Vulnerability Analysis of Road Networks

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ABSTRACT

Due to a number of catastrophic events, vulnerability analysis has been an area of increasing interest and research since the mid 1990s. This paper seeks to apply some vulnerability measures to the city of Adelaide. It considers the existing vulnerability metrics of importance and exposure and compares results to these measures as used in alternative networks, and how network layout may account for some of the differences. Comparison of these results then provides guidance on the important aspects of each. It also considers the measures for accessibility. The paper uses the case study of the road network disruption associated with the South Road / Anzac Highway underpass construction. As a two-year construction project at a major Adelaide intersection, long-term disruptions were faced by many travellers along the route. This implies that people eventually became accustomed to the changes in conditions before making their trips and hence adjusted their routes and trip timing accordingly.

1. INTRODUCTION

Vulnerability analysis has been an area of increasing interest and research since the mid 1990s. There have been a number of major events that have disrupted transport networks around the world, but there are also everyday events that can cause disturbances such as accidents, road works or vehicle breakdowns. Vulnerability analysis is relevant as it is important that people can travel for work or recreational activities and it is vital that emergency services can gain access to wherever they are needed.

Vulnerability, in terms of transportation networks, considers the susceptibility of the network to disruptions or degradation that will significantly reduce the efficiency or capability of the operation of the transport system, and the impacts this degradation could have. Vulnerability analysis is typically divided into two categories; accessibility and reliability. Two measures of reliability will be considered and analysed in this paper and they are importance and exposure. They will be applied to the metropolitan area of Adelaide and the results from this modelling will be compared to the results of a similar analysis carried out in Sweden. Accessibility will be considered in this paper, but as yet has not been modelled in the Adelaide network. This will be part of the work performed in the future, along with defining a new measure for vulnerability as will be discussed later in the paper.

1.1 The Adelaide Transport Network

Adelaide is the capital city of South Australia and is located in south eastern Australia along the Gulf of St Vincent. Its current population is approximately 1.2 million and it covers and area of approximately 1800 km^2. Given Adelaide is geologically stable the main causes of disruption to the interurban network of Adelaide are when there is a vehicle accident or road works. However on the outskirts of Adelaide there are also disruptions caused by bushfires, particularly to the east and south of the centre of Adelaide.

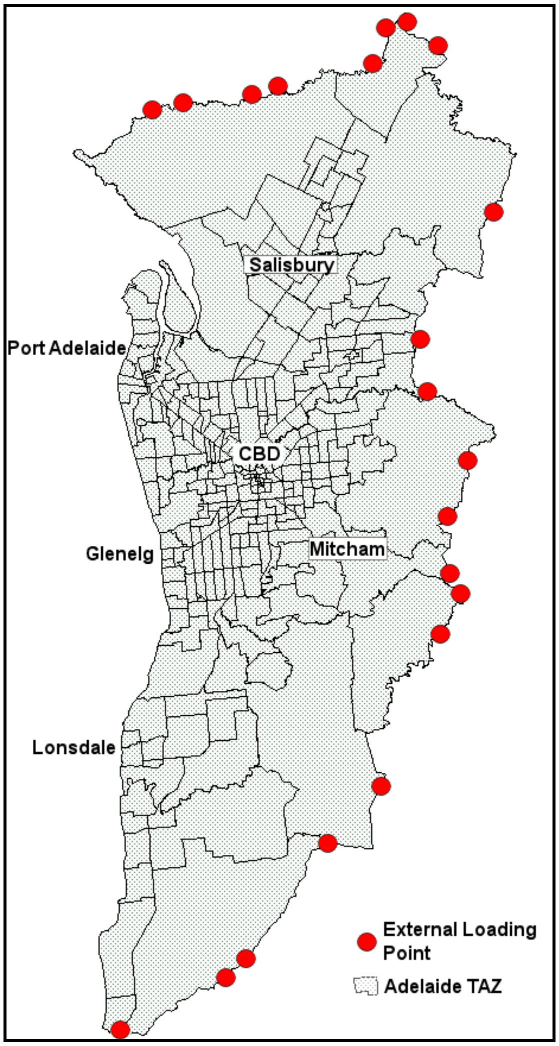

Figure 1: Map of metropolitan Adelaide. Source: (Holyoak et al., 2005)

Figure 2: Road network of metropolitan Adelaide as modelled in Cube Voyager

Figure 1 above shows a map of Adelaide and how it has been divided up into Travel Activity Zones (TAZ) with a total of 283 internal zones and 21 external loading points. These loading points are where traffic originating from outside of the metropolitan Adelaide area is added into the network. Figure 2 shows the road network of metropolitan Adelaide as it has been modelled in Cube Voyager, a program developed by Citilabs in order to model traffic flow in road networks. The developed Cube-based model is called the Metropolitan Adelaide Strategic Transport Evaluation Model or MASTEM. This is the model that will be used to test and analyse the importance and exposure measures of vulnerability. It can be seen from the previous figure that within the centre of Adelaide the road network is quite dense so users have a number of alternative routes when travelling, however to the east, south and north it is a lot sparser so there are fewer alternatives associated with route choice. The density of the TAZ definitions match with the density of the network and with the density of activity.

