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Vulnerability Analysis of Macroscopic and Mesoscopic 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 look at the results of two vulnerability measures, importance and exposure, applied to networks for macroscopic and mesoscopic modelling within the city of Adelaide. The paper looks at 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. These disruptions had a severe impact on the local area, with slightly less of an impact on the network as a whole. The paper compares the results of each network and considers how network layout and size may account for some of the differences and consistencies in each of the measures. Comparison of these results then provides guidance on the important aspects of each measure, and how each measure changes with the size of the network being considered.

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 other activities and it is vital that emergency services can gain access to wherever they are needed (Freeman 2008).

There have been many recent events that highlight the need for an understanding of the vulnerability of road networks including the Queensland flooding in early 2011 which resulted in many roads been blocked or washed away and many towns becoming isolated with no entry or exit via roads possible. There have also been earthquakes in Christchurch in late 2010 and early 2011 which have resulted in some areas becoming inaccessible.

This paper contains seven sections with the next section considering the different levels of modelling, in terms of level of detail and size of the included network that are currently in practice around the world. The third section looks at vulnerability analysis and in particular defines two measures; importance and exposure. The fourth section develops the case study area that is modelled for this paper, followed by a section outlining how the modelling and analysis was undertaken. This is then followed by the results and finally conclusions are drawn and suggestions are made for further research to be undertaken.

2. Transport Modelling Hierarchy

Within the hierarchy of models applied to the analysis of transport systems and travel behaviour as suggested by Taylor (1991, 1999) there are three scales that emerge as being widely applied in practice and growing in popularity; macroscopic, mesoscopic, and microsimulation. Each of these will be described individually in the following with two measures of vulnerability applied to a macroscopic and a mesoscopic model followed by a comparison of results.

2.1. Macroscopic modelling

Macroscopic modelling is generally applied to transport networks at a strategic level. It considers roads of strategic importance within a city or the highways in a regional model, and covers a larger area than the mesoscopic or microsimulation models. It does not attempt to model every road within a study area, rather the main roads that the majority of traffic uses to get from each origin to destination. The model aggregates vehicle flow and often uses demographic and land use data to estimate supply and demand between zones. Macroscopic models use a static assignment to allocate vehicle flow to the network for each origin and destination and the resulting output simplifies travel behaviour, representing only total flow patterns over the time period.

The strategic-level or macroscopic model of Adelaide (the capital city of South Australia) that is used for planning purposes is known as MASTEM (Metropolitan Adelaide Strategic Transport Evaluation Model) and is described in Holyoak et al (2005). MASTEM has been developed in the Cube Voyager software environment and has been used here to apply the importance and exposure measures of vulnerability to the Adelaide network under various scenarios.

2.2. Microsimulation modelling

Microsimulation modelling is used at a local level, considering individual intersections or road corridors. The model is at a much finer level than a macroscopic model, however it still does not necessarily include every single road in the study area. Microsimulation also models the traffic flow at the vehicle level, rather than as an aggregation of vehicle flow, including interaction between vehicles and driver behaviour, as described in (Holyoak & Stazic 2009). The data requirements are much more detailed than for a macroscopic model and generally include traffic counts, both manual counts and data from signalised intersections, and details of the actual road layout and design within the network area being studied.

Microsimulation uses a dynamic assignment of the vehicle flow to the network, with the frequency of when to recalculate the best path being set by the user. A simulation can be run showing the individual vehicles as they travel through the network, including the traffic flow stopping and starting at intersections, and queuing and blocking along links.

2.3. Mesoscopic modelling

Mesoscopic models operate at a level of detail somewhere in between macroscopic and microsimulation models. They model vehicle flow in platoon movements, where the user defines the number of vehicles within each platoon. If the platoon size is set to one it becomes very much like a microsimulation model. The changes in detail mean it is possible to quickly model travel in large areas with a more detailed model while overcoming some of the limitations of the macroscopic models. It can enforce capacity limitations and model the effects of queuing as well as allowing for the consideration of intersection configuration and control. It provides more detailed estimates of delay, travel time and capacities.

