An Accessibility Based Method for Vulnerability Analysis in Strategic Transport Networks

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1 Introduction

Considerations of critical transport infrastructure are now a major concern in Australia as in many other countries. The concern stems from a variety of causes, including the state of development, condition and level of use of existing transport systems; difficulties associated with public sector provision of new infrastructure; public-private partnership arrangements for infrastructure provision; and perceptions of risks and threats to infrastructure from both natural disasters (e.g. floods, fire or earthquake) and from human malevolence such as acts of sabotage, war or terrorism. The Australian Government has defined critical infrastructure as:

> 'that infrastructure which if destroyed, degraded or rendered unavailable for an extended period, will significantly impact on social or economic well-being or affect national security or defence' (Attorney-General's Department, 2003).

A pertinent question is then how to identify critical locations in a network. For example, the road network is large, wide and diverse in nature. Are there particular locations or facilities in that network where loss or degradation of certain road sections (links) will have significant impacts? How should such impacts be assessed? Thus there are needs for the development of methods to assess risk and vulnerability of transport networks. Decision support tools are needed that allow planners and policy makers to make rational assessments of threats to facilities and infrastructure; the consequences of network degradation and failure at various locations and under different circumstances; and what to do about these. Social and economic benefits flow from the ability to plan for and manage the impacts of transport network degradation to minimise wider consequences on economic, employment, trade and social activities in cities and regions.

This paper provides an introduction to current research on developing a methodology for transport network vulnerability analysis, based on considerations of the socio-economic impacts of network degradation. At one level this involves considerations of alternative paths through a network and the relative probabilities of use of those paths. Whilst probability of use is important in defining potential weak spots in a network, this probability is not of itself a complete measure of vulnerability – the most critical locations in a network will show the most severe (socio-economic) consequences resulting from network failure at those locations. The methods therefore consider vulnerability assessment in terms of a planning systems process in which the performance of network components is tested against established performance criteria. The risks and consequences associated with failures at different locations need to be accounted for.

The concept of network vulnerability is new, and it is important to define what is meant by vulnerability. For instance, there are several possible responses to the reduced performance of a degraded network, or in dealing with the perceived risks of degradation at different locations. In some cases, an appropriate response may be to upgrade key transport infrastructure, for instance by raising it above expected maximum flood levels or by adding more capacity. But sometimes this simply makes the network more reliant on those key links and more vulnerable to their failure. An alternative approach is to add links to the network. These links may normally be redundant but provide alternative routes when key network links are broken. At the urban network level there may already be many such latent alternative routes, but at the regional or national strategic network level this is less likely to be the case. Extra links would make the transport network more robust, but this may add unnecessary cost to the provision of transport infrastructure. The question is where are these locations of potential network vulnerability and what is the best response.

The starting point for our research of network vulnerability is the study of transport network reliability, which has been the subject of intense international research interest over the last decade, following the Kobe earthquake of 1995.

2 Network Reliability

Transport network reliability has the subject of considerable international research interest in recent years (Lam (1999), Bell and Cassir (2000), Iida and Bell (2003), Nicholson and Dante (2004)). Much of this research has focused on congested urban road networks and the probability that a network will deliver a required standard of performance. The urban studies are important, but they are not the only areas of concern, especially when considering the wider implications of transport systems performance. At the regional and national strategic level, accessibility, regional coverage and inter-urban connectivity are the primary considerations. In these sparse networks, 'vulnerability' of the network can be more important than 'reliability' because of the potentially severe adverse consequences of network degradation. As noted by the Bureau of Transport and Resource Economics (BTRE, 1999) in its analysis of the effects of flooding on road access,

> 'the vast distances involved means that access to alternative services (such as hospitals and business) often do not exist … disruption costs to households, businesses and communities can therefore be more important in rural and remote communities'.

In both urban and rural areas, the concept of vulnerability or incident audit – the proactive determination of locations in a transport network that may be most sensitive to failure and where network failure may have the gravest consequences – requires detailed research. The transport planner may seek opportunities to reduce vulnerability – and the community will demand such action.

Network reliability became an important research topic in transport planning during the 1990s, although some elements had been the subject of research interest for some time before that (e.g. Lee 1946, Richardson and Taylor 1978, Taylor 1982). The Kobe earthquake of 1995 and its aftermath stimulated an interest in *connectivity reliability*. This is the probability that a pair of nodes in a network remains connected – i.e. there continues to exist a connected path between them – when one or more links in the network have been cut. Bell and Iida (1997) provided an analytical procedure for assessing connectivity reliability, and a summary of the procedure is given by Iida (1999). Subsequent research was directed at degraded networks, usually urban road networks subject to traffic congestion, in which the network remained physically intact but the performance of one or more links could be so severely affected by congestion that their use by traffic is curtailed. This led to the definition of two additional forms of reliability: travel time reliability and capacity reliability.

