An accessibility approach in assessing regional road network vulnerability

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1 Introduction

Transport network reliability has been of interest for research for more than a decade because of the high demand for a robust transport network in order to accommodate the emergency services as well as the just in time services. The prior transport reliability studies have tended to focus more on the urban network reliability which mainly concerns connectivity reliability, travel time reliability and capacity reliability (Nicholson *et al*., 2003) and have been a lack of the assessment of the consequences of network failure. However, as a result of the negative consequences of network degradation in rural area road networks where the road network sparser, network vulnerability method needs to be considered to make up this deficiency (D' Este and Taylor, 2003).

The definition of transport network vulnerability has not been commonly accepted yet (Husdal, 2004). Husdal (2006) reported that the vulnerability idea can not be easily agreed as the opposite concept of reliability which means the bigger the reliability of the transport system the less vulnerable. Berdica (2002) described transport system vulnerability can be denoted as the susceptibility as well as the serviceability of the transport system. Moreover D' Este and Taylor (2003) introduced transport network vulnerability as the consequences of the link failure in accordance with accessibility measures.

Given the common characteristic of rural settlements in Australia whereby most of them are sparsely distributed, the road networks are sparser with fewer good alternative roads than in urban areas. In this case, transport networks become critical lifelines for accessing better community services. Moreover, the failure of one particular link within the rural road networks will probably have significant effects to the community. Previous research has assessed the negative impact of the degraded links on Western Australia and South Australia communities particularly in accessing vital services by measuring the changes of the accessibility index (Taylor *et al*., 2006; Taylor, 2007). As prior research investigated transport network vulnerability at the national level, this study will focuses on the transport network vulnerability measurement at the regional level. The Green Triangle Region has been chosen as the case study area due to its location at the Southern end of the border between Victoria and South Australia and mid way between two large metropolitan cities (Adelaide and Melbourne). In addition, based on the importance of the economic growth of the Green Triangle Region in relation to the forestry and tourism industries, the road networks within the Green Triangle region should cater for the future demand by reducing its vulnerability. With regard to those issues, this research studies road network vulnerability in the Green Triangle Region by using two accessibility indices. The first is the Hansen indices which measure the integral accessibility of certain places and the second is the Accessibility/Remoteness Index of Australia which is developed by the Department of Health and Aged Care (DHAC) in terms of measuring remoteness to access the service centre.

By considering the effect of the failure of some important links, this research aims:

1. to assess the accessibility indices of cities in Green Triangle area both with Hansen Accessibility index and ARIA index
2. to suggest an appropriate method for assessing the network vulnerability in regional area
3. to identify the critical links within the road network of the Green Triangle Region.

The next section reviews both the reliability road network and vulnerability road network concept and current research in this field. The following section will discuss vulnerability measurement in relation to measure the accessibility indices changes. The next section presents the result and discussion by applying the accessibility approach in road network vulnerability measurement at the Green Triangle Region. The final section is conclusion and suggestions for some refinements for further research.

2 Literature review

The concept of road network reliability and road network vulnerability are relatively new. In general, according to Wakabayashi and Iida (1992) reliability may be defined as "the probability of a device performing its purpose adequately for the period of time intended under the operating conditions encountered". This definition is very general and has given different meanings to different users. Thus, recently there are several approaches in order to measure transport network reliability and transport network reliability. This section will more detail discusses those measurement and the current research at those areas.

2.1 Road network reliability

Earlier studies of road network reliability were grouped this reliability into two broad categories: connectivity reliability and road network performance reliability. Connectivity reliability relates to successful travel between the origin and destination in residual networks after one or more links were closed or degraded. Road network performance reliability concerns the changes of the travel time and travel cost in order to reach destination after one or more links were closed and degraded.

Since the transportation system is a dynamic system which is not only built by the transportation infrastructure but also formed by the road network performance and the road user behaviour, transportation system reliability analysis should be able to handle the different level of the degradation. Several approaches were used in order to increase the reliability of the transport network systems. The previous studies suggested that road network reliability can be increased by emphasising the strengthening the road network and relocating the infrastructure in terms of reducing the direct costs. Due to the potentially severe socio-economic consequences of a degraded transportation network on a community, Nicholson (1997) suggested that transport network reliability can be improving by;

1. improving the network configuration
2. having stand by components
3. monitoring critical components
4. undertaking regular preventive maintenance
5. identifying priorities for repairing degraded components to minimise the socio economic impacts.

However, since road network reliability more concern on the urban road networks and lack of measuring the consequences of link failure to the community then road network vulnerability idea might be an alternative way to fill some of road network reliability deficiency particularly in assessing the adverse socio-economic impact to community (Taylor *et al*., 2006).

2.2 Road network vulnerability

Due to the potential socio-economic cost of degraded transport network to community, the concept of road vulnerability has been developed by researchers under transport network reliability umbrella. The definition of vulnerability has not yet been generally accepted yet. Based on the ideas of several authors, the notion of the vulnerability focuses more on the negative events that significantly reduce the road network performance. Berdica (2002) defined vulnerability as 'a susceptibility to incidents that can result in considerable in road network serviceability'. The link /route/road serviceability described the possibility to use that link/route/road during a given period of time. Furthermore, since accessibility depends on the quality of the function of the transportation system, this concept relates to the adverse consequences of the vulnerability in terms of reducing accessibility that occurs for the different reasons. As the idea of network vulnerability relates to the consequences of link failure and the potential for adverse socio–economic impacts on the community (Taylor *et al*., 2006), vulnerability can be defined in the following terms:

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

Therefore, it is concluded that road vulnerability assesses the weakness of road network to incidents and adverse impacts of degraded road network serviceability on the community.

Recently, there are several road network vulnerability concepts which have been proposed. Berdica (2002) given a coherent road vulnerability definition by considering the relationship between the serviceability of the road and the incidents that occur on it and how well the transport system work in different respects (full and degraded networks). In relation to measurement of the road network performance, Taylor *et al*. (2006) studied the network vulnerability at the level of the Australian national road network and the socio-economic impact of degradable links in order to identify critical links within the road network, by using three different accessibility approaches. The first method was the measurement of the change of the generalised travel cost between the full network and the degraded one. This method concluded that degrading one particular link will increase the generalised travel cost. Then the links which gave the highest travel cost was determined as the most important link. The second method used the changes of the Hansen integral accessibility index (Hansen 1959). It was assumed that the larger the changes after cutting one link, the more critical that link was on the basis of the adverse socio-economic impacts on the community. The last approach considered the changes of the Accessibility/Remoteness Index of Australia (ARIA) (DHAC, 2001). This method was similar with the second method which sought the critical link depending on the difference between the ARIA indices in the full network and the ARIA indices in the degraded network.

Moreover, Taylor *et al*. (2006) also studied the application of the third approach at the regional level in Western Australia. This study concluded that by removing one link gave different impact on the cities. For example, by cutting one link, the impacts on the several cities were local; in contrast, other cities with similar alternative road available did not give significant changes in the ARIA indices.

Due to the importance of the particular link within the wide road networks, Jenelius *et al*. (2006) introduced a similar approach to Taylor *et al*. (2006). They studied the link importance and the site exposure by measuring the increase in generalised travel cost in the road network of the Northern Sweden where the road networks are sparser and the traffic volumes are low. By assuming the incident was a single link being completely disrupted or closed so the generalised cost increases, then the most critical link of the operation of the whole system and the most vulnerable cities because of the link disruptions were determined. The study concluded that the effect of closing a link was localised and the worst effect was in the region where the road networks were sparser with fewer alternative roads.