Mesoscopic models can use either static or dynamic traffic assignment, or even a mixture of both, and a simulation can be run which visualises the platoons as they move through the network, rather than individual vehicles (unless platoon size is set to one) and some travel demand variations can be captured. The model does require more calibration (compared to a macroscopic model), but does allow the user to assess some network elements that macro models can not (e.g. signal linking). The user can also enforce capacity limitation and re-route vehicles.

As stated in (Citilabs 2006), "analysts can study problems for which traditional models don't provide enough data and for which microscopic models provide too much data."

In this paper a subarea extraction has been performed in MASTEM and then this smaller model has been analysed using the mesoscopic modelling software Cube Avenue.

3. Vulnerability

There are generally two types of vulnerability analyses when considering the operation of a transport network. These are accessibility and reliability. Reliability is defined by (Husdal 2006) as "the degree of stability of the quality of service that a system offers" and (Taylor 2008) defines accessibility as "the ease for people to participate in activities from specific locations to a destination using a mode of transport at a specific time". The research detailed in this paper focuses on two measures of reliability.

When looking at the reliability of a transport system, things to consider include the connectivity of the network, especially when considering cut links – or roads that are no longer able to be used by traffic, the travel time from each origin to destination in the network, and the capacity of the network to cater for the demand. These reliability measures are looking at the physical characteristics of the network. Two such measures of reliability that have been developed and modelled in Sweden are importance and exposure. These will be defined in the following sections. They consider the impacts on regions within a network when a link somewhere in the network fails.

3.1. Importance

In (Jenelius, E., Petersen & Mattsson 2006), importance is described as "conditional criticality". This is a measure of the consequences to the overall network of a selected location having a failing link or group of links. (Jenelius, Erik. 2009) explains that a region in a network is considered to be important if a link failing in that region has a severe impact on overall network.

The mathematical definition of importance of link k is:

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

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) in the original network. It is link k that has failed and k is in the set of non-cut links, E^{nc}, a set for which there is at least one alternative route available when the link fails.

The link importance parameter indicates the increase in travel cost (in this paper time is used as the measure of cost) per OD (origin-destination) pair when the link is cut (Freeman 2008).

3.2. Exposure

In (Jenelius, E., Petersen & Mattsson 2006) exposure is described as "conditional vulnerability". This is a measure of the consequences at a selected location of an incident resulting in a failing link somewhere in the network. (Jenelius, Erik. 2009) explains that a region is exposed if a failed link somewhere in the network has a severe impact on that region.

The mathematical definition of exposure for municipality m is:

$$\text{Exposure}(m) = \frac{\sum_{i \in V_{dm}} \sum_{j \neq i} w_{ij} \left(c_{ij}^{(k)} - c_{ij}^{(0)}\right)}{\sum_{i \in V_{dm}} \sum_{j \neq i} w_{ij}} \qquad \textbf{Equation 1}$$

