excess” traffic volume (and the associated extra queuing time), although this does not occur in reality since the vehicles in question simply cannot come through. Thereby a secondary purpose of the study crystallises, and that is how well the traffic equilibrium model that was used in this study is suited for this purpose. To shed some light upon this, a small comparative study was performed using an alternative network equilibrium model that was under development at the time (see Section 4), which uses a different approach as far as solution algorithm and vd-functions are concerned.

1.3 Building Scenarios

In addition to the Base Scenario, in which today’s traffic (base year 1997) is assigned without “interference” in the network, the study includes a total of twelve scenarios as listed in Table 1.

The Stockholm road network stretches over a number of islands and the function of the system very much depends on the connecting bridges being passable. From this structure it is easy to realise that some of the most crucial spots in Stockholm are the passages over the waters of Saltsjö-Mälaren. Therefore the five main bridges were chosen for the study of critical links (Fig.3: reference capacities according to Table 2) and it is interesting to note that about 14% (485 per year) of the Stockholm Road Assistance Service commissions concern these very bridges. Closures of one or more lanes due to e.g. traffic accidents or physical failure were modelled by simply putting the respective link capacities equal to zero (Scenarios 1-7).

Considering the Swedish climate, one of the most common reasons for general capacity reductions in the road network is snow and/or sleet. According to Swedish Meteorological and Hydrological Institute (SMHI) statistics, days with snow additions of 20 mm or more come about approximately 15 times per season (November – April; Table 3). General reductions in road network capacity due to winter weather were modelled by altering the free flow speed in and the form of the link vd-functions. The modifications assume a 15% reduction in vehicle speed based upon the results from studies at the Swedish National Road and Transport Research Institute (VTI) of how different road weather conditions influence e.g. driving speed (Wallman, 1996). Scenario 8 can be said to represent slippery roads in general, while Scenario 9 simulates snow-clearing prioritisation in part of the network. The same fixed OD-matrix was used in both scenarios, as the VTI studies concluded that the presence of snow/sleet did not influence traffic demand noticeably. One would suspect that very bad overall weather has a greater effect but that is not within the scope of this study.
As in most major cities, the seemingly ever-increasing traffic volume in Stockholm is becoming of growing concern. More or less normal travel demand variation around the average could also have a great effect when the system is operating close to capacity limits. Scenarios 10-12 concern this issue and variation in travel demand is modelled simply through a decrease/increases in traffic volumes in the OD-matrix representing the travel demand. The factor of 8% was obtained as the estimated average standard deviation for daily maximum traffic volumes registered during two months 1998 (weekdays in February and October) at six SNRA traffic count sections in Greater Stockholm.
2. RESULTS IN GENERAL

2.1 Result Presentation

Travel demand is assigned in three different time periods: morning rush-hour (7-8 a.m.), evening rush-hour (4-5 p.m.) and an estimated typical “middle hour”. These have then been weighted together, presenting the results on a 24-hour basis. The principle direction of flow during the morning peak is toward the city centre, therefore this period is chosen for the presentation when relevant (basically in Scenarios 1, 2, 4 and 5).

The Stockholm Region is divided into 1246 OD-zones (six of these are areas outside the region itself) and calculated travel distances and travel times have been assembled into OD-matrices aggregated to the level of municipalities. For manageability and clearer presentation of the results, the municipalities have been aggregated further, into a total of five zones. However, the municipality of Stockholm is kept in four subdivisions, in order to allow for a closer study of the Saltsjö-Mälaren passages. This results in a total of ten zones, listed in Table 4 and depicted schematically in Figure 4. All results are weighted averages over the involved OD-relations. The speed measure used is simply total distance travelled divided by total time taken for all trips in the respective aggregates.

Please note that the average change in comparison with the Base Scenario is calculated over all trips in the whole Stockholm Region and not only over the critical passage over Saltsjö-Mälaren. The “maximum change” presented is simply the greatest time/distance/speed change (weighted average values) compared to the Base Scenario from the $9 \times 9 = 81$ aggregated OD-relation matrix, i.e. the OD relation that is “worst off” in respective scenario. The remaining 19 OD-cells that pertain to so-called bypass traffic, i.e. traffic to and from the external zone (denoted 0), are analysed separately.

Finally, a short note should be included regarding the convergence of the model for the different scenarios. It can be noted that of the twelve scenarios × three time periods = 36 model runs, eight were interrupted by the maximum number of iterations stopping criterion. However, if a 1% relative gap criterion had been used, only three runs are insufficiently converged.\(^2\)

\(^{2}\) The stopping criterion used is a maximum of 30 iterations; or 0.2% relative gap; or 0.2 minutes normalised gap; any of which occurs first. Empirically, a relative gap of 1% or less is considered sufficiently close to a perfect equilibrium (INRO, 1998; p 6-17).
for Scenarios 2 and 3 the final equilibrium solution was not always obtained, the greatest deviation being 2.5% for the afternoon rush hour in Scenario 3. Detailed analysis of the result report shows, however, that the remaining differences are small and very unlikely to significantly influence the general results and conclusions drawn.

2.2 Winners – Losers – Net Effects

In the base scenario there are about 111,000 trips during the morning rush hour, and a total of 1.6 million trips per day in the Stockholm Region. Average travel time, trip length and travel speed under “normal” conditions (as calculated by EMME/2) are:

<table>
<thead>
<tr>
<th></th>
<th>time</th>
<th>length</th>
<th>speed</th>
</tr>
</thead>
<tbody>
<tr>
<td>Morning rush hour</td>
<td>28 min</td>
<td>17 km</td>
<td>37 km/h</td>
</tr>
<tr>
<td>Daily</td>
<td>25 min</td>
<td>14 km</td>
<td>34 km/h</td>
</tr>
</tbody>
</table>

It may seem counter intuitive at first that average speed during the morning rush hour is higher although the level of congestion is greater. This is explained by differences in the composition of trip purposes, which in turn has implications for the destination choices and trip lengths. The overall average effects (regional level) on travel time, trip length, and travel speed in the different scenarios are presented in Tables 5 and 6. It should be noted that in virtually all scenarios (except the ones where it gets worse or better for everybody – basically Scenarios 8-12) there are both winners and losers, although the former are most often in a minority.

The closure of one link will force travellers on routes including the link in question to choose another route to their destination. This means that travel demand is also reduced on other links on the abandoned route, leaving them less congested for traffic that is unaffected by the closure. These remaining travellers will therefore experience a travel time reduction. Route choice is based upon minimisation of travel time, which means that the chosen route is not necessarily the shortest. Changes in traffic load on certain links may, however, turn a previously shorter but slower route into the fastest alternative. Hence, the closing of a link can also result in trip distance becoming less in some travel relations. Because of this, the average effect in terms of an absolute figure can sometimes seem insignificant (Tables 5 and 6). It is then of greater interest to study the effects in specific travel relations etc, which will be done in later sections. Average effect can, however, be revealed to be quite large when related to the normal situation, as seen from the percentages for e.g. Scenario 3.
2.3 Total Cost Estimation

Later the focus will be on effects for the average trip at either a regional level or in various aggregated travel relations. For an assessment of the effects in economic terms, it is instead of interest to consider total extra travel time and/or trip kilometres (compared to the Base Scenario) experienced by all travellers as a collective.

Total travel time in the road traffic system in the Base Scenario is just over 660,000 hours per day. Using the official Swedish travel time value of 35 SEK per hour (private regional trips < 100 kilometres in length, 1999) and occupancy rate of 1.46 persons per vehicle, the total cost of travel under normal conditions is about 34 million SEK per day. This means 34 million \( \times \) 250 days = 8.5 billion SEK per year are put into car travel. The increase in total travel time of 7% in Scenario 2 may seem small, but expressed in a similar monetary fashion (Table 7) it means that about 2.3 million SEK extra are spent on travelling each day that the Essinge Route is closed in the northbound direction. If we were not dealing with a “perfect information” case this cost would undoubtedly be higher, not only because of a non-equilibrium situation, but also because unforeseen delay is usually assigned a greater discomfort factor and hence a higher cost.

An important clarification is that the travel time differences in the last three scenarios are calculated with respect to the number of trips in the Base Scenario. The stated effect of e.g. Scenario 12 does not include the extra costs that follow implicitly from a 16% increase in traffic. In other words, if Scenario 12 became a reality, the car travellers of today would face a total extra cost of 1.57 million \( \times \) 250 days = about 390 million SEK per year.

The first scenario apparently gives a slight travel time reduction at the regional level, corresponding to costs decreasing by about 80 000 SEK. This is caused by travel time decreasing in the “middle hour” run of the scenario. Braess Paradox (e.g. Sheffi, 1985) shows that this is theoretically possible, but it has not been analysed further whether the effects in this case can be explained by such a phenomenon.

Concerning changes in trip length, the different scenarios cause very little in terms of percentage extra kilometres travelled at the regional level (see Table 5). Still, using the perceived marginal cost of 1.3 SEK per kilometre (1999), there is a noticeable extra cost due to this extra distance. The total distance travelled daily in the system under normal conditions is about 22.5 million vehicle kilometres. The greatest change is trip length is an increase of 2% in Scenario 7, when Danvikstull Bridge is impassable. This increase of 374 000 vehicle kilometres per day translates into roughly 0.5 million extra in vehicle
operating costs. For simplicity, the cost per vehicle kilometre used in the estimates above is only concerned with the owners’ perceived operating costs. The effect of Scenario 7 is even worse when considering first: the limited number of travel relations affected (to/from the Eastern Zone), and second: a clear concentration of increased traffic volumes in the southeastern part of the region. Assessing these effects at the regional level is hence less appropriate, since the most “damage” is caused along the alternative route that is actually chosen. It is also difficult to put a total price tag on these extra vehicle kilometres. Individuals experiencing increasing vehicle operating costs (apart from the induced increase in travel time cost) is fairly simple to price. Costs for the whole of society due to external effects like increased pollution and noise is a more difficult issue, and further analysis is not within the scope of this study.
3. RESULTS IN PARTICULAR

In this section, the extensive data material resulting from running the scenarios (some of which have already been presented in previous tables) is analysed and discussed in more detail, with the purpose to highlight the more local effects. A detailed listing of results (matrices and maps) can be found in Berdica (2000).

3.1 The Saltsjö-Mälaren Passage

The critical link scenarios are divided into, and compared to each other, in two categories. In Scenarios 2, 4 and 5 the links are closed in the northbound direction. Since this is the prevailing direction of flow during the morning rush hour, that is the period discussed in the following. Please note that the number of trips across the Saltsjö-Mälaren passage is constant by assumption (Table 8).

From the changes in traffic volume it is clear that the chosen bridges are the main alternative routes for each other, in the case of an interruption of such duration that a new equilibrium route choice has been made. Since there are only these five bridges (“other”= two small bridges from the Old Town) for crossing the central water strait of Saltsjö-Mälaren, the traffic pressure naturally increases on remaining connections. Closing the Essinge Route (Scenario 2) gives rise to an increase in demand for travel over Western Bridge of almost 150%, resulting in 2050 vehicles per hour and lane while reference capacity is set to 1550. It is then important to remember that all the extra vehicles on e.g. Western Bridge cannot possibly pass during the morning rush hour and the number of vehicles should be interpreted as the demand for passing, rather than actual traffic flow over the bridge.

To judge from the changes in travel distance in Table 9, incidents on Central Bridge give rise to the longest detours when considering maximum change. The average speed reduction is less than half the one resulting from Scenario 2, though. Hence the system has a better capacity for “swallowing” the traffic from Central Bridge, one reason being that the longer distance involves a greater geographical spread. However, speed is not a very appropriate effect indicator since longer travel time on a longer route may in fact give a speed increase, thus “concealing” the adverse effect, if the detour is long enough. The relatively speaking small effects of the Western Bridge-scenario is probably explained partly by its location in-between the other two bridges, partly by its lower traffic load in the Base Scenario.
The most affected travel relations are naturally from the zones south of, to the zones north of, the Saltsjö-Mälaren passage. For these, travel time increases with as much as 20-40 minutes per trip in Scenario 2. From this point of view, a closure of the Essinge Route in the northbound direction is the most critical one, as far as consequences are concerned.

Essinge Route 3, Traneberg Bridge and Danvikstull Bridge are scenarios in which the links are completely cut off. This comparison is made on a daily basis (Table 10). In case of a complete closure of the Essinge Route, again the most crucial travel relations are across the central water strait in the city. The effect in terms of number of relations affected is of course greater, since vehicles in both directions experience the altered conditions. The increase in travel time results in decreased travel speed, since Scenario 3 does not result in significant detours. Only just under 10% of the travel relations experience increased trip distance by half a kilometre or more. As expected, Scenario 6 affects trips to and from Western Stockholm the most, but there are effects in some north-south (and vice versa) relations as well. For Danvikstull Bridge the travel time increases are without exception concentrated to journeys from and to the Eastern Region, hence the great difference compared to the average regional effects of Scenario 7. The differences between Scenarios 6 and 7 regarding increased trip length are expected, considering that Traneberg Bridge is more centrally located, with more alternative routes closer at hand.

3.2 Bad Weather

In two of the case study scenarios, snow is assumed to cause capacity reductions in the road network. In Scenario 8 the whole network is subjected to a 15% reduction in free-flow speed, while the main road network (= superior network + primary and secondary network, including European highways, main arterial roads, county roads in urban or rural areas; local municipal links and city centre are excluded) is left unaffected in Scenario 9. The presentation (Table 11) is based on the morning rush hour, simulating the effects of a snowfall very early in the morning, i.e. just before and then a short time after snow clearing has begun.

As expected, trip lengths do not change considerably and travel time increases when free flow speed decreases. The difference between the whole and only part of the road network being affected is quite large, though. In Scenario 8 the 15% decrease in free flow speed causes travel time increases of 15-20% (10-15 min) in about 40% of the travel relations. For about one third of the OD-relations the relative increase is even greater (max ~25%). In Scenario 9, however, the increase in travel time is only 2-4 minutes between a majority of the zones and the maximum relative increase (as opposed to the
maximum absolute increase of 6% presented in Table 11) is ~9%. The prioritised network amounts to around 1/3 of the total model network in length, but generates almost ¾ of the vehicle kilometres in the system. The effect is (as usual for this time of day) greatest in south-north relations. Also, travellers to/passing e.g. the city centre are worse off, which is natural considering the roads included in the prioritised network.

When considering the changes in speed in terms of percentages, it is found that a 15% reduction in free flow speed on all links (Scenario 8) gives rise to reductions in travel speed below that value just about as often as above it. When only part of the network is affected (Scenario 9), 95% of travel relations experience travel speed losses of only 6% or less. The brief conclusion drawn from this is that reductions in capacity due to weather can result in considerable delays. However, it is possible to reduce these effects to quite an extent by e.g. a well-planned snow clearing prioritisation.

3.3 Varying Link Capacity

The Essinge Route is one of Stockholm’s main arterial roads, with three lanes in each direction\(^3\). Closing one lane results in a reduction from 5100 to 3850 vehicles passing the bridge at Gröndal, which in turn gives an increase in traffic volume from 1700 to 1925 vehicles per remaining lane. By comparing the results of closing one out of three lanes in the northbound direction (Scenario 1), with a complete closure of the same link (Scenario 2), it should be possible to study the effect of different degrees of capacity reductions (Table 12).

From the data above it is clearly seen that the effect of closing all three lanes is much worse than three times the effect of closing one lane. The resulting effects of Scenario 1 are however questionable, although the equilibrium assumption does lead to lower values as traffic has made the necessary adjustments to the new situation. The road in question is very heavily trafficked and deemed as operating close to its capacity limit, hence extremely sensitive to disturbances. Therefore one would expect larger effects than indicated by these values even in Scenario 1.

The resulting volume of 1925 vehicles per hour and lane in Scenario 1 is just under the reference capacity of 2000. It is hence on the polynomial side of the vd-function and the problem discussed earlier (see Section 1.2) should then not be an issue in this case. However, the results will be strongly dependent on how well the vd-functions are calibrated. It is obvious that the calculated effects may be smaller than expected simply because the vd-

\(^3\) An additional two lanes, one in each direction, have been added in early 2002.
functions do not describe traffic conditions well enough. In other words, maybe the curves are too flat near the reference capacity, which leads to an underestimation of the effects resulting from an increase in traffic load. Hence there is probably a need for complementary work on revising the “real” time-flow relationships and their function representation.

3.4 Travel Demand Variation

The OD-matrices used to describe travel demand are determined by combining various sources of information (including traffic counts, travel surveys etc) and are supposed to represent the average traffic volume during the chosen time period. In reality traffic fluctuates more or less randomly around these levels and the effects of these variations on e.g. travel times cannot be expected to be linear. To study this, the last three scenarios involve all entries of the OD-matrix being altered by −8%, +8% and +16% respectively (Table 13).

Regarding travel time, the relationship seems near to linear between decreasing and increasing the OD-matrix by the same factor (8%) and the result matrices are fairly similar. There is nevertheless a faint tendency, in 2/3 of the travel relations, for the gain at lower traffic levels being a little less than the loss from a corresponding increase in traffic load. Hence, instead of cancelling out compared to the Base Scenario, the average of Scenario 10 and 11 tips over to “favour” our hypotheses of non-linear effects from variations in traffic demand. This shows even more when relating Scenario 11 to Scenario 12. In the latter, more than double the travel time increase of the former is experienced in almost 90% of the travel relations. This non-linear effect is not so clearly observed for trip length or travel speed.

Generally speaking, the closer to its capacity limit a link operates, the greater the non-linearity. In fact, only a few links do lie close to these their reference capacities, which could explain the relatively speaking small average effect at the regional level. This can, on the other hand, also be caused by the way the vd-functions are constructed around reference capacities, as mentioned in previous sections. There is hence a risk of link travel time being underestimated.

3.5 Bypass Traffic

As described above, zone 0 consists of six areas outside the Stockholm Region. Trips to and from this zone are travellers leaving and entering the region respectively, and trips in the 0-0 relation are simply traffic passing by. How are these road users affected in the different scenarios? (Please note that there are no results tables compiled for the following discussion.)
In the critical link scenarios, interruptions on the more centrally located bridges do not significantly affect external traffic. It should be noted that the six areas in question are quite dispersed, and the aggregation does not allow for a distinction between the trips that involve passing the central water strait of Stockholm and those that do not. It is clear, however, that the Essinge Route is a crucial link even for travellers passing in/out/through the region. A closure in the northbound direction during the morning rush hour means that travelling from the Western Region and out takes on average just about half an hour longer.

If the Essinge Route is completely cut off in both directions, average travel time for bypass traffic is increased by some 20 minutes per trip on a daily basis. Trip distance does not change very much – in fact the overall effect on a daily basis is that average trip distance is somewhat decreased for most external travel relations (see Section 2.2).