1.2 South Road / Anzac Highway Underpass Construction

South Road is one of the most heavily trafficked roads in metropolitan Adelaide. Due to the presence of congestion and poor performance of the road the government of South Australia has developed a plan to make South Road a continuous non-stop route (Infrastructure: South Road Upgrade 2009) from the Southern Expressway, Bedford Park, to the Port River Expressway, Wingfield. The first step in this plan is the construction of the South Road underpass at the intersection with Anzac Highway (see figure 3). The construction of the underpass has been divided into two stages. Stage 1 started in July 2007 and was completed in July 2008. Stage 2 then began and was due to be completed in July 2009 but is still continuing, due to be finished by late 2009. This second stage includes the building of an overpass for the tramline crossing South Road just south of the South Road / Anzac Highway intersection. The construction has required many diversions, banned movements and reduced speed limits for the traffic using South Road and Anzac Highway. As a result the level of service of these roads has been dramatically reduced, both in and around the intersection and has led to many road users finding alternative routes. As this construction work is ongoing for two years it is an example of a long term disruption to the road network. This means that people are aware of the conditions (they have the information before making any trips) and hence have adjusted their routes and trip timing accordingly. The particular details of the disruption in terms of the intersection geometry will vary over the two years depending on the stage and progress of the construction, so this will affect the knowledge and decision making of travellers.

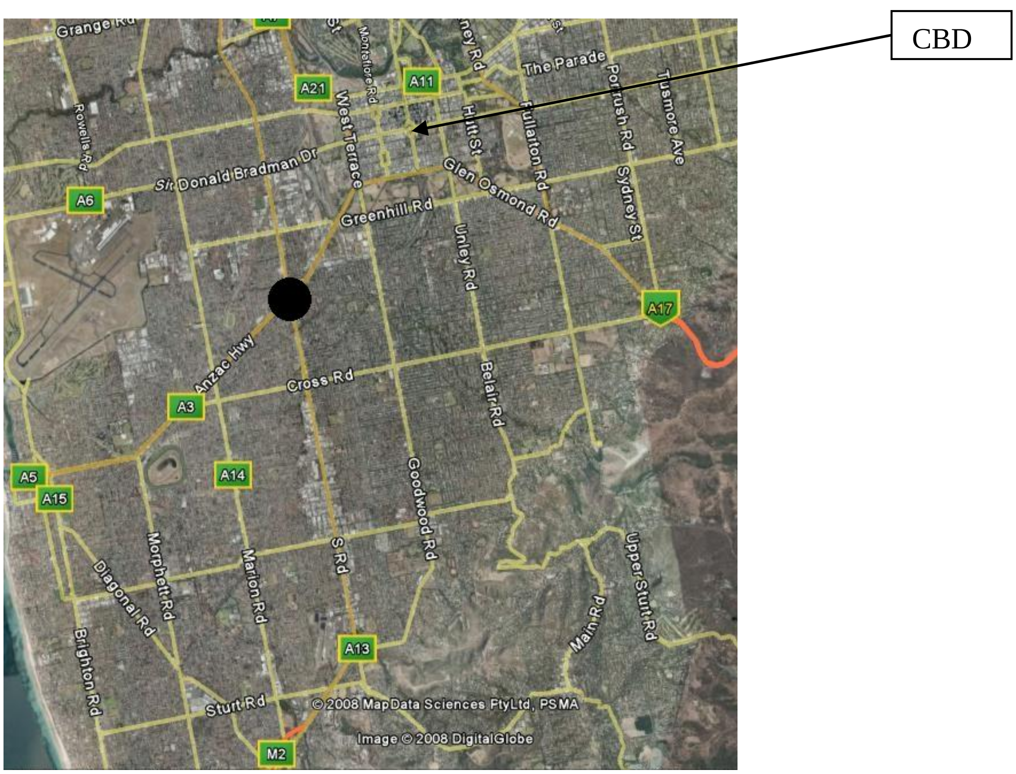

Figure 3: Map showing location of underpass construction

In this paper the importance and exposure measures will be applied to this intersection in the 2006 base year model to act as a base for which future results can be compared against to analyse the impact the construction has had on road users both during construction and after it has been completed.

2. VULNERABILITY MEASURES

Vulnerability, in terms of transportation networks, considers the susceptibility of the network to disruptions or degradation that will significantly reduce the efficiency or capability of the operation of the transport system, and the impacts this degradation could have. Vulnerability analysis tends to be divided into two types of analyses; accessibility and reliability. These will be discussed individually.

Reliability has been defined as “the degree of stability of the quality of service that a system offers” (Husdal 2006). There are different types of reliability measures for transport systems, including connectivity, travel time and capacity. If we consider a cut link as part of a road that is no longer able to be used, connectivity measures investigate whether all nodes are still connected with each other node they were previously connected to, travel time measures investigate how much travel time has increased due to the cut link, and capacity measures investigate how much traffic flow can now be accommodated. These measures are all purely based on the physical network. The main input variables for these measures are the distance and traffic flow of each link. There are also the two measures of importance and exposure that will be defined and analysed in the next section.

Accessibility has been defined as “the ease for people to participate in activities from specific locations to a destination using a mode of transport at a specific time” (Taylor, 2008a). Rather than just considering the physical network, accessibility investigates what activities are in each location and hence what attractions or opportunities are there for travellers. This aligns the road network with the land uses and explains some of the interaction between the two. Some of the factors that affect accessibility are the characteristics of the people at each location (e.g. socio-economic conditions, needs, and behaviors), different possible destinations for each activity, the mode of travel chosen and the day and time of day chosen to travel (Primerano and Taylor, 2005).

Within a network a node is vulnerable if the loss (or substantial degradation) of a small number of links significantly diminishes the accessibility of the node, and a link is critical if the 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 (Taylor,Sekhar and D’Este, 2006).

3. IMPORTANCE AND EXPOSURE

3.1 Definitions

There has been much research performed in Sweden regarding measuring the importance and exposure of regions and individual links in the Swedish road network. Importance has been described as “conditional criticality” and as such is a measure of the consequences to the overall network of a selected location having a failing link or group of links (Jenelius, Petersen & Mattsson, 2006). Jenelius (2007b) states that a region is important if the consequences of failed links in that region have a severe impact on the overall network.