Taylor (2007) also studied road network vulnerability in the South Australia road network which included all freeways, highways and main major roads. This research used a large complex road network and evaluated the ARIA index changes for 161 locality centres with populations exceeding 200 people. This study found the top ten critical links for the South Australia road networks. This study concluded that the Hansen Index is more suitable to assess network vulnerability at the national level but less applicable at the regional level or inter urban area and the rural area because of the index is a discrete measure. Therefore, the ARIA index is an appropriate approach to measure the socio-economic impact of degraded road networks in rural areas (Taylor 2007).

2.3 Accessibility indices

Accessibility can be defined as some measure of spatial separation of human activities (Morris *et al*., 1978). Hansen (1959) defined accessibility as ‘the potential for the interaction’. As accessibility can be seen as the fundamental concept in transportation planning, generally, accessibility can be defined as the ease for people to participate in activities from specific location using a transport mode thus it can be used to evaluate the performance of the transport system. In conclusion, accessibility is denoted as the ease by which activities can be reached from a given location using a specific transport system which is a measure of spatial separation of human activities (Primerano and Taylor, 2005).

2.3.1 Hansen index

An accessibility measure is the integration of accessibility indicators into a single measure. Hence, in order to measure the accessibility indicator of particular area, the most commonly method is relative accessibility. Relative accessibility measures of effort in making a trip, in this case the travel time and travel cost to the nearest health centre can be defined as a relative accessibility, it is calculated using Equation 1:

$$A_{ij} = O_j f(C_{ij}) \qquad \text{Equation (1)}$$

where A_{ij} is the accessibility from zone i to zone j, O_j is the opportunities present in j and $f(C_{ij})$ is the impedance function of generalised cost for travel from i to j.

Moreover, the integral accessibility can be measured by summing the total potential for travel opportunities at particular area. According to Hansen accessibility index, in measuring the accessibility index not only consider the generalised travel cost but also consider about the attractiveness of location which represent the size of activity such as the population, the number of theatre seats, the number of jobs, as well as the size of shopping centre (Hansen, 1959). The Hansen Integral accessibility index for location can be written as Equation 2:

$$A_i = \sum_j B_j f(c_{ij}) \qquad \text{Equation (2)}$$

where A_j is the integral accessibility,
B_j is the attractiveness of the location (city),
j is the number of opportunities available at j,
B_j is often taken of the population of city j, and
$f(c_{ij})$ is the impedance function represent the separation between i and j.

By giving the weight, the normalised version of Equation 2 is also often used (Equation 3):

$$A_i = \frac{\sum_j B_j f(c_{ij})}{\sum_j B_j}$$ Equation (3)

The impedance function $f(c_{ij})$ in the equation above can be the travel time and travel cost. This means that the higher the impedance function, the lower the accessibility index at the particular area. Taylor (2007) used the reciprocal of the distance between two cities (x_{ij}) as the impedance factor (Equation 4).

$$f(c_{ij}) = \frac{1}{x_{ij}}$$ Equation (4)

2.3.2 ARIA index

Since the Hansen index is less applicable in assessing the network vulnerability in rural areas, an alternative measure such as the Accessibility/Remoteness Index of Australia (ARIA) index should be applied (Taylor *et al*., 2006). ARIA (DHAC, 2001) is an index which was developed by the Department of the Health and Aged Care. ARIA is a remoteness index which measure the distance from the populated localities to the vital service centres (DHAC). This index can also be defined as the accessibility of populated locality centre to the various sizes of vital services such as health, finance and education. Based on this index, the remote populated localities are that one which have lower index and the least remote populated localities are that one which have bigger index. The range of the ARIA index is from 0 to 15 which mean the greater the index value, the more remote the particular area.

The service centre can be defined as populated localities where the population exceeds 200 persons. There are six categories of service centres which are tabulated in Table 1. The distance calculation for each locality centre to service centres is performed by using the transportation networks ignoring the road type. Given the minimum distance from each populated location to the nearest service centres, thus for each category has six measurement per locality, each representing the minimum distance to nearest service centre in a particular category. When the minimum distance to larger service centre category is less than the minimum distance to lower service centre category, then the minimum distance for the higher service centre category was applied. In order to get the continuous variable with values of between 0 and 15, minimum distance to all the service centre were divided by the national mean distance for each category and then were summed up (DHAC 2001).

Table 1 – ARIA Service Centre Category (DHAC, 2001)

Service Centre Category	*Population*
A	≥ 250,000
B	48,000 – 249,999
C	18,000 – 47,999
D	5,000 – 17,999
E	1,000 – 4,999
F	200 – 999

Then ARIA index can be calculated by considering the distance by road from a locality to the nearest service centre in each category (Equation 5):

$$ARIA_i = \sum_L \min\left\{3, \frac{x_{iL}}{\bar{x}_L}\right\}$$ Equation (5)

where $\bar{x}_L$ is the mean road distance of all localities to the nearest category L service centre, as given in Table 2.

Table 2 – National mean distance for each category

Service Centre Category	*Mean Distance*
A	413
B	239
C	139
D	88
E	43

2.4 Vulnerability measurement

As has been mentioned earlier, this research measures the changes of the Hansen Index and ARIA indices after cutting one particular link. The section below reviews the approach in order to measure the accessibility indices changes. According to Taylor (2007), in general the integral accessibility of object can be represented as (Equation 6):

$$A_i = fn(N, X_i, S_{jk}, j \in J, k \in K)$$ Equation (6)

Where A_i is the object accessibility, N is the transport network in its present state, X_i represents the object i and its location and characteristics, and S_{jk} represents facility type j located at site k, which thus describes the land use distribution and intensity in the study area. This equation means that the object accessibility are affected by the of the transport network configuration, the operational state of that network, and the facilities and services accessible using the network.

By assuming that A_i^0 is the accessibility object at the full network, N^0, and A_i^1 as the accessibility object at the degraded network, N^1, thus the relative accessibility changes can be determined as (Equation 7):

$$\Delta RA = 1 - \frac{A_i^1}{A_i^0}$$ Equation (7)

Then, degraded links which give the biggest changes in the accessibility indices can be identified as the most critical links.

3 Methodology

As the objectives of the study are to find out the vulnerability road network at the regional level by measuring the changes of the Hansen accessibility indices and ARIA index after degraded one or more links at the particular road network at The Green Triangle Region, thus Geographic Information system. The basic methodology is outlined below:

1. Data collection, which covers road network data and its attributes especially for freeways, highways and major roads at the Green Triangle Region, locality centres population and the traffic volume.

2. Develop a road network database and revising and correcting the current road network database.

3. Extract locality centres based on populations of more than 200 peoples.

4. Calculate ARIA and Hansen indices for the full road network.

5. Select the candidate links by overlaying the shortest path from all locality centres to A, B, C and D service centres, then select the link which are used to access those locality centres.

6. Calculate ARIA and Hansen indices for the degraded networks.

7. Calculate changes in ARIA and Hansen indices and select critical links.

8. Develop a new method to assess the vulnerability of the road network by considering the changes of the contour interval of surface area.