General capacity reductions in the whole road network increases average trip travel time for bypass traffic by approximately 17-20 minutes, depending on which time period is considered. The corresponding effect in Scenario 9 (selective reduction of capacity) is only about 1-2 minutes. This is expected, since it seems reasonable to assume that the greater part of the external traffic uses the prioritised network left undisturbed in Scenario 9. As far as variation in travel demand is concerned, the vaguely non-linear effect is observed also in the external travel relations of the region.
4. APPLICATION OF AN ALTERNATIVE MODEL

4.1 General

As was mentioned before, the EMME/2 solution algorithm is based on link flows only and links downstream overloaded links are also experiencing the extra queuing time. Also, the construction of the vd-functions beyond reference capacity means that all traffic being let through is just a question of time, hence no actual capacity limit is imposed. The Disaggregate Simplicial Decomposition – Implicit Route Storage model (DSD-IRS; Larsson & Patriksson, 1992; Tatineni et al, 1998) also solves the traffic assignment problem according to the Wardrop principle, but is not based on link flows but on route flows. Therefore it can keep track of all routes used in every unique OD-relation. In this model system it is also possible to take capacity restrictions into account, by exchanging the linear part of the vd-functions for a deterministic queuing time (its length depending on the time period for which the over-saturated conditions are assumed to last) to be added to travel time on identified “bottle necks” only. In this way, there is no double counting through undue “punishing” of traffic on downstream links. On these, the traffic flow is set to reference capacity – which in this case actually is a capacity limit – and travel time is calculated accordingly. Effects upstream the bottle-necks are not modelled, other than in that the extra travel time imposed on the critical link causes alterations in route choice.

A small complementary study using DSD-IRS was performed to see how big a difference this improvement of the travel time calculation makes. Included Scenarios are 1, 2, 4, and 5, as well as the Base Scenario for the morning rush hour. Results for the Base Scenario by this method are practically the same as for EMME/2. The outcome in the other scenarios is all but obvious, since the alteration may lead to downstream links being less congested, making average effects smaller. On the other hand, we cannot say if the overall redistribution of traffic will affect the system in the other direction. The results are summarised in the following, while detailed tables can be found in Berdica (2000).

---

4 Stopping criteria and degrees of convergence similar to the EMME/2 runs
4.2 The Saltsjö-Mälaren Passage

Compared to Table 9, the changes in average travel times in Table 14 show an overall increase in average effect at the regional level. The maximum values are also considerably higher. The more detailed tables in Berdica (2000) display the same patterns, with the most affected travel relations being from the zones south of, to the zones north of, the Saltsjö-Mälaren passage. For Scenario 2, however, the increase in average travel time in relations from the South inner city to the zones north of the water strait is about 14% less according to the DSD-IRS method. Higher values from EMME/2 may well be the result of the “double-counting” feature described. The differences in trip distance change between the models are negligible, while travel speed reductions are generally greater in the DSD-IRS case for all three scenarios – for all but the previously mentioned travel relations in Scenario 2, which is to be expected.

4.3 Varying Link Capacity

Comparing the DSD-IRS runs of Scenarios 1 and 2 to each other shows, just like the EMME/2 results, that a complete closure in the northbound direction is not proportional to closing only one out of three lanes. Much more interesting, however, is the difference in Scenario 1 using the two methods. Although the average changes in Table 15 do not appear to have changed drastically, a closer look on a more detailed level shows that DSD-IRS yields travel time increases of 3-4 times those of EMME/2, in affected travel relations. The corresponding differences for Scenario 2 are not so great. It may hence be the case, that DSD-IRS takes better account of partial closures of a link.

4.4 Brief Conclusions

This comparison of the DSD-IRS and EMME/2 methods is rather crude, it is true, but nevertheless some brief conclusions can be outlined from the result. The altered method in DSD-IRS corresponds better to intuitive notions, and seems to support the ideas of EMME/2 tending to underestimate effects, especially in case of partial closures. The effect of decreasing congestion downstream bottle-necks due to no “double-counting” can be at least vaguely discerned, but the overall effect at the regional level is still increasing travel times and decreasing travel speed.
5. CONCLUSIONS

It can be discussed to what extent it is possible to use the link flow based EMME/2 to study vulnerability issues. Since bottleneck effects are not taken into consideration, modelling partial capacity reductions (e.g. one of three lanes closed) seems to give unrealistically small effects. This is supported by the complementary study using the route flow based DSD-IRS method. Also, using EMME/2 to study effects of drastic capacity reductions may be to push the model over the boundaries for its validity, since queuing times when demand exceeds reference capacity are difficult to represent in a realistic way. Then again, effects being intuitively too small could be a question of vd-function calibration in general – they may be too flat near the reference capacity, which if so leads to an underestimation of travel time increases.

It is, however, important to again remember the conditions and assumptions that lie behind the present approach to the problem. The user equilibrium assignment means that all travellers have chosen their minimum time route with respect to a system status that is known beforehand. Therefore one cannot expect the model result to display the same drastic travel time increase that results from the immense queues caused by unforeseen incidents in real life traffic. Modelling the effects of sudden interruptions calls for microsimulation and so far this is not a realistic approach for a large-scale regional level implementation. A similar study using a microsimulation approach has been performed (Nicholson et al., 2001; Berdica et al., 2002) but for a much smaller network: an area of roughly 16 km² compared to 6500 and only a tenth of the number of trips during the morning rush hour. Also, the present method gives the traveller only one option for resolving their “trip problem”, and that is the choice of an alternative route. In reality, some may change their mode of transport, choose to travel at a different time of day or maybe even change their destination (e.g. shop at a different super market), which is why the results cannot be transferred to a real life situation on a one to one scale. As was mentioned in previous sections, the excessive link flows, which quite obviously cannot pass during the time period modelled, are to be interpreted as the demand for passage on that particular link.

Nevertheless, keeping these limitations and reservations in mind, the main points resulting from the effect analysis of the various scenarios are:

- The bridge at Gröndal (Essinge Route), Western Bridge and Central Bridge can be regarded as main alternative routes for each other in the case of an incident.
For a closure in the northbound direction during the morning rush hour, the Essinge Route is the most critical one as far as consequences are concerned, resulting in 20-40 min extra per trip across the Saltsjö-Mälaren passage.

Closing Danvikstull Bridge results in daily travel time increases of well over 20 minutes for most journeys to/from the Eastern Region, which is quite different from the effect of just over one minute per trip at the regional level.

Snow/sleet in the whole road network (≈15% decrease in free flow speed) during the morning rush hour causes travel time increases of 10-15 minutes in about 40% of the travel relations, while keeping a priority network “clear” reduces this to only 2-4 minutes extra between a majority of the zones.

There is a faint tendency of non-linear effects from variations in traffic demand, which shows most clearly when increasing traffic by 16% results in more than double the extra travel time caused by increasing traffic by 8%.

The Essinge Route is a crucial link also for travellers passing in/out/through the region: a complete closure results in average travel time for bypass traffic increasing by some 20 minutes per trip on a daily basis.

General capacity reductions in the whole road network increases average trip travel time for bypass traffic by approximately 17-20 minutes, while the corresponding effect in the selective reduction of capacity scenario is only about 1-2 minutes.

In virtually all scenarios there are both winners and losers, which in turn results in the average effects at the regional level sometimes seeming insignificant in terms of absolute figures. On the other hand, they can be revealed to be quite large when related to normal conditions.

Calculating effects in monetary terms (35 SEK/h, 1.3 SEK/km; 1999) shows extra costs ranging from 200 000 to about 5 million SEK per day, depending on which scenario is considered. The corresponding costs, were the situations modelled as “unforeseen”, are probably considerably higher.

According to these calculations, keeping the main road network “clear” from snow and sleet leads to an estimated daily travel saving of about 3 million SEK.

Even though the numbers stated above are subject to uncertainty, they clearly indicate the Stockholm road transport system’s weaknesses and give a fair idea as to the relative size of the expected consequences. Translating this into monetary terms can then give values of a wide range, depending on how one values the effects, for which there is no consensus. Setting aside the specifics, this model-based case study has shown that the central water strait
– and the consequent dependency on a limited number of bridges – is a crucial feature from a vulnerability point of view. Also, there is at present little, if any, extra capacity to handle rerouting in case of incidents, let alone to swallow a more permanent increase in traffic volume. This puts high demands on the operations management and maintenance of the system infrastructure by e.g. detecting and attending to occurring disturbances within a minimum time span. These reactive measures must be combined with the proactive approach of identifying critical links that are to be prioritised for enhancement. Also, the undertaking of any measure should be planned carefully to minimise disturbances from the roadwork itself.

A more general conclusion is that the transport models and methods of today can be used to conduct vulnerability studies, although they are not yet ideally adjusted to suit this specific purpose. From the vulnerability perspective it is crucial how well the model reproduces effects around reference capacity, so in the short term the currently used vd-functions should be revised. In the longer perspective there is a need for developing better tools in general, probably in the form of microsimulation approaches. When using network equilibrium models, it is important that the assignment problem is solved accurately. A major advance in this field has already been made with the recent Bar-Gera algorithm (Bar-Gera, 2002; Bar-Gera & Boyce, 2002), whose origin-based approach yields solutions of higher accuracy and more detail with quicker convergence than the now commonly used link-based methods. Considering in this case Stockholm’s growing population and the continuous increase in traffic, the importance and usefulness of further engagement in this area is evident.

Acknowledgements

We would like to thank the SNRA and VTI who provided data, material and technical support vital for carrying out this study, as well as the Swedish Agency for Innovation Systems and the Swedish Agency for Civil Emergency Planning for their financial support.
References

Berdica K (2000) Analysing vulnerability in the road transportation system – putting theory into practice using Sweden as an example. TRITA-IP FR 00-76, Department of Infrastructure, Royal Institute of Technology, Stockholm.
Figure 1. The Stockholm Region with its 26 municipalities

Land area: 6490 km²
Pop. (Dec 01): 1,823,210

1. Norrtälje
2. Sigtuna
3. Vallentuna
4. Österåker
5. Upplands-Bro
6. Upplands-Väsby
7. Täby
8. Vaxholm
9. Värmdö
10. Järfälla
11. Sollentuna
12. Danderyd
13. Lidingö
14. Nockeby
15. Ekerö
16. Stockholm
17. Sundbyberg
18. Solna
19. Södertälje
20. Nykvarn
21. Salem
22. Botkyrka
23. Huddinge
24. Tyresö
25. Nynäshamn
26. Haninge
Figure 2. Vd-functions used in EMME/2 for links of length 1 km and speed limit 50 km/h in various locations in the network, the numbers in the graph indicating reference capacity.
Figure 3. Chosen critical links over Saltsjö-Mälaren, Stockholm:
(i)  Tranberg Bridge
(ii) Western Bridge
(iii) Central Bridge
(iv) Essinge Route (Bridge at Gröndal)
(v)  Danvikstull Bridge

Figure 4. Schematic illustration of the zone aggregation
Vulnerability – A Model Based Case Study: Figures and Tables

Table 1. Description of case study scenarios.

<table>
<thead>
<tr>
<th>Scen</th>
<th>Denomination</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Essinge Route 1</td>
<td>One lane closed, north bound direction</td>
</tr>
<tr>
<td>2</td>
<td>Essinge Route 2</td>
<td>Complete closure, north bound direction</td>
</tr>
<tr>
<td>3</td>
<td>Essinge Route 3</td>
<td>Complete closure, both directions</td>
</tr>
<tr>
<td>4</td>
<td>Central Bridge</td>
<td>Complete closure, north bound direction</td>
</tr>
<tr>
<td>5</td>
<td>Western Bridge</td>
<td>Complete closure, north bound direction</td>
</tr>
<tr>
<td>6</td>
<td>Traneberg Bridge</td>
<td>Complete closure, both directions</td>
</tr>
<tr>
<td>7</td>
<td>Danvikstull Bridge</td>
<td>Complete closure, both directions</td>
</tr>
<tr>
<td>8</td>
<td>General red. in cap.</td>
<td>Reduced &quot;free flow speed&quot;, all links</td>
</tr>
<tr>
<td>9</td>
<td>Selective red. in cap.</td>
<td>Reduced &quot;free flow speed&quot;, non-priority net</td>
</tr>
<tr>
<td>10</td>
<td>Car traffic 1</td>
<td>Today’s traffic –8%</td>
</tr>
<tr>
<td>11</td>
<td>Car traffic 2</td>
<td>Today’s traffic +8%</td>
</tr>
<tr>
<td>12</td>
<td>Car traffic 3</td>
<td>Today’s traffic +16%</td>
</tr>
</tbody>
</table>

Table 2. Reference capacities [vehicles per lane and hour] and number of lanes for the five bridges.

<table>
<thead>
<tr>
<th>Bridge</th>
<th>Direction</th>
<th>Reference Capacity</th>
<th>No of Lanes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Essinge Route</td>
<td>Both</td>
<td>2000</td>
<td>3</td>
</tr>
<tr>
<td>Central Bridge</td>
<td>Both</td>
<td>2000</td>
<td>3</td>
</tr>
<tr>
<td>Western Bridge</td>
<td>Southbound</td>
<td>2000</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>Northbound</td>
<td>1550</td>
<td>2</td>
</tr>
<tr>
<td>Traneberg Bridge</td>
<td>Both</td>
<td>1550</td>
<td>2</td>
</tr>
<tr>
<td>Danvikstull Bridge</td>
<td>Both</td>
<td>1150</td>
<td>2</td>
</tr>
</tbody>
</table>

Table 3. Snow and temperature statistics for Stockholm-Bromma meteorological station. (Source: SMHI; author’s adaptation)

<table>
<thead>
<tr>
<th>Statistics Nov-Apr 1961-90</th>
<th>Average</th>
<th>Max</th>
<th>Min</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total amount (cm) of snow per winter</td>
<td>79.2</td>
<td>185</td>
<td>12</td>
</tr>
<tr>
<td>No of days with newly fallen snow of &lt; 2 cm</td>
<td>9.8</td>
<td>21</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>2-5 cm</td>
<td>9.6</td>
<td>18</td>
</tr>
<tr>
<td></td>
<td>5-7 cm</td>
<td>2.0</td>
<td>7</td>
</tr>
<tr>
<td></td>
<td>7-10 cm</td>
<td>1.8</td>
<td>4</td>
</tr>
<tr>
<td></td>
<td>&gt; 10 cm</td>
<td>1.4</td>
<td>4</td>
</tr>
<tr>
<td>No of days with temp. passing 0°C a</td>
<td>73.3</td>
<td>103</td>
<td>51</td>
</tr>
</tbody>
</table>

a) At least once during 24 hours
Table 4. Description of the zone aggregation used in the case study.

<table>
<thead>
<tr>
<th>Denomination</th>
<th>Description</th>
<th>No of zones</th>
</tr>
</thead>
<tbody>
<tr>
<td>(0) External areas</td>
<td></td>
<td>6</td>
</tr>
<tr>
<td>(1) Western Stockholm</td>
<td></td>
<td>88</td>
</tr>
<tr>
<td>(2) North inner City</td>
<td></td>
<td>133</td>
</tr>
<tr>
<td>(3) South inner City</td>
<td></td>
<td>44</td>
</tr>
<tr>
<td>(4) Southern Stockholm</td>
<td></td>
<td>135</td>
</tr>
<tr>
<td>(5) North-western region</td>
<td>A Solna, Sundbyberg, Sigtuna, Upplands-Väsby, Sollentuna, Upplands-Bro, Järfläla, Ekerö</td>
<td>250</td>
</tr>
<tr>
<td>(6) North-eastern region</td>
<td>D Danderyd, Lidingö, E Vallentuna, Täby, Österåker, Vaxholm, F Norrtälje</td>
<td>248</td>
</tr>
<tr>
<td>(7) Eastern region</td>
<td>G Nacka, H Värmdö</td>
<td>87</td>
</tr>
<tr>
<td>(8) Southern region</td>
<td>J Tyresö, Haninge, K Nynäshamn</td>
<td>96</td>
</tr>
<tr>
<td>(9) Western region</td>
<td>L Salem, Huddinge, Botkyrka, M Södertälje, Nykvarn</td>
<td>159</td>
</tr>
<tr>
<td>SUM</td>
<td></td>
<td>1246</td>
</tr>
</tbody>
</table>

Table 5. Mean effects at the regional level in different scenarios compared to the Base Scenario, calculated on a daily basis.

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Travel time</th>
<th>Trip length</th>
<th>Travel speed</th>
</tr>
</thead>
<tbody>
<tr>
<td>0. Base Scenario</td>
<td>25.0</td>
<td>14.2</td>
<td>34.1</td>
</tr>
<tr>
<td>1. Essinge Route 1</td>
<td>-0.1</td>
<td>0%</td>
<td>0.0</td>
</tr>
<tr>
<td>2. Essinge Route 2</td>
<td>1.7</td>
<td>7%</td>
<td>-2.2</td>
</tr>
<tr>
<td>3. Essinge Route 3</td>
<td>3.7</td>
<td>15%</td>
<td>-4.5</td>
</tr>
<tr>
<td>4. Central Bridge</td>
<td>0.6</td>
<td>2%</td>
<td>-0.6</td>
</tr>
<tr>
<td>5. Western Bridge</td>
<td>0.1</td>
<td>1%</td>
<td>-0.3</td>
</tr>
<tr>
<td>6. Traneberg Bridge</td>
<td>0.5</td>
<td>2%</td>
<td>-0.4</td>
</tr>
<tr>
<td>7. Danvikstull Bridge</td>
<td>1.2</td>
<td>5%</td>
<td>-1.1</td>
</tr>
<tr>
<td>8. General reduction in cap.</td>
<td>3.5</td>
<td>14%</td>
<td>-4.3</td>
</tr>
<tr>
<td>9. Selective reduction in cap.</td>
<td>1.0</td>
<td>4%</td>
<td>-1.2</td>
</tr>
<tr>
<td>10. Car traffic 1</td>
<td>-0.5</td>
<td>-2%</td>
<td>0.6</td>
</tr>
<tr>
<td>11. Car traffic 2</td>
<td>0.5</td>
<td>2%</td>
<td>-0.7</td>
</tr>
<tr>
<td>12. Car traffic 3</td>
<td>1.1</td>
<td>4%</td>
<td>-1.5</td>
</tr>
</tbody>
</table>
Table 6. Mean effects at the regional level in different scenarios compared to the Base Scenario, calculated for the morning rush hour.