Travel time reliability considers the probability that a trip between an origin-destination pair can be completed successfully within a specified time interval (Bell and Iida 1997). This can be affected by fluctuating link flows and imperfect knowledge of drivers when making route choice decisions (Lam and Xu, 2000). One measure of link travel time variability is the coefficient of variation of the distribution of travel times (Richardson and Taylor, 1978). Measures of travel time variability are useful in assessing network performance in terms of service quality provided to travellers on a day-to-day basis (Yang, Lo and Tang, 2000). Thus travel time variability can be seen as a measure of demand satisfaction under congested conditions (Asakura, 1999).

A supply-side measure of network performance in congested networks is *capacity reliability* (Yang, Lo and Tang 2000). Capacity reliability is defined as the probability that a network can successfully accommodate a given level of travel demand. The network may be in its normal state or in a degraded stated (say due to incidents or road works). Chen, Lo, Yang and Tang (1999) defined this probability as equal to the probability that the reserve capacity of the network is greater than or equal to the required demand for a given capacity loss due to degradation. Yang, Lo and Tang (2000) indicated that capacity reliability and travel time reliability together could provide a valuable transport network design tool. Taylor (1999, 2000) demonstrated how the concepts of travel time reliability and capacity reliability could be used in planning and evaluating traffic management schemes in an urban area.

Further research on network reliability is required to develop these concepts into practical traffic planning tools. In addition, there is a need for further research to properly specify travellers' responses to uncertainty (Bonsall (2000), Van Zuylen (2004)) so that reliability research can be used to properly inform developments of new driver information systems and to influence the design of traffic control systems.

3 Network Vulnerability

The standard approaches to transport network reliability have focused on network connectivity and travel time and capacity reliability. While this provides valuable insights into certain aspects of network performance, reliability arguments based on probabilities and absolute connectivity may obscure potential network problems, especially in large-scale, sparse regional or national networks. In these networks the consequences of a disruption or degradation of the network become important. For example, D'Este and Taylor (2001) used the example of the Australian land transport system to illustrate the potential consequences of the severance of certain transport connections in this multimodal network. In this example the system reliability was considered, in terms of a cut to the Eyre Highway and transcontinental rail line between Perth and Adelaide for instance by flood, see Figure 1.

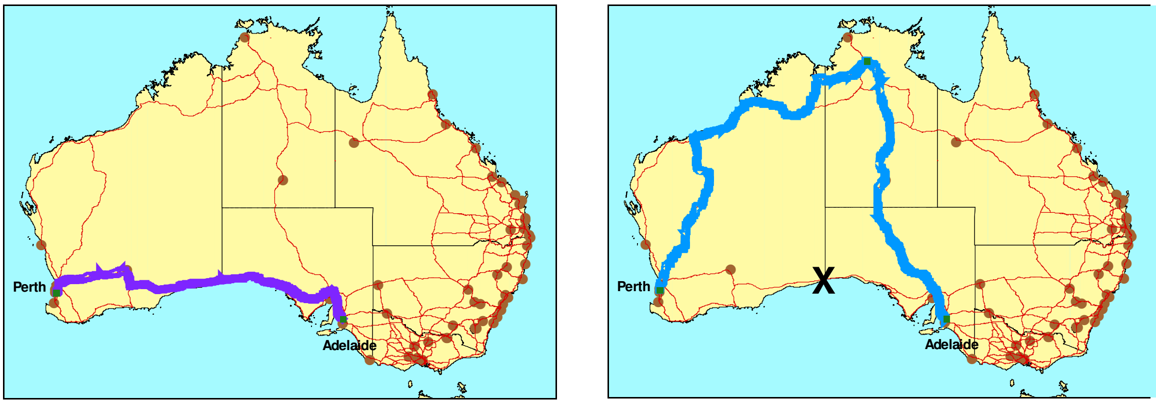

Figure 1 **Effect of a loss of connectivity in the Australian road network – shortest path from Perth to Adelaide in (1) full network and (2) network with Eyre Highway cut**

As shown in Figure 1, the overall network remains connected and the probability that the route in question is cut by flood or other natural cause is extremely small (but not zero since it has happened), so the travel time and capacity reliabilities are high. Therefore the established measures of network reliability would not indicate any major problem with the network. However the consequences of network failure are substantial – in this case the next best feasible path through the network involves a detour of some 5000 km! In reality the

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alternative route via Broome would not be used – it is more likely that shipments would be delayed or cancelled thereby producing a different but no less significant economic impact. Nicholson and Dalziell (2003) pointed to similar circumstances in their study of the regional highway network in the centre of the North Island of New Zealand, a region subject to blizzards and volcanic eruptions, sometimes simultaneously.

