Adapting to climate change – implications for transport infrastructure, transport systems and travel behaviour

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Abstract

This paper reviews land based transport related issues from considerations of climate change adaptation in Australia. The two main issues for climate change adaptation are sea level rise and the increased frequency and intensity of extreme weather events. These issues are considered in the paper. It considers the risks to existing transport infrastructure and the resulting considerations necessary in planning new infrastructure, transport systems operations under changing climatic conditions, and potential changes in travel behaviour. The use and capability of regional rural networks in emergency evacuation planning emerges as one particular area for further research. More generally, recognition of the risks associated with climate change is required for better planning of new infrastructure and mitigating potential damage to existing infrastructure. Climate change poses a significant risk to infrastructure and its owners, managers and operators. There is a need to undertake research into the likely impacts of climate change on Australia's transport infrastructure, establish the categories of infrastructure most at risk and outline opportunities for adaptation responses, and examine the current governance structures. Then the administrative, legal and other issues that may impact on climate change adaptation can be identified.

1. Introduction

Scientific evidence identifies climate change as a serious global risk that requires immediate response from the global community (Stern 2006; Chapman 2007; IPCC 2007a, 2007b, 2007c; Garnaut 2008; Ball 2009). The extended effects of climate change and the actions required to adapt to the evolving conditions will change the way individuals, communities and businesses function. Climate change needs to be addressed using a combination of mitigation and adaptation measures along with technological advances. Rigorous mitigation efforts are presently required to reduce the severity of future consequences to the climate (Stern 2006; IPCC 2007b). However, despite these actions, some degree of climate change is now unavoidable regardless of future reductions in emissions (IPCC 2007b). As a result, adaptation strategies are integral in climate change policy, not only to minimise the expected negative impacts but to capitalise on any supplementary benefits from climate change (Jaroszweski et al. 2010).

The Australian Federal Government has identified infrastructure as one of the national priorities for adaptation action (CoA 2010a). The key purpose for this precedence is to ensure that the owners and operators of nationally significant infrastructure, such as transportation infrastructure, provide continued and uninterrupted functioning of these assets, which are critical in supporting the national economy (CoA 2010a). Climate change poses a significant risk to infrastructure and its owners, managers and operators (and, perhaps, users). The interconnectivity of urban systems means that negative impacts on one system could influence the functioning of another. Negative impacts on transport infrastructure have been shown to generate one of the widest spread set of implications across the functioning of various urban systems (Jollands et al. 2007).

Recognition of the risks associated with climate change is required for better planning of new infrastructure and mitigating potential damage to existing infrastructure. There is a need to undertake research into the likely impacts of climate change on Australia's transport infrastructure, establish the infrastructure most at risk and outline opportunities for adaptation responses, and examine the current governance structures. Then the administrative, legal and other issues that may impact on climate change adaptation can be identified.

This paper identifies the possible impacts of climate change relevant to the physical environment in which land based transportation systems operate and the possible risks and implications for land based transportation infrastructure in Australia resulting from climate change.

2. Climate change in Australia

2.1. Observed climate changes

The Bureau of Meteorology has been collecting climate data across Australia for over 100 years (CSIRO & BOM 2010). The analysis of this significant data set has revealed long term trends and changes in the climatic observations around Australia. These analyses depict the changing nature of the Australian climate and illustrate the fact that climate change is not simply a future problem, but an issue that is already affecting the environment with impacts on human systems. Observed changes that have possible long term implications for land based transport infrastructure include (CSIRO & BOM 2007, 2010):

- the mean temperature across Australia increased by 0.7^{o}C over the last 50 years. The regional variation of this trend was significant with some observed temperature increases recorded between 1.5 to 2^{o}C over the same time period. This was compounded by an increasing number of hot days and decreasing number of cold days being recorded over the 50 year period. 2000-09 is Australia's hottest decade on record
- changes in rainfall patterns have also been observed in Australia over the last 50 years. In northern and central Australia rainfall tended to be increasing, whereas in southern and eastern Australia the tendency is for decreasing rainfall
- Australian sea level monitoring observed an average increase in sea level by around 10cm from 1920 to 2000. More recently, in the period 1993 to 2009, Australian sea levels rose by 1.5 to 3mm per year in southern and eastern Australia compared to 7 to 10mm in northern and western Australia.