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Travel time [min/trip]</th>
<th>Trip length [km/trip]</th>
<th>Travel speed [km/h]</th>
</tr>
</thead>
<tbody>
<tr>
<td>0. Base Scenario</td>
<td>27.8</td>
<td>16.9</td>
<td>36.5</td>
</tr>
<tr>
<td>1. Essinge Route 1</td>
<td>0.1</td>
<td>1%</td>
<td>0.0</td>
</tr>
<tr>
<td>2. Essinge Route 2</td>
<td>4.1</td>
<td>15%</td>
<td>0.1</td>
</tr>
<tr>
<td>3. Essinge Route 3</td>
<td>5.3</td>
<td>19%</td>
<td>0.2</td>
</tr>
<tr>
<td>4. Central Bridge</td>
<td>1.6</td>
<td>6%</td>
<td>0.1</td>
</tr>
<tr>
<td>5. Western Bridge</td>
<td>0.3</td>
<td>1%</td>
<td>0.0</td>
</tr>
<tr>
<td>6. Traneberg Bridge</td>
<td>0.8</td>
<td>3%</td>
<td>0.2</td>
</tr>
<tr>
<td>7. Danvikstull Bridge</td>
<td>1.7</td>
<td>6%</td>
<td>0.2</td>
</tr>
<tr>
<td>8. General reduction in cap.</td>
<td>4.6</td>
<td>17%</td>
<td>0.0</td>
</tr>
<tr>
<td>9. Selective reduction in cap.</td>
<td>1.2</td>
<td>4%</td>
<td>0.1</td>
</tr>
<tr>
<td>10. Car traffic 1</td>
<td>-0.7</td>
<td>-3%</td>
<td>0.0</td>
</tr>
<tr>
<td>11. Car traffic 2</td>
<td>0.7</td>
<td>3%</td>
<td>0.0</td>
</tr>
<tr>
<td>12. Car traffic 3</td>
<td>1.9</td>
<td>7%</td>
<td>0.1</td>
</tr>
</tbody>
</table>

Table 7. Economic implication of change in total travel time (35 SEK/h) and trip length (1.3 SEK/km) in different scenarios, compared to the Base Scenario, calculated on a daily basis.

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Change in total cost [million SEK]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Travel time</td>
</tr>
<tr>
<td>1. Essinge Route 1</td>
<td>-0.08</td>
</tr>
<tr>
<td>2. Essinge Route 2</td>
<td>2.26</td>
</tr>
<tr>
<td>3. Essinge Route 3</td>
<td>5.04</td>
</tr>
<tr>
<td>4. Central Bridge</td>
<td>0.74</td>
</tr>
<tr>
<td>5. Western Bridge</td>
<td>0.20</td>
</tr>
<tr>
<td>6. Traneberg Bridge</td>
<td>0.70</td>
</tr>
<tr>
<td>7. Danvikstull Bridge</td>
<td>1.64</td>
</tr>
<tr>
<td>8. General reduction in capacity</td>
<td>4.76</td>
</tr>
<tr>
<td>9. Selective reduction in capacity</td>
<td>1.40</td>
</tr>
<tr>
<td>10. Car traffic 1</td>
<td>-0.65</td>
</tr>
<tr>
<td>11. Car traffic 2</td>
<td>0.63</td>
</tr>
<tr>
<td>12. Car traffic 3</td>
<td>1.52</td>
</tr>
</tbody>
</table>
Table 8. Comparison of traffic volumes [vehicles] over the bridges (northbound direction) in Scenarios 2, 4 and 5 during the morning rush hour.

<table>
<thead>
<tr>
<th>Bridge</th>
<th>Base Scenario</th>
<th>Scenario 2: Essinge Route 2</th>
<th>Scenario 4: Central Bridge</th>
<th>Scenario 5: Western Bridge</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bridge at Gröndal</td>
<td>5100</td>
<td>–</td>
<td>+1500</td>
<td>+1000</td>
</tr>
<tr>
<td>Central Bridge</td>
<td>4500</td>
<td>+1500</td>
<td>–</td>
<td>+ 400</td>
</tr>
<tr>
<td>Western Bridge</td>
<td>1700</td>
<td>+2500</td>
<td>+1700</td>
<td>–</td>
</tr>
<tr>
<td>Other</td>
<td>1500</td>
<td>+1100</td>
<td>+1300</td>
<td>+ 300</td>
</tr>
</tbody>
</table>

Table 9. Comparison of average travel time, trip length and travel speed in Scenarios 2, 4 and 5 during the morning rush hour (changes in relation to Base Scenario).

<table>
<thead>
<tr>
<th>Information</th>
<th>Scenario 2: Essinge Route 2</th>
<th>Scenario 4: Central Bridge</th>
<th>Scenario 5: Western Bridge</th>
</tr>
</thead>
<tbody>
<tr>
<td>Travel time</td>
<td>4.1 15%</td>
<td>1.6 6%</td>
<td>0.3 1%</td>
</tr>
<tr>
<td></td>
<td>Max. change [min/trip]</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>39.9 91%</td>
<td>16.6 37%</td>
<td>5.4 13%</td>
</tr>
<tr>
<td>Trip length</td>
<td>0.1 1%</td>
<td>0.1 1%</td>
<td>0.0 –</td>
</tr>
<tr>
<td></td>
<td>Max. change [km/trip]</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>1.5 5%</td>
<td>3.0 8%</td>
<td>0.7 5%</td>
</tr>
<tr>
<td>Travel speed</td>
<td>Mean change [km/h]</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>-4.4 -12%</td>
<td>-1.7 -5%</td>
<td>-0.4 -1%</td>
</tr>
<tr>
<td></td>
<td>Max. change [km/h]</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>-19.0 -41%</td>
<td>-7.6 -16%</td>
<td>-4.5 -12%</td>
</tr>
</tbody>
</table>
Table 10. Comparison of average travel time, trip length and travel speed in Scenarios 3, 6 and 7 on a daily basis (changes in relation to Base Scenario).

<table>
<thead>
<tr>
<th>Information</th>
<th>Scenario 3: Essinge Route 3</th>
<th>Scenario 6: Traneberg Bridge</th>
<th>Scenario 7: Danvikstull Bridge</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Travel time</strong></td>
<td>Mean change [min/trip]</td>
<td>3.7 15%</td>
<td>0.5 2%</td>
</tr>
<tr>
<td></td>
<td>Max. change [min/trip]</td>
<td>30.2 55%</td>
<td>7.7 19%</td>
</tr>
<tr>
<td><strong>Trip length</strong></td>
<td>Mean change [km/trip]</td>
<td>0.0 –</td>
<td>0.2 1%</td>
</tr>
<tr>
<td></td>
<td>Max. change [km/trip]</td>
<td>1.0 3%</td>
<td>3.3 11%</td>
</tr>
<tr>
<td><strong>Travel speed</strong></td>
<td>Mean change [km/h]</td>
<td>-4.5 -13%</td>
<td>-0.4 -1%</td>
</tr>
<tr>
<td></td>
<td>Max. change [km/h]</td>
<td>-17.9 -37%</td>
<td>-3.0 -7%</td>
</tr>
</tbody>
</table>

Table 11. Comparison of average travel time, trip length and travel speed in Scenarios 8 and 9 during the morning rush hour (changes in relation to Base Scenario).

<table>
<thead>
<tr>
<th>Information</th>
<th>Scenario 8: General red. in capacity</th>
<th>Scenario 9: Selective red. in capacity</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Travel time</strong></td>
<td>Mean change [min/trip]</td>
<td>4.6 17%</td>
</tr>
<tr>
<td></td>
<td>Max. change [min/trip]</td>
<td>14.9 23%</td>
</tr>
<tr>
<td><strong>Trip length</strong></td>
<td>Mean change [km/trip]</td>
<td>0.0 –</td>
</tr>
<tr>
<td></td>
<td>Max. change [km/trip]</td>
<td>-0.6 -1%</td>
</tr>
<tr>
<td><strong>Travel speed</strong></td>
<td>Mean change [km/h]</td>
<td>-5.2 -14%</td>
</tr>
<tr>
<td></td>
<td>Max. change [km/h]</td>
<td>-8.9 -19%</td>
</tr>
</tbody>
</table>
Table 12. Comparison of average travel time, trip length and travel speed in Scenarios 1 and 2 during the morning rush hour (changes in relation to Base Scenario).

<table>
<thead>
<tr>
<th>Information</th>
<th>Scenario 1: Essinge Route 1</th>
<th>Scenario 2: Essinge Route 2</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Travel time</strong></td>
<td>Mean change [min/trip]</td>
<td>0.1</td>
</tr>
<tr>
<td></td>
<td>Max. change [min/trip]</td>
<td>1.7</td>
</tr>
<tr>
<td><strong>Trip length</strong></td>
<td>Mean change [km/trip]</td>
<td>0.0</td>
</tr>
<tr>
<td></td>
<td>Max. change [km/trip]</td>
<td>0.2</td>
</tr>
<tr>
<td><strong>Travel speed</strong></td>
<td>Mean change [km/h]</td>
<td>-0.2</td>
</tr>
<tr>
<td></td>
<td>Max. change [km/h]</td>
<td>-1.4</td>
</tr>
</tbody>
</table>

Table 13. Comparison of average travel time, trip length and travel speed in Scenarios 10, 11 and 12 on a daily basis (changes in relation to Base Scenario).

<table>
<thead>
<tr>
<th>Information</th>
<th>Scenario 10: Car traffic 1</th>
<th>Scenario 11: Car traffic 2</th>
<th>Scenario 12: Car traffic 3</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Travel time</strong></td>
<td>Mean change [min/trip]</td>
<td>-0.5</td>
<td>-2%</td>
</tr>
<tr>
<td></td>
<td>Max. change [min/trip]</td>
<td>-3.6</td>
<td>-6%</td>
</tr>
<tr>
<td><strong>Trip length</strong></td>
<td>Mean change [km/trip]</td>
<td>0.0</td>
<td>–</td>
</tr>
<tr>
<td></td>
<td>Max. change [km/trip]</td>
<td>-0.2</td>
<td>-1%</td>
</tr>
<tr>
<td><strong>Travel speed</strong></td>
<td>Mean change [km/h]</td>
<td>0.6</td>
<td>2%</td>
</tr>
<tr>
<td></td>
<td>Max. change [km/h]</td>
<td>3.4</td>
<td>7%</td>
</tr>
</tbody>
</table>
Table 14. Comparison of average travel time, trip length and travel speed in Scenarios 2, 4 and 5 during the morning rush hour (changes in relation to Base Scenario) using DSD-IRS.

<table>
<thead>
<tr>
<th>Information</th>
<th>Scenario 2: Essinge Route 2</th>
<th>Scenario 4: Central Bridge</th>
<th>Scenario 5: Western Bridge</th>
</tr>
</thead>
<tbody>
<tr>
<td>Travel time</td>
<td>4.6 16%</td>
<td>2.4 9%</td>
<td>0.7 3%</td>
</tr>
<tr>
<td></td>
<td>Mean change [min/trip]</td>
<td>Mean change [min/trip]</td>
<td>Mean change [min/trip]</td>
</tr>
<tr>
<td></td>
<td>44.7 83%</td>
<td>24.7 55%</td>
<td>9.3 21%</td>
</tr>
<tr>
<td>Trip length</td>
<td>0.1 0%</td>
<td>0.1 1%</td>
<td>0.0 –</td>
</tr>
<tr>
<td></td>
<td>Mean change [km/trip]</td>
<td>Mean change [km/trip]</td>
<td>Mean change [km/trip]</td>
</tr>
<tr>
<td></td>
<td>1.6 5%</td>
<td>2.1 8%</td>
<td>0.7 5%</td>
</tr>
<tr>
<td>Travel speed</td>
<td>-5.0 -14%</td>
<td>-2.6 -7%</td>
<td>-0.9 -3%</td>
</tr>
<tr>
<td></td>
<td>Mean change [km/h]</td>
<td>Mean change [km/h]</td>
<td>Mean change [km/h]</td>
</tr>
<tr>
<td></td>
<td>-20.3 -44%</td>
<td>-10.8 -23%</td>
<td>-6.6 -18%</td>
</tr>
<tr>
<td>Max. change</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 15. Comparison of average travel time, trip length and travel speed in Scenario 1 (changes in relation to Base Scenario) using EMME/2 and DSD-IRS respectively.

<table>
<thead>
<tr>
<th>Information</th>
<th>Scenario 1 using EMME/2</th>
<th>Scenario 1 using DSD-IRS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Travel time</td>
<td>0.1 1%</td>
<td>0.4 1%</td>
</tr>
<tr>
<td></td>
<td>Mean change [min/trip]</td>
<td>Mean change [min/trip]</td>
</tr>
<tr>
<td></td>
<td>1.7 4%</td>
<td>4.5 10%</td>
</tr>
<tr>
<td>Trip length</td>
<td>0.0 –</td>
<td>0.0 –</td>
</tr>
<tr>
<td></td>
<td>Mean change [km/trip]</td>
<td>Mean change [km/trip]</td>
</tr>
<tr>
<td></td>
<td>0.2 1%</td>
<td>0.1 1%</td>
</tr>
<tr>
<td>Travel speed</td>
<td>-0.2 0%</td>
<td>-0.5 -1%</td>
</tr>
<tr>
<td></td>
<td>Mean change [km/h]</td>
<td>Mean change [km/h]</td>
</tr>
<tr>
<td></td>
<td>-1.4 -4%</td>
<td>-3.6 -9%</td>
</tr>
<tr>
<td>Max. change</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
PAPER III
Simulating Road Traffic Interruptions – Does it Matter What Model We Use?

Katja Berdica, Royal Institute of Technology, Stockholm, Sweden
Zarko Andjic, Gabites Porter Consultants, Christchurch, New Zealand
Alan J Nicholson, University of Canterbury, Christchurch, New Zealand

Abstract

Computer models are often used for studying the effects of changing conditions in the road network. State-of-the-art macroscopic models generally take some kind of network equilibrium approach and therefore have difficulties in appropriately representing short-term capacity reductions, probably resulting in too low estimates of delays. Recently developed dynamic models may be more promising. The purpose of this paper is to investigate the implications of model choice further, as well as the possibilities to study effects of short-term incidents. Three different computer programs were used: TRACKS, SATURN, and Paramics. The results show that microsimulation is a feasible tool for studying short-term disturbances in the road transportation system.
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INTRODUCTION
Road transports are tightly linked to everyday life, both private and business, and problems in the road network can have wide spread repercussions. Extreme weather conditions and other natural phenomena can make large parts of the road network impassable. More rare events like collapsing bridges, as well as every day incidents like traffic accidents or closures due to maintenance activities, can reduce the capacity of the traffic system. The resulting delays cause serious losses in terms of travel time, as well as other costs in the case of disrupted “just in time” deliveries etc. The road network is also one of our most important lifeline systems – crucial for assisting, maintaining, and repairing other infrastructures and for evacuation in a disaster. All this put together makes reliability in the road transportation system a highly important subject in terms of public economy and welfare (Berdica, 2002).

Since controlled, real life, field experiments are somewhat difficult to perform, computer models are often used for studying the effects of changing conditions in the road network. Recently, the EMMA model (the everyday name for the Swedish implementation of the traffic analysis package emme/2) was used in a case study of the road network in Stockholm, Sweden, to study how closures and capacity variations influence the users’ travel time, trip length, etc (Berdica, 2000). EMMA belongs to the group of state-of-the-art models, in which traffic flow is handled on the approximate, macroscopic level. These generally take some kind of network equilibrium approach, in which the road-user is assumed to have perfect information on the system status (i.e., they can be said to simulate the effects of long-term disturbances). Once an equilibrium route choice pattern has been determined, the travellers do not deviate from it. This may be appropriate when modelling a bridge failure, say, but many of the every day incidents causing reductions in road serviceability are of short duration and a new equilibrium is never reached; the road-user has to revise his/her course of action continuously during the journey, as he/she encounters unexpected events and changing conditions. Using a network equilibrium approach could underestimate the effect of the disturbance since this transient state is not captured (see Figure 1). Dynamic models, where changing conditions like congestion are taken into account by regular “updating” of route choice, may be more promising for studying short-term capacity reductions. In their most disaggregate form, traffic is modelled by microsimulation of individual vehicles in the road network.
The purpose of the study presented here is twofold: to investigate the implications of model choice in further detail, as well as the practicability of studying the effects of short-term incidents. The first objective is achieved by simulating the same range of closures, in the same road network, for the same traffic demand, by means of three different computer programs: TRACKS, SATURN, and Paramics. These represent macroscopic, mesoscopic, and microscopic modelling respectively. Running and analysing a number of scenarios with short-term incidents in Paramics achieves the second objective. The three models are described in the second section, followed by the study design, analyses of the results, and the summarised conclusions.

**MODEL CHARACTERISTICS**

The programs TRACKS, SATURN and Paramics can be said to represent three different levels of detail for modelling road traffic. They have all been implemented and calibrated for the road network around the University of Canterbury campus in Christchurch, New Zealand, over the last few years (Cameron, 1996; Laird and Nicholson, 2000; Andjic, 2000). This provides an opportunity for a comparative study not often encountered. The coded network, with the simulation network used for the comparison being the portion within the polygon, is shown in Figure 2.
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Figure 2. Coded road network: simulation network within the marked polygon. (Adapted from: Andjic, 2000)

TRACKS is a suite of programs developed by Transportation and Traffic Systems Ltd in New Zealand over the years since the late 1970’s. It consists of a complete set of programs for performing the traditional four-stage transport planning process of trip generation, distribution, mode choice and assignment, but only the assignment part was used in this study. TRACKS was chosen to represent the traditional macroscopic models. These are generally based on the Wardrop condition of user equilibrium, which means that individuals choose routes in order to minimise their generalised travel costs and in an equilibrium situation all used routes between any origin-destination pair have equal costs, not greater than those on unused routes. However, for this application the TRACKS option of a time-dependent incremental assignment was chosen, rather than the true equilibrium

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assignment. This involves dividing the total trip matrix into fractional matrices that are assigned one at a time until the whole travel demand has been loaded onto the network, with re-calculation of optimum paths between increments. The results can be interpreted as the build up of congestion for the peak period. One might expect that the smaller the increments the closer the final solution will be to the equilibrium solution, although Ortuzar and Willumsen (1990) state that the “algorithm does not necessarily converge to Wardrop’s equilibrium solution even if the number of fractions... is large and the size of the increments... is small”. The basis for the route choice is a function of travel time and travel distance summed over links and intersections. Each link in the network is assigned one of twenty link types, for which a predetermined speed-flow relationship describes the average speed and response to flow variations (i.e. the rate of increase in travel time as a function of traffic flow assigned to the link). For intersections, the delay is estimated for signals and roundabouts using the algorithm in SIDRA (Akcelik, 1986) and a modification of Tanner’s queuing theory (Fisk & Tan, 1986; Gabites Porter, 1991) for priority intersections, for the calculated flow rates and a number of user-specified parameters.