Exposure has been described as “conditional vulnerability” and as such is a measure of the consequences at a selected location of an incident resulting in a failing link somewhere in the network (Jenelius, Petersen & Mattsson, 2006). Jenelius (2007b) states that a region is exposed if a disturbance somewhere in the network results in severe consequences for the network users in that region.

3.2 Application to MASTEM

Both Jenelius and Berdica have performed studies using the national road network in Sweden. Jenelius, Petersen & Mattson (2006) introduced importance and exposure parameters as indicators of the impacts of the degradation or failure of specified links in a network. The link importance parameter indicates the increase in travel cost per OD (origin destination) pair when the link is closed. Link exposure indicates the relative level of impact of a failure of the link on a given set of nodes (a “municipality”) in the network. The analysis of importance and exposure in this paper is based on, and compared to, the work done by Jenelius (2006). Both importance and exposure have been modelled MASTEM based on the network for the year 2006 before construction of the underpass began. The formulae used are:

$$\text{Importance}_{\text{net}}(k) = \frac{\sum_i \sum_{j \neq i} w_{ij}\,(c_{ij}^{(k)} - c_{ij}^{(0)})}{\sum_i \sum_{j \neq i} w_{ij}} \qquad k \in E^{nc} \qquad \textbf{Equation 1}$$

Where w_{ij} is the weight of the link (i,j) and $c_{ij}^{(k)}$ is the cost of link (i,j) in the network where k is the link that has failed, $c_{ij}^{(0)}$ is the cost of the link (i,j) and in the original network. The link that has failed is k, and k is in the set of non-cut links, E^{nc}, which means that there is at least one alternative route available when it fails.

$$\text{Exposure}(m) = \frac{\sum_{i \in V_{dm}} \sum_{j \neq i} w_{ij}\,(c_{ij}^{(k)} - c_{ij}^{(0)})}{\sum_{i \in V_{dm}} \sum_{j \neq i} w_{ij}} \qquad \textbf{Equation 2}$$

Where w_{ij}, $c_{ij}^{(k)}$ and $c_{ij}^{(0)}$ are as defined above in Equation 1, and V_{dm} is the set of demand nodes in municipality m. In MASTEM, the TAZs assume the definition of the municipalities (i.e.

regions), the cost is the travel time on each link and the weight is the traffic flow on each link of the network with the failed link.

For this paper nine test cases have been chosen to fail links across the network. The first and second test cases are South Road and Anzac Highway, with each leg north, south, east and west of the intersection failing individually. There are also tests done that go through the intersection, along South Road and along Anzac Highway. These two runs will be representative of the finalised underpass. Following this are a number of failed links in different locations to test the measures under varying conditions or physical layouts. The third test case is failing the South Eastern Freeway which is a freeway out of the Adelaide Hills in the east. It is not only a major route to many towns in the hills but is the main highway to Melbourne. Following this, the Southern Expressway is failed which is a major road that is one-way but its direction depends on the time of day. On weekdays it is a northbound road in the mornings and southbound in the afternoons and evenings. On weekends it is southbound in the mornings and northbound in the afternoons and evenings to accommodate the difference in traffic patterns. As the AM peak is considered, the flow direction of the Southern Expressway is northbound, heading towards the CBD. The next two test cases are links from a major intersection north of the CBD. The links failed are on Main North Rd and Regency Rd on the north and east of the intersection respectively. The seventh test case involves two links on Port Rd, a major road that heads north west out of the CBD. The first link is right on the edge of the CBD and the second link is close by, heading north from Railway Tce. The next case is a street in the CBD, Pulteney Street, so in this case the link is relatively small with many alternative routes but in the AM peak is very busy. The final test case is Arthur Street, Unley which is a minor road in an inner suburb just, south of the city centre that does not have much traffic so should not have much affect, if any, on the exposure of the TAZs. This last case is used as a base case to compare all the others to.

The locations of these test cases are shown in Figure 4 below.