2.2. Predicted climate changes

In order develop appropriate long term adaption strategies, it is necessary to understand the long term predicted changes in the climate and the corresponding changes in the biophysical environmental that may impact on land based transport infrastructure. The science of predicting future climate change is relatively uncertain and relies on various models, assumptions and scenarios to generate indications of the future state of the climate. The impacts discussed are indicative of the changes that may occur with climate change. The predicted changes for the Australian climate can be summarised from the leading climate science as (McLean et al. 2001; Nicholls & Lowe 2004; CSIRO & BOM 2007; Nicholls 2008; Maunsell 2008; Monash 2008; Koetse & Rietveld 2009; CSIRO & BOM 2010):

- the climate models predict an increase in the severity and frequency of extreme events. Monash (2008) in a background study on the effect of climate change on extreme events for Garnaut (2008) defined extreme events as '*infrequent events at* *the high or low end of a particular climate or weather variable that is rare*[1] *at a particular place and time of year'*. These extremes include temperature extremes including heatwaves and frosts, heavy rainfall, drought, floods, hail, thunderstorms, tropical cyclones, bushfires, and extreme winds

- by 2030 average temperatures are predicted to increase from 0.6 to 1.5°C from present. Temperature increases are expected to vary regionally with lower increases near the coast and larger increases in central and north-western Australia. Climate models also predict statistically significant decreases in cold days and nights, decreases in frost days and cold spells, and increases in extremely warm nights. This corresponds to an increase in the frequency and length of drought periods especially over southern Australia
- the number of days with no precipitation is expected to increase in the future, corresponding to a decrease in mean rainfall across Australia. However, it has been predicted that there will be an increase in intense rainfall events in many areas. Climate projections also predict precipitation change in the form of decreased snow cover, shorter season lengths, decreased peak snow depths and changes in the timing of snow seasons
- the global average sea level is predicted to rise by 18 to 59cm by 2100. The melting of ice sheets could potentially contribute a further 10 to 20cm rise. Sea level rise and the associated increase in the frequency and intensity of storm surges and flooding incidences are perhaps among the most worrying consequences of climate change due to the tendency in Australia for concentrated populations in close proximity to the coast. Sea level rise has a number of related biophysical impacts on coastal areas, resulting in inundation, flood and storm damage, wetland loss and changes, erosion, salt water intrusion, rising water tables which in turn impede drainage, and a decline in soil and water quality
- corresponding to warmer temperatures, evaporation is predicted to increase. Combined with reduced precipitation it is expected that soil moisture is likely to decline over southern Australia
- climate models predict increased wind speeds in most coastal areas
- the predicted weather conditions result in a substantially higher fire weather risk, culminating with increased frequency of bushfires over a wider area
- solar radiation is predicted to increase moderately in southern Australia especially in winter and spring

With increased frequency of extreme events it is more possible for concurrent climate extremes to occur, increasing the impact that would result from a single extreme event, for example (Nicholls 2008; Monash 2008):

- extreme winds accompanied by extreme rainfall. The rainfall weakens the hold of tree roots, increasing the likelihood that the tree would be uprooted in heavy winds
- extreme winds and high sea levels have the potential to significantly increase the risk of coastal inundation.

There has been a lack of research into the risks and frequency of these joint climate event occurrences or to estimate the costs and impacts of concurrent events compared to singular events (Monash 2008).

[1] Rarer than the 10th or 90th percentile of the observed probability density function

3. Implications for transport systems

To date, there has been surprisingly little research conducted in the public domain on the impact of climate change on transportation systems, despite the likely widespread implications for economics, design, materials specifications, operations, maintenance, planning, liability and insurance, user behaviour and emergency evacuation, transport network and vehicle function. The actual impacts of climate change on transport infrastructure will differ depending on the particular mode of transportation, its geographic location and its condition (Suarez et al. 2005). The possible implications of climate change on land based transport infrastructure are discussed in the following sections.