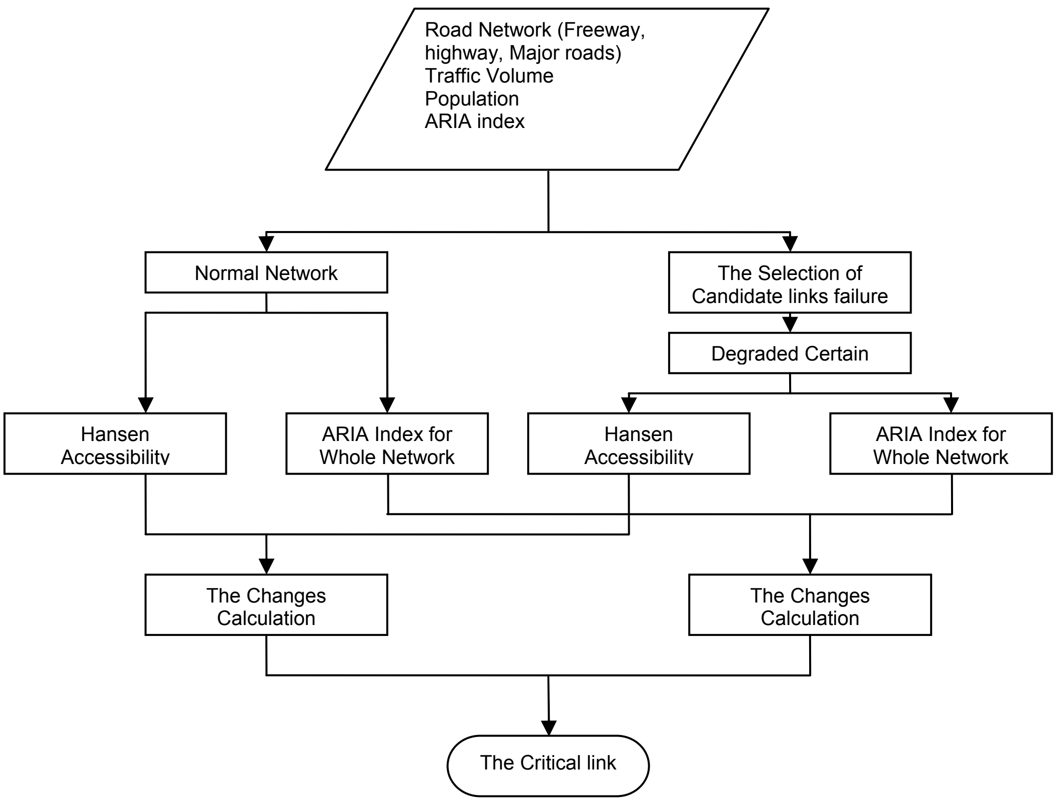

Figure 1 – Research methodology flowchart

4 Results

4.1 Hansen indices and ARIA indices for the full network

Based on Appendix 1, the range of the Hansen indices at the Green Triangle Region is from 2.143 to 7.608. Hence, the most accessible town is MacArthur with the population is 242 people and the less accessible city is Balmoral with the population is 202 people. The average of the Hansen Indices at the Green Triangle Region is 3.3. It can be concluded that overall the Green Triangle Region is accessible due to the availability of good topological transportation networks. In addition, the range of the ARIA indices at the Green Triangle Region is from 1.457 to 6.254, then, the most accessible city is Warrnambool which has been categorised as C service centre with population 26,669. On the other hand, the least accessible town is Edenhope with the population 774 people.

In relation with the ARIA category which has been grouped by the DHAC, the Green Triangle Region can be classified into three classes of accessibility, namely highly accessible, accessible, and moderately accessible. In general, according to the DHAC classification the service centres in the Green Triangle Region are accessible.

4.2 Hansen indices for the degraded networks

After selecting some candidate links which would be degraded, the new shortest paths were developed. Then by using the new shortest path, the Hansen indices for all population centres were calculated for the degraded network, by using equation 6 the changes of the Hansen indices can be measured.

Figure 2 illustrated the four links which will be discussed in the next section.

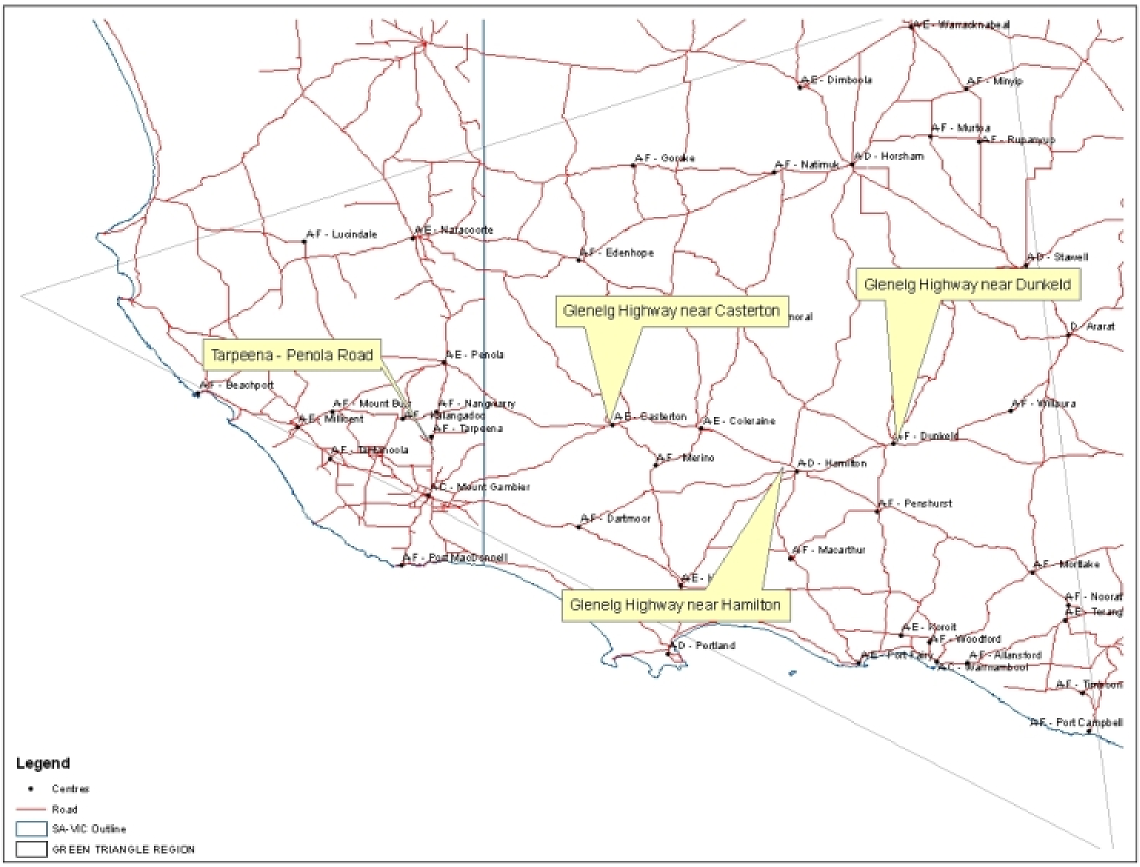

Figure 2 – The most critical links in the Green Triangle region

Appendix 2 tabulates changes in the Hansen indices. In general, by cutting any one link there were no significant changes in Hansen indices and the impacts are quite local. Figure 2 illustrates the percentage of Hansen indexes changes for only selected important links in the region. The blue line represents the percentage of the Hansen Indexes changes after degrading Glenelg Highway near Dunkeld, the red line illustrates the percentage of the Hansen Index change after cutting Glenelg Highway near Hamilton and the green line represents the percentage of Hansen Index changes because of Glenelg Highway near Casterton is closed. According to the network simulation, the most significant link in the Green Triangle Region is the short section of Glenelg Highway near Casterton which gives the most significant impact on the Casterton's Hansen indices (19% changes). Other interesting findings were the degradation of the section of Glenelg Highway near Dunkeld and the section of the Glenelg Highway near Hamilton as shown in Figure 2, which gave significant Hansen indices changes for almost all the cities at the Green Triangle region. By degrading the section of the Glenelg Highway near Dunkeld, 27 adjacent population centres were affected. The most severe effect was for Balmoral with the Hansen indices changes was 6.56%. Moreover the biggest Hansen indices changes after degraded the Glenelg Highway near Hamilton was Coleraine at about 10.94% and this affected 25 adjacent population centres. Failure of the rest of candidate links slightly disrupted the performance of the road network in the region thus the Hansen indices changes were not big and did not give significant impact on the adjacent population centres. In general, it can be concluded that though the Hansen indices changes were quite small, the degraded links impacted on almost the population centres in the region as well as reducing the accessibility of the community.