These examples illustrate the concept of network vulnerability and the difference between network reliability and vulnerability. The concept of vulnerability is more strongly related to the consequences of link failure, irrespective of the probability of failure. In some cases, link failure may be statistically unlikely but the resulting adverse social and economic impacts on the community may be sufficiently large to indicate a major problem warranting remedial action – akin to taking out an insurance policy for an extremely unlikely yet potentially catastrophic event. For example, consider the impact on a rural community of loss of access to markets for its produce and to vital human services (such as a hospital). Low probability of occurrence and network performance elsewhere does not offset the consequences of a network failure. Thus network reliability and vulnerability are related concepts but while reliability focuses on connectivity and probability, vulnerability is more closely aligned with network weakness and consequences of failure. Berdica (2002) proposed that vulnerability analysis of transport networks should be regarded as an overall framework through which different transport studies could be conducted to determine how well a transport system would perform when exposed to different kinds and intensities of disturbances. From her study of the road network in central Stockholm she suggested three main questions that might be posed in these studies:

1. How much do interruptions of different critical links affect system performance?
2. How is network performance affected by general capacity reductions and possible changes to traffic management and road space allocation in a subregion of the network?
3. How is the system affected by variations in travel demand?

These questions provide a starting point the development of a methodology for study of vulnerability in transport networks and infrastructure. They highlight the key issue of the identification of critical components of the networks. Vulnerability analysis is intended to address these questions and the perhaps more important questions that flow from them – when we know where the vulnerable elements (the ‘weakest links’) of a transport network are, what is the best response, what can we do about it?

3.1 Vulnerability and risk

Vulnerability, reliability and risk are closely linked concepts. In broad terms, risk is something associated with negative outcomes for life, health, or economic or environmental condition. Risk can be defined in many different ways, but most definitions focus on two factors: the probability that an event with negative impacts will occur, and the extent and severity of the resultant consequences of that event. Commonly, the product of probability and a measure of consequence is used as an index of risk. Risk and reliability analysis generally considers situations where increasing probability and increasing consequences combine. Nicholson and Dalziell (2003) applied this framework to the risk assessment of transport networks in New Zealand. They measured risk as simply the sum of the products of the event probabilities and the economic costs of the event (e.g. the expected annual economic cost of a given event). Their risk evaluation process involved the following steps:

1. establish the context (i.e. the technical, financial, legal, social and other criteria for assessing the acceptability of risk)
2. identify the hazards (i.e. the potential causes of closure)
3. analyse the risks (i.e. identify the probabilities, consequences and expectations)
4. assess the risks (i.e. decide which risks are acceptable and which are unacceptable).

If any risk is found unacceptable, it needs to be managed. This generally involves either (1) treating the unacceptable risks, using the most cost-effective treatment options, or (2) monitoring and reviewing the risks (i.e. evaluating and revising treatments).

The study of vulnerability extends this risk assessment framework in several ways. Firstly it extends the region of interest to areas of high consequences and low or unquantifiable (but non-zero) probability of occurrence – on the basis that measurement of occurrence probability and consequences (human and economic) is imprecise for many types of incidents, and society may well consider some consequences to be unacceptable and worthy of safeguarding against, despite uncertainty about their probability of occurrence (e.g. Evans, 1994). Secondly, vulnerability analysis provides a framework for targeting risk assessment. One of the key conclusions of the Nicholson-Dalziell risk assessment of the New Zealand highway network was that it is impractical and financially infeasible to conduct detailed geophysical and other risk assessment across an entire transport network. The costs of deriving accurate location-specific risk probabilities across a range of risk factors are too high to make it viable – what is needed is a way of targeting risk assessment resources to get best value from them. Vulnerability analysis provides another way of approaching this problem. It can be used to find structural weaknesses in the network topology that render the network vulnerable to consequences of failure or degradation. Resources can then be targeted at assessing these 'weak links'. Thirdly, vulnerability auditing admits a more proactive and targeted approach to the issue of transport network risk assessment and mitigation.

3.2 Definitions

We have defined vulnerability by using the notion of accessibility, i.e. the ease by which individuals from specific locations in a region may participate in activities (e.g. employment, education, shopping, trade and commerce) that take place in other physical locations in and around the region and by using a transport system to gain access to those locations (Taylor and D'Este 2004a). Then vulnerability is defined in the following terms:

- a network *node* is *vulnerable* if loss (or substantial degradation) of a small number of links significantly diminishes the accessibility of the node, as measured by a standard index of accessibility
- a network *link* is *critical* if loss (or substantial degradation) of the link significantly diminishes the accessibility of the network or of particular nodes, as measured by a standard index of accessibility.

This broad definition can then be further refined by the selection of specific indices of accessibility. Amongst others, Morris, Dumble and Wigan (1979), Koenig (1980), Niemeier (1997) and Primerano (2003) provide discussions of alternative accessibility indices. For the case of strategic level networks such as a regional or national network, relatively simple indices are appropriate. Two specific indices are considered in this paper. The first is the Hansen integral accessibility index (Hansen 1959) which provides an overall measure of the accessibility of one location to a set of other locations. This index is useful in assessing accessibility between major population or activity centres. In the case of regional analysis involving locations outside major population centres, some other measure of accessibility is needed. This is of particular interest in vulnerability studies of regional and remote areas such as those comprising the geographic mass of mainland Australia. The Australian Government has adopted a 'remoteness' index known as ARIA (Accessibility/Remoteness Index of Australia) to assess the level of government and private sector services (e.g. in health, finance and social welfare) available to residents of regional and remote areas (DHAC, 2001). In our research we are using ARIA to estimate the consequences of network degradation on communities in regional and remote parts of Australia.