SATURN (Simulation and Assignment of Traffic in Urban Road Networks) has been developed at the Institute for Transport Studies, University of Leeds (UK) since the late 1970’s. The model is based on an iterative loop between a detailed simulation model to estimate delays at junctions, and an assignment model to identify the routes taken given such junction delays. The simulation model represents traffic by so called “cyclic flow profiles”. A more detailed account of the process can be found in Hall et al. (1980). SATURN uses an equilibrium-based assignment, but it is more of a mesoscopic model thanks to the more detailed modelling of junctions. It is hence essentially node-based (as opposed to TRACKS, which is primarily link-based and uses link speed-flow relationships), with the philosophy being that the relationship between flow and delay is largely determined by the interaction of queues at intersections. One very important feature is the blocking-back facility in SATURN (i.e. modelling of excessive queues). This makes it possible to take into account when a queue on a link extends back as far as the upstream junction, reducing the flow of vehicles entering the link. This is very different from TRACKS, in which all traffic is let through with the only consequence being a higher calculated delay, and is an important consideration when assessing the effects of closures in the road network.

Paramics is an acronym derived from Microscopic Simulation on Parallel Computers. This microsimulation traffic model is the result of a 6-year collaboration between Quadstone and SIAS in Edinburgh (UK), although these two firms have developed their own Paramics software independent of
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each other since 1998. Each individual vehicle is modelled for its entire trip through the road network. Neither the flow-delay relationships commonly used as a proxy for driver behaviour in traditional models, nor travel times or junction capacities, are defined. Speed is instead a result of the interaction between all vehicles, with their movements being governed by models for vehicle following, gap acceptance and lane changing, within the constraints formed by the physical properties or layout of the road network (i.e. lane arrangement, on-street parking, traffic signal timings, etc.). Individual driver characteristics include the level of aggression (used for determining the critical gap for lane changing) and the level of awareness, which distinguishes between drivers who are familiar or unfamiliar with the road network. The latter are essentially confined to the main roads, while the former can use minor roads as well. In addition, familiar drivers can at certain intervals be presented with feedback information on the level of congestion in the network and can re-route accordingly, giving a dynamic assignment.

STUDY DESIGN

The incident simulated was a complete closure about halfway up Creyke Road (see Figure 2), which was chosen because of its major importance to traffic both to/from and through the area, and its location in the centre of the network. The modelled time period is the 1999 morning peak hour (8-9 AM), with an average travel demand of 10,796 trips. Apart from a base scenario of normal operation, closures of 10, 20, 30, 40, 50 and 60 minutes were modelled. In Paramics, the length and time for occurrence of the desired incidents are specified and can be seen graphically during the simulation as vehicles “breaking down” to block the road. The incident was set symmetrically around the middle of the morning peak hour, i.e. the 20-minute closure was coded to start at 8:20 and end 20 minutes later. The simulation was set to run beyond 9 AM to allow for the effects of the incidents to fully disperse. Also, because of the stochastic nature of Paramics, it is necessary to do multiple runs with different seed values for randomisation of trip release so the results presented are the average of five runs.

For a 1-hour closure in SATURN, cars were simply prohibited from using that particular link during that model run, while to simulate shorter closures the method chosen was to reduce the capacity; halving the saturation flow of a dummy node in the middle of Creyke Road corresponds to an incident blocking the road for 30 minutes out of the modelled hour. This rather crude method was chosen rather than the time-slice method available in SATURN, to retain the equilibrium-based assignment that was essential for our
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comparison. Also, time slicing would have involved substantial model alterations and recalibration would have been needed. In TRACKS, the already available option of an incremental assignment procedure makes it possible to code the particular link as missing for certain increments only, to simulate a closure of shorter duration.

The input data relating to the travel supply (i.e. physical properties/layout of the road network) and travel demand (i.e. trip matrix) were as consistent as possible. There are differences in the travel supply input requirements for the different models, and whenever there was an overlap in the input data requirements, the same values were used. If an item of data was required by only one model, then the most appropriate value (to describe accurately e.g. the physical properties of the network) was input.

RESULTS

As was mentioned before, the Paramics simulation was set to run for up to three hours, to allow for the effects of the incidents to fully disperse. However, for the 50 minutes and 1-hour closures the network became so congested that many trips were not completed by the end of this period. This is seen in the constant increase in accumulated travel time in Figure 3 for these two scenarios, which were therefore left out in the subsequent comparisons and analyses. Also, since the traffic system is not really congested (i.e. not operating close to its capacity limit during normal conditions) even the half-hour closure in SATURN did not show any substantial effects, so SATURN results for closures shorter than 30 min are therefore omitted.

Model Comparison

The comparison is made for net effects at the system level and concentrates on the time spent and distance travelled in the road network. These represent two important areas in terms of travel costs and thereby also possible savings: operating cost savings and user-time savings. The effect of closure duration on total travel time and total travel distance is shown in Figures 4 and 5 respectively.

It should be noted that there are differences between the three models for the base scenario (i.e. no closure). The difference in travel distance is mainly explained by the way that trips enter/exit the network from/to the origin/destination zones. TRACKS connects zone centroids to dummy nodes located somewhere in the middle of the links. Each centroid connector has its length specified and travel on it is included in the trip length calculations.
In SATURN, centroid connectors are connected to links and trips into/out of the zone are assumed to enter/exit at the intersections. Neither travel on the links in question, nor travel on the centroid connectors, is recorded in the calculations. Paramics simply loads trips from a zone onto the links in that zone in proportion to their length, the vehicles appearing at the upstream end of the link in question when there is a suitable gap in the traffic flow (if not, vehicles form a “virtual queue” in the zone until there is a suitable gap). The above also explains part of the difference in total travel time, but the main reason for this is most likely that the three models use different methods for assessing intersection delays. The models have been calibrated to give a good match between observed and predicted flows but it is not known precisely how well they predict travel time. Part of the differences may therefore also be explained by initial calibration discrepancies, but this has not been investigated further as model calibration was not part of this study.

Figure 3. Total system travel time for different closures in Paramics.
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Figure 4. Model comparison of system travel time for different closure durations.

Figure 5. Model comparison of system travel distance for different closure durations.
The Network Reliability of Transport

From Figure 4 it is clear that Paramics is more sensitive to disturbances. Already a closure of 10 minutes increases system travel time by 18%, compared to a 1% increase in TRACKS. Closures shorter than half an hour in SATURN do not (as mentioned above) result in any noticeable difference. The microsimulation model is also more sensitive to incident duration, as shown by a higher rate of increase for longer closures. An interesting result is that the possibility of coding the link closure for only certain increments in the TRACKS assignment apparently makes this model more sensitive in terms of changes in travel time than SATURN, which is otherwise more detailed in its formulation. As for the total distance travelled the intuitive notion is that trip lengths should generally increase compared to the base scenario, due to detours caused by the closures. This is true for TRACKS and Paramics, although the effect isn’t very big, and Paramics is again the most sensitive. One might expect a longer closure to generally lead to longer detours, as in the TRACKS results, but this seems to be true only to a certain point. A longer closure may well cause such an extensive spread of queues that further re-routing is useless and the only option is to wait. This is especially true for small networks, such as the one in this study, in which there is only a limited number of alternative routes. Also, route choice was based upon minimising travel time, which means that the chosen route is not necessarily the shortest. As traffic conditions change in the network, a previously shorter but slower route may well become the fastest alternative.

Paramics is clearly a more sensitive model when simulating short-term road interruptions. It probably presents a more realistic picture of the resulting consequences, as travellers in the microsimulation are faced with the closures and the subsequent changes in congestion conditions en-route and can change their route choice accordingly. In the equilibrium-based models, the status of the road network is assumed to be known beforehand and route choice does not change en-route, which clearly fails to correspond with reality. All three models have a weakness when considering real traffic behaviour, in that they do not allow vehicles to simply make a U-turn to avoid a queue (something that quite often occurs in a real life situation). Paramics can allow U-turns at discrete locations, where dummy nodes allowing U-turns have been coded. This was deemed impractical since such dummy nodes would have to be put in at a large number of discrete locations, to allow for dynamic changes in queue lengths. Paramics may therefore over-estimate the effects of incidents to some extent.
Figure 6. Average travel times (line) and distances (bars) for different closures in Paramics.

Figure 7. Average travel times for different closures in Paramics.
The Network Reliability of Transport

Short-term Incidents in Paramics

In Paramics, the average travel time during normal operation is around 3 min/trip, increasing drastically with increasing closure time, and for a 40-minute incident it is over 18 min/trip (Figure 6). The effect on average trip distance on the other hand is not as great. From 1.68 km/trip during normal conditions, it reaches a maximum of 1.83 km/trip for a half-hour closure. However, this is reasonable considering the size of the network, as was mentioned above. Figure 7 shows the average travel time distribution for trips with respect to their start time during the simulation and it is clear that trips released before and after the incidents aren’t affected as much as trips released during the closure itself. It is interesting to notice the resemblance to the hypothetical illustration in Figure 1. The graph does in fact depict that problematic adjustment phase previously discussed, to some extent.

Another way of illustrating the effect on overall travel conditions in the network from various closures is the total travel time distribution (Figure 8). For shorter closures a majority of the trips are completed within some 10 minutes but this proportion quickly becomes smaller as the closure time increases. For the 40-minute closure half of the trips take longer than this, and as much as 30% have travel times exceeding half an hour. A very rough estimate of the economic impact for the system as a whole, based on user travel time and vehicle operating costs (i.e. distance) only, is presented in Figure 9. The values used are 27 cents/min and 21 cents/veh-km, in accordance with the New Zealand standard procedure for economic appraisal of urban travel (Transfund New Zealand, 1999). Expressed at the level of the individual, the average cost for travel during the morning rush hour is $1.35 and $5.40 per trip during an incident closing Creyke Road for 10 and 40 minutes respectively, compared to $1.20 during normal conditions.

It was noted above that the two longest closures were not successfully modelled in Paramics. The main reason was the occurrence of “routing errors” during the simulation, due to vehicles waiting for more than an arbitrary time to make a turn, which was then deemed impossible, leaving the driver without a route to the destination. It is also likely that the small size of the network contributes to the severe congestion and routing problems. For longer closures, it is likely that drivers would in reality use more of the surrounding street network to avoid congestion. Since these more peripheral routes are not included in the current simulation network, the system simply comes to a stand still and never clears.
Figure 8. Travel time frequencies for different closures in Paramics.
Figure 9. Cost estimation of different closures in Paramics.

Rather than going through the cumbersome process of increasing the size of the coded road network for the Paramics model, maybe the problem mentioned above can be ameliorated by changing the frequency of information supply and the weight attached to new information. The travel cost information given to familiar drivers as a basis for their route choice in the next period is a combination of the current cost ($V_{new}$) and the value in the previous period ($V_{old}$). That is $V_{new} = a \cdot V_{new} + (1-a) \cdot V_{old}$. The feedback factor ‘a’ determines the amount of smoothing, and it determines how much account the drivers take of prior knowledge and new information in making their next decision. The feedback interval is then the frequency with which new information is provided. When the feedback interval for familiar drivers was reduced from the default value of 5 minutes to 3 minutes, the system actually cleared within the simulation run time of three hours for the 50-minute closure for one seed value. It could be that, if left for longer than three hours, the other four runs would also have finished successfully. A quick sensitivity analysis shows negligible differences in results for varying feedback intervals in the base scenario. For a closure of half an hour, total system travel time (compared to that for a 5-minute feedback time) is roughly 8% and 13% lower for intervals of 3 and 1 minute(s) respectively. A similar sensitivity analysis was performed varying the feedback factor, and again no significant difference could be seen for the base scenario. For the 30-minute closure, increasing or decreasing ‘a’ from the default value of 0.5
resulted in reductions in total system travel time of 7% (a = 0.75) and 5% (a = 0.25). Judging from the small effects in the base scenario, it may be that changes to these parameters do not influence initial calibration to any appreciable extent, but further studies should be carried out to verify this.

**CONCLUSIONS**

The results show that Paramics is not only more sensitive to a disturbance as such, but is also more sensitive to the disturbance duration, than are SATURN and TRACKS as used in this study. This supports the hypothesis that the use of equilibrium-based models for studying short-term incidents underestimates the effects of the disturbances. However, it should be noted that there is a possibility of Paramics over-estimating the effects because of its present inability to allow vehicles to simply make a U-turn to get out of a queue. Thanks to the incremental assignment procedure in TRACKS, this model seems to be more responsive to incidents than is SATURN as used here. However, it should be noted that we have not made use of the time-slice feature available in SATURN, a choice that to some extent puts this model in an unfavourable light. It was, however, the equilibrium property of the existing SATURN model that we wanted to focus upon. Hence, the focus of the study has been assessing different modelling approaches, rather than comparing particular models. Problems and possibilities involved in traffic model comparisons are discussed further in Nicholson et al. (2001).

The different types of models are usually used for different sized networks but here all three were used for a small network. As network size increases the scope for traffic to find alternative routes will generally increase, unless the system as a whole is severely congested. With growing network size, however, it becomes less practical to use a microscopic model (and, to a lesser extent, a mesoscopic model) due to the greater level of detail in network coding and the computer capacity needed for running the program. We need to identify the separate effects of network size and modelling assumptions, of which we have looked only at the latter so far. One hypothesis that could and should be tested is that the effect of different modelling assumptions (e.g. using a static equilibrium assignment method rather than a dynamic method as in Paramics) will perhaps diminish as the network size increases, especially for large duration closures, but will remain important.

During this study we identified a number of principal features desirable in a program for modelling short-term disruptions in road networks. The ability to vary network characteristics during the model period is of course essential, as is the possibility of dynamic adjustment to varying conditions,
especially re-routing of vehicles en-route. Detailed interaction of vehicles on the individual level, together with randomness in their release onto the network, is also important when trying to match the real life situation. It seems that Paramics possesses more of these features than the other models used, and microsimulation thus seems the most suited to studying the effect of short-term incidents in the road transportation system. Future work should also include a closer look into what, if any, are the advantages of adjusting the feedback interval and/or the feedback factor.

On a more general note, none of the models used today seem to be designed with reliability studies of this kind in mind. The current development in urban areas all over the world, however, makes it necessary to get the most out of our existing road systems through better traffic management etc. It is also important to remember that although a model may be well calibrated for normal conditions, there is no guarantee that it will also predict abnormal conditions correctly. It would be good to have empirical data about actual traffic behaviour during a closure, to enable calibration of the model for closure conditions. It would also allow a comparison of the effects predicted by each model with the observed effects, rather than just comparing the results from one model with those from another model. Further development of modelling tools is clearly needed to increase our knowledge about the status of the road network, the expected effects when incidents do happen, and possible mitigation measures.

ACKNOWLEDGEMENT

Our deepest gratitude goes to Axel Wilke and Jonathan Harrington, for helping out with running the Paramics program. Special thanks also go to James Laird for his advice on how Paramics works. Last but not least, thanks to the Erik Philip Foundation at the Royal Institute of Technology for their financial support.

REFERENCES


Simulating Road Traffic Interruptions


PAPER VI
Comparing traffic models: two case studies

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ABSTRACT: This paper describes two studies involving the comparison of computer models/programs for predicting traffic behaviour in a road network and estimating how well the network performs. The network concerned is that around the University of Canterbury in Christchurch, New Zealand, and the three programs used are TRACKS, SATURN and Paramics. Development, calibration and the results of the two comparative studies are briefly described. The paper also discusses a number of issues surrounding the comparison of models/programs in general, revolving around two main questions: why and how to compare models/programs. Although great caution is required in comparing the results from the two studies as described here, they do suggest that different models have distinctive strengths and weaknesses, which affect how readily they can be used for accurately modelling traffic.

1 INTRODUCTION

This paper describes two studies involving the comparison of computer models/programs for predicting traffic behaviour in a road network and estimating how well the network performs. The network concerned is that around the University of Canterbury in Christchurch, New Zealand. Three programs (TRACKS, SATURN and Paramics) were used, representing three different levels of detail in traffic modelling:

1. the TRACKS program (developed in New Zealand by Gabites Porter) comprises software for performing the traditional four-stage transport planning process (trip generation, trip distribution, mode split and route assignment); delays are estimated using 'flow-delay' relationships for links and queueing theory for intersections, and TRACKS represents the traditional macroscopic models;

2. the SATURN program (developed in England by the University of Leeds and W S Atkins) comprises software for iterating between simulation (to estimate the travel costs for alternative routes) and assignment (to identify the routes followed by vehicles given those travel costs); the travel costs are estimated using cyclical flow profiles to assess the interaction of queues at intersections and estimate the delays, and SATURN represents a mesoscopic model;

3. Paramics (developed in Scotland by SIAIS) is a microsimulation program, and involves modelling the movement of individual vehicles through the network, allowing for their interaction with other nearby vehicles; Paramics thus represents a microscopic model.

All three models have been implemented and calibrated for the road network around the University of Canterbury campus over the last few years (Cameron, 1996; Laird and Nicholson, 2000; Andjic, 2000).

The TRACKS program was chosen to represent traditional strategic/macrosopic models. The assignment process in such programs is commonly based on Wardrop's condition for user equilibrium, with users choosing routes in order to minimise their generalised travel costs and, in an equilibrium situation, all used routes between any origin-destination pair have equal costs, not greater than those on unused routes. TRACKS does provide the option of a time-dependent incremental assignment procedure; this involves dividing the total trip matrix into fractional matrices that are assigned one at a time until the whole travel demand has been loaded onto the network, with re-calculation of optimum paths between increments. The results can be interpreted as the build up of congestion for the peak period. One might expect that the smaller the increments the closer the final solution will be to the equilibrium
solution, but Ortuzar and Willumsen (1990) state that
the ‘algorithm does not necessarily converge to
Wardrop’s equilibrium solution even if the number of
fractions ... is large and the size of the increments
... is small’.

The TRACKS assignment procedure is based on each
link in the network being assigned one of twenty
pre-determined speed-flow relationships to describe
the change in the average speed with increasing link
flow. For intersections, the delay is estimated for sig-
nals and roundabouts using the algorithm in SIDRA
(Acekil, 1986) and a modification of Tanner’s queu-
ing theory (Fisk and Tan, 1986; Gabites Porter, 1991)
for priority intersections, for the calculated flow rates.

The SATURN simulation model represents traffic
using ‘cyclic flow profiles’ (Hall et al., 1980). SATURN
uses an equilibrium assignment procedure, but it is
more of a mesoscopic model thanks to its more de-
tailed modelling of junctions, with which all delays
are assumed to be associated. SATURN is essentially
node-based (unlike TRACKS, which is primarily
link-based), with the delay being largely determined
by the interaction of queues at intersections.

One very important feature is the blocking-back fa-
cility in SATURN for dealing with excessive queues.
This makes it possible to take account of a queue on
a link extending back as far as the upstream junc-
tion, thus reducing the flow of vehicles into the link.
This is very different from TRACKS, in which all traf-
ic is let through, with the only consequence being a
higher calculated delay.