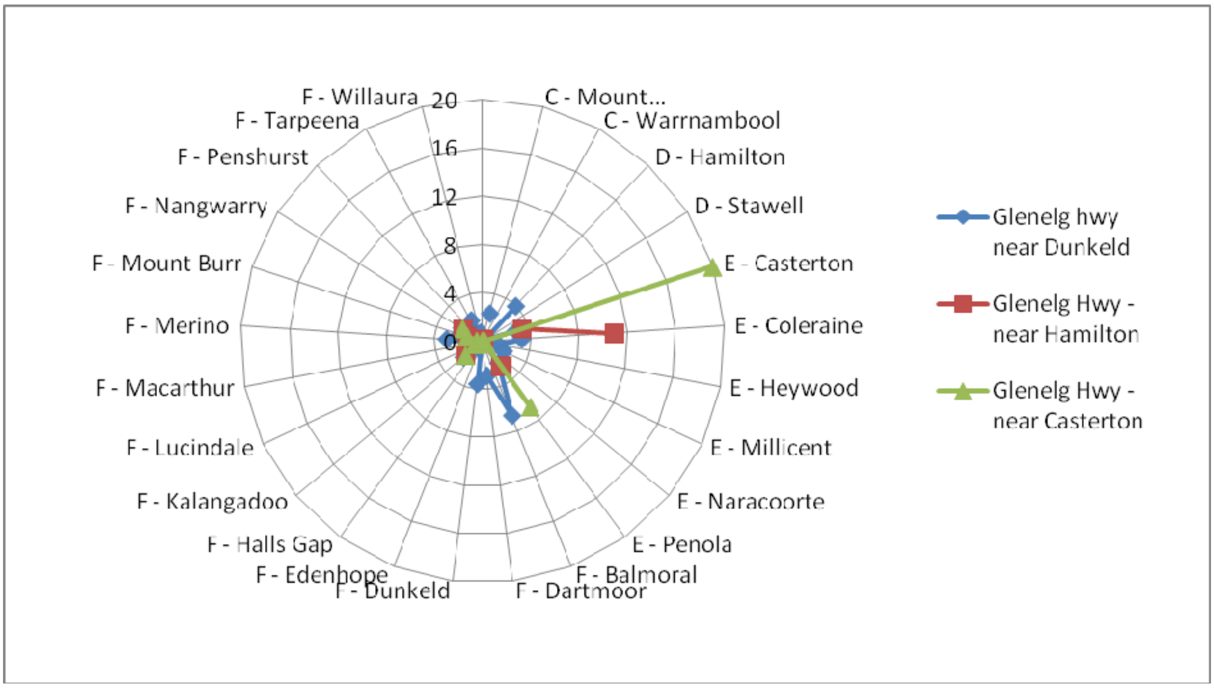

Figure 3 – The percentage of Hansen indices changes

For more detail, all of the Hansen indices changes for each selected link are given in Appendix 2.

4.3 ARIA indices for degraded networks

Similar to Figure 3, Figure 4 illustrates the most important links at the Green Triangle Region based on the percentage of ARIA index changes. The blue line represents the percentage of ARIA index changes after degrading Glenelg Highway near Dunkeld, the red represents for

Glenelg Highway near Hamilton, the green line for Glenelg Highway near Casterton and the puple line for the percentage of ARIA index changes after cutting Penola Rd – Tarpeena section. The interesting finding was that by degrading one short link at the network i.e. on the Glenelg Highway near Dunkeld as shown in Figure 8, the impact on the neighbourhood population centres was quite significant, it can be seen from the indices change, there were 15 population centres were affected after degrading this link. In addition, by cutting this link the impact on the nearby city i.e. Dunkeld was very large by more than 57% of the ARIA indices changes. This big change was because of the detour from Dunkeld needed to reach the nearest C and D category service centres by more than 30km. Similarly to the changes of the Hansen index, the link section of Glenelg Highway near Hamilton and Casterton also gave big impacts to Hamilton and Casterton. The Casterton ARIA indices change by degrading Glenelg Highway near Casterton is 21.3% then other 10 population centres were also affected, though the ARIA indices changes were not too big. The degradation of the Glenelg Highway near Hamilton changed the ARIA indices of Coleraine by 29.1% and affected another 10 population centres in the Green Triangle Region.

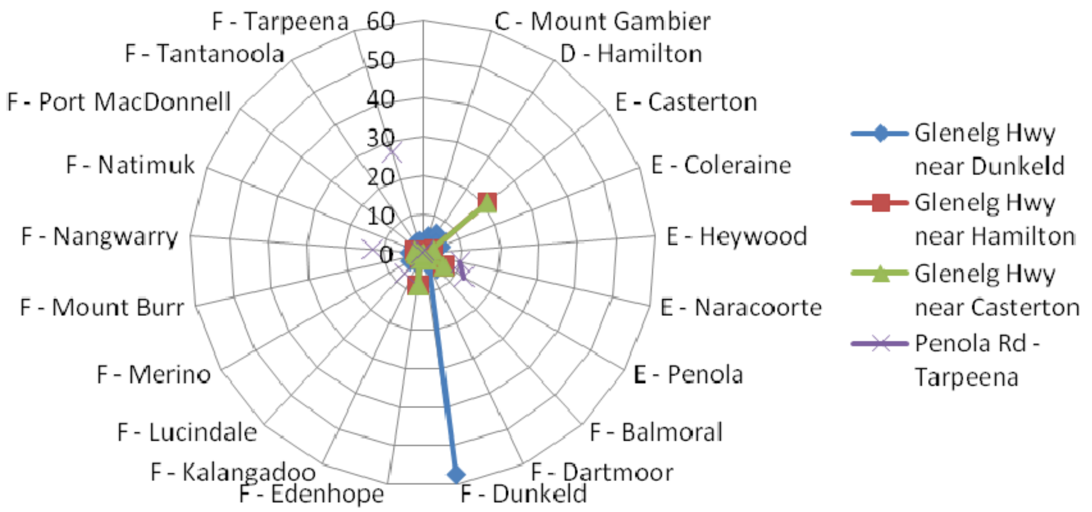

Figure 4 – The ARIA changes

For more detail all of the ARIA changes for each selected link are given in Appendix 3.

Furthermore, in relation with the degraded or closed long road section links in the region which had heavy traffic volumes as well as being used as key road sections to connect the lower category population centres to the higher category ones in terms of reaching the better service centres on the networks, the consequences of closure or degradation of those links were not generally severe on the community. Based on the data analysis, this was due to the existence of equally attractive route in the region.