4 SPECIFIC ACCESSIBILITY INDICES

The Hansen integral accessibility index (A_i) for location (city) i may be written as

$$A_i = \sum_j B_j f(c_{ij}) \tag{1}$$

where B_j is the attractiveness of location (city) *j*, e.g. the number of opportunities available at *j*. In the strategic network application described in this paper B_j is taken as the population of city *j*. Equation (1) is often used in a normalised form, viz

$$A_i = \frac{\sum_j B_j f(c_{ij})}{\sum_j B_j} \tag{2}$$

and this is the version used in our research, where the Hansen index has been used to consider changes in accessibility between the Australian mainland capital cities (Adelaide, Brisbane, Canberra, Darwin, Melbourne, Sydney and Perth) for degradations of the strategic road network in the Australian National Transport Network (NTN). The NTN is shown in Figure 2, and is fully described in the AusLink White Paper (DOTARS, 2004).

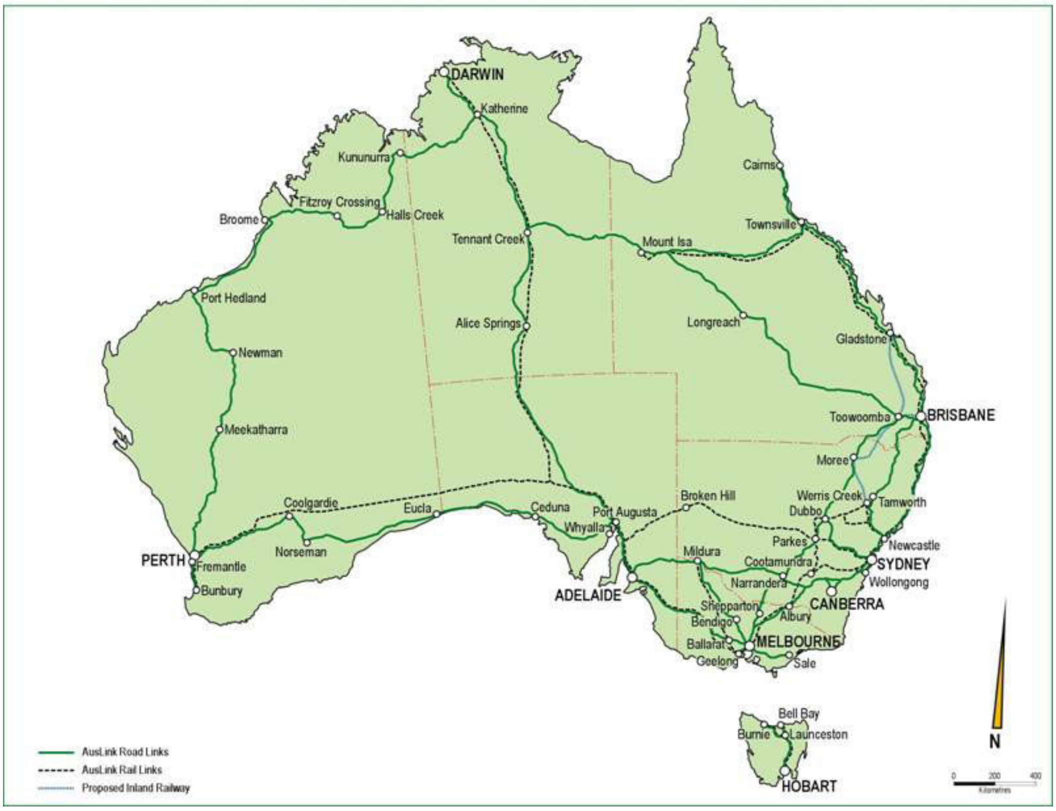

Figure 2 **The Australian National Transport Network (NTN), showing the strategic road links connecting the major cities [source: DOTARS (2004)]**

The impedance function *f(c_{ij})* of equations (1) and (2) represents the separation between the two cities and is defined so that the higher the cost of travel between the two cities, the lower the accessibility between them. The definition adopted in this current work is the conventional definition, i.e. the reciprocal of network travel distance

$$f(c_{ij}) = \frac{1}{x_{ij}} \qquad (3)$$

ARIA (DHAC 2001) is an index of remoteness derived from measures of road distance between populated localities and service centres. These road network distance measures are then used to generate a remoteness score for any location in Australia. ARIA is a continuous varying index with values ranging from 0 (high accessibility) to 15 (high remoteness), and is based on road network distance measurements from populated localities to the nearest service centres in five size categories based on population. The five distance measurements, one to each level of service centre, are recorded for each populated locality and standardized to a ratio by dividing by the Australian mean for that category. After applying a capped maximum value of three to each of the ratios, these are summed to produce the total ARIA score for each populated locality. ARIA is seen as having the following advantages for application to sparsely settled regions (DHAC 2001):

- it is a purely geographic measure of remoteness, which excludes any consideration of socio-economic status, rurality and population size factors (other than the use of natural breaks in the population distribution of urban centres to define the service centre categories)
- it is flexible and can be aggregated to a range of spatial units, used as a continuum or classified
- it is stable over time.