3.1. Infrastructure design, materials selection, operations and maintenance

The predicted climate changes outlined in Section 2 may push environmental conditions beyond the range for which transport systems and infrastructure were designed to handle. This in turn could necessitate changes in design, materials, and operating and maintenance practices. The relatively long design life of transport infrastructure means that the infrastructure designed today will need to be able to resist climatic pressures and extremes in 50 or 100 years from now (TRB 2008; Meyer 2010; CoA 2010a). However, adaptation of infrastructure is likely to only occur as structures reach the end of their design life, as such maintenance and operations impacts on existing infrastructure also need to be considered.

The potential impacts on infrastructure from climate change in Australia can be summarised as (USDOT 2002; Austroads 2004; CSIRO 2006; ATSE 2008; TRB 2008; Maunsell 2008; Evans et al. 2009; Jaroszweski, Chapman & Petts 2010; Meyer 2010):

- temperature extremes increase the expansion stress and movement experienced on steel bridges and rail tracks, and also cause the expansion of concrete joints, protective cladding, coatings and sealants on bridges. Higher temperatures combined with increased solar radiation may reduce the life of asphalt road surfaces through an increase in the embrittlement of the surface chip seals that represent more than 90 per cent of the rural sealed roads in Australia. Embrittlement causes surface cracks to form such that water can infiltrate the road surface resulting in potholes and rapid loss of surface condition. Increased maintenance would be necessary to manage this phenomenon. High temperatures also result in the softening of asphalt and may lead to traffic related rutting. Pavement can also buckle under extreme temperatures. Temperature extremes and the general warming of the climate may also limit the undertaking of maintenance and construction activities due to heat stress conditions for workers. The increased number of hot days is expected to have minimal impact on pavement or structural design in the short term (30 to 40 years), however a significant change would be required long term (40 to 100 years) on pavement and structural design, the substitution of materials, and a higher level of maintenance service

- decreased precipitation, especially in southern Australia, has the potential to result in increased ground movement, changes in the watertable and associated increases in the salinity of soils. The combination of these changes has the potential to accelerate the degradation of materials, structures, reinforcement and foundations, reduce the life expectancy of the transport infrastructure, increase maintenance costs and may eventually contribute to structural failure when stressed by extreme climate events. Significant flood damage to road, rail, bridge and tunnel infrastructure may result from the increased frequency and intensity of extreme rainfall events. The magnitude and frequency of floods also plays an important role in the design and planning of land based transport infrastructure. The short term impacts of precipitation changes relate to pavement and drainage design, foundation conditions, the approach used to estimate the design flood and the development of targeted maintenance schemes. Longer term impacts may require changes in culvert design and the design and materials specifications of road subgrade

- sea level rise and the increased potential for storm surge may affect transport infrastructure in coastal areas. Tunnels and culverts are particularly prone to damage due to increased tidal and salt gradients, ground water pressure and corrosion of materials. In order to adapt to predicted sea level rise short term design changes are required to bridge height in vulnerable areas and the approach to predicting, planning and designing for storm surges. Over the long term in response to greater inundation of coastal areas there may be a requirement for setting more rigorous design standards for flooding and construction of infrastructure in saturated soils, and changes in materials specifications to cope with the corrosive nature of the coastal environment
- bridges are susceptible to the predicted increase in coastal winds. Increased coastal wind requires action in the short term to update design factors for design wind speeds and testing of infrastructure designs under more turbulent conditions. Over the long term, current bridge construction materials may need to be substituted for those with greater strength. Some research also indicates that the hot, dry conditions are likely to increase drying and loosening of unsealed road surfaces and when combined with increased wind there exists the potential to increase dust storms impacting usability of the road and resulting in additional maintenance costs, environmental impacts through the smothering of vegetation, and social impacts due to dust infiltration of residential properties.