With Paramics, each individual vehicle is modelled
for its entire trip through the road network. Neither
flow-delay relationships, commonly used as a proxy
for driver behaviour in traditional models, nor travel
times or junction capacities, are defined. Speed is
the result of the interaction between all vehicles, with
their movements being governed by models for ve-
cicle following, gap acceptance and lane changing,
within the constraints formed by the physical prop-
eries or layout of the road network (i.e. lane arrange-
ment, on-street parking, traffic signal timings, etc.).
Individual driver characteristics, including the level
of aggression (used for determining the critical gap
for lane changing) and the level of awareness, which
distinguishes between drivers who are familiar or
unfamiliar with the road network, are user-specified.
Unfamiliar drivers are essentially confined to the
main roads in the network, while familiar drivers
can use minor roads as well. In addition, Paramics
models drivers being presented with information on
the level of congestion in the network at certain in-
tervals, with familiar drivers being able to reroute
accordingly, giving a dynamic assignment.

This paper briefly describes the development and
calibration of the models, and the results of the two
studies involving comparisons of the models. There
are, however, numerous issues surrounding the com-
parison of models/programs in general. Those is-
ues revolve around two main questions:

1. why compare models/ programs?
2. how to compare models/ programs?

These issues are discussed in the next section, as they
set the scene for the discussion of the model com-
parisons and the subsequent conclusions.

2 PURPOSE AND METHOD OF MODEL
COMPARISON

The purpose of comparing models/ programs might
simply be to identify the variations in the results (i.e.
the predictions of traffic behaviour and network per-
f ormance) obtained using different programs, as a
matter of curiosity. Such comparisons might then
lead to the owners/ developers of the programs, if
they are made aware of the variations, modifying
their programs in an effort to ‘improve’ their per-
formance. This should in turn lead to an overall im-
provement in traffic modelling programs, given the
competition that exists. The comparison may also be
motivated by a desire to identify the ‘best’ model,
which traffic modellers would then be encouraged
(or required) to use, in an effort to increase the com-
parability of economic appraisal results for transport
projects around the country. An example of such a
study in New Zealand is that of Fisk and Dunn
(1992), who did recommend certain programs as
‘best’, unlike a later European study (TASTE Conso-
r trium, 1997), which stopped short of such a recom-
 mendation. The recommendations of the Fisk and
Dunn study were eventually not used for the origin-
al purpose. This was rather fortunate, as it would have

1. constrained traffic modellers from exercising
proper professional judgement in their choice
of the most appropriate model for the circum-
cstances,
2. reduced that level of competition between the
 owners/ developers of models, and
3. reduced the incentive for the further develop-
ment of models to obtain a competitive advan-
tage.

These disadvantages would probably have out-
weighed the advantages of having ‘standard’ traffic
models to reduce the variations involved in economic
appraisals.

Both the Fisk and Dunn (1992) and TASTE Conso-
r trium (1997) studies involved identifying the charac-
teristics of the alternative programs from published
literature describing them. That is, neither study in-
volving running the programs. The appropriateness
of comparing programs without running them is very doubtful, especially if the intention is to select programs that traffic modellers would be required to use.

Whatever the purpose of model comparisons, there are thus a number of important issues that need addressing and resolving. These include:

1. how is 'best' defined (via comparison of a model's predictions of traffic behaviour and network performance with observations of actual traffic behaviour and network performance, and how reliably can the latter be identified)?
2. is the 'best' model the 'best' in all circumstances, and if not, what are the circumstances in which it is the 'best' model and what are the 'best' models in the other circumstances?
3. is the 'best' model now going to be the 'best' model in the future, given that developments in models may well affect their relative merits?
4. are there any advantages of making the use of the 'currently best' model mandatory?

Given the considerable latitude for users to affect model outputs through their choice of options available within the program, there is also considerable scope for unfairness to arise when comparing models. How should a comparison be done so that it is fair and what exactly constitutes a fair comparison? Should one expert who is equally familiar with all the models to be compared do the comparison, and how readily can such a person be found? Should several experts, each of whom is equally expert in one model, do the comparison? How is the level of expertise measured? Should the comparison be done for just one network or several networks with different characteristics, to allow for variation in model performance with variations in network characteristics?

The three models of concern here were set up for the University of Canterbury network for two main reasons:

1. to enable students to obtain experience using a range of programs involving quite different levels of modelling detail, for a network with which they are familiar and for which empirical data can readily be obtained to enable a comparison of actual and predicted traffic behaviour;
2. to enable the assessment of various alternatives for managing traffic on the network; the University of Canterbury is located in a residential area, daily vehicle movements to/from the campus during term time are increasing noticeably, and there are growing concerns among residents of the area about the adverse effects of the increasing traffic and parking on streets around the campus.

That is, the original reason for setting up the models was not a comparison study. However, the models have been used for two studies as described below, and while great caution is required in comparing the results, they do suggest that different models have distinctive strengths and weaknesses, which affect how readily they can be used for accurately modelling traffic flows and network performance under different circumstances.

3 DEVELOPMENT AND CALIBRATION OF MODELS

The SATURN model was initially developed and calibrated by Cameron (1996), while the Paramics model was developed and calibrated by Laird and Nicholson (2000). The SATURN model was subsequently extended by Andjic (2000), who also developed the TRACKS model, in order to cover a network consistent with that used for the Paramics model. The SATURN program allows for a network to be described at two levels of detail. The more detailed network description is required for the portion of the network for which traffic flow simulation is required (to estimate intersection delays), with the simulation network being surrounded by a buffer network, for which less detailed information is necessary (delays are estimated from speed-flow relationships for links). Figure 1 shows the extent of the full network, which covers an area of about 4 x 4km, centred approximately upon the University of Canterbury. The simulation network covers the area inside the polygon shown in Figure 1, while the buffer network covers the area outside the polygon.

The TRACKS model covers the whole area at a level of detail between the SATURN simulation and buffer network levels of detail. The Paramics model covers only the area within the polygon, but at a very high level of detail. When results were being generated with a view to their comparison, the inner simulation network area was used. This involved turn-off the TRACKS and SATURN models, to exclude the outer area.

The zoning system was the same for all three models, with the origin-destination matrix being derived from the Christchurch Transportation Study (Roberts, 1996) trip matrix, the 1993 University of Canterbury travel survey (Laird and Nicholson, 1994), and the census data (at the mesh block level) for 1996. Details of the derivation of the trip matrix are described in Andjic (2000).

The three programs differ with respect to the arrangements for traffic entering/exiting the network from/to the origin/destination zones, respectively. With TRACKS, zone centroids are connected to dummy nodes in the middle of links in the network, with
each centroid connector having its length specified and travel on it being included in the trip length calculations. For SATURN, however, centroids are connected to links and trips from/to the zone are assumed to enter/exit the network at the downstream/upstream intersections, respectively, with neither travel on the links in question, nor travel on the centroid connectors, being included in the trip length calculations. Paramics simply loads/unloads trips from/to a zone onto/from the links in that zone in proportion to their length, the vehicles appearing/disappearing at the upstream/downstream end of the links, respectively.

The three models use quite different methods for assessing intersection delays and hence travel times. While both SATURN and TRACKS use queuing theory models, there are substantial differences between those models. Travel time estimates in Paramics are the result of interactions between individual vehicles, the drivers of which can have different characteristics (e.g. desired speed, gap acceptance and lane changing behaviour).

Both the SATURN and Paramics models allow for blocking-back, whereby vehicles are unable to enter a link if the queue from the intersection at the downstream end of the link extends back as far as the entry to the link. There is no such facility in TRACKS.

All three models were calibrated to give a good match between observed and predicted flows on links within the network, as well as across various screen lines. It is not known how well the predicted travel times agree with the actual travel times. While the descriptions of the network for each model were much the same prior to calibration, the characteristics of some links and nodes will have been changed during the calibration process, and may not have remained consistent.

Figure 1: Coded road network – simulation network within the marked polygon
(adapted from: Andjic, 2000)
4 COMPARISON RESULTS

4.1 SATURN and TRACKS

The SATURN and TRACKS models were developed and calibrated for the 8-9 am peak period, for the existing road network with all roads open and functioning properly (unlike for the comparison described in the next section). The network is not highly congested, and an equilibrium method was used to estimate the traffic flow pattern in the network.

The models can be compared with respect to various model outputs. Figure 2 shows the correlation between the link flows predicted by SATURN and TRACKS, for those links crossing the ten screen lines defined for the network, and it can be seen that there is a high level of correlation (or agreement). Indeed, the GEH and other statistical measures for comparing the predicted link flows did not show any significant differences between the SATURN and TRACKS models. If we compare the predicted flows for each model with the observed flows, for the links crossing all the screen lines, the level of correlation is noticeably less, as shown in Figures 3 and 4.

A model output that is often used for economic and operational assessments is the travel time. No observed travel times were available for comparing with the SATURN and TRACKS results, so travel times from the Paramics model (Laird and Nicholson, 2000) were used for the comparison. Three major routes through the network and two directions (eastbound is towards the CBD, and westbound is away from the CBD) were used (see Figure 1). The results are shown in Table 1, with the numbers in parentheses being the percentage difference relative to the Paramics values. It can be seen that there are some substantial differences. Another test involved multiplying the base trip matrix by a factor varying from 0.125 to 2.0, to see how the total vehicle kilometres (TVK) and total vehicle minutes (TVM) of travel for the SATURN and TRACKS models might change with varying levels of congestion in the network. The results are shown in Figures 5 and 6. It can be seen that the differences are relatively small for non-congested conditions, but as the level of congestion increases the difference in the total vehicle minutes of travel becomes greater. This may well be due to the blocking-back facility, which is available in the SATURN model but not in TRACKS.

4.2 Paramics, SATURN and TRACKS

The previous model comparison was made under stable network conditions. This second study, on the other hand, concentrated on the effects of changing conditions in the road network. The underlying hypothesis was that since abnormal conditions (such as when a link is temporarily blocked due to for instance a traffic accident) are often of short duration and a new equilibrium traffic flow pattern is never obtained, equilibrium based models might underestimate the effects of the consequent disturbance (Berdica, 2000). Dynamic models, which take changing conditions like congestion into account through the possibility of rerouting en-route, may be more appropriate for this purpose. The study therefore involved simulating the same range of closures, in the same road network, for the same traffic demand, by means of the three different computer programs described previously. The incidents simulated were complete closures about halfway up Creyke Road (see Figure 1), with durations of 10, 20, 30, 40, 50 and 60 minutes respectively.

![Figure 2: Correlation of TRACKS and SATURN flows – all screenlines](image-url)
Table 1  
Morning peak travel times (minutes:seconds) for key trips

<table>
<thead>
<tr>
<th>TRIP</th>
<th>PARAMICS</th>
<th>TRACKS</th>
<th>SATURN</th>
</tr>
</thead>
<tbody>
<tr>
<td>Riccarton Rd (eastbound)</td>
<td>3:04</td>
<td>3:06 (1.58%)</td>
<td>2:31 (-17.90%)</td>
</tr>
<tr>
<td>Riccarton Rd (westbound)</td>
<td>2:42</td>
<td>3:15 (20.65%)</td>
<td>3:04 (13.87%)</td>
</tr>
<tr>
<td>Maidstone/Croyke (eastbound)</td>
<td>3:27</td>
<td>3:37 (4.93%)</td>
<td>2:46 (-18.94%)</td>
</tr>
<tr>
<td>Maidstone/Croyke (westbound)</td>
<td>3:28</td>
<td>3:41 (6.62%)</td>
<td>2:53 (-16.98%)</td>
</tr>
<tr>
<td>Memorial Ave (eastbound)</td>
<td>4:20</td>
<td>3:41 (-17.25%)</td>
<td>3:19 (-23.38%)</td>
</tr>
<tr>
<td>Memorial Ave (westbound)</td>
<td>3:38</td>
<td>3:45 (3.21%)</td>
<td>3:20 (-4.32%)</td>
</tr>
</tbody>
</table>

Figure 3: Correlation of predicted and observed Flows (TRACKS)

Figure 4: Correlation of predicted and observed Flows (SATURN)
In Paramics, the length and time for occurrence of the desired incidents are specified and can be seen graphically during the simulation as vehicle 'breaking down' to block the road. The simulation was set to run beyond the 08:00-09:00 peak period to allow for the congestion effects of the incidents to fully dissipate. For a one-hour closure in SATURN, cars were simply prohibited from using that particular link during that model run, while to simulate shorter closures the method chosen was to reduce the capacity, halving the saturation flow of a dummy node in the middle of Crewse Road corresponds to an incident blocking the road for 30 minutes out of the modelled hour. This rather crude method was chosen rather than the time-slice method available in SATURN, to retain the equilibrium-based assignment that was essential for our comparison. In TRACKS, the already available option of an incremental assignment procedure made it possible to code the particular link as missing for certain increments only, to simulate a closure of shorter duration.

The comparison concentrated on changes in the time spent and distance travelled in the whole of the simulation network (i.e. the area inside the polygon in Figure 1). The effect of closure duration on total travel time and total travel distance is shown in Figures 7 and 8 respectively. The 90-minute and one hour closures in the Paramics model rendered the network so congested that the system did not clear despite a simulation run time of three hours. Also, since the traffic system is not operating close to its capacity limit during normal conditions, closures shorter than half an hour did not show any substantial effects in the SATURN model. These scenarios were therefore left out in the comparison and analyses.
The reason for the differences between the base scenarios (i.e. no closure) as given by the three models can probably be found in the way that trips enter/exit the network from/to the origin/destination zones, as well as the different methods used by each model for assessing intersection delays, as described above. Another source of explanation can also be initial calibration for goodness of fit between predicted and observed traffic flows, which is discussed further in the next section.

From Figure 7 it is clear that Paramics is more sensitive to disturbances. It is also more sensitive to incident duration, as shown by a higher rate of increase for longer closures. It is interesting that although TRACKS is less detailed in its formulation compared to SATURN, the incremental assignment option apparently makes it more sensitive in terms of changes in travel time. Regarding total distance travelled (Figure 8), the intuitive notion is that the detour caused by a closure should generally result in increased trip length compared to the base scenario, which is the case for TRACKS and Paramics. Also, one might expect a longer closure to generally lead to longer detours, as in the TRACKS results. However, this seems to be true only to a certain point. A longer closure may well cause such an extensive spread of queues that further rerouting is not possible when modelling a small network (as the one in this study) where there is only a limited number of alternative routes. This is illustrated further in Figure 9, depicting average times and distances for trips during different closures in Paramics. The effect on average trip distance is not so great, the maximum being not even a ten per cent increase for the half-hour closure. The average travel time increases drastically with increasing closure time, a trip taking about six times longer in the 40-minute closure scenario compared to normal conditions. The effect of closure can be seen by plotting the distribution of average travel time for all trips versus their start time. From Figure 10 it is clear that trips started before and after an incident (the duration of which has been centred around 08:30) are not affected as much as trips started during the closure itself.

It seems clear that Paramics is a more sensitive model when simulating short-term road interruptions, and probably represents a more realistic picture of the resulting consequences. In reality, travellers faced with closures and the subsequent congestion effects en-route can change their route choice accordingly, and Paramics allows for this. Equilibrium-based models assume, however, that the status of the road network is fully known before trips commence and once an equilibrium route choice pattern has been determined, the travellers do not deviate from it. All three models, however, have a weakness when considering real traffic behaviour, in that they do not allow vehicles to simply make a U-turn to avoid a queue. Paramics can allow U-turns at discrete locations, if dummy nodes allowing such turns are coded but this was deemed impractical here. The microsimulation model may therefore over-estimate the effects of incidents to some extent.
Figure 8: Model comparison of system travel distance for different closure durations

Figure 9: Average travel times and distances for different closures in Paramics
5 DISCUSSION

The two studies described in the previous section give good examples of the different issues raised in section 2, and that need to be addressed when dealing with model comparisons. For simplicity, the SATURN-TRACKS and the Paramics-SATURN-TRACKS comparisons previously described are referred to as the S-T and the P-S-T study respectively.

A fair comparison requires consistency. This may be easier to achieve by assigning one person the task, but learning how a program package works and how to use it is generally a time consuming process. The result is that people tend to become experts in one program only, and finding a person who has extensive in-depth knowledge of two or more may prove difficult. It is then a question of deciding whether it is easier to bridge the differences in one person's familiarity with two or more models, or the differences between two or more separate experts. The S-T study is an example of standard modelling of 'normal' conditions (i.e. all links and nodes operational), while the P-S-T comparison is concerned with interruptions (i.e. 'abnormal' conditions). The latter probably requires a better knowledge of the software capabilities than does the former, given that the latter entails using the programs for a task for which they were not designed, so it is likely that the level of expertise needed for a 'fair comparison' increases with the complexity of the scenarios. The focus of the P-S-T study was assessing different modelling approaches, rather than comparing particular programs. Therefore it was deemed acceptable to not extend the SATURN model to make use of the time-slice feature available in SATURN, although this put the model in a somewhat unfavourable light.

Any model is, when at its best, still only an imperfect reflection of reality. Therefore, a model that yields predictions of traffic flows on links that are close to observed traffic flows is in general regarded as a good model. However, in the process of calibrating the models to obtain this high level of correspondence, network attributes may be changed and the objective is achieved by different network adjustments in different models. The question is then whether a comparison of calibrated models is fair? In the S-T comparison, the two models were not calibrated to get closer to observed flows. Instead the emphasis was put on making sure that the two networks were coded identically (as much as the level of detail for network coding allowed), with identical physical properties of the road network (i.e. lane arrangement, on-street parking, traffic signal timings, link speeds etc). When an identical trip matrix is assigned to two 'identical' networks, the resulting flows and delays will show 'pure' differences in how the two models handle the demand with 'identical' supply. This is clearly illustrated by the high level of agreement between predicted flows in Figure 2 ($R^2 = 0.99$) and the much lower levels of agreement in Figures 3 and 4 ($R^2 = 0.66$ and $R^2 = 0.73$, respectively) when predicted flows are compared to observed flows.

When it comes to comparing a microsimulation model to so called conventional models, the issue of using calibrated or identically coded models is not as easily addressed, since it is virtually impossible to find equivalent coding solutions. This probably
explains part of the great differences in TVM and TVK for the base scenario in the P-S-T study (Figures 7 and 8). Also, it is not very likely that better calibrated TRACKS and SATURN models would show more sensitivity in modelling the short-term interruptions of interest in this case. A question that deserves to be raised here is of course whether there is any meaning at all in comparing a microsimulation model with conventional models, since they are so fundamentally different. Nevertheless, reliability modelling of this kind can be one aspect in assessing strengths and weaknesses of different models and one interesting finding from the P-S-T study was that TRACKS by its incremental assignment was actually more sensitive than expected.