DHAC (2001) indicates that as an index of remoteness that covers the whole of Australia, ARIA provides a measure of remoteness (or accessibility to services) that is suitable for a broad range of applications including community service planning, demographic analysis and resource allocation. Service centres are defined as populated localities where the population is greater than 1000 persons. There are five categories of service centre, split in terms of population as shown in Table 1, with each category assessed as having distinct levels of public and private sector facilities available (e.g. health, social welfare, education, finance and banking, retail, etc).

Table 1 ARIA service centre categories (DHAC 2001)

Service Centre category	4.1.1 Population
A	≥250 000
B	48 000 – 249 999
C	18 000 – 47 999
D	5000 – 17 999
E	1000 - 4999

The ARIA index is then calculated by considering the distance by road from a locality *i* to the nearest service centre in each category (x_{iL} for category L, for $L = A, B, C, D, E$). Then

$$ARIA_{iL} = \sum_{L} \min\{3, \frac{x_{iL}}{\bar{x}_L}\} \qquad (4)$$

where $\bar{x}_L$ is the mean road distance of all localities to the nearest category *L* service centre. With the upper limit of three on the ratio between x_{iL} and $\bar{x}_L$, the maximum value of $ARIA_{iL}$ is 15, and this represents an extremely remote location. Values of $ARIA_{iL}$ are thus in the range [0, 15]. In the calculations, if a higher category service centre (say category *A*) is closer to a given locality than (say) a category *B* centre, then the higher category centre takes the place of the lower category centre in the calculations. Note that ARIA is intended for regional and remote area analysis only – for instance all urban centres with populations of 250 000 or more automatically have a zero value of their ARIA index. The index does not consider intra-city accessibility at all.

In our ongoing research we are using ARIA to estimate the social impacts on rural communities of network degradation and thus as a measure of regional network vulnerability. This paper does not consider these results (see Sekhar and Taylor (2005) instead), as the analysis in it focuses on accessibility between the major cities. The paper is intended as an overall illustration of network vulnerability analysis at the national, strategic network level. Nevertheless we believe it important to include a discussion of ARIA for completeness, and to indicate that a set of alternative measures of accessibility is required for the regional studies.

5 THE AUSTRALIAN ROAD NETWORK

The analysis reported in this paper is based on the road network in the NTN, which forms the basic skeleton of the national road system of Australia (see Figure 2). This subset of the national main road network has been designated in AusLink as of prime importance in providing a national road transport system. The full main road network connecting cities and regions is of course much more extensive than the NTN road network (see Figure 3).

The full main road network may be split into three subnetworks, which relate to the national, state or regional importance of the individual roads and highways. Besides the NTN, the other subnetworks are the state highways and designated main roads, which provide connectivity at the state level and are the direct responsibility of the state governments, and the other main roads, which provide regional connectivity and for which responsibility may be shared between state and local government. Figure 3 highlights the NTN and state highways and designated roads subnetworks as a skeleton amidst the matrix of the full road network. In the more densely settled regions of the southeast, east coast and south west, there is a substantial main road network. The network coverage away from those regions, in the less settled parts of the nation, is much sparser and here the NTN and state highways really do represent almost the entirety of the navigable road system. This may be seen in Figure 4, which shows the NHS and the designated state highway networks

A GIS database of the entire strategic road network of Figure 3 has been set up using the ArcGIS package. This database holds a number of attributes for all of the identified road links, including:

- road classification (NTN, stage highway, other main roads)
- road type (e.g. freeway, divided carriageway, two-lane two-way road)
- region (urban, regional, remote)
- pavement type (sealed or unsealed)
- speed limit
- average operating speed
- bridge locations

In addition, attributes concerning pavement condition and traffic volume (AADT) are being progressively added to the database as they become available, using data supplied by the various state road authorities.