3.2. Economic

The direct economic costs associated with the impact of climate change on land based transportation systems relate to the monetary cost of repairing or rebuilding damaged infrastructure. Analysis of direct disaster costs on a global scale has shown that the annual direct losses from significant natural catastrophes increased over 10 times from the 1950s to the 1990s, with these costs inflated by another factor of two when damage from lesser weather events are included (MunichRe 2000; Auld et al. 2006). In the Australian context, a review of natural catastrophes between 1980 and 2008 showed that for the decade 1999 to 2008 insured losses were approximately $US7 billion, almost doubling the losses recorded for the previous two decades (MunichRe 2009). Climate change has been identified as one contributing factors to increasing event costs, along with population growth, urbanisation of vulnerable regions, the concentration of population and assets, improved living standards, vulnerability of modern technology systems and societies reliance on uninterrupted service, increased insurance, and global networking (e.g. tourism) (Auld et al. 2006; Monash 2008; MunichRe 2010). The greatest public costs have been found to be related to disaster assistance, and road maintenance, relocation and repair (Middlemann 2007).

Aside from the direct costs related to infrastructure damages, substantial indirect costs are likely to be experienced due to network effects including costs due to delays, losses from toll roads, freight supply interruption, detours and trip cancellations (Middlemann 2007; Maunsell 2008; Koetse & Rietveld 2009).

3.3. Planning

As climate change alters the biophysical environment and impacts on the environmental serviceability of urban systems, planning principles and practice will play an important role in adaptation to climate change complementary to the design, maintenance and operation of transport infrastructure. Land use planning can provide a powerful tool to help reduce the loss of life, property, and assets. Aside from the effects of climate change, Section 3.2 identified the causes of increased costs due to natural disaster damages which included the urbanisation of vulnerable regions and the tendency for concentrated population and asset centres (Auld et al. 2006; Monash 2008; MunichRe 2010). Through efficient planning the threat of climate change impacts to transportation systems can be minimised by separating infrastructure and the associated population and resources in high risk areas such as floodplains and coastal zones threatened by inundation.

Brown et al. (1997) provide an example of efficient planning to reduce the impact of flooding associated with extreme storm events. This study compared the impacts from storm events in Michigan, USA and adjacent Ontario, Canada. The comparison found that non-agricultural flood damage in Michigan exceeded the damage in Ontario by a factor of approximately 900, despite the fact that the flood magnitudes experienced in Ontario were greater than Michigan. Further analysis revealed that this was due to the differences in land use planning systems applied in the two cities, where Michigan had a lower design threshold for residential development in flood prone areas. This example demonstrates how land use planning can significantly reduce the impact and damages related to climate change, and how Australian planning systems need to evolve in response to climate change (as well as concurrent changes in demographic and settlement patterns).

3.4. Liability and insurance

The increasing frequency and severity of extreme climate events impacting on land based transport infrastructure has the potential to produce a corresponding increase in the risk of potential accidents involving property damage, injuries and fatalities (CSIRO 2006; Middlemann 2007; Maunsell 2008). This impact will in turn increase the potential liability and insurance costs to transport authorities, managers, operators and owners.

CSIRO (2006) conducted an infrastructure and climate change risk assessment for Victoria and determined that *'it is the ultimate owner of any piece of infrastructure who must ensure that it is designed to operate effectively for its design life, since they will bear the primary liability in the event of failure'*. This study also found that many of the risks identified for land based transport infrastructure, inclusive of those listed in Section 2, are covered under existing insurance arrangements. Insurance and financial markets disperse the risks of climate change impacts across a wide base of industries, communities, regions, and countries, moderating the losses experienced by particular groups of people (Garnaut 2008). The dilemma lies in the likelihood that as the understanding and occurrence of climate change impacts increases, insurers may act to reduce their potential exposure through limitations in event coverage. If insurance claims greatly increase as a result of severe weather events, then highly correlated risks across regions may overwhelm the ability for the industry to provide insurance coverage (Garnaut 2008). Land use planning mechanisms as described in Section 3.3 may act to improve insurability and minimise pressure on the insurance sector.