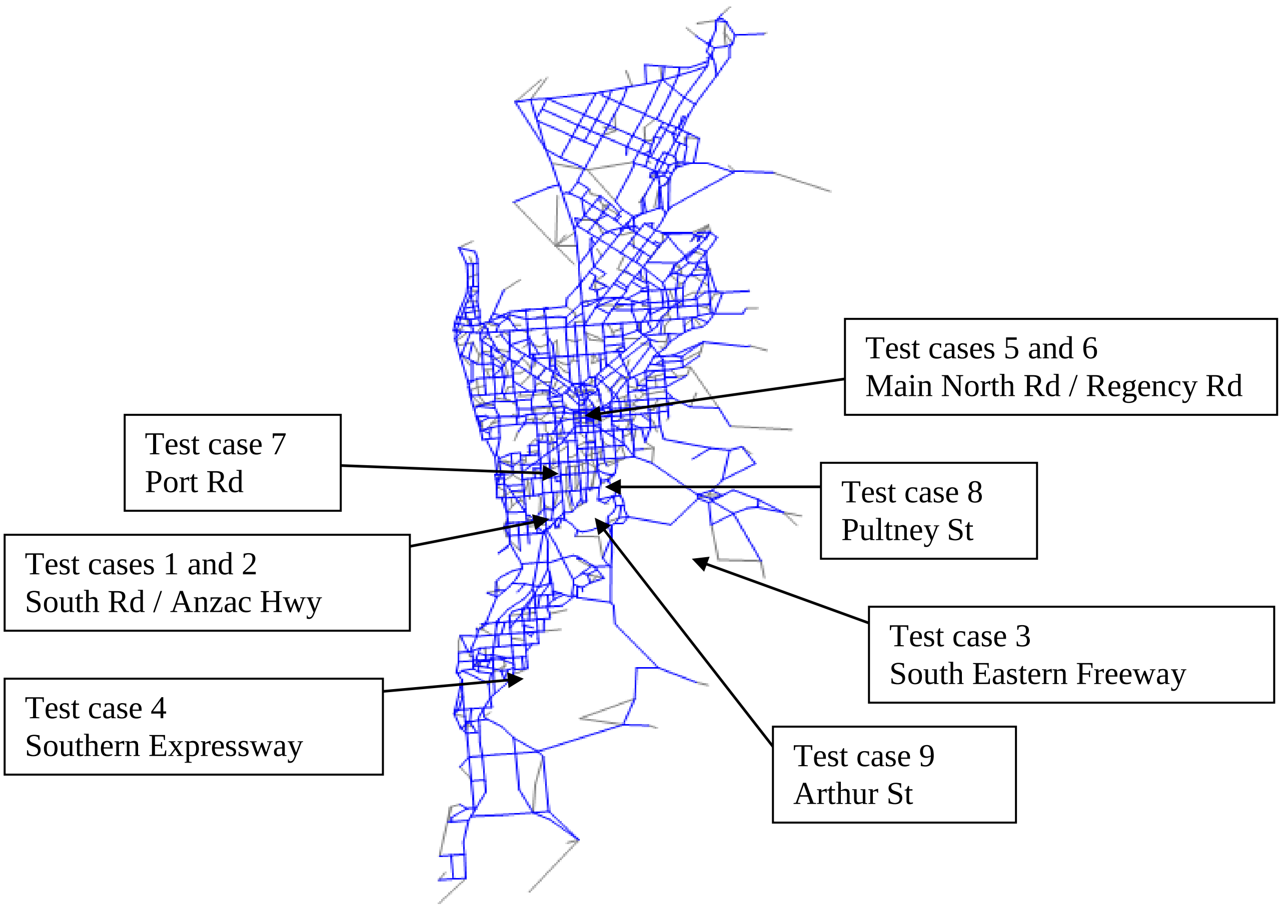

Figure 4: Location of test cases in MASTEM

3.3 Results

When considering a failed link in this paper, the link has been deleted in both directions so there is no capacity for vehicle flow. To show the detail of the effects of failing each link mentioned above, the maps below show the surrounding area that is affected rather than the whole network. Also, as many of the TAZ boundaries are along major roads it is often the case that one road is the boundary for two TAZs in which case the two directions of the road relate to two different TAZs. Note that all maps have the same legend so this is only shown for the first map.

3.3.1 Importance

The first table below shows the importance values of closing links around the South Road / Anzac Highway intersection and the second table shows the importance values of closing various links around metropolitan Adelaide. Importance and exposure are both measured in vehicle minutes / vehicle. The reason that the time looks so small in the importance tables is because it is the importance of that link in relation to the whole network. This means that since the network is quite large all the vehicles that are not in the area of the failed link reduce the average of the importance value. As can be seen in the exposure section below, when considering just a local area (since the exposure values are just for municipalities) the more localized affect of the failed link can be seen.

Considering the first table below, it shows that closing links on Anzac Highway, both through the intersection with South Road and to the east of the intersection, has the largest affect. The next most significant value is for South Road south of the intersection. This makes sense because in the AM peak a reasonable proportion of the traffic travels east along Anzac Highway or north along South Road, then turning right into Anzac Highway, to head for the CBD. The two roads heading away from the CBD have the two lowest important values.

Importance	Location
1.2303	Anzac Hwy through intersection with South Rd
1.1382	Anzac Hwy east of intersection with South Rd
0.8603	South Rd south of intersection with Anzac Hwy
0.7236	South Rd through intersection with Anzac Hwy
0.6249	Anzac Hwy west of intersection with South Rd
0.4797	South Rd north of intersection with Anzac Hwy

Table 1: Importance values for the South Rd / Anzac Hwy intersection

In Table 2 below it can be seen that the South Eastern Freeway has the largest importance value, more than double that of Main North Road which is second highest. This is to be expected since the South Eastern Freeway is the easiest and quickest route into the city for the hills residents, and the alternative route used when the Freeway is closed is much longer and has a lower speed limit increasing the time required. The second most important link in this table is Main North Road north of the intersection with Regency Road. Main North Road is a major route into the city for people from the north and for light and heavy vehicles also. Just north of this link is the Gepps Cross intersection which is one of the largest and busiest intersections in Adelaide, sending a lot of traffic south down Main North Road in the AM peak. The next important links are those on Port Rd. Port Rd is a major route for those travelling from the western and north western suburbs and is a major 3-laned road. The Southern Expressway is a major route for the southern traffic heading into the city as it is shorter and has a higher speed limit than the alternative route of Main South Road. Regency Road is also a major road but is less important than Regency Road at that intersection as most of the traffic comes from the north as described for the Main North Road value. The table also shows that Pulteney Street, north of Wakefield Street, is not important. This is because the CBD is a grid that has many alternative routes for the traffic so it is not difficult to adjust to that segment of Pulteney Street having failed. Arthur Street is the least important, as expected, as it is just a local road so there is not much traffic that needs to be re-routed.