4.4 The ARIA contour map

This section discusses the ARIA contour map which was derived from the ARIA indices in the Green Triangle Region. As a contour represents the surfaces on the map then this section tends to explore deeply the distribution of the ARIA indices across the region and the scale of the consequences of link closure by analysing the contour pattern changes after one link is degraded. In addition the changes of the contour pattern can represent the changes of

ARIA indices in different way. Therefore by analysis of the contour pattern, the affected centres as well as the scale of impact on the community can be identified across the region. Similar to the previous discussion that the most critical link in the region is the short link near the E and F category population centres and the consequences of degradation or closure of one link on the regional community are local and quite small. Thus, by presenting the ARIA changes in the contour map the movement of the changes can be recognized as well.

4.4.1 The full network ARIA contour map

Figure 5 represents the contour map of the ARIA indices for the full network. In order to give better description of the study area, the contour interval was assigned as 0.5 ARIA points. From the figure, it can be seen that the Green Triangle Region was covered by 1.5 contour interval to 7 contour interval. This picture also draws the most accessible and the least accessible areas in the region. As discussed previously, the most accessible centre in the Green Triangle Region is Warnambool in this map it was indicated by the green color at the contour map. The least accessible centre is Edenhope which was indicated by the red colour.

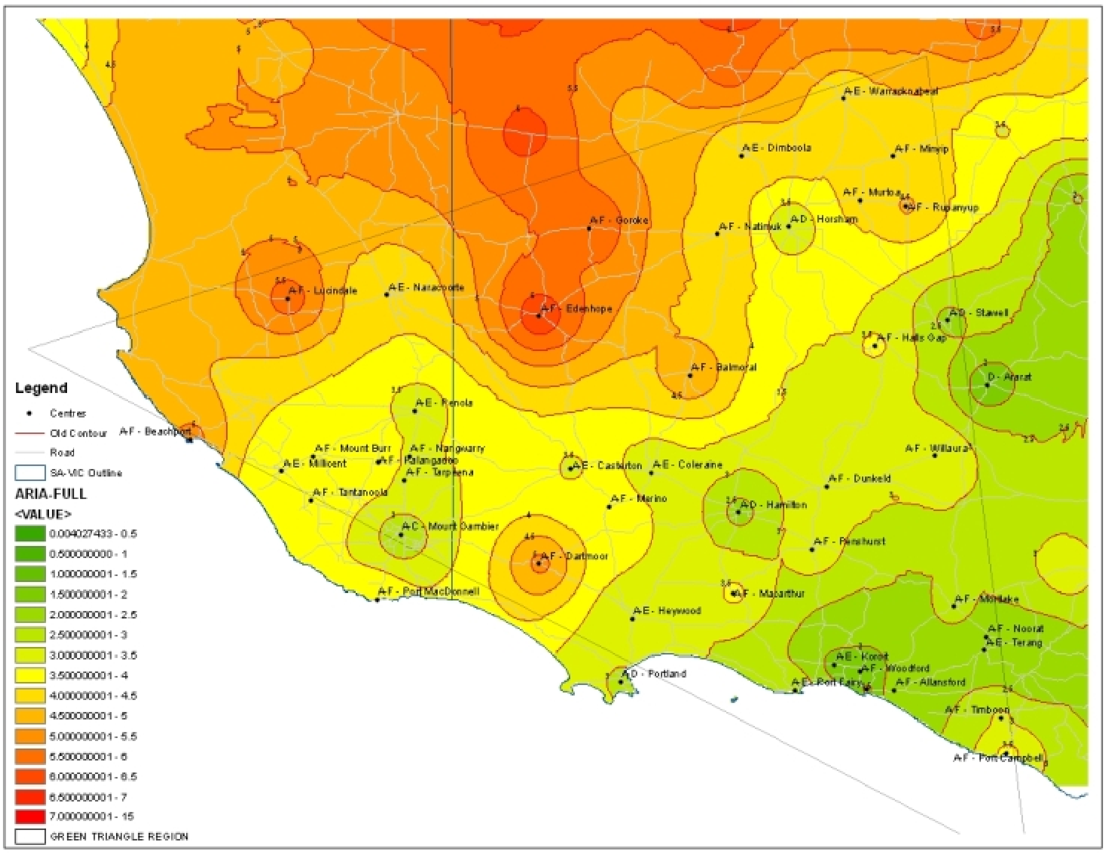

Figure 5 – ARIA indices for the full network

4.4.2 The degraded road network

With regard to the contour pattern changes in the degraded network, Figure 6 depicts the changes of contour line pattern after degraded the short section of the Glenelg Highway near Dunkeld. From Figure 6 it can be seen that there were several changes in the contour pattern after this degradation. As discussed previously that this link is perhaps the most critical link in the networks, as the changes of Dunkeld ARIA indices was more than 57% and had impact on 15 centres. Moreover, from the figure, it can be seen that there were five severely affected areas. Those areas which are arranged in an order of severity are as follows : the area near Dunkeld, the area near Dartmoor, the area near Mount Gambier and

Tarpeena, as well as the adjacent area of Portland and Hamilton. The area near Dunkeld was severely affected, this was indicated by four different contour lines appear in the region, previously the area was covered by one contour line (3.5). After degradation of this link this area was altered into four different contour intervals namely the 3.5, 4.0, 4.5 contour interval and the highest contour interval of 5 at Dunkeld. Other significant changes occured in the Hamilton region. Previously, Hamilton region was covered by the 2.5 contour interval, but after degrading this link, it changed to 3 contour intervals. Similarly Merino and Balmoral contour intervals were also changed from 3.5 to 4 contour intervals and 4.5 to 5 respectively. Kalangadoo and Dartmoor were also affected, This can be seen from the changes of the contour interval from 3.5 to 4 at Kalangadoo and 0.5 contour interval change for Balmoral.

Figure 7 below draws the impact of the closure of the Glenelg Highway near Casterton. From this figure, it can be seen that the effect was not too large and the most severe area was that near Casterton with the interval contour changes from 3.5 to 4. The other finding is Kalangadoo which was previously covered by the 3.5 contour interval and then was covered by the 4 contour interval. As most of the new contour lines were overlayed with old contour lines, the changes of the interval contours in the rest of the region were not significant. Similarly to Figure 7, Figure 8 below represents the contour interval changes after closure of the Glenelg Highway near Hamilton. Figure 8 shows that most of the new contour was overlayed with old contour. Moreover the biggest contour pattern changes are in the area near Coleraine and Dartmoor. Previously those areas were covered by the 3 contour interval but after degrading this link the contour changes to 3.5 contour interval.

In relation with the impact of the closure of the Penola – Tarpeena Road near Mount Gambier, Figure 9 below represent the contour changes. It can be seen that the figure is similar with Figure 7 and Figure 8 that almost of new contour lines were overlayed with old contour lines. An interesting finding is that the contour pattern changes at Tarpeena and Dartmoor respectively. It is clear from the figure that the area near Tarpeena was changed from the 3.5 to 4 and the area near Dartmoor was also slightly changed, from 3.5 to 4.

4.5 Hansen Index and ARIA Index for regional road network vulnerability measurement

Previous section has discussed the Hansen and ARIA index changes as well as the different pattern of ARIA index contour maps. There is a significant difference between the characteristic of the Hansen and ARIA indices. As the Hansen index is a discrete measure which only represents the accessibility of one particular locality centre into one single value, it has been identified that this index is more appropriate in national level road network vulnerability which concern upon large population cities. In other side, since the settlements in the Green Triangle Region are spreadable and sparse, the aggregate data might be useful to represent the distribution of locality centre accessibility to the nearest service centre over the study area. As the ARIA indices provide aggregate data, then the ARIA index might be more appropriate to measure regional road network vulnerability.