Depending on the problem to be solved and the prevailing circumstances, different models are suitable for different tasks and different situations. In the S-T study the two models were shown to have their strengths and weaknesses in different areas. Andjic (2000) found that TRACKS was far easier to use, especially for coding and editing the network attributes, modelling outputs are customised for easy interpretation, and there is a wide range of comparison options available for loaded networks, supported by a graphical interface. This might well reflect the ease of accessing technical support for the TRACKS program within Christchurch. Some weaknesses were noticed in TRACKS (e.g. the limited number of signal phase combinations available for coding traffic signals). The SATURN model on the other hand is more sensitive to medium and high levels of congestion, and identifies potentially problematic intersections at an earlier stage. This is explained by the very nature of the two models, and the sizes of networks they can be used to model. A macroscopic strategic model (such as TRACKS) can be used to identify small parts of the network that require traffic management schemes to be applied, and a more detailed model (such as SATURN) could be used to evaluate such schemes. This is an example of how two models can complement each other very well.

6 CONCLUSION

Comparing programs or models is fraught with dangers, due to the difficulty in finding a method for comparison, such that the comparison is fair. Nevertheless, such comparisons are probably worthwhile, provided they lead to improvements in the programs. This is unlikely to occur if the purpose is to restrict traffic modellers to using particular programs, which appear to be the 'best' at some point in time.

One develops a much better appreciation of the strengths and weaknesses of alternative programs as a result of using them, rather than simply reviewing what is written about them. One can then make sound decisions regarding how to use them in series or in parallel, to take advantage of the strengths and avoid the weaknesses.

This study has not involved comparing programs so much as comparing modelling approaches. There are generally several modelling options available within each program (e.g. incremental, deterministic user equilibrium, stochastic user equilibrium, and logit trip assignment techniques), and the variations within the results obtained using different options within the same program can be substantial. They may even be greater than the variations between the results obtained using different programs.

Comparing the output of a program (or model) with the output of another is not as good a test as comparing the outputs with properly observed data, as evidenced by the much higher correlations between two sets of predicted flows than between the predicted and observed flows.

Despite the dangers, it does seem that microsimulation has some distinct advantages over traditional equilibrium models when modelling a network subject to short-term disruptions. In such circumstances, it is unlikely that traffic conditions will approach an equilibrium state. In addition, the ability to allow for traffic re-routing while en-route accords well with anecdotal evidence of traffic behaviour during such events.

REFERENCES


PAPER V
2+1 ROADS WITH CABLE BARRIERS
– TRAFFIC SAFETY AND
TRANSPORT QUALITY EFFECTS

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Submitted to: Accident Analysis and Prevention

Abstract
With the objective to improve traffic safety, the Swedish National Road Administration decided to replace the traditional 13 m road with a 2+1 design, i.e. a middle lane changing direction every 1-2.5 km, with a median cable barrier separating the two directions of travel. The decision to implement this new concept as a standard was based mainly on the expected traffic safety effects, which are found to be substantial. The number of severe and fatal injuries is significantly reduced, yielding traffic safety effects not far from those of a full extension to motorway. However, the question is raised whether the new lane arrangement in combination with a physical barrier has a negative impact on serviceability. A model for vulnerability analysis is developed and applied to two road objects of 2+1 design with a median cable barrier, describing their traffic performance during abnormal conditions. Reduced serviceability is found to be the result to some extent from physical obstructions and quite often due to winter weather, while temporary increases in travel demand can cause rather great disturbances. The concluding discussion touches on the trade-off between traffic safety and serviceability in terms of transport policy goals.

Keywords:
median cable barrier, traffic safety, vulnerability, 2+1 roads
1. BACKGROUND

1.1 Introduction

There is a significant gap in traffic performance, safety, investment and maintenance costs, land requirement and intrusion between 2-lane and four-lane cross-sections. In Sweden, this gap has so far been filled by a 13 m cross-section with two traffic lanes of 3.75 m each with 2.75 m hard shoulders and dotted road markings. The Swedish national road network of approximately 10 000 km includes some 3 600 km of 13 m roads with speed limit 90 or 110 km/h and an average annual daily traffic (AADT) varying from 4000 to 20 000 vehicles per day. Only some 300 km are semi-motorways, i.e. grade separated with full access control and no pedestrians, bicycles or slow-moving traffic. The last official guidelines from the 90's state 13 m roads as an alternative in the traffic interval from 2000 to 12 000 vehicles per day (AADT opening year).

The safety performance on 13 m roads has been found to be some 10 % better than on normal two lane roads with a 9 m cross-section. Still, almost 100 people are killed and about 300 people are severely injured every year on these high speed 13 m national roads in Sweden due to their huge traffic load. This equals 25 % of all fatalities and 20 % of all severe injuries on national roads (Bergh, 1999). The main problem on all 2-lane roads (including 13 m cross-sections) is run-off and head-on/meeting accidents, which account for more than 50 % of all casualties. With the objective to improve safety, alternatives to the 13 m cross-section with wide shoulders (Figure 1a) were introduced in the 1990’s. Some 800 km were converted to 5.5 m lanes with 1.0 m hard shoulders separated with embossed edge markings (Figure 1b) and some 100 km were converted to road marking based 2+1-designs, i.e. with a middle lane changing direction every 1-2.5 km (Figure 1c).

\[
\begin{array}{|c|c|c|}
\hline
2.75 & 3.75 & 1.0 \\
3.75 & 5.5 & 3.75 \\
2.75 & 1.0 & 1.0 \\
\hline
\end{array}
\]

\[
\begin{array}{|c|c|c|}
\hline
3.75 & 3.50 \\
3.75 & \\
1.0 & \\
\hline
\end{array}
\]

\[
\begin{array}{|c|c|c|}
\hline
\text{a) wide shoulders} & \text{b) wide lanes} & \text{c) 2+1 design road marking} \\
\hline
\end{array}
\]

Figure 1. Swedish intermediate cross-sections.
However, wide lanes have not turned out to be a traffic safety success so far (Brüde et al., 1996) and the very limited Swedish experiences from 2+1-designs with road markings (Brüde et al., 1997) have not been by far as promising as the German findings (Brannolte, 1993).

1.2 2+1 Roads with Median Cable Barriers

In 1998, the Director General of the Swedish National Road Administration (SNRA) decided on a full-scale program to improve traffic safety on existing 13 m roads using low-cost measures, preferably within existing right-of-way. The main alternative solution was the 2+1-solution with a separating median cable barrier, henceforward denoted 2+1cb. The main objectives were to develop design and maintenance standards for the new road type, some of the critical issues being:

(a) Would it be acceptable not to widen the 13 m cross-section, despite risks for blockage and other problems on narrow 1-lane segments?
(b) Would maintenance operations, especially for expected frequent median barrier repairs, be acceptable?
(c) Would the public accept the concept?

The traffic safety effect was judged to be major, up to a 50% reduction in the number of severe injuries and fatalities.

The experiences from the first pilot project on the E4 semi-motorway Gävle-Axmarfatan (172 km north of Stockholm) were already after 18 months very promising and eventually, in spring 2001, the SNRA decided to replace the traditional 13 m road with the 2+1cb concept as a standard cross-section for new constructions as well as for rehabilitation measures. Up to the 1 January 2002 a total of 300 km semi-motorways and about 150 km on ordinary 13 m roads (i.e. non-grade separated and allowing pedestrians, bicycles and slow-moving traffic) have been opened to traffic with 2+1cb cross-sections. The 2+1cb road is a less spacious and hence cheaper alternative (see Table 1) for avoiding head-on/meeting accidents than a full extension to motorway, which has been the most effective solution so far.

<table>
<thead>
<tr>
<th>Measure</th>
<th>2+1cb [SEK/m]</th>
<th>MW [SEK/m]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rehab. ordinary 13 m roads</td>
<td>5000-15 000</td>
<td>25 000-35 000</td>
</tr>
<tr>
<td>Rehab. semi-motorways</td>
<td>1000-3000</td>
<td>20 000-30 000</td>
</tr>
<tr>
<td>New construction</td>
<td>20 000-25 000</td>
<td>30 000-40 000</td>
</tr>
</tbody>
</table>
The design concept for a 2+1-design with a median cable barrier on an existing 13 m road is as follows. One continuous lane runs in each direction and one middle lane changes permitted direction of travel at intervals of 1.5-2.5 km, depending on road alignment, locations of intersections etc. At long bridges expensive to widen and on sections with frequent access roads, pedestrians and bicyclists, where grade separation is costly or impossible, 1+1-designs can be used. On the other hand, 2+2-sections may also be used in order to avoid 1-lane segments on up-hills and to improve traffic performance on sections where widening is possible at low costs.

The proposed cross-section within the existing paved width normal 13 m roads is presented in Figure 2. It is proposed to comprise of a 1.25 m median with a continuous cable barrier\(^1\), 3.25 m wide traffic lanes in the 2-lane direction and 3.75 m in the 1-lane direction. If not semi-motorway, outer hard shoulders of 0.75 m facilitate very low volumes of pedestrians and bicyclists, although these should be separated when possible at reasonable costs. Access roads should also be taken away, remaining ones designed as “right turns”, normally with left turn bays. A strip of 1.0 m with full bearing capacity but without overlay on 1-lane sections can be added for emergencies. The main problem is the narrow 1-lane segments and it is judged on a project-basis whether to widen the cross-section in order to facilitate passage of break-down vehicles etc.

![Figure 2. Design principles for 2+1 lane transition zones.](image)

Transition zones from 2 to 1 lane are 150 m long in each direction (i.e. total length of 300 m), with delineators on the cable poles at a distance of 10 m, double-sided lane closure information signs 400 m ahead and at the start of the transition zone (Figure 3). Quick-locks are recommended in order to make it possible to open the cable barrier in each transition. Transition zones from 1 to 2 lanes have a total length in the range of 50-150 m.

\(^1\) CEN containment class N2 and working width W5
Figure 3. Design principles for 2+1 lane transition zones.

The existing roadside areas should be smoothed within the right-of-way, i.e. solid objects, trees etc. should be taken away and culvert ends tapered. Side cable barriers should be used at dangerous locations such as right bends in rock cuts and on low cuts, as well as on all embankments in forest areas. The maintenance standards include that bridge inspections, overlay repairs etc. should be co-ordinated to minimize the number of traffic diversions. Delineator post washing etc. should be performed during low traffic volume conditions. Snow should be removed in the first 0.4 m of the median and edge lines should be visible. Special traffic management plans for standard maintenance operations were prepared and approved. Permanent emergency openings in the cable barrier are to be established every 3-5 km in order to allow rescue vehicles to turn.

1.3 Scope of this Paper

The very first 2+1cb object on E4 north of Gävle was from the start in June 1998 subject to extensive studies of traffic safety performance etc. and new 2+1cb roads have been included in this systematic follow-up concurrently with their opening to traffic (Carlsson et al., 2002). The decision to actually implement the 2+1cb was based mainly on the expected traffic safety effects and the second part of this paper presents the results from a traffic safety

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2 This paper is produced jointly by the authors, although Bergh, Carlsson and Berdica assume main responsibility for the first, second and third part, respectively.
analysis summarised for all 2+1cb semi-motorway objects opened to traffic so far in Sweden. However, there is a need to find a balance between traffic safety on the one hand and level of service on the other, and the decision was therefore preceded by thorough discussions regarding the acceptability of introducing this concept without widening the road section. Some of the main problems/difficulties are connected to maintenance operations such as snow clearing, cable barrier repairs, new overlays, roadside grass cutting, delineator post washing etc., especially on 1-lane segments. Also there is the risk of road blockage due to e.g. vehicle breakdowns on these segments. In order to assess what implications the new lane arrangement in combination with a physical barrier has on passability, a case study was carried out, aiming to characterise the 2+1cb solution from this vulnerability perspective (Berdica, 2002b). The main results from this study are presented in the third part of this paper. The fourth section then presents a concluding discussion. For simplicity, the 2+1cb denomination henceforward refers to semi-motorways with median cable barriers only, thus excluding the converted so called ordinary 13 m roads mentioned earlier.

2. TRAFFIC SAFETY

2.1 Introduction

The main reason behind the 2+1-design with a median cable barrier is to decrease the number of meeting- and overtaking accidents with severe and fatal consequences. In the feasibility study (Bergh, 1997), cable separation in combination with roadside area measures was estimated to reduce the number of severe injuries and fatalities in the range of 20-30, maybe up to 50% (including road side area measures). This should be compared to the reduction of 65 % resulting from a full extension to motorway, which is probably the maximum effect attainable. On the other hand it was judged that the number of slight accidents without personal injuries would increase due to the cable barrier and narrow 1-lane segments.

An analysis of the alternative consequences, would a median cable barrier have been installed, was performed for 41 accidents with fatal or severe injuries which all occurred on E4 Gävle-Axmartavlan before 1999. The results indicated that a median barrier could have reduced the severity of the consequences in 27 cases, that is almost 70%. For the object on E18 Västerås (106 km southwest of Stockholm) the same type of analysis estimated that as severe consequences could have been avoided in over 80% of accidents.
2.2 Accident Analysis

For a general safety assessment all accidents that occurred up until 1 January 2001, on all 2+1cb semi-motorways in operation, have been analysed. These 18 objects constitute a total length of 290 km and a total traffic mileage of 890 million axle pair km (Mapkm). About half of this mileage has been executed on 6 objects with a 110 km/h speed limit and the remaining half on objects with a speed limit of 90 km/h. The average AADT is 12000 axle pairs, ranging from 6000 to 22 000. They are with a few exceptions not widened but have on average new over-lays and major roadside improvements, as well as slight betterments of entry lanes at interchanges. The maintenance standard is considerably increased.

The total outcome is 253 accidents on road links (i.e. excluding junctions, as well as accidents involving game) with in total 102 injuries, of which one is fatal and 15 are determined as severe. This gives an average accident rate of 0.28 per Mapkm, which is about 30% higher than the rate on ordinary semi-motorways with a corresponding 50/50-distribution of mileage on 90/110 km/h stretches of road. However, this is a doubtful comparison because since the year 2001 accidents with property damage only are normally not reported. Also, the median barrier design gives a number of “new” accidents with property damage only. The average injury rate is 0.11 persons per Mapkm. This is about 20% lower than on ordinary semi-motorways, for which the corresponding value is 0.14 for road links.

The most valuable and interesting comparison, though, is for the rate of severe injuries and fatalities. For all 18 objects this rate is 0.018 per Mapkm. This is significantly lower than for ordinary semi-motorways, for which this rate is 0.042 per Mapkm on road links. A more detailed comparison with corresponding values for different road types with a 50/50 mileage distribution on 90/110 km/h stretches gives the following results:

- a) Semi-motorway with roadside area C, i.e. no special measures: 0.0418 per Mapkm, which implies a reduction of 57%
- b) Semi-motorway with roadside area B, i.e. cleaning and smoothing: 0.0376 per Mapkm, which implies a reduction of 52%
- c) Semi-motorway with roadside area A, i.e. side barrier or flat slopes: 0.0334 per Mapkm, which implies a reduction of 46%
- d) Motorway with median barrier: 0.0149 per Mapkm, which is 17% lower than for 2+1cb roads

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3 This is an average for semi-motorways with 90 and 110 km/h speed limits, without any special measures for the roadside area.
e) Motorway with median barrier and roadside area A: 
0.0119 per Mapkm, which is 34% lower than for 2+1cb roads

The design of the roadside area on the 18 objects prior to reconstruction into 2+1-roads was varying but on average the standard can be said to have been corresponding to class B. This means that all the measures taken on 2+1cb roads have resulted in a 52% reduction of the rate for fatal and severe injuries on road links, when considering the outcome during the time each individual object has been open to traffic. The best motorway design has a rate which is 34% lower, and if the comparison is limited to motorways with a 110 km/h speed limit the difference is a mere 13%.

In the 1990’s the SNRA made a special investigation of traffic safety on motorways. This investigation showed a rate for fatal and severe injuries of 0.014-0.020 (depending on the roadside area standard) per Mapkm on stretches with the speed limit 110 km/h. Thus the 2+1cb roads from the beginning of the 21st century have an average rate which is about the same as for motorways with median barriers and corresponding roadside standards from the 1990’s.

The traffic safety outcome presented above can also be used to assess the expected reduction in injuries etc. from implementing the 2+1cb design. The SNRA safety prediction model (SNRA, 2000), used in the cost-benefit calculation program for investment planning, was used to calculate the expected (predicted) accident outcome on an ordinary semi-motorway link with speed limit 90/110 km/h (50/50 distribution) and roadside standard C. Table 2 presents a comparison of these predicted numbers of accidents, injuries and fatalities to the actual outcome (observed numbers) on the 18 objects.

Table 2. Expected number of accidents and injuries compared to actual outcome up until 1 Jan 2001, on all 2+1cb semi-motorways in operation (=18 objects).

<table>
<thead>
<tr>
<th>Number of:</th>
<th>Predicted</th>
<th>Observed</th>
</tr>
</thead>
<tbody>
<tr>
<td>accidents</td>
<td>195</td>
<td>253</td>
</tr>
<tr>
<td>injuries</td>
<td>124</td>
<td>102</td>
</tr>
<tr>
<td>severe injuries and fatalities</td>
<td>37.3</td>
<td>16</td>
</tr>
<tr>
<td>fatalities</td>
<td>9.6</td>
<td>1</td>
</tr>
</tbody>
</table>

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4 Median cable barrier, 2+1 lanes, roadside area measures, new pavements etc.
The observed number of severe or fatal injuries indicates a reduction of 57% and it is significantly different from the predicted one. With a probability of 95% the effect is a reduction of more than 32% in severe injuries. The outcome of one fatal injury also implies a significant difference compared to the predicted 9.6 fatalities. The observed total number of injured is about 20% lower than the predicted, but this difference is inside the confidence interval (upper limit 125) for the outcome. On the other hand, the observed number of accidents in Table 2 is greater than the predicted, a significant difference of about 30%. This is in agreement with the expectations in the feasibility study, though, being that the number of slight accidents without personal injuries would increase. It should also be noted that the observed number should probably be even higher, since accidents with only property damage are not reported for some of the objects. Table 3 lists the total number of 253 accidents in terms of type and severity. The fatal accident must be characterised as an extreme exception, since it involved a bicycle running in the wrong direction toward oncoming vehicles on a semi-motorway, in the dark without lighting.

Table 3. Distribution of the 253 observed accidents on type and severity.

<table>
<thead>
<tr>
<th>Accident</th>
<th>Number of injuries</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>number</td>
</tr>
<tr>
<td>Single</td>
<td>148</td>
</tr>
<tr>
<td>Overtaking</td>
<td>50</td>
</tr>
<tr>
<td>Catching up</td>
<td>26</td>
</tr>
<tr>
<td>Various</td>
<td>24</td>
</tr>
<tr>
<td>Crossing/turn off</td>
<td>3</td>
</tr>
<tr>
<td>Vuln. road users</td>
<td>2</td>
</tr>
<tr>
<td>SUM</td>
<td>253</td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
</tbody>
</table>

As can be observed, meeting accidents have so far not appeared and the number of single accidents with severe injuries has been significantly reduced. The severe injuries normally appear in right hand run off accidents, sometimes after bouncing on the median barrier. It should be noted that the most serious single accidents occurred on 2-lane segments. Also, most of the severe single accidents start with the vehicle running outside of the pavement to the right, resulting in the driver losing control of the vehicle. This was the course of events in a single accident where the vehicle overturned the median barrier and crashed in the ditch on the other side of the road. All the five occupants in the car were belted, which – in combination with otherwise very lucky circumstances – resulted in only one slight injury. However, the majority of single accidents are property damage only, after a crash into the cable barrier. Overtaking accidents with severe
consequences have not occurred as yet\textsuperscript{5} but there have been two overtaking accidents in which there was a collision with a stationary vehicle in the left lane, resulting in totally crashed vehicles although no one got severely injured. Catching up accidents could be a problem at high traffic volumes.