Importance	Location
2.6498	South Eastern Freeway
1.2787	Main North Rd north of Regency Rd
0.8975	Port Rd north of Railway Tce
0.7927	Port Rd west of intersection with North Tce and West Tce
0.7375	Southern Expressway
0.302	Regency Rd east of intersection with Main North Rd
0.2829	Pultney St north of intersection with Wakefield St
0.1786	Arthur St, Unley local road

Table 2: Importance values for the remaining test case links

3.3.2 Exposure

Each of the maps shown here have TAZs that are white, relating to a negative exposure value implying a quicker travel time under the failure conditions. This can be explained, at least in part, by Braess's Paradox. Part of Braess's Paradox states that if you remove a link in a network the network can, in some cases, actually become more efficient (Braess, Nagurney, & Wakolbinger, 2005).

Figure 5 below shows the second Port Rd test case and how there is a large exposure value along the city bound side of the road and high exposure values nearby. This is one of the cases where the one road belongs to two TAZs. It shows how the impact of the failed link extends right down Port Road, not just around the link.

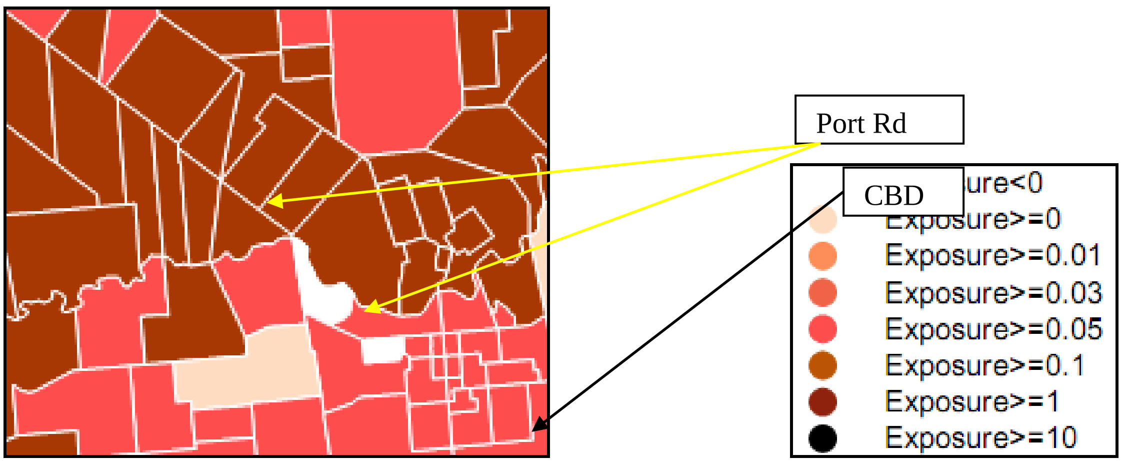

Figure 5: Exposure values for Port Rd, north of Railway Tce

The Southern Expressway also shows very high exposure values along itself. Even though there are alternative routes nearby, which must be taken when travelling at a time that the Expressway is open in the opposite direction, the alternative routes are longer in distance and have a lower speed limit so take extra time, which means higher cost values. Not only is the traffic from that area affected, but a number people from the southern hills area travel down to the Expressway so they have a higher exposure as well when the link fails, as seen in Figure 6 below.

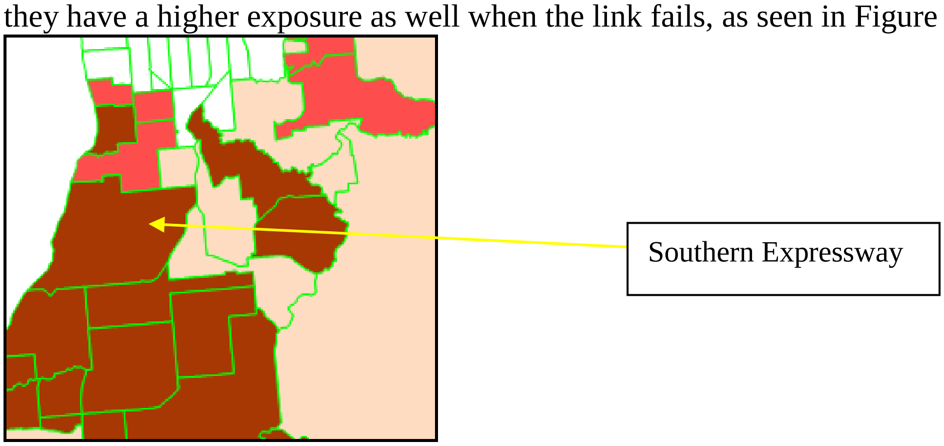

Figure 6: Exposure values for the Southern Expressway

Similarly to the Southern Expressway, the South Eastern Freeway has alternative routes that are longer in distance and have a lower speed limit, thus incurring higher cost values. It can be seen from the map below (Figure 7) that failing the main link of the South Eastern Freeway has a major effect on travellers in the hills, both near the freeway and to a lesser extent to the east of the CBD. Although it is longer in distance for the travellers in the eastern hills to drive down to the freeway to get into the CBD under normal circumstances it can be quicker than going through the northern suburbs, hence the large impact of this failure. This result is similar to that found by Taylor (2008b), who used change in an accessibility index (the 'consumer surplus' in the Primerano-Taylor accessibility framework model, see Primerano and Taylor (2005)) as a measure of network vulnerability, with a case study of the closure of the Heysen Tunnels on the South Eastern Freeway.