The ARIA indices contour map was developed in order to obtain better figure of the impact of the road degradation. This new method can recognize the changes of different pattern of ARIA indexes contours which might give better acknowledging of the ARIA index changes and the specific areas which were much affected by road degradation. Indeed, this new method did not only consider how much the ARIA index changes in one particular locality centre but also identify the changes pattern. Moreover, by applying this method give the three dimensional effect of link degradation.

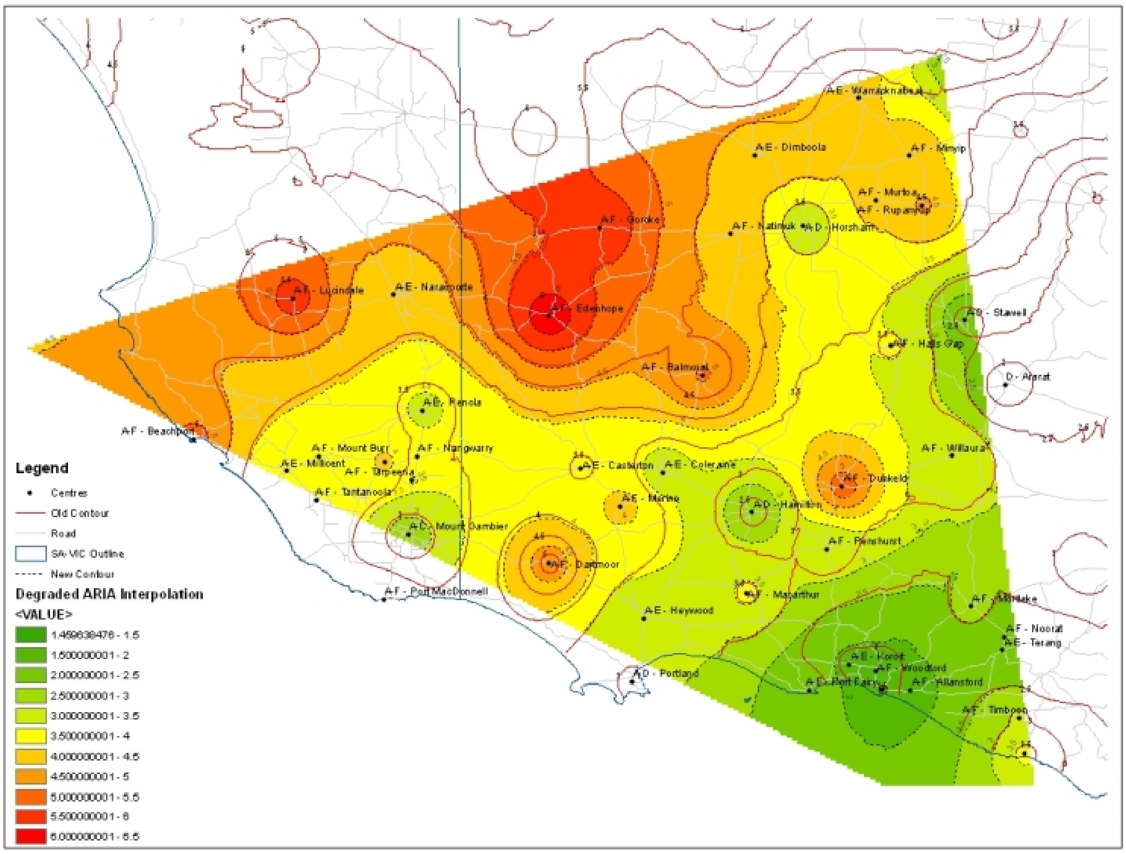

Figure 6 – ARIA indices with the degraded link of Glenelg Highway near Dunkeld

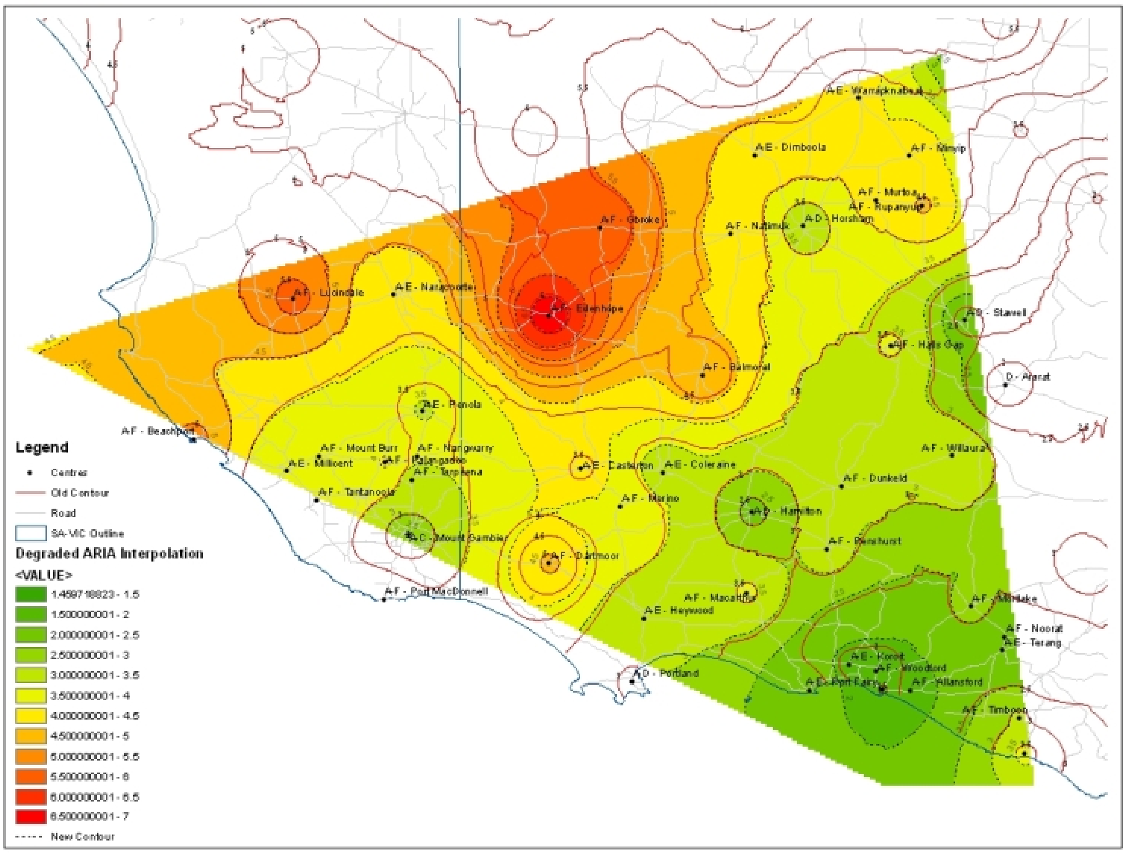

Figure 7 – ARIA indices with the degraded link of Glenelg Highway near Casterton

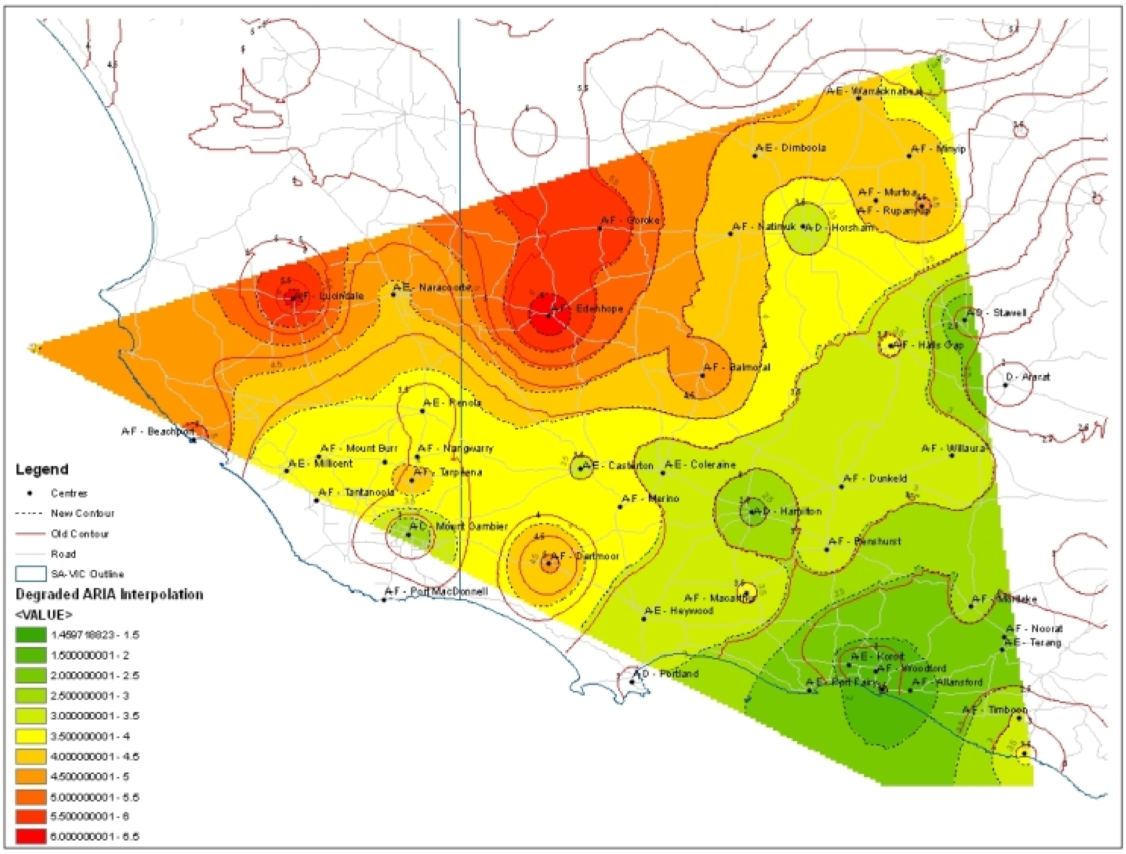

Figure 8 – ARIA indices with the degraded link of Glenelg Highway near Hamilton

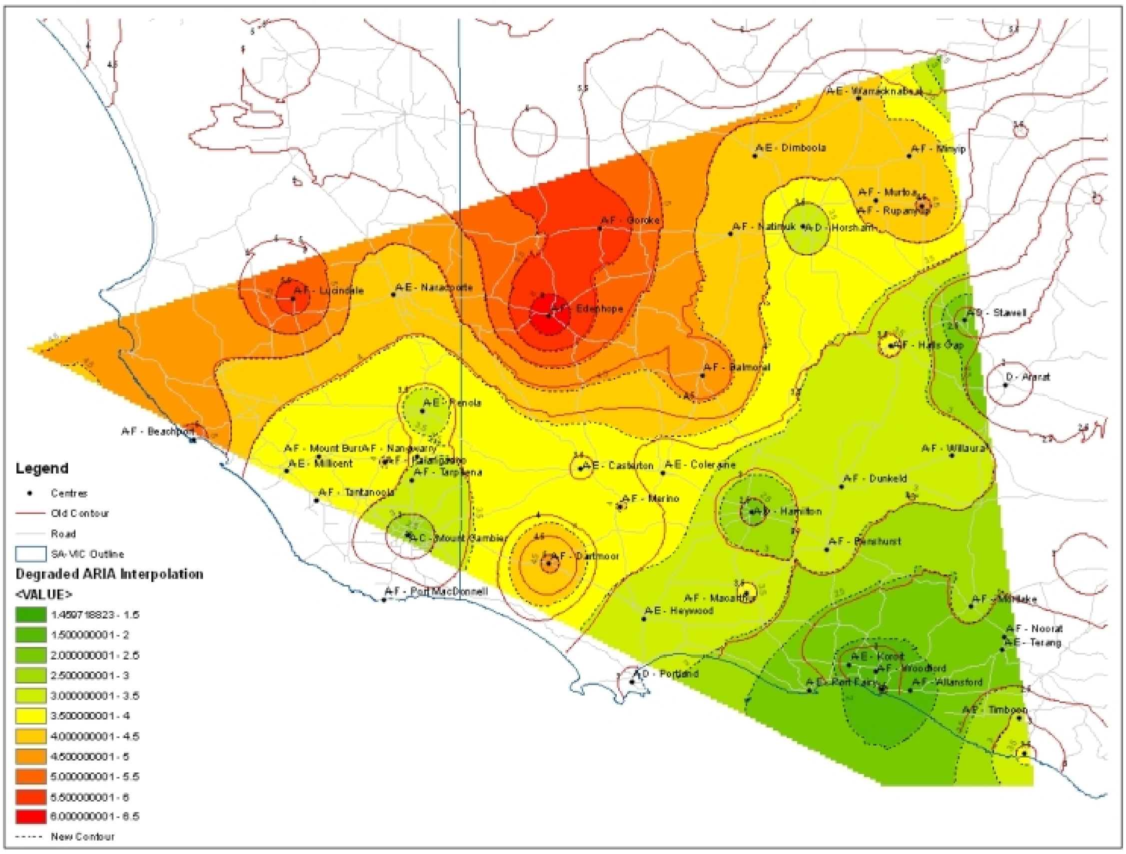

Figure 9 – ARIA indices with the degraded link of Tarpeena–Penola Road near Mount Gambier

5 Conclusion

Since much of the research on transportation network reliability focuses on the urban road network problems where the big concerns are congestion and travel time variability, the study of road network vulnerability which analyses the social-economic consequences on the community, particularly in rural areas, may be more important. In most of the methods of determining road network vulnerability studied, the differences between a road vulnerability index in the full network and that in the degraded network. In conjunction with the previous study, one of the road network vulnerability measurements is the use of the accessibility approach. By considering the changes in accessibility using both the Hansen index and the ARIA index, this study concluded that the most critical link in the Green Triangle Region is the short link in the Glenelg Highway near Dunkeld. The closure or degradation of this link affected almost all of the centres in the region and increased the Dunkeld ARIA indices by more than 57%. In addition, the short sections of the Glenelg Highway near Hamilton and Casterton were identified as the second and the third most critical links in the region. This is due to the severe socio-economic consequences of closure or degradation of those links. In general, the other candidate links also gave large impacts for the adjacent centres but the impacts were local and quite small.

In terms of assessing the road vulnerability in the Green Triangle region, the most appropriate measurement is to use the ARIA index changes. It is due to the characteristic of the ARIA index which provides the aggregate value. Then the Hansen index is less appropriate in assessing the vulnerability road network because it is better suited to studies of large population centres. The other finding is the development of a new method for measuring the regional road network vulnerability: this study suggested identifying the ARIA index contour patterns then the three dimensional effect of link degradation can be figured.