A reasonable conclusion drawn from the data presented above is that accidents with severe consequences have been effectively prevented by the cable barrier and converted into cable crashes, mainly with property damage only. This is valid for meeting accidents in particular but also for single accidents, which have turned out to involve significantly less severe injuries in general. These results provide a basis for an adjustment of the initial judgement of traffic safety effects of 2+1cb roads presented in the feasibility study. The long term effect on severe injuries and fatalities can in a conservative manner be estimated to be a reduction in the range of from at least 40\% and up to 55\% (including roadside area measures). This should be compared with motorways where the maximum reduction attainable is 65\%. The effect regarding only fatalities is probably higher. This reduction for an extension to motorway is 80\%, wherefore the effect of the 2+1cb road may be estimated to a 60-70\% reduction in the number of fatal injuries.

It can be added that a special analysis of the accident data has been performed, dividing it by speed limit (90 and 110 km/h). The results show that the 110 km/h roads have a somewhat better accident situation than the 90 km/h objects, with an accident rate of 0.26 compared to 0.31 per Mapkm. The rate for injured persons is 0.09 compared to 0.14. The differences in these two rates are, however, on the limit for the stochastic variation. The rate for fatal or severe injuries is 0.018 per Mapkm for the 110-roads, which is just slightly higher than for motorways with a median barrier and the same speed limit. The corresponding value for the 90-roads is also 0.018. A possible explanation for the better outcome on roads with a 110 km/h speed limit is that their design standards are in general somewhat higher compared to the 90-roads. The higher speed level could thus from a safety aspect be compensated for by the higher design standard. Still, the most serious accidents with overturned vehicles etc. have occurred on 110 km/h roads.

2.3 Median Cable Crashes

From the beginning it was expected that the number of median cable crashes would be high, in the range 0.5-1.0 per Mapkm. The outcome so far is on average 0.54 for all objects. On roads with higher traffic volumes the rate is in the interval 0.60-0.90, although no significant traffic flow relation has been found. The most extensive/comprehensive data for cable crashes is

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\textsuperscript{5} These accidents generally constitute only about 6\% of all severe injuries.
reported from E4 Gävle-Axmartavlan and includes a total of 180 crashes since the time it was first opened, about 3.5 years ago. About 30% of these are also reported to the police and can be investigated. Then again, only 30% of these police reported crashes were primarily direct cable crashes and then probably due to lack of concentration. The remaining 70% were all preceded by skidding, flat tyres, uncontrolled manoeuvres including driving outside the right asphalt edge and similar incidents.

About 60% of all cable crashes have occurred in 1-lane segments and only 7% have occurred in a transition zone from 2 to 1 lane. This proportion is slightly less than the proportional length of transitions, which is about 10%. About 52% of the crashes have occurred during winter, December-March. The proportion of the yearly mileage executed during these months is only 25-27%. Skidding is often the primary cause for a cable crash, another problem being very bad sight conditions during “snow-smoke”.6

There is one other object with comprehensive reports of cable crashes, and that is E4 Ljungby. Here 96 crashes have occurred over the course 14 months, of which 74% were in 1-lane segments and only one crash in the transition zone from 2 to 1 lane. Of the crashes, 41% have occurred during the winter period. This is a somewhat higher share than the corresponding proportion of “wintertime” since the object was opened to traffic. As for the normally lower traffic volumes during winter, the value for comparison is about 30%. An influencing element of winter surface conditions can be observed on this object as well, although not as strongly as for E4.

The rate of cable crashes shows a decreasing tendency, especially on E4 Gävle-Axmartavlan. After October 1999 the cable crash rate has decreased with 35% compared to the first 15 months after opening. The rate decreased after the pavement width in 1-lane segments was increased by one meter (from 4.75 up to 5.75 m). However, the reduction is just slightly larger in 1-lane segments compared to 2-lane segments. The reason behind this reduction in the cable crash rate is not so easy to explain. It could be the widening of the pavement – about 57% of the cable crashes occurred in 1-lane segments after the widening as opposed to 65% for the time before – or road users are growing more accustomed to the design. As an attempt to reduce cable crashes the painting of the edge line towards the median barrier in the southbound direction was changed. In June 2001 the earlier smooth edge line was replaced by a so called “profiled rainflex” line with higher visibility. This has, however, not affected the number of cable crashes notably and since June 2001 there have been 11 crashes in the southbound direction compared to 9 in the northbound.

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6 Snow-smoke = dry snow whirling around behind heavy vehicles.
As mentioned above there is no obvious relation between the rate of crashes and traffic volumes. However, roads with high volumes have higher rates in general and almost all 2+1cb objects with a rate over 0.60 per Mapkm have an AADT of more than 9 000 axle pairs per day. A relevant reason for this is that the proportion of vehicles driving in the left lane in 2-lane segments is in general higher. About 25-35% of the crashes occur in 2-lane segments at an AADT of 9-10 000 axle pairs. Assuming a constant rate in 1-lane segments, this implies that a higher proportion of vehicles in the left lane will give a total higher crash rate. The number of times that vehicles catch up, and consequently the number of overtakings, is proportional to the traffic volume squared. Thus the proportion of vehicles in the left lane causing cable crashes is proportional to the total traffic flow. In theory, if the AADT value is doubled the cable crash rate will increase by 30%, which would explain the difference between low volume and high volume roads.

Further investigations show that a total paved width of 14 m instead of 13 m is not enough to significantly reduce the number of cable crashes and high rates can be a fact despite a wider pavement. There is, however, one 2+1cb object with low traffic volumes and a 14 m cross-section where the rate is extremely low. On the other hand, that road has a median width of 2.25 m. Hence a median width of more than 2 m could reduce the number of cable crashes, although this has not been investigated further.

It is obvious that the number of cable crashes depends on the winter road surface conditions. On roads with a high degree of snowy and icy conditions there are significantly higher rates of crashes during the winter period. If the 18 objects are divided into two groups, the first one consisting of the roads in the northern part of Sweden and the second one of the roads located in the southern part/close to the coasts, the following results are obtained:

a) The roads in group 1 have an average rate of 0.62 per Mapkm.
b) The roads in group 2 have an average rate of 0.28 per Mapkm, only 45% of the rate for the northern ones.
c) At the most 10% of the difference of 0.34 per Mapkm can be explained by the lower average traffic volumes during winter.

The most important conclusion of the cable crash analysis is that the major part of observed differences in crash rates can be explained by road conditions during winter time, a special problem being snow-smoke. Other conclusions are that there seems to be an effect of the driver getting accustomed to the design in that the crash rate is decreasing with time. No significant difference has been detected for a wider, 14 m paved width but it

7 North of Lake Mälaren
seems that a wide median has positive effects, keeping the vehicles more to the right. Changing the edge line towards the median has no effect so far.

2.4 Safety Aspects of Maintenance Operations

As mentioned previously, the 2+1cb design gives rise to some new problems regarding road maintenance operations that in some respects influence traffic safety. Cable repairs is the biggest problem, with work zone area safety being a major concern. So far, the work is conducted from the overtaking lane (closed by a heavy lorry with TMA-protection at the back), i.e. with full traffic in one remaining lane in each direction. However, passing traffic shows little consideration and one serious incident has occurred when a passenger car simply crashed into the road closure device at high speed. Winter maintenance also causes some problems. The snow clearing speed is unaffected but the snowplough drivers complain that their task is more stressing compared to working on normal roads. There have been some incidents with minor collisions between cars and the snowplough vehicle, luckily with no personal injuries so far. Normal fixed works as delineator post washing, bridge washing, ditches and roadside cultivation etc. is recommended to be performed during low traffic volume conditions. On E4 Gävle-Axmartavlan these tasks are carried out with one-way traffic, the other direction being redirected to a parallel road by means of stationary re-directional signs and variable message signs at each end of the 2+1cb object.

3. TRANSPORT QUALITY

3.1 Introduction

The 2+1-design with a median cable barrier is a less spacious and thereby cheaper way of avoiding head-on and overtaking accidents, compared to building motorways. However, apart from the expected safety effects – which have been found to be substantial – introducing this type of road should also affect traffic performance, on the one hand during normal conditions due to the strict control of overtaking possibility, on the other hand during various incidents due to limited space on 1-lane segments. Is it hence possible that, with the new lane arrangement in combination with a physical barrier, another kind of vulnerability has been built in? Vulnerability is here regarded as a susceptibility to incidents that may cause considerable reductions in road network serviceability (Berdica, 2002a). In this chapter we present some results from a case study, in which a model for vulnerability analysis in general is developed, proposing a number of indicators of reduced serviceability (Berdica, 2002b). This is then applied to two 2+1cb roads in Sweden, aiming to describe their traffic performance.
focusing on abnormal conditions. The main situations that are dealt with are physical obstructions (accidents, break-downs, management operations etc.), extreme weather (mainly snow) and temporary increases in travel demand (peak hour as well as holiday traffic), the underlying hypothesis being that 2+1cb roads are sensitive to disturbances in these circumstances.

3.2 Vulnerability Analysis Model and Indicators

Road vulnerability analysis can be regarded as the hub for a whole battery of transport studies needed to gain insights into how well our transport systems work in different respects (Berdica, 2002a). However, vulnerability problems have until now received rather limited attention. In this case the aim is to illustrate the traffic performance, or serviceability, of a stretch of road in different key situations using a number of suitable indicators. This is done by on the one hand describing the propensity for serviceability reductions, on the other hand describing the reduced serviceability itself. In other words, the first is attributed to probabilities while the other is a measure of consequences. These two together can then be said to describe the risk for experiencing a reduced serviceability level. The conceptual model proposed here sets out from the supposition that different events in the transport system give rise to disturbances, which in turn can be detected in traffic measurement data. The basic measure of traffic performance chosen is the weighted average speed\(^8\) for all vehicles. First, overall average speed \(V\) is calculated, as well as to which extent it has fallen below a chosen criterion level \(v\). The latter is expressed in two ways:

1) \(D(v) = \text{share (\%)}\) of total number of days for measurement on which average speed has fallen below \(v\) km/h for at least one hour\(^9\).

2) \(T(v) = \text{share (\%)}\) of total number of hours (see previous foot note) for which an average speed below \(v\) km/h has been registered.

\(D(v)\) can be said to estimate the probability that the hourly average speed at least once during one day falls below \(v\), while \(T(v)\) estimates the probability that average speed falls below \(v\) in an hour picked at random\(^10\).

\(^8\) Please note that this is a point measurement and the value calculated is the arithmetic average of vehicle speeds during a certain time interval (time mean speed), which could hence differ from average speed defined in some other way or calculated by some other method.

\(^9\) Depends on the time interval chosen for aggregation of traffic data

\(^10\) One could also chose a vehicle at random and ask for the probability that it will pass during an hour with average speed below \(v\), in which case the hours should be weighted with the number of passing vehicles before \(T(v)\) is estimated.
Consequently, the probability that average speed will keep at an “acceptable” level is $1-T(v)$. This can be regarded as a measure of actual serviceability, which may be preferred as an indicator depending on the context.

The next step focuses on a number of key situations for which $T_x(v)$ is calculated. The consequences are then described by calculating the weighted average speed $V_x(v)$ for the occasions when speed has fallen below $v$, as well as giving their frequency distribution ($x$ = suitable index to distinguish between key situations). In this way, average effects as well as the worst-case scenarios are illustrated. The picture may be supplemented by other factors (rescue operations, total closures etc.) that may contribute to describing the situation. The reduced serviceability described in this fashion can then be evaluated/compared to the normal situation $V_v$ defined in some suitable manner. For e.g. incidents, average speed for the *days in question* could be used in order to eliminate concurrent effects of a bad winter state of the road, while snow effects and high demand could be compared to average speeds over the whole *measurement period*.

---

**Figure 4**. Schematic of conceptual model for vulnerability analysis.
The proposed model is described schematically in Figure 4, where the wheel comes full circle via “actions”. A further elaboration on this is, however, outside the scope of this study. The model also indicates an interaction with set serviceability goals, although this is wishful thinking at present since no such goals have been introduced as yet.

3.3 Vulnerability on 2+1cb Roads

The two stretches of road chosen for the case study are E4 Gävle-Axmartavlan and E18 Västerås. The E4 object is 32 km long with a cross-section of 14 m, due to the addition of an extra meter of paved shoulder on 1-lane segments. The length of 1-lane/2-lane segments varies between 1 and 1.8 km. The AADT is 7 500 vehicles per day with 15% heavy vehicles. The E18 object is 29 km long with a cross-section of 13 m, although there is a supporting strip added inside the side barrier where such are present on 1-lane segments. The 1-lane/2-lane segments are between 1 and 2.5 km in length. The AADT varies between traffic interchanges along the way from about 10 000 to 19 000 vehicles per day, with a distance weighted average of about 12 500 and 14% (range 11-16%) heavy vehicles. There is one permanent point for flow and speed measurements on E4 and two on E18 (A1 and A2). The former is situated roughly in the middle of the object, at the end of a 2-lane segment northbound/beginning of a 1-lane segment southbound. The two latter are located as shown in Figure 5. On this part (about 5 km long) the speed limit is lowered to 90 km/h, while it is otherwise set to 110 km/h on both objects. According to SNRA (2001b), free-flow speed for cars on 2+1cb semi-motorways is 107 km/h where the speed limit is 110 km/h and 96.5 km/h where the speed limit is 90 km/h.

Figure 5. Location of traffic data measurement points on E18.

The case study was started in late summer 2001 and most of the data material belongs to the period from June 2001 to May 2002, with some variation between different sources and between the two road objects. Already established sources of information used were the SNRA Traffic Information Centres (TIC), police reports, SNRA Road Weather Information Stations (VVIS), operations management contractors and traffic data.
measurements. In addition, a special survey was carried out in co-operation with the rescue corps working on each stretch of road, in order to gain information on incidents not serious enough to attract the attention of e.g. the police but still with a potential for causing traffic disturbances and queues. This provides a so far unused opportunity to gain more direct information on frequencies for incidents, reasons for different types of break-downs and the resulting consequences. Therefore some results from this particular study are presented before going on to the application of the proposed vulnerability analysis model.

Results from Special Survey
A total of 245 reported rescue operations over a period of 330 days gives a frequency of 0.026 per km and day and a rate of 2.03 per million vehicle kilometres of travel (MVKT) on E18. The corresponding figures for E4 are 201 rescue operations over 354 days, yielding frequency 0.018 and rate 2.34. These figures can be compared to statistics from the Road Assistance Service in Stockholm\(^\text{11}\). From April 1996 to May 1999 a total of 956 alarms were registered for a section of motorway 1.9 km long (Berdica, 2000). With an AADT of 100 000 vehicles per day this yields an alarm rate of 1.9 per MVKT. All in all the special survey gives a rate a little over 2 rescues per MVKT, which is roughly 10% higher. The figures are of the same magnitude but further conclusions are difficult to draw due to considerable differences in both traffic load and design.

The proportion of rescues involving light and heavy vehicles is roughly equivalent to their respective total traffic share, which indicates that the “risk for being rescued” is not connected to type of vehicle. The different reasons for rescue are dominated by various types of technical vehicle problems, the main reason being engine failure. Vehicle breakdowns are a little less common on E18 (1.25/MVKT), while collisions occur more often (0.54/MVKT), than on E4 (1.58/MVKT and 0.44/MVKT, respectively). This is the first study of its kind for ordinary roads and therefore data for a comparison is hard to come by. An international study of safety in tunnels (PIARC, 1995) can, however, be used for an overall assessment. It states for a rate of 3 to 6 vehicle breakdowns per MVKT for one-way motorway tunnels. The categories correspond well with those used in present case study and the values above may seem notably low. The PIARC figure for accidents is 0.3-0.95 per MVKT, compared to which the collision rates on both E4 and E18 seem similar. An explanation could be that our data only includes vehicles that have actually been towed. Even if it is not stated exactly how the data in the tunnel study was collected, it is reasonable to

\(^{11}\) Their purpose is to quickly intervene and restore passability when breakdown cars, accidents or other incidents block/disturb traffic.
suspect a higher rate of detection by e.g. camera surveillance systems. There is also reason to believe that help is called for from outside more often, due to the restrictions – both actual and perceived – that being in a tunnel implies. That the collision rate shows a better correspondence also seems reasonable, since an accident or a collision should result in a rescue operation to a greater extent regardless of location.

From E18 there is information on actual working times on site, vehicle placement and passability problems. A vehicle breakdown takes on average 11.3 minutes to clear while a collision takes 17.5 minutes (significant difference at 1% level). The time needed to rescue a light vehicle is on average 12.8 minutes, while a heavy vehicle takes 27 (significant difference at 1% level). Further subdivision into vehicle type and reason is only relevant (i.e. statistically significant; 5% level) for collisions, which take 12.5/37.5 minutes for light/heavy vehicles. The difference in working time on 1-lane compared to 2-lane segments is negligible and it does not matter if it is a car or a truck that is being rescued. This can, however, be a result of some rescue corps having made it a rule to always call for police assistance when going out to a 1-lane segment, which may help to reduce the time taken. Overall, the distribution of rescue operations on 1-lane/2-lane segments is 39% and 61% respectively. Since the distribution between sections is roughly 50/50, this indicates that the driver tries to get to a 2-lane segment where there is more space while waiting for assistance. This is also confirmed by drivers’ comments. On 2-lane segments over 50% of the vehicles are left in the normal lane, compared to only 25% on 1-lane segments. For the latter the greater share (just over 40%) are left by the roadside. This also supports the hypothesis that drivers do not experience the same necessity to get out of the way, since remaining traffic can pass in the overtaking lane. There seem to be no differences in placement connected to vehicle type.