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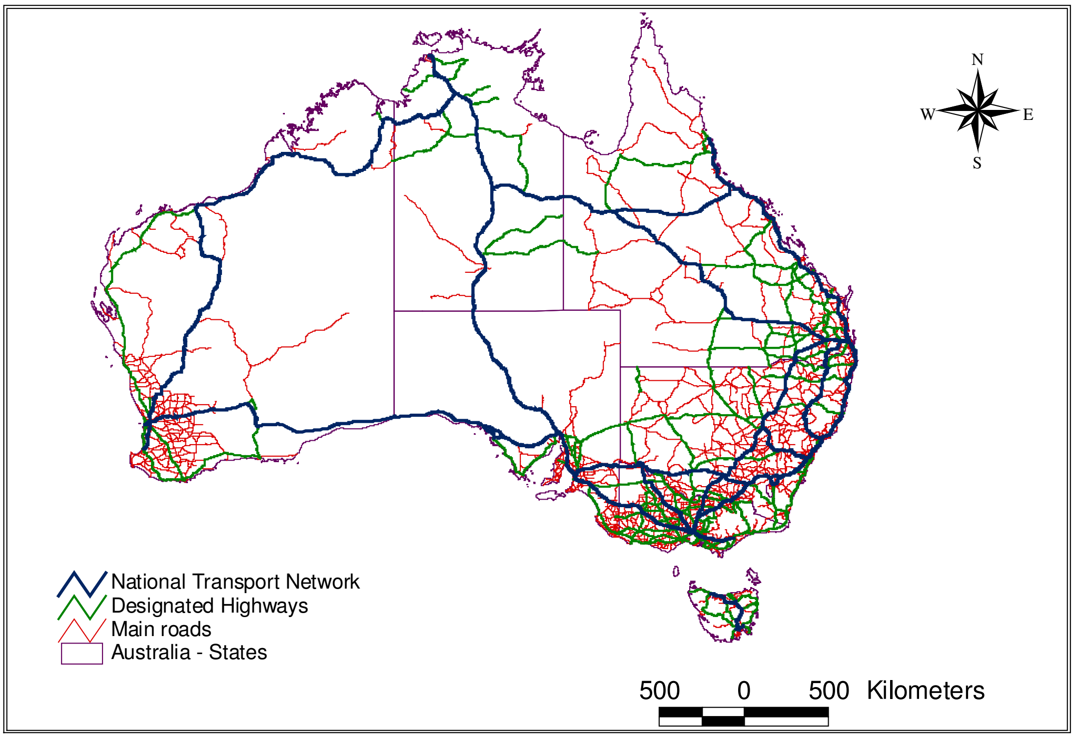

Figure 3 The Australian main road network showing all main roads, designated state highways and the National Transport Network (NTN) subnetworks

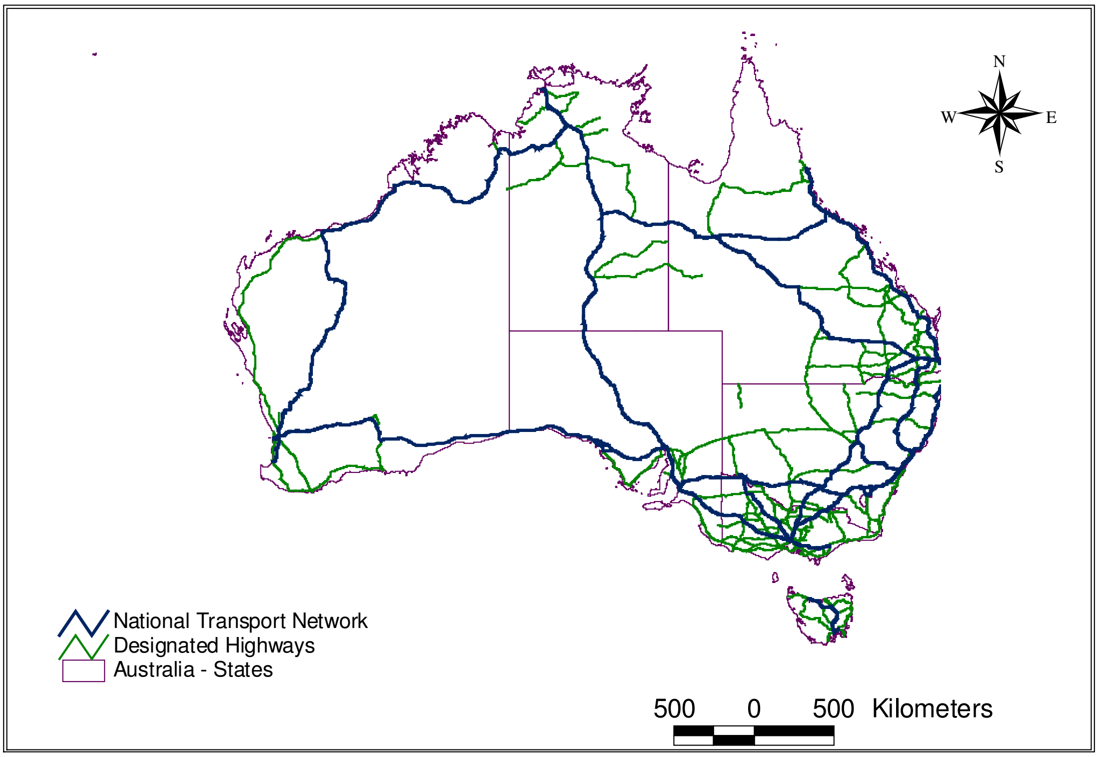

Figure 4: The Australian NTN road network and designated state highways form a subnetwork of the full Australian main road network

This full database will be used to study vulnerability at national, state and regional levels and to locate critical locations (links and nodes) in the network, using the accessibility indices and the network scanning procedures discussed previously.