5.1 Further research

As the network vulnerability research was only developed within the last decade, this study only focus on the accessibility indices changes under the static conditions. This means that the study only considered the changes of the minimum shortest path matrices and the serviceability of road network; however it ignores the availability of the information to road users and road user behaviour under uncertainty condition. Additionally, this study also built on the idea that all of the road networks can cope with the increased demand due to the diverting routes. This is reasonable in uncongested networks of the type found in the Green Triangle region, but may not be so in more congested areas.

Moreover, this study did not also take account the increases of travel time when the road user can not receive sufficient information therefore the road user needs additional extra time to reverse and to find the alternative road. For further discussion, the increase of travel time and cost due to the different degree of road user information can be taken into account in the measurement of the accessibility indices, for both the Hansen and the ARIA indices.

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Appendix 1 –ARIA and Hansen indices for the full network

Service Centre	ARIA Index	Hansen Index	Green Triangle Region
A - Adelaide	0	1.726	
A - Melbourne	0	4.318	
B - Ballarat	0.294	6.843	
B - Bendigo	0.355	5.601	
B - Geelong	0.186	10.402	
C - Mount Gambier	2.479	2.316	✓
C - Warrnambool	1.457	3.295	✓
D - Hamilton	2.374	3.072	✓
D - Horsham	3.105	3.09	✓
D - Portland	2.962	2.581	✓
D - Stawell	2.141	3.771	✓
E - Casterton	3.452	2.694	✓
E - Coleraine	3.089	2.877	✓
E - Dimboola	4.021	2.932	✓
E - Heywood	3.089	2.708	✓
E - Koroit	1.924	3.431	✓
E - Millicent	3.617	2.268	✓
E - Naracoorte	4.057	2.374	✓
E - Penola	3.265	2.448	✓
E - Port Fairy	2.252	3.2	✓
E - Terang	2.107	3.982	✓
E - Warracknabeal	4.026	2.911	✓

Service Centre	ARIA Index	Hansen Index	Green Triangle Region
F - Allansford	1.848	3.921	✓
F - Balmoral	4.772	2.862	✓
F - Beachport	5.099	2.143	✓
F - Dartmoor	4.551	2.594	✓
F - Dunkeld	3.322	3.423	✓
F - Edenhope	6.254	2.561	✓
F - Goroke	5.826	2.693	✓
F - Halls Gap	3.523	3.532	✓
F - Kalangadoo	3.99	2.352	✓
F - Lucindale	5.663	2.223	✓
F - Macarthur	3.563	2.95	✓
F - Merino	3.978	2.711	✓
F - Minyip	4.376	3.094	✓
F - Mortlake	2.645	3.919	✓
F - Mount Burr	3.851	2.295	✓
F - Murtoa	4.056	3.232	✓
F - Nangwarry	3.442	2.38	✓
F - Natimuk	4.316	2.997	✓
F - Noorat	2.326	3.983	✓
F - Penshurst	3.204	3.272	✓
F - Port Campbell	3.625	3.733	✓
F - Port MacDonnell	3.831	2.359	✓
F - Rupanyup	4.548	3.269	✓
F - Tantanoola	3.658	2.341	✓
F - Tarpeena	3.376	2.323	✓
F - Timboon	3.048	3.905	✓
F - Willaura	3.435	3.686	✓
F - Woodford	1.878	3.856	✓

Appendix 2 – Changes in Hansen indices for several degraded links

Feature Name	Penola - Tarpeena Road	Casterton - Penola Road	Glenelg Hwy near Dunkeld	Glenelg Hwy near Hamilton	Glenelg Hwy near Casterton	Glenelg Hwy between Coleraine & Hamilton	Henty Hwy between Hamilton & Heywood	Princes Hwy near Kingston	Princes Hwy near Millicent	Western Hwy
A-C - Mount Gambier	0.561		2.366	0	0.042	0.042				0.042
A-D - Hamilton			3.976	0.195			0.189			
A-D - Stawell			0.243				0.025			
A-E - Casterton		0.699	2.826	3.452	19.937	3.126	0.067			3.126
A-E - Coleraine			3.228	10.949	0.162	0.162	0.106			0.162
A-E - Heywood	0.295		1.324				1.705			
A-E - Millicent		0.003	1.915		0.003	0.003		0.994	0.89	0.003
A-E - Naracoorte	0.463	0.294	0.012	0.21	0.294	0.189				0.189
A-E - Penola	1.348	6.701	2.193	2.539	6.727	2.239				2.239
A-E - Port Fairy			0.029	0.125						
A-F - Balmoral			6.567		0.109	0.109	0.075			0.109
A-F - Dartmoor	0.424		2.844							
A-F - Dunkeld			3.524				0.082			
A-F - Edenhope			0.202	0.078	0.196		0.043			
A-F - Kalangadoo		1.824	2.05	1.828	1.824	1.824				1.824
A-F - Lucindale	0.27	0.607	0.255	0.449	0.607	0.416		0.556		0.416
A-F - Macarthur			0.389	0.169			0.057			
A-F - Merino		0.491	2.969	0.406	0.491		0.081			
A-F - Mount Burr		1.348	1.983	1.351	1.348	1.348		0.928		1.348
A-F - Nangwarry	3.277	1.915	2.066	1.953	1.944	1.944				1.944
A-F - Natimuk					0.053	0.038	0.037			0.038
A-F - Penshurst			0.526	0.092			0.025			
A-F - Port Campbell				0.027						
A-F - Tarpeena	7.792		1.979	0.04	0.044	0.044				0.044
A-F - Willaura			0.754				0.042			

Appendix 3 – Changes in ARIA indices for several degraded links

Feature Name	Princes Hwy near Kingston	Princes Hwy near Millicent	Casterton - Penola Road	Glenelg Hwy near Dunkeld	Glenelg Hwy near Hamilton	Glenelg Hwy (Casterton - Hamilton)	Glenelg Hwy near Casterton	Western Hwy	Penola Road - Tarpeena	Henty Hwy	Dartmoor - Hamilton Road	Hamilton Hwy	Princes Hwy (Terang – Camperdown)	Princes Hwy near Warrnambool
C - Mount Gambier				4.67					1.02		0.902			
C - Warrnambool												1.204		
D - Hamilton				6.27										1.52
D - Portland				0.93						0.9				
E - Casterton				4.31	21.29	4.67	21.29							
E - Coleraine				4.82	2.89	29.15	2.89							
E - Dimboola								16.95						
E - Heywood				3.07						3.27				
E - Millicent	1.18	5.638												
E - Naracoorte									9.863					
E - Penola			6.16	3.559	6.19	2.15	6.19		12.198					
E - Port Fairy												0.974		
E - Terang													3.684	
F - Allansford													0.688	
F - Balmoral				5.345	2.03		2.03							
F - Beachport		3.809									0.005			
F - Dartmoor				3.274							2.544			
F - Dunkeld				57.337										2.489
F - Edenhope					8.19		8.19							
F - Goroke		6.227							0.387					
F - Kalangadoo	0.77		1.374	2.91	1.37	1.37	1.37							
F - Lucindale									7.031					
F - Macarthur				0.185								0.676		
F - Merino				3.745	0.467	0.71	0.467							
F - Mount Burr	0.96		1.07	2.49	1.07		1.07							
F - Nangwarry			1.657	3.37	1.682	1.68	1.682		13.148					
F - Natimuk					2.23		2.23							
F - Noorat				0.2									3.653	
F - Penshurst												0.752		3.168
F - Port MacDonnell				3.03					0.22		0.606			
F - Tantanoola	1.01	14.43		3.17							0.616			
F - Tarpeena				3.442	0.089	0.04	0.089		27.37					
F - Woodford												1.168		