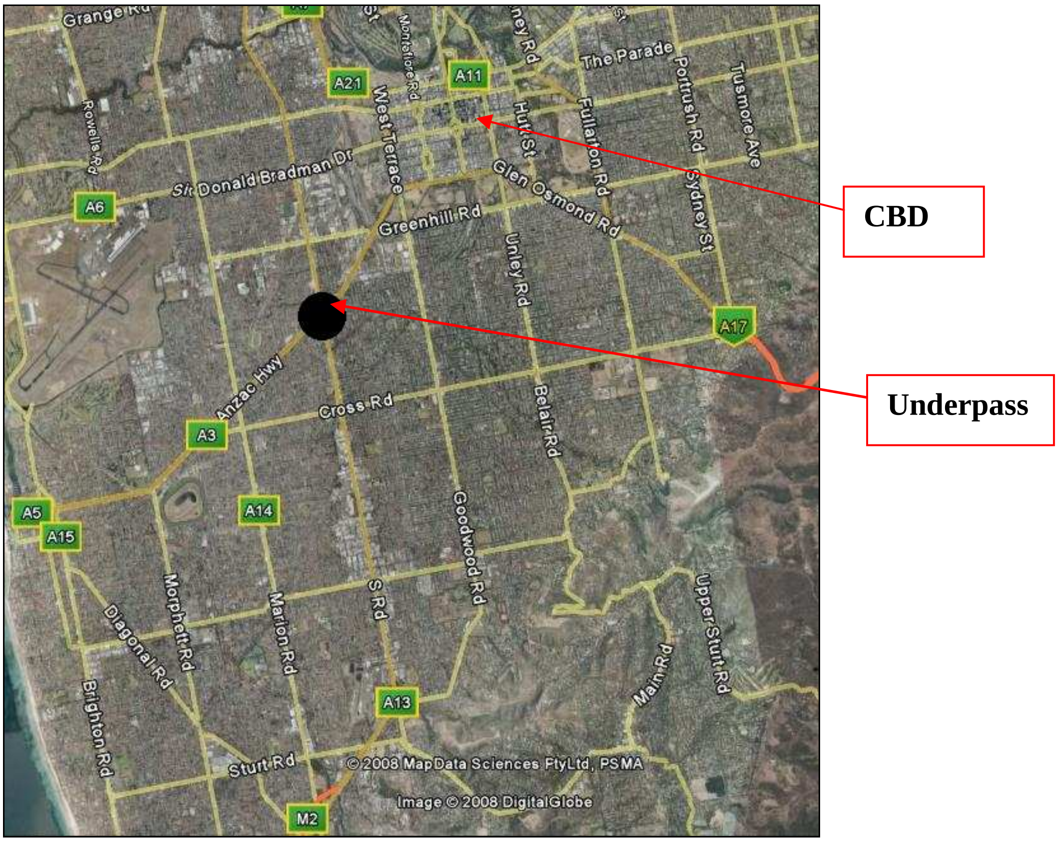
Where w_{ij}, $c_{ij}^{(k)}$ and $c_{ij}^{(0)}$ are as defined above in Equation 1, and V_{dm} is the set of demand nodes in municipality m.

Link exposure indicates the relative level of impact of a failure of the link on a given set of nodes or a region (a "municipality") in the network. (Freeman 2008).

4. Case Study Development

Adelaide is the capital city of South Australia with a population of approximately 1.2 million. The Adelaide CBD was built according to a grid system, with a number of major arterial transport links extending out from the CBD into the suburbs and connecting with activity centres. One road that runs north-south to the west of the CBD is South Road. South Road is one of the busiest roads in metropolitan Adelaide and due to its congestion and increased demand, in 2006 the State Government announced a plan to make South Road a non-stop route from the Southern Expressway, Bedford Park, to the Port River Expressway, Wingfield. This is a section of road 22km in length and the first step in making this a continuous, non-stop route was to build a grade separated intersection of South Road and Anzac Highway, now known as the Gallipoli Underpass. Anzac Highway runs from the southwestern corner of the CBD in a southwesterly direction to Glenelg. See Figure 1 for the location of the underpass relative to the Adelaide CBD.

Figure 1: Location of Gallipoli Underpass



The construction of the Gallipoli Underpass began in 2007 and was completed in 2009, with South Road being realigned to travel under Anzac Highway. These road works were disruptive to traffic, with many motorists required to find an alternative route and an increase in travel times especially in the AM and PM peak periods, and as such, were an example of a long term disruption to the transport network. The construction 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 was dramatically reduced, both in and around the intersection (Freeman 2008).

For the research described in this paper, the study area is only analysed for 2006, which is before construction of the underpass began. It is expected that in the future the years 2008 and 2010 will also be modelled to assess the changes in the vulnerability measures for before, during, and after construction.