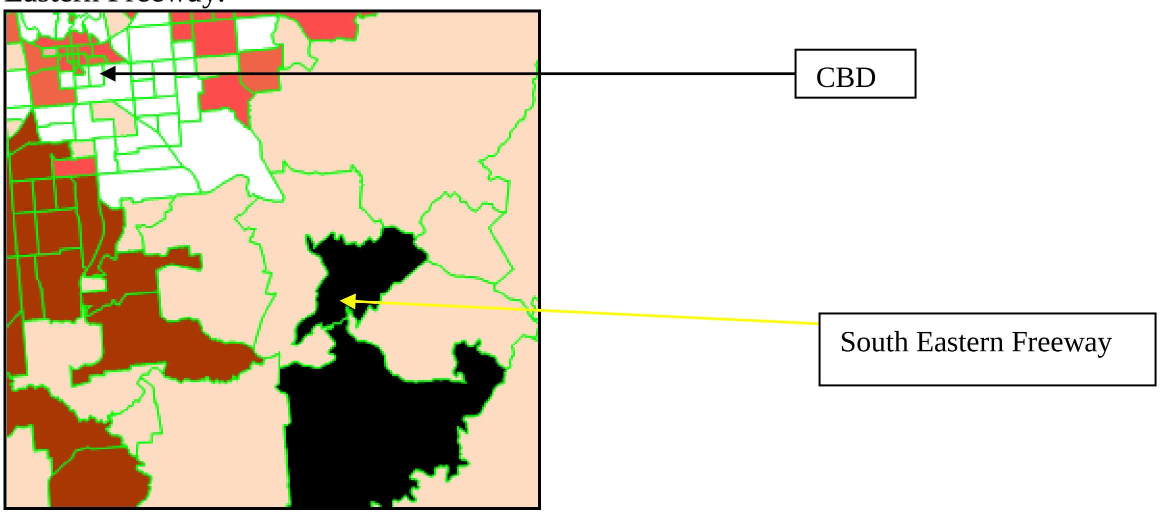

Figure 7: Exposure values for the South Eastern Freeway

As mentioned previously in the importance results, the southern links of South Road were more important than the northern links, and this is the case with the exposure results as well. It can be seen from figures 8, 9 and 10 below that the exposure in the south-western corner of the intersection is much greater for the southern and through link cases and in general there is worse exposure for the southern test case than the northern test case, and worse again for the through test case (although this is not quite so evident from the figures below).

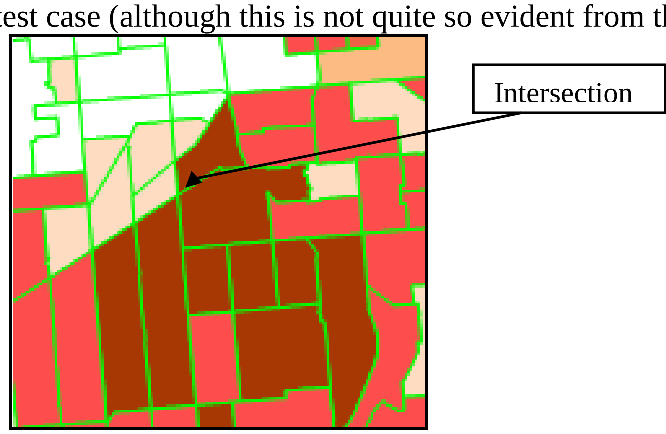

Figure 8: South Road north of the intersection with Anzac Highway

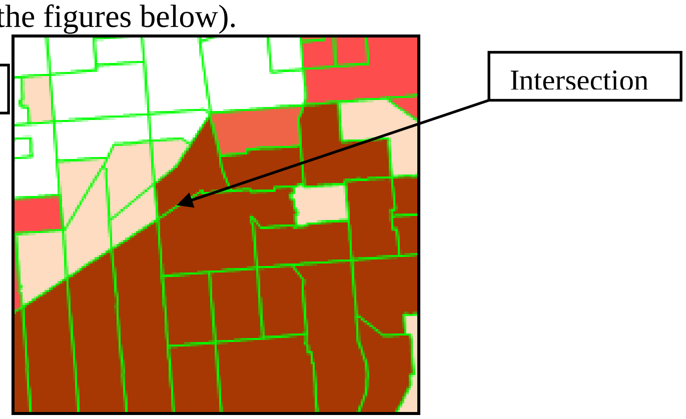

Figure 9: South Road south of the intersection with Anzac Highway

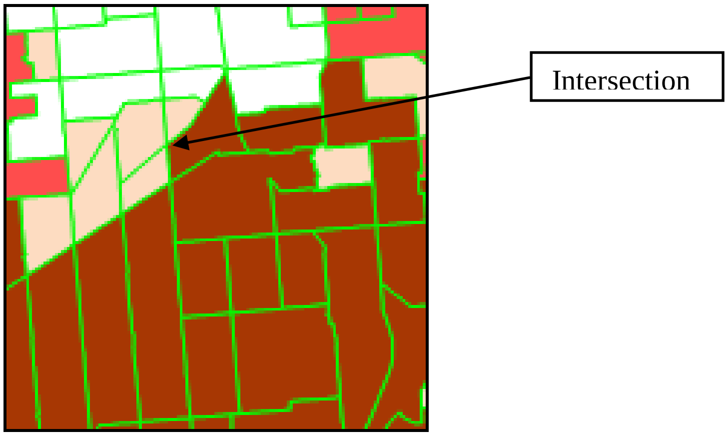

Figure 10: South Road through the intersection with Anzac Highway

It is a similar situation for the Anzac Highway test cases. It is easily observed from Figure 11 that the test case for west of the intersection, overall for the whole map, has the lowest exposure values,indicating the other sections are not affected as much by the failed links. It is difficult to distinguish between the through and eastern test cases (figures 12 and 13 respectively), however the case of the through movement does have a slightly higher average exposure value. It appears that for this particular intersection, whether it is South Road or Anzac Highway that has a failed link, it is the TAZs east and south-east of the intersection that are most affected. The maps also show that a link failing on Anzac Highway has a slightly larger impact on surrounding areas than a link failing on South Road.