6 SAMPLE NETWORK SCAN OF THE NTN ROAD NETWORK

This section presents an illustrative application of our vulnerability scan methods, using the NTN roads (see Figures 2 and 4) as an initial case study. As such, this example is restricted to considerations of the accessibility provided by the NTN as the sole road network for travel between the mainland capital cities. This is a gross simplification of the real world situation but it may be used for a simple demonstration of the techniques for network scans and vulnerability analysis, and thus to suggest a way forward for further studies of more complex networks.

The Hansen integral accessibility index of equation (2) was used to perform an analysis of the NTN roads in terms of the connections between the mainland capital cities, as an initial test of this index for vulnerability analysis. Table 2 shows the input data (populations and inter-city travel distances) and the computed Hansen indices for each city and for all of the cities, when the full NTN road network is available.

Table 2 Hansen accessibility indices in full NTN road network

	Adelaide	Brisbane	Canberra	Darwin	Melbourne	Perth	Sydney
Population (2001 census)	1 002 127	1 508 161	339 727	71 347	3 160 171	1 176 542	3 502 301
Travel distance via NTN roads (km)							
Adelaide	-	1985.65	1167.53	2622.94	722.51	2691.74	1341.89
Brisbane		-	1004.55	3102.96	1536.12	4643.25	796.07
Canberra			-	3756.33	636.23	3828.58	235.48
Darwin				-	3345.45	3465.77	3873.15
Melbourne					-	3414.25	810.60
Perth						-	3999.49
Sydney							-
Hansen accessibility index	0.000871	0.000836	0.002161	0.000294	0.000999	0.000272	0.001152
Total Hansen index summed over all cities = 0.006585							

A vulnerability scan was then undertaken. In this scan, each link of the minimum travel time path tree from each city was broken in turn, new minimum paths determined for the degraded networks, and revised values of the Hansen indices computed for the degraded networks.

Table 3 summarises the results of this analysis. Five road sections were identified as critical (most vulnerable) parts of the network, in terms of the reduced levels of overall accessibility (between all cities) for the NTN road network. These sections all produce a decrease in overall accessibility of all the mainland capital cities by five per cent or more. The worst case is a closure in the Sydney-Yass section of the Hume Freeway, which leads to an overall reduction in the total accessibility of all the capital cities of some 25 per cent. Thus this is the most critical section of the network identified in the analysis (see Table 3). The further advantage of the Hansen accessibility index is that it also reveals the effects on the individual cities of link closures, as can be seen in Table 3. For example, a closure on the

Sydney-Yass section leads to a 53 per cent decrease in the accessibility of the national capital Canberra, a 23 per cent decrease in the accessibility of Sydney, and a two per cent decrease in the accessibility of Perth. Likewise, a cut to the Stuart Highway (north of Katherine) has a 100 per cent effect on the accessibility of Darwin to the other capital cities (in the NTN road network, see above) and a seven per cent decrease in accessibility overall. These individual changes as well as the overall change help to more clearly define the vulnerability of specific road sections. Figure 5 identifies the critical road sections on a map of the NTN road network.

Table 3 Relative values of Hansen accessibility index in degraded NTN road network, as proportions of index values for full network

Proportionate Hansen accessibility index with cut to Hume Freeway (Sydney-Goulburn section)							
Adelaide	Brisbane	Canberra	Darwin	Melbourne	Perth	Sydney	Total
0.958	0.986	0.467	1.000	0.848	0.983	0. 728	0.746
Proportionate Hansen accessibility index with cut to Hume Freeway (Melbourne-Seymour section)							
Adelaide	Brisbane	Canberra	Darwin	Melbourne	Perth	Sydney	Total
1.000	0.925	0.885	1.000	0.666	1.000	0.786	0.864
Proportionate Hansen accessibility index with cut to Hume Highway (Sturt Highway-Yass section)							
Adelaide	Brisbane	Canberra	Darwin	Melbourne	Perth	Sydney	Total
0.946	1.000	0.869	0.998	0.811	0.978	0.862	0.896
Proportionate Hansen accessibility index with cut to Stuart Highway (north of Katherine)							
Adelaide	Brisbane	Canberra	Darwin	Melbourne	Perth	Sydney	Total
0.970	0.997	0.994	0.000	0.997	0.992	0.998	0.948
Proportionate Hansen accessibility index with cut to Federal Highway							
Adelaide	Brisbane	Canberra	Darwin	Melbourne	Perth	Sydney	Total
1.000	0.998	0.864	1.000	1.000	1.000	0.965	0.949

7 DISCUSSION

This paper has discussed the development of techniques to identify specific ‘weak spots’ – critical infrastructure – in a network, where failure of some part of the transport infrastructure would have the most serious effects on access to specific locations and overall system performance. The Australian National Transport Network road system is used as a simple case study, but the concepts and techniques described in this paper have much wider application. In particular and as a next part of our research and development of the vulnerability method, we will be adapting and applying the methods for use in the much larger and more complex road networks that exist in the real world, such as the full main road network shown in Figure 3. What we can say at present is that our research has yielded useful concepts and a method for analysis of network vulnerability in terms of the spatial or topological configuration of the network and possible socio-economic impacts assessed in terms of changes in accessibility to markets, service and facilities resulting from site-specific failure of transport infrastructure. Further research is needed to:

- develop more efficient algorithms for network vulnerability scans in large and complex networks
- develop better and more comprehensive vulnerability metrics
- refine techniques for identifying network weaknesses

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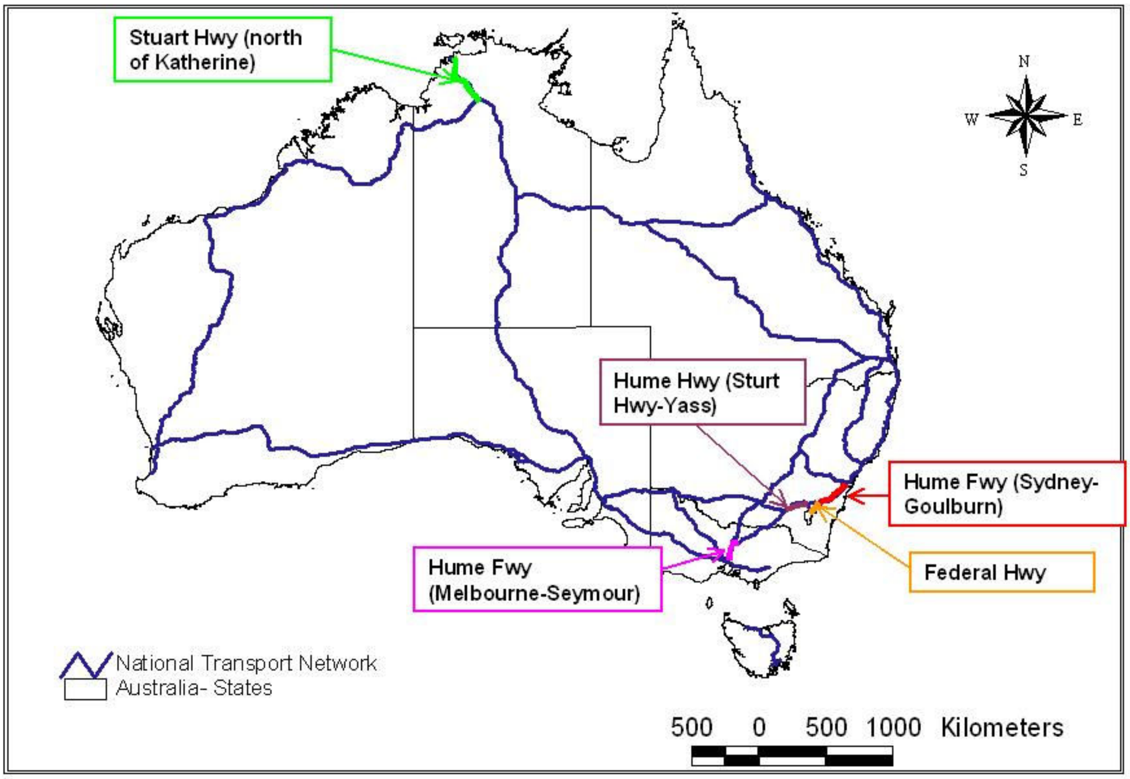

Figure 5: **Critical sections of the NTN road network identified by a vulnerability scan using accessibility to the mainland capital cities**

- extend and refine the use of network vulnerability indicators for use in studies of critical infrastructure and the implications of network degradation
- develop techniques for recommending and evaluating cost-effective risk management and remedial responses (such as reducing risk profile, upgrading existing infrastructure, adding alternative routes, and so on). This may involve trading off the level of resources put into managing the risk against a measure of vulnerability that takes into account the implications of network failures as well as path probabilities
- develop visualisation tools for interpreting and communicating results

Candidate vulnerability metrics belong to a composite set including:
- indices of network connectivity and accessibility
- probability distributions for travel times and costs to specified destinations
- measures of change in the utility of travel
- spatial distributions of changes in the above metrics
- indices of risk, including expected values of costs, changes in these values under different network conditions, propensity for component failure, and performance thresholds.

This set of measures is being designed to reflect both the intensity of vulnerability and its extent, both spatially and demographically, across a study region. The techniques to apply these measures to vulnerability analysis will be based on the complex system paradigm, thus focusing the research on the required methodology, process and tools. Validation of the techniques will require careful appraisal of the modelled consequences of network failure for real world systems.

In the longer term we seek the development of a form of network scanning that might be termed ‘incident audit’ – perhaps akin to road safety audit. This analysis will also account for traffic congestion and its effects on network performance. The aim is to provide a methodology that can identify where infrastructure failure will have the worst consequences for movement of people and goods. It includes tools for engineers and planners to determine critical network locations, and devise strategies and remedial measures to safeguard network performance. These tools can be applied at a variety of planning levels, from strategic planning to tactical planning and operational management and control.

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