5. Modelling Methodology

The measures importance and exposure have been applied to a subarea of the MASTEM network that considers the location of the Gallipoli Underpass and the major roads that surround it. The entire MASTEM transport network can be seen in Figure 2 below, and the subarea model network can be seen in Figure 3. The subarea model was created by drawing a polygon around the required network area in Cube Voyager, making sure no centroid connectors were cut in the process, and then applying the subarea extraction process to produce the network and associated OD matrices based on assigned traffic flow in MASTEM. This was carried out for the AM Peak period. The program Cube Avenue was then configured and run to assign the traffic volumes from the OD matrices to the subarea model. This set up the base case for which other scenarios (where various links are cut) can be compared against.

Figure 2: MASTEM road network

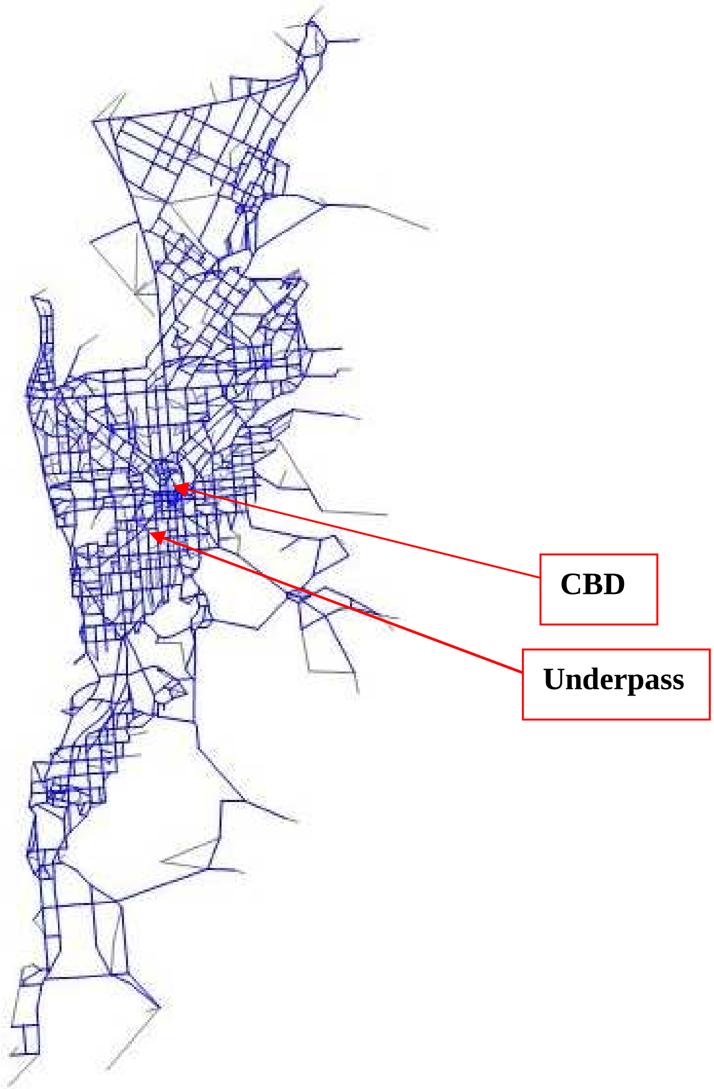
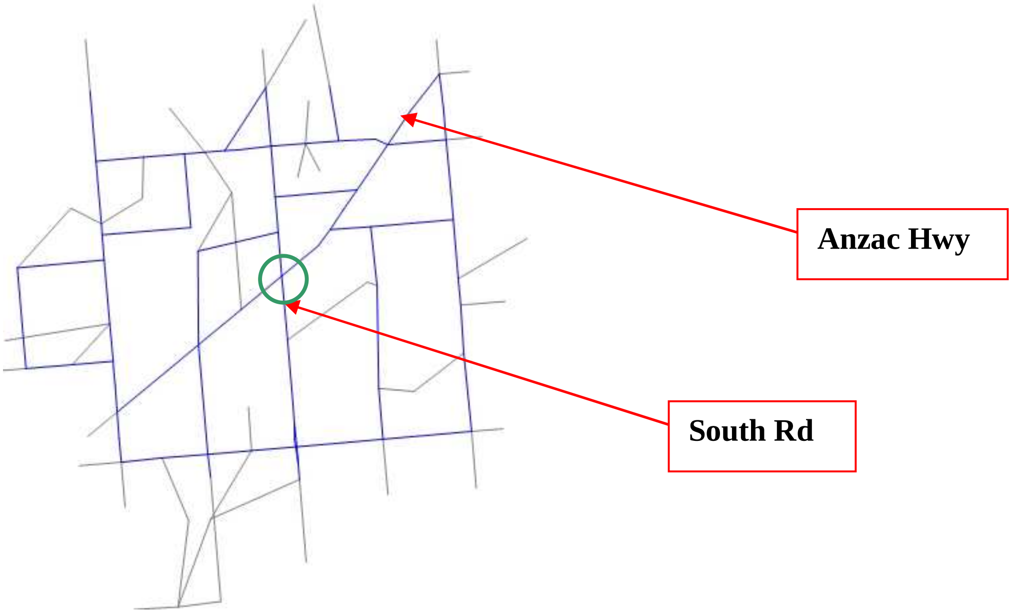