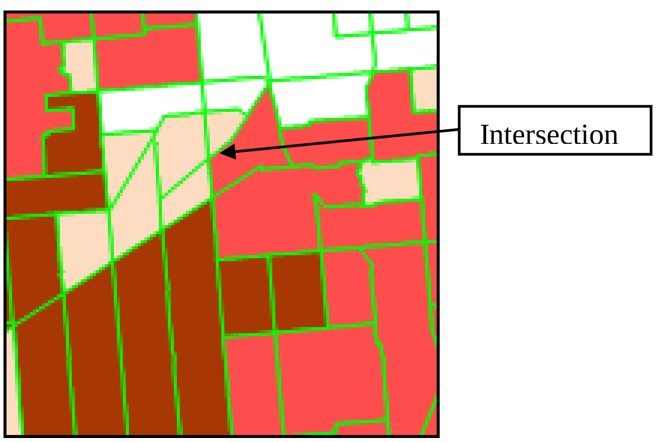

Figure 1: Anzac Highway west of intersection with South Road

Figure 2: Anzac Highway through the intersection with South Road

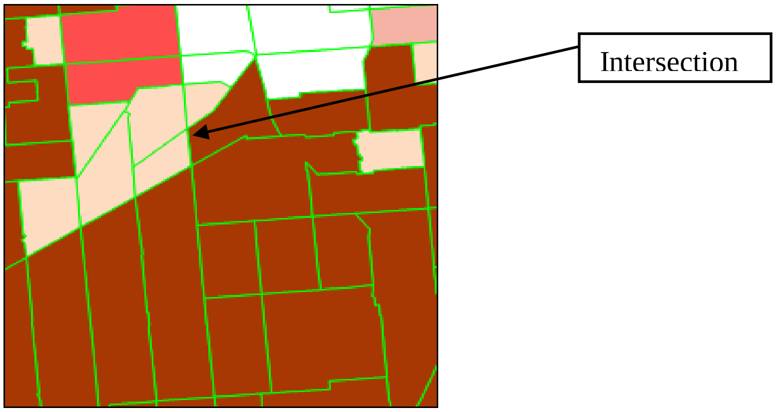

Figure 3: Anzac Highway east of the intersection with South Road

These maps show that the disruption to the local areas of the South Road and Anzac Highway intersection is quite significant. For the traffic travelling towards the CBD (both south and east of the intersection) the exposure values of the TAZs are between 1 and 10. This means that for each vehicle originating in one of these TAZs, their travel time will increase by between 1 and 10 minutes. Of course there is then the problem of traffic originating further south or west which have their route through this intersection also. The result is further congestion and poorer travel conditions. This suggests that when the construction of the underpass begins the build up of traffic could be quite severe. Many travellers will be forced to find alternative routes in order to reduce their total travel time.

Since construction began in July 2007 the initial evidence of traffic counts and travel times shows there has indeed been a build up of congestion on South Road and Anzac Highway. Also seen is an increase in traffic flow on nearby major roads, including Goodwood Road which can be seen in Figure 3. This is in line with what the results above indicated and shows the vulnerability of the network in this area. The next step is to calculate the accessibility of these areas under the various network constraints. These results, along with the importance and exposure results, will be compared against the counts and travel times mentioned. Then the measures will all be combined to produce a new measure of vulnerability that takes into account both reliability and accessibility and can be tested against the conditions of the base year, 2006, and then validated against the mid-construction timing, 2008. The new measure can then be used to measure the vulnerability improvement once the underpass has been completed and opened to all traffic, and also to look at changes in other areas of the network. Defining a new vulnerability measure is the primary purpose of this research.

3.4 Comparison with Swedish Results

In Sweden the north is less densely populated than the south and hence the road network is sparser in the north. They have a large area in the north and west with few people living in it, then have a higher population per square kilometre down the eastern side of Sweden and then the most densely populated area is in the south. This is different to the Adelaide network where the population is fairly dense for most of the metropolitan region. The Adelaide hills are less densely populated; however they are still denser than the north and west of Sweden.

When comparing the exposure values in the Swedish and Adelaide maps the north of Sweden is often very exposed to a link closure. Due to there being a very limited road network in the western area of Sweden, for certain link closures in the south and east it could result in the northern area being cut off making it difficult for users to travel south. In Adelaide's less dense areas, i.e. in the hills and far south, the regions are generally less exposed due to a denser transport network that spreads across the whole region rather than being cut off in parts. It is these differences in population and road network attributes that explain some of the differences between the results of the Adelaide network and the Swedish network.

Jenelius (2009) looks at a failure of just one road at a time also and uses travel time as an indicator of cost. In his paper it is found that the user exposure is worse in sparser, less populated, areas of Sweden where the travel times are often longer. This is consistent with the exposure results above for the South Eastern Freeway failing as the hills are less populated than the suburbs in and around the CBD. Jenelius also found that total travel time has a larger influence on total exposure than the actual network of alternative routes available. Again this is consistent with the failure of the South Eastern Freeway, and also with the failure of the Southern Expressway.

Jenelius found that traffic flow has a larger impact on importance than the physical network layout. In terms of the Adelaide network this could, in part, account for Main North Road and Port Road having higher importance values than Pulteney St. Urban networks tend to be more dense and to have higher levels of connectivity than rural networks. The impact of network connectivity on vulnerability assessment is an important area for further research.