Blockage and/or queues due to rescue operations have been registered for 66% of the cases on 1-lane segments and 15% of 2-lane cases. A contributing factor could, however, be the police attendance mentioned previously. This could well result in remaining traffic not pushing past on the narrower segments even if there may be some space left. Analysed by vehicle type, rescue of heavy vehicles cause blockage/queues to a greater extent than rescue of light vehicles – 2/3 of cases compared to some 1/4. The average time for registered blockages is about 31 minutes. The variation is great, though, wherefore the median value of 15 minutes may be a more appropriate measure. Average queue length was estimated to 50 vehicles, with the median of about 20. Significant effects on blockage time and/or queue length could not be found for neither rescue reason nor vehicle type.
As for effects detectable in traffic measurement data, one would expect a
general decrease in speed with increasing traffic volume, and that speeds
would be lower while rescue was under way. This is also in principle the
tendency for both road sections, although there is an overrepresentation of
vehicles driving at low speed (i.e. trucks etc.) at times with small flows (i.e.
late night/early morning) since the analysis is made for all vehicles together.
The speed reduction seems to be less on E4 (rescue: 101.1 km/h; no rescue
102.7 km/h) than on E18 (rescue: 90.5 km/h; no rescue: 84.5 km/h), which
could be explained by its wider cross-section and smaller traffic load. It
should be noted, however, that the reduction may not be caused by the
rescue action but due to bad weather/winter state of the road in general. This
in turn may be the reason behind the incident that caused the rescue effort,
hence imposing an overrepresentation of low speed hours in this data.
Matching separate rescue occasions with traffic data shows no visible effect
on E4. The comparison is difficult though, since information on the exact
location and direction for the incident is missing. Since traffic data is
collected at a point, possible speed effects will dissipate more and more the
farther away from the point of measurement the incident has occurred.
Location data is present to a greater extent for E18 and for basically all big
(in terms of registered work times/blockages/queues) incidents speed
reductions are detectable. However, the earlier mentioned correlation with
winter weather is quite clear and an overall low average speed on the day in
question indicates that there may be another main reason for reduced speeds.
Another piece of evidence for this synergy effect is that more rescue
operations are registered during winter months (November-March) than
during the summer season (May-October).

Results from the Application of the Vulnerability Analysis Model
In this vulnerability study of 2+1cb roads the criterion level $v = 80$ km/h was
chosen. Depending on the context, however, “considerable effects” could
mean both higher and lower limits and the choice of $v$ should therefore be
discussed for every separate case. The key situations dealt with are physical
obstructions, winter weather and temporary increases in travel demand.
These are indexed below by $i$ for incident, $w$ for winter roads and $h$ for high
demand. How one chooses to categorise the data material in time (e.g.
season) and space (e.g. direction and/or measurement point) etc. as well as
the level defining high demand (here set to 1000 veh/h) can vary depending
on what is suitable or most illustrative from case to case. Summaries for
each of the two road objects are presented in the result schedules below
(there is some repetition of conclusions valid for both sections but charts are
only included once), followed by related comments and points of discussion.
Result Schedule 1: Vulnerability Analysis Summary E18 Västerås

<table>
<thead>
<tr>
<th>Period</th>
<th>Point</th>
<th>Overall results</th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Eastbound</td>
<td>Westbound</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>V</td>
<td>D(80)</td>
<td>T(80)</td>
<td>V</td>
<td>D(80)</td>
<td>T(80)</td>
<td></td>
</tr>
<tr>
<td>Winter</td>
<td>A1</td>
<td>85</td>
<td>38.5</td>
<td>8.6</td>
<td>92</td>
<td>19.7</td>
<td>3.5</td>
<td></td>
</tr>
<tr>
<td></td>
<td>A2</td>
<td>92</td>
<td>16.6</td>
<td>3.0</td>
<td>93</td>
<td>16.6</td>
<td>2.3</td>
<td></td>
</tr>
<tr>
<td>Summer</td>
<td>A1</td>
<td>88</td>
<td>5.9</td>
<td>0.6</td>
<td>95</td>
<td>2.0</td>
<td>0.1</td>
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<tr>
<td></td>
<td>A2</td>
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<td>4.3</td>
<td>0.2</td>
<td>95</td>
<td>6.0</td>
<td>0.4</td>
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</tr>
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</table>

Rescue Corps Study

<table>
<thead>
<tr>
<th>Reason</th>
<th>Incid/MVKT</th>
<th>Av Work Time</th>
<th>Blockage</th>
<th>Queues</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vehicle</td>
<td>1.25</td>
<td>11 min</td>
<td>15 min*</td>
<td>20 vehicles*</td>
</tr>
<tr>
<td>Collisions</td>
<td>0.54</td>
<td>18 min</td>
<td></td>
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</tr>
<tr>
<td>Other</td>
<td>0.32</td>
<td>17 min</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*median values

Rescue operations distr: 40% 1-lane, 60% 2-lane
Share blockage/queues: 66% 1-lane, 15% 2-lane

Physical Obstructions

<table>
<thead>
<tr>
<th>T(80)</th>
<th>V(80)</th>
<th>V(24h*)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.0</td>
<td>62</td>
<td>79</td>
</tr>
</tbody>
</table>

*days on which the incidents in question occurred

Total closure for maintenance: 0 hours

Few clear speed reductions caused by physical obstructions have been identified. A more systematic study, foremost with respect to location and direction information for incidents (rescue actions, maintenance operations etc.) in relation to the points for traffic data measurements, should be conducted. Another contributing factor could be the choice of criterion level.

Winter Weather

<table>
<thead>
<tr>
<th>T&lt;sub&gt;w&lt;/sub&gt;(80)</th>
<th>V&lt;sub&gt;w&lt;/sub&gt;(80)</th>
<th>V&lt;sub&gt;av&lt;/sub&gt;</th>
<th>V(clear*)</th>
</tr>
</thead>
<tbody>
<tr>
<td>18.7</td>
<td>73</td>
<td>86</td>
<td>92</td>
</tr>
</tbody>
</table>

*no frost and/or snowfall registered
Winter weather is defined as times when frost and/or snowfalls were registered in relevant VVIS stations. Winter roads often cause speeds to fall below the criterion level but average speed still remains over 70 km/h in about 80% of cases. Effects of possible queues behind the snowplough are difficult to catch in a point measurement and should be looked into closer. It could also be of interest to study whether road users drive slower in general during winter road conditions on 2+1cb roads.

<table>
<thead>
<tr>
<th>Point</th>
<th>Period</th>
<th>Eastbound</th>
<th>Westbound</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>$T_h(80)$</td>
<td>$V_h(80)$</td>
</tr>
<tr>
<td>A1</td>
<td>Winter</td>
<td>14.3</td>
<td>78</td>
</tr>
<tr>
<td></td>
<td>Summer</td>
<td>6.7</td>
<td></td>
</tr>
<tr>
<td>A2</td>
<td>Winter</td>
<td>4.5</td>
<td>77</td>
</tr>
<tr>
<td></td>
<td>Summer</td>
<td>0.0</td>
<td></td>
</tr>
</tbody>
</table>
There is a certain sensitivity at hourly flows >1000 veh/h although speeds below criterion level occur relatively seldom. On the other hand, when this does happen average speed is lower than 60 km/h in over 50% of cases at the transition from 2 to 1 lanes in the westbound direction. This indicates great vulnerability with risks for traffic break down on e.g. national holidays.
Result Schedule 2: Vulnerability Analysis Summary E4 Gävle-Axmartavlan

<table>
<thead>
<tr>
<th>Period</th>
<th>Overall Results</th>
<th>Northbound</th>
<th>Southbound</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>V</td>
<td>D(80)</td>
</tr>
<tr>
<td>Winter</td>
<td></td>
<td>102</td>
<td>19.9</td>
</tr>
<tr>
<td>Summer</td>
<td></td>
<td>107</td>
<td>1.1</td>
</tr>
</tbody>
</table>

Rescue Corps Study

<table>
<thead>
<tr>
<th>Reason</th>
<th>Incid./MVKT</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vehicle</td>
<td>1.58</td>
</tr>
<tr>
<td>Collisions</td>
<td>0.44</td>
</tr>
<tr>
<td>Other</td>
<td>0.31</td>
</tr>
</tbody>
</table>

Physical Obstructions

<table>
<thead>
<tr>
<th></th>
<th>T(80)</th>
<th>V(80)</th>
<th>V(24h*)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0.0</td>
<td>69</td>
<td>84</td>
</tr>
</tbody>
</table>

*days on which the incidents in question occurred

Total closure for maintenance: 16 hours

Few clear speed reductions caused by physical obstructions have been identified. A more systematic study, foremost with respect to location and direction information for incidents (rescue actions, maintenance operations etc.) in relation to the points for traffic data measurements, should be conducted. Another contributing factor could be the choice of criterion level.

Winter Weather

<table>
<thead>
<tr>
<th></th>
<th>T_w(80)</th>
<th>V_w(80)</th>
<th>V_w</th>
<th>V(clear*)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>14.0</td>
<td>75</td>
<td>92</td>
<td>103</td>
</tr>
</tbody>
</table>

*no anti-slip measures/snow clearing performed

Frekv(w): see Result Schedule 1 above!

Winter weather is defined as times when the snow clearing contractors have performed anti-slip measures and/or snow clearing. Winter roads often cause speeds to fall below the criterion level but average speed still remains over 70 km/h in over 85% of cases. Effects of possible queues behind the snowplough are difficult to catch in a point measurement and should be looked into closer. It could also be of interest to study whether road users drive slower in general during winter road conditions on 2+1cb roads.
Flow rarely exceeds 1000 veh/h and registrations below 80 km/h have not occurred. The serviceability was hence found to be good but there are indications of traffic break downs in connection with national holidays from earlier and this should be further looked into.

**Comments and Points of Discussion**

According to the traffic data measurements, the overall time mean speed is 93 km/h on E18 and 105 km/h on E4, with average flows of 403 and 345 vehicles per hour respectively. As stated previously, model free flow speeds (flows up to 500 vehicles/h) are 96.5 and 107 km/h, but the figure for comparison should be the time mean speed, which is generally some 1.5 to 2 km/h higher. The speeds from the case study are hence somewhat low, which is explained by not distinguishing between heavy/light vehicles as well as dry/wet road conditions. On the whole, the two road objects seem to correspond well to “theoretical standards” on average. In more detailed terms, average speed is lower during winter (Nov-Mar) than during summer (Apr-Oct) on both road objects and serviceability is also less during the cold months of the year, although problems occur in summertime as well on E18. Average speed is generally lower and more often below 80 km/h in the eastbound direction on E18, with the most pronounced difference in point A1. This is probably, however, due to the location of the measuring point, at the end of the 1-lane segment. On E4 the difference in average speed between directions is negligible. The less frequent fall below 80 in the southbound lane is most likely also attributed to measure point location, at the beginning of the 1-lane segment.

Very few of the occasions when average speed fell below 80 km/h could with any certainty be attributed to physical obstructions, neither the previously analysed rescue corps activities nor any other incidents. According to the operations management contractors, a routine cable barrier repair takes about 2 hours. Still, no connection could be made to effects visible in traffic data. One aggravating circumstance is that information on
the exact time for the repair work is too often missing, although no matches were found for the occasions on E4 for which this data was supplied either. On the other hand, as most repairs are performed from the overtaking lane at such time of day as to minimise any disturbance (i.e. during hours with low traffic flow) speed effects are most likely very local and would only be visible in traffic data if the repairs were made very close to the point of measurement. Data on other maintenance work such as post washing, ditch and roadside clearance etc. was found to be insufficient for further analysis.

Total closures with redirection of traffic to alternative roads due to maintenance activities etc. are not captured in $D(v)$ and $T(v)$ as calculated here. In theory, this could be interpreted as 0 speed, which is certainly below 80 km/h, and such occasions should then be included in these indicators. This we deemed as somewhat misleading, since such interruptions are planned and the road users are otherwise catered for. The fact that such closures have to be made are, however, an indicator of vulnerability and is therefore presented separately in the Result Schedules above.

There is a clear correlation between winter roads and lower average speeds and the worse the conditions, the greater the reduction. The speed distribution during summer and on “clear” winter roads are significantly (1% level) different from each other, as are the latter compared to slippery/snow road conditions. The levels may still seem somewhat high, but it should be noted that it is most likely a question of speeds on remedied winter roads. Data from E4 are based on the snow clearing contractors’ work records and for E18 information on frost and snowfalls was withdrawn from three relevant VVIS stations. The reduction due to winter roads as such is deemed to be on average 15 km/h for light vehicles (SNRA, 2001b). Whether the noted speed reductions in this case study should be attributed to a bad state of the road in general or to vehicles being stuck behind the snowplough (normal speed 30-40 km/h) on 1-lane segments is difficult to say due to the previously mentioned point measurement issues. The E4 has in fact been supplied with maintenance parking bays to allow traffic to pass, thereby minimising queues and the risk for hazardous overtaking. Reasons for road users to drive slower in general on 2+1cb roads in winter could be that 1-lane segments seem even narrower during these conditions and/or that the cable prevents the snow from spreading, hence it remains as an “obstacle” in the overtaking lane on 2-lane segments.

Regarding high travel demand, there are clear increases in flow on Fridays and Sundays on E4, but without remarkable speed reductions. This is also the case during Christmas, New Years and Easter. On E18 higher travel demand with resulting lower average speeds is notable between 4 and 5 pm on weekdays, more still on Fridays, in general. It is unusual, however, that
these high flows cause speeds as low as 80 km/h and below even if it does occur in some cases. Whitsun was such an occasion, with speeds as low as 40 km/h. The capacity limit for a 2+1cb semi-motorway according to SNRA standards is estimated to be 1650 vehicles per hour and direction and in this analysis a flow exceeding 1000 vehicles per hour and direction was simply chosen to represent the level for a “serious disturbance”.

Concluding Remarks

The key situations in which reduced serviceability could be the case, and that have been analysed in this study are physical obstructions, winter weather and temporary increases in travel demand. The underlying hypothesis was that 2+1cb roads are sensitive to disturbances in these circumstances. Still, the conclusion in the feasibility study was that these effects were to be minor and even less than the disturbances due to accidents before the 2+1-implementation. The results show that physical obstructions from e.g. rescue operations could cause considerable speed reductions but it takes a relatively long lasting incident in order for it to be detected through traffic data. Routine activities have not been found to show any speed effects. However, this should be studied in further detail, foremost with respect to location and direction information for incidents in relation to the traffic data measurement points. Winter weather accounts for a large share of registered speed reductions, even if the consequences do not seem to be that great. Winter roads are also likely to be the reason behind many incidents that in turn result in rescue operations. Temporary increases in travel demand certainly do not seem to result in average speeds below criterion level all that often, but when it happens the speed reductions can be very great. There are indications of great vulnerability with risks for traffic break down on e.g. national holidays in the westbound direction on E18. In an overall perspective, however, it seems that the negative consequences of implementing the 2+1cb solution without widening the 13 m cross-section on semi-motorways are fairly moderate so far. One major issue that needs to be resolved, though, is work zone safety when performing maintenance operations etc.

Finally it can be stated that the proposed vulnerability analysis model is based on data that is relatively easy to obtain and a comparison between speed distributions, average speeds, rescue frequencies/rates etc. are easily performed as well as simple to comprehend. It gives an overview of the serviceability on chosen road objects and points to areas where further studies may be needed. The method is flexible in that criterion levels, the so called ”normal situation” etc. are simple to adjust depending on the prerequisites and purpose for the study at hand. It also supports a more strictly quantitative consequence analysis in comparison with set goals.
(although tangible such goals still remain to be set, at least in a Swedish context), with subsequent proposals of remedial measures and a follow-up of the results. However, further elaboration on this falls outside the scope of this particular study.

4. CONCLUDING DISCUSSION

An accident analysis of all 2+1cb semi-motorway objects opened up to the present indicates that many accidents with severe consequences are effectively prevented by a cable barrier and converted into less severe cable crashes, mainly with property damage only. The traffic safety effect of 2+1cb roads is estimated to be a reduction in severe injuries and fatalities in the range of 40-55%. This should be compared to the alternative situation “changing into motorway”, where the maximum reduction attainable is 65%. The effect regarding only fatalities is probably even higher, with a reduction of some 60-70%. As for serviceability, negative effects of physical obstructions could not be identified in the present case study but this should be investigated further. Winter road conditions is a major cause of reduced serviceability and there are indications of risk for traffic break down when travel demand is high, i.e. we are approaching the capacity limit for this concept. So far, the negative consequences of keeping within the 13 m bounds seem to be limited, apart from work zone safety aspects.

The case study characterises some serviceability aspects of 2+1cb semi-motorways through a number of examples based on experiences and available data. As opposed to the accident analysis, the evaluation as to whether this road type is actually better or worse compared to its predecessor (the ordinary semi-motorway) is never really made. However, traffic safety effects are apparently substantial and this seems to be enough to motivate the inauguration of 2+1cb roads, strictly speaking making it less important whether they are in fact better in terms of serviceability or not. Can it be that, as long as traffic performance is fair, the traffic safety gains make some degree of serviceability loss “worth while”? Hence, the critical issue can be summarised in two questions: At which point is serviceability unacceptable, and how do we keep from reducing serviceability to this point? Among the criteria used by the SNRA it is stated that for a new 2+1cb semi-motorway, AADT in the opening year should not exceed 15 000 vehicles. Traffic on the E18 object is not far from AADT 20 000 and this does seem to cause problems at times. As mentioned before, it is also assessed from case to case whether to widen the cross-section in order to facilitate e.g. passage of breakdown vehicles etc. This has been done on the E4, which in some respects seems to “work better” than the E18. Then again, this may also be a result of its lesser traffic load. According to the present study results, none of
these effects are that extreme, but the evaluation as to whether they are acceptable or not no doubt needs to be discussed further. Also work zone safety needs to be thoroughly investigated, not only for road maintenance operations but for the rescue corps’ crews as well.

To conclude, regular before/after or twin-studies of the 2+1cb design would be useful, not only to see just how much of any effects can actually be attributed to the new cross-sectional design but also to gain information for setting the level for acceptable serviceability etc. Among other things, it would be interesting to study the speed reductions likely to occur during normal conditions, due to the mere fact that there are 1-lane segments with no possibility of overtaking. This could be done by for instance developing a theoretical model which, in combination with empirical studies of the kind presented here, should be included in a comprehensive vulnerability analysis. This in turn could prove to be an important tool for the SNRA in their work toward a reliable transport system, an aspect recently added to the transport quality goal in the Swedish national transport policy (Prop 2001/02:20). When focus moves toward providing a high level of service during a trip in its entirety, rather than just minimizing travel time, vulnerability in the road transportation system becomes crucial in the overall assessment of transport quality.

Acknowledgements

We would like to thank the Swedish National Road Administration and the Swedish Research Council for Environment, Agricultural Sciences and Spatial Planning for their financial support.

References

Berdica, K (2000) Vulnerability – A Model Based Case Study of the Road Network in the City of Stockholm. TRITA-IP AR 00-83, Department of Infrastructure, Royal Institute of Technology, Stockholm.
Berdica, K (2002a) An introduction to road vulnerability – what has been done, is done and should be done. Transport Policy 9, 117-127.
Berdica, K (2002b) 2+1 Roads With Cable Barriers – A Vulnerability Study (in Swedish). TRITA-INFRA 02-022, Department of Infrastructure, Royal Institute of Technology, Stockholm.