Figure 3: Subarea model from Cube Avenue



When applying the measures of importance and exposure to these models, the Travel Activity Zones (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.As reported in (Freeman 2008), when considering a failed link in this analysis, the link has been deleted in both directions so there is zero capacity for traffic flow.

When validating traffic flow for the subarea model of the Gallipoli Underpass area, it was found that the traffic demand being loaded into the network at the major intersections significantly exceeded the demand derived from SCATS traffic counts. This meant that the network was too congested and traffic was unable to move through the network to get to its destination. For this reason the demand at the major intersections around the boundary of the model was recalibrated against the SCATS traffic count data for the month of August 2006.

6. Analysis of Modelling Output

6.1. Results from the macroscopic model

As demonstrated in (Freeman 2008), the modelling results when applying the importance measure to the MASTEM network when links were deleted around the South Road / Anzac Highway intersection can be seen in Table 1 below.

Table 1: Importance values for the South Road / Anzac Highway intersection in MASTEM

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

Considering these results, it shows that reproducing an event that forces the closure of links on Anzac Highway, both through the intersection with South Road and to the east of the intersection, has the largest impact. The next most significant value is for South Road, south of the intersection. This is a logical result 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 directed away from the CBD have the two lowest important values.

The legend below in Figure 4 applies to each of the following figures. Note that the white zones indicate a negative exposure value, implying the travellers in that zone have an improvement in travel time when the respective link being tested fails. This is partly explained by Braess's Paradox which states that if you remove a link in a network the network can, in some cases, actually become more efficient (Braess 2005).

For the measurement of exposure, it is the case that (as with the importance results above) the southern links of South Road were more important than the northern links. It can be seen from Figure 5, Figure 6 and Figure 7 below that the exposure south of Anzac Highway is much greater when the link south of the intersection, or both links through the intersection fail rather than the link north of the intersection. That is, in general there is worse exposure for the southern test case than the northern test case, and is marginally worse again for the through test case.

Figure 4: Legend for measure of exposure

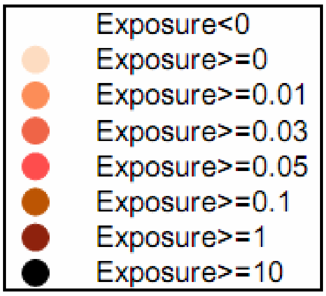


Figure 5: Failed link on South Road north of the intersection with Anzac Highway

Figure 6: Failed link on South Road south of the intersection with Anzac Highway

Figure 7: Failed links on South Road through the intersection with Anzac Highway

6.2. Results from the mesoscopic model

When applying the measures of importance and exposure to the mesoscopic model that is the subarea of MASTEM shown previously in Figure 3, the cost parameters are calculated slightly differently given the traffic undergoes a dynamic assignment rather than the static assignment used in MASTEM. Unlike in MASTEM, here the time calculated for each platoon to get from its origin to destination takes into account the effects of queuing and blocking along the links. This has an impact when an intersection is operating at capacity and hence vehicles queue back potentially blocking other vehicles from entering that link until it has cleared some of the traffic flow. The dynamic assignment was coded to recalculate the best path for each OD pair every 15 minutes for one AM peak hour plus a 15 minute warm up period. In this case, 2 time values have been output from each 15 minute time segment relating to the peak hour, giving a total of 8 time matrices. These have then been averaged and weighted by the total demand matrix.