4. CONCLUSIONS AND FUTURE RESEARCH

Two measures of reliability, importance and exposure, were considered and analysed in this paper and applied to the Cube-based model of the road network of metropolitan Adelaide. There were nine test cases in which one link was failed and the importance of those links were calculated and the exposure of the network to those links was also analysed. These nine test cases looked at the South Road / Anzac Highway intersection links where there are currently major roadworks underway, a few major roads and intersections, a road in the CBD and finally a local road south of the CBD. The greatest impact occurred when the South Eastern Freeway was closed, with the smallest impact being when one part of Pulteney Street in the CBD failed. The differences were largely due to the availability of alternative routes and their length and speed limits in relation to the failed link.

The broad aspects of these results were compared to the results of a similar analysis carried out in Sweden. The two networks were compared and possible links between the Swedish results and Adelaide results were considered.

Accessibility was considered and briefly described however as yet has not been modelled in the Adelaide network. This will be part of the research performed in the future along with defining a new measure for vulnerability. In order to achieve this an appropriate accessibility measure will be modelled in MASTEM and the results will be compared to the importance and exposure results. Taylor (2008b) has suggested the use of the Primerano-Taylor accessibility framework as a suitable metric of accessibility for urban road networks, and this will provide a starting point for our future research.

Following this a microsimulation model of the local area network including the South Road / Anzac Highway intersection will be set up and each of the measures will be applied to it. This will give results for a small, dense road network that does not have any sparse network or population attributes. These measures will be applied to the model before, during and after construction to see how the construction impacted the network while it was underway and then how it improved the network once it was completed.

These results will then be compared with those from MASTEM and will assist in determining the important aspects of each measure. From these results the differences and similarities will be used to derive a new measure of vulnerability that takes into account both accessibility and reliability. This new measure will also be tested in MASTEM to ensure consistency and sensibility in the results.

Use of a micro-scale model will also provide an opportunity to study the like impacts of short-duration link degradation or closure, which would enable the study of the likely effects of incidents, roadworks, or other episodes of non-recurrent congestion. Then, in the longer term, this research should open the door to the development and testing of methods for assessing critical locations – congestion 'hot spots' – in urban road networks, and to the development of diagnostic tools for urban road system managers to anticipate potential vulnerabilities to incident-related congestion, and take proactive action to avoid excessive congestion rather than be obliged to react to it.

5. REFERENCES

Braess, D, Nagurney, A & Wakolbinger, T 2005, 'On a Paradox of Traffic Planning', Transportation Science, vol. 39, pp. 446-450.

Infrastructure: South Road Upgrade 2009, viewed 22nd July 2009, <www.dtei.sa.gov.au/infrastructure/south_road_upgrade/content>.

Berdica, K 2002, 'An introduction to road vulnerability: what has been done, is done and should be done', Transport Policy, vol. 9, pp. 117-127.

Berdica, K & Mattsson, L-G 2007, 'Vulnerability: A model-based case study of the road network in Stockholm', in Critical Infrastructure: Reliability and Vulnerability, eds. AT Murray & TH Grubesic, Springer, pp. 81-106.

Gandhi, S 2008, 'Evaluating the intersection of Anzac Highway and South Road using AIMSUN NG V5.1 and assessing the requirements of proposed underpass', School of Natural and Built Environments, University of South Australia.

Gu, A, Holyoak, N & Benham, G 2007, MASTEM: Base Model Report.

Holyoak, N, Taylor, MAP, Oxland, L & Gregory, J 2005, Development of a New Strategic Transport Planning Model for Adelaide, Sydney, Australia.

Husdal, J 2006, Transport network vulnerability - which terminology and metrics should we use?, Molde, Norway.

Jenelius, E 2007(a), 'Approaches to Road Network Vulnerability Analysis', Department of Transport and Economics, Royal Institute of Technology (KTH).

Jenelius, E 2007(b), 'Considering the user inequality of road network vulnerability', In Press.

Jenelius, E 2007(c), Incorporating Dynamics and Information in a Consequence Model for Road Network Vulnerability Analysis. Proc 3rd International Symposium on Transportation Network Reliability. July, The Hague. Research School for Transport, Infrastructure and Logistics (TRAIL), Delft University of Technology, Delft, The Netherlands.

Jenelius, E 2007(d), 'Spatial patterns of road network vulnerability', In Press.

Jenelius, E 2009, 'Network Structure and Travel Patterns: Explaining the Geographical Disparities of Road Network Vulnerability', Journal of Transport Geography, vol. 17.

Jenelius, E, Petersen, T & Mattsson, L-G 2006, 'Importance and exposure in road network vulnerability analysis', Transportation Research Part A: Policy and Practice, vol. 40, pp. 537-560.

Primerano, F & Taylor, MAP 2005, 'An accessibility framework for evaluating transport policies', in Access to Destinations, eds. DM Levinson & KJ Krizek, Elsevier Ltd, pp. 325-346.

Taylor, MAP 2007, Using accessibility metrics for road network vulnerability analysis and the identification of critical infrastructure locations, Netherlands.

Taylor, MAP 2008(a), Vulnerability analysis of regional road networks. Proc 23rd ARRB Conference. August, Adelaide. Paper 321, Session 'Traffic Network Management'. (ARRB Group Ltd: Melbourne) (CD-ROM ISBN 1 8765 9254 0).

Taylor, M A P 2008(b), 'Critical transport infrastructure in urban areas: impacts of traffic incidents assessed using accessibility based network vulnerability analysis', Growth and Change, vol. 39, pp. 593–616.

Taylor, MAP, Sekhar, SVC & D'Este, GM 2006, 'Application of Accessibility Based Methods for Vulnerability Analysis of Stategic Road Networks', Networks and Spatial Economics, vol. 6, pp. 267-291.