It was also the case that the junction file specifying the operations of signalised intersections within the model area were not considered at this stage, allowing all junctions to operate as priority intersections. This is one component of the model development to be improved upon in future research. The results for the importance measure in the subarea model can be seen in Table 2 below.

Table 2: Importance values for the South Road / Anzac Highway intersection in subarea model

Importance	Location
10.8642	Anzac Hwy through intersection with South Rd
9.8462	Anzac Hwy east of intersection with South Rd
4.6054	South Rd south of intersection with Anzac Hwy
5.0074	South Rd through intersection with Anzac Hwy
1.2878	Anzac Hwy west of intersection with South Rd
0.7165	South Rd north of intersection with Anzac Hwy

As can be seen from this table, the relativeness of these results are very similar as for the importance measures coming out of MASTEM, however they are on a significantly larger scale. The through movement along Anzac Highway is still the most important movement in this intersection, closely followed by the eastern link of Anzac Highway at this intersection. Closing the link on South Road north of the intersection has the least impact.

For the analysis of the measure of vulnerability, the same legend applies to the following figures as for those in MASTEM. The legend is repeated here for ease of comparison between figures. The following figures show the results of applying the vulnerability measure to the subarea network surrounding the intersection of Anzac Highway and South Road.

Figure 8: Legend for measure of exposure

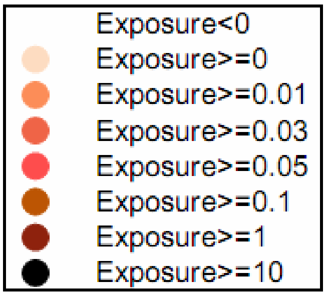


Figure 9: Failed link on South Road north of the intersection with Anzac Highway

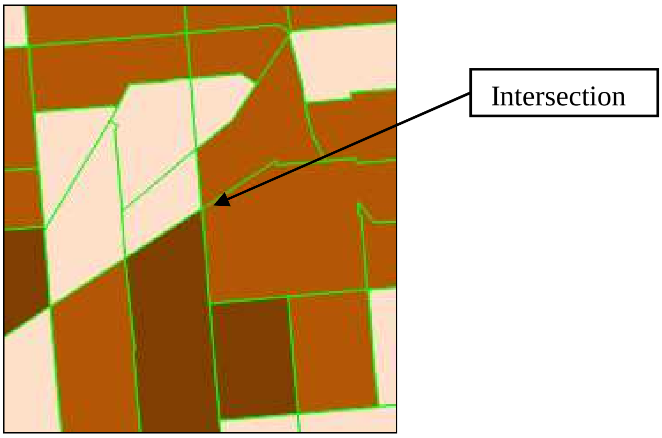


Figure 10: Failed link on South Road south of the intersection with Anzac Highway

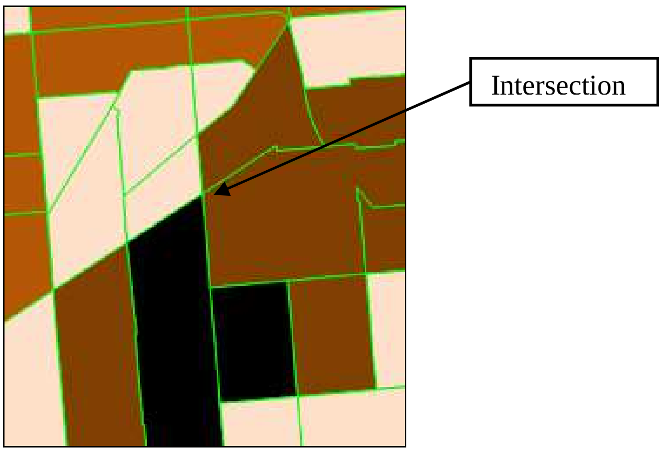
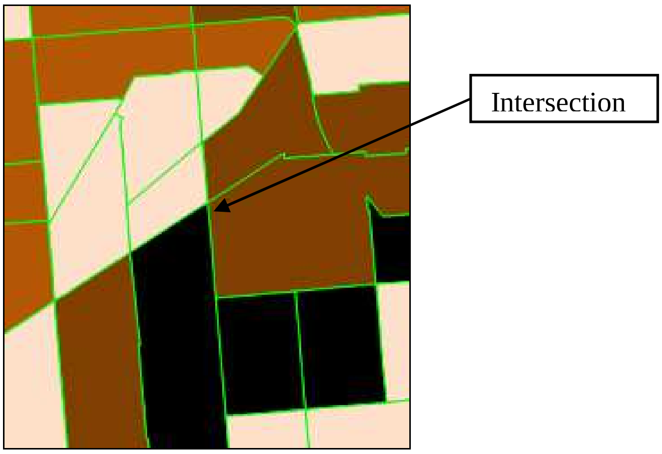


Figure 11: Failed links on South Road through the intersection with Anzac Highway



It can be seen from Figure 9 above that the zones south of Anzac Highway are not as exposed when South Road fails north of the intersection with Anzac Highway as when South Road fails south of the intersection Figure 10). Figure 11 shows that when South Road fails through the intersection the zones southeast of the intersection are much more vulnerable to this disruption.

6.3. Comparison of the two models

In general, the subarea model of the South Road / Anzac Highway intersection shows a much more vulnerable network when calculating the importance and exposure as defined in sections 3.1 and 3.2 than compared to the same area in MASTEM. This is largely due to the fact that in MASTEM the traffic travelling from the south into the city has more alternative route options to chose from to travel into the city, whereas in the subarea model it has been assumed that the same amount of traffic has no alternative but to enter the network on Anzac Highway and South Road as when there is no disruption. In this case there are only a limited number of alternative routes contained within this sub-area network which would all reach capacity fairly quickly, reducing the actual link speed and increasing travel times. This leaves the zones that are most affected by the road closures in a more vulnerable state.

The fact that some of the zones south of the intersection have exposure values greater than 10 could be indicative of the amount of traffic still entering the network on South Road despite the closure of 1 or 2 links. In reality, the travellers may have chosen an alternative route further south (for example may choose to travel along Marion Road or Goodwood Road), thus reducing the demand on South Road and hence the exposure to those zones. This demand may therefore be inflating the real vulnerability of those particular zones.

These results indicate that when choosing a measure to apply to a network in order to consider the vulnerability of the network, or a particular area of the network, care must be taken when choosing the size and detail of the network to account for alternative routes where appropriate.

7. Conclusions and Further Research

When testing the importance and exposure measures of vulnerability, the size of the transport network included in the model did not greatly affect the relativity of zone vulnerable, however it did affect the magnitude of the vulnerability. These measures were applied to a strategic macroscopic model and a mesoscopic model which was a subarea of the original strategic model. Consideration must be given to each model that uses these measures as to whether the alternative routes available in reality are reflected in the model, and whether the demand on each of the major links is still appropriate under the scenarios being modelled.

The current mesoscopic model may produce slightly different results if the signalised junctions were coded as such, although this is not expected to greatly affect the overall results. Further work is still required to test the model with disaggregation of the zones and the use of microsimulation. The disaggregation could provide more alternative routes if more minor roads are also included in the model which would then reduce the magnitude of the results. Microsimulation could also provide more detailed timing and route choice that could affect the outcomes. Further work is also anticipated to test other measures of vulnerability on different sized networks, particularly some measures of accessibility.

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