3.5. User behaviour

There also exists the potential for climate change to impact on the way people use transportation infrastructure with shifts in demand in response to climate factors, and in their travel behaviour.

Climate change may result in shifts in demographics as currently populated areas become less desirable, changes in tourism markets and production and industries shift according to the impacts of climate change, such as excessive heat or coastal inundation (USDOT 2002; TRB 2008; Koetse & Rietveld 2009). These shifts in turn have implications on transport demand and patterns, infrastructure maintenance and operation on a local, regional and global scale.

Travel behaviour also varies according to weather conditions. Research has revealed that an overall reduction in traffic volume in Melbourne of 2 to 3 per cent occurs in response to 2 to 10mm of rain during daytime, with reductions in spring somewhat larger than those in winter

(Keay & Simmonds 2005). Increased extreme precipitation events therefore may periodically increase pressure on alternative transport modes. Adverse weather conditions are also a recognised risk factor known to affect crash rates in Australia (Rowland et al. 2007; Koetse & Rietveld 2009). Rain and wet road conditions have been found to be significant contributors to road fatalities and crashes as a percentage of the total road toll in Australia (Rowland et al. 2007). This correlation suggests that the changes in driver behaviour under adverse conditions are insufficient to account for the resultant hazards such as reduced road/tyre friction, loss of vehicle control and poor visibility (Edwards 1999; Unrau & Andrey 2006). Koetse and Rietveld (2009) summarised that adverse weather conditions resulted in substantial reductions in traffic speed, travel time and travel time reliability. Stern and Zehavi (1990) also found substantially increased risk of an accident, particularly in single vehicle accidents, under heat stress conditions induced by extremely hot days and heat waves. The increased risk for bushfires may also alter driver behaviour due to a reduction of visibility due to smoke (TRB 2008). Driver education and increased deployment of advisory systems have the potential to provide an adaptation mechanism for user behaviour in the changing climate conditions.

3.6. Emergency evacuation, transport network and vehicle function

As discussed in the previous section, climate change will affect the function of traffic systems by reducing traffic speed and volume, increasing travel time delay, and decreasing roadway capacity. The functioning of traffic systems will be further hampered by the impact of climate change conditions on the efficiency and functioning of vehicles. Increased temperatures are predicted to result in more vehicle overheating and breakdowns, and lead to faster tyre deterioration resulting in blow outs, thereby further increasing traffic disruptions (TRB 2008; Evans et al. 2009; Jaroszweski et al. 2010).

Predicted increases in hot days and heat waves attributed to climate change are likely to impact on vehicle efficiencies. Warming conditions are proposed to lower engine efficiency resulting in increasing fuel use, which is amplified further by the increased use of air conditioning in vehicles (TRB 2008; Evans et al. 2009).

A robust transport network is required to offer alternative travel paths to ensure the effective functioning of systems. In urban settings there tends to exist access to alternative paths, in rural settings however the road networks are sparser with fewer good quality alternative roads. The failure of one particular link within a rural road network potentially has significant effects on the community (Jenelius et al. 2006; Susilawati & Taylor 2008).

A robust transport network is essential in order to accommodate emergency services and planning particularly with respect to emergency evacuations. The increasing occurrence and severity of extreme weather events including cyclones, coastal inundation, bushfires and floods may result in the increased frequency of evacuation potentially over larger areas, with risks exacerbated by increasing populations in exurban areas, and especially in coastal zones. In the past there has been little research focussed on increasing the efficiency of evacuation due to the low demand for evacuations and the perception that the evacuation of a major city would create demands that would overwhelm the capacity of the transport infrastructure (Wolshon & Meehan 2003). Past and present practice has tended to disregard evacuation considerations in transport planning, design and analysis.

In 1999, Hurricane Floyd triggered the third largest evacuation in US history when 2.6 million coastal residents of five states were evacuated as the hurricane approached (Wolshon & Meehan 2003). The issues apparent during this evacuation caused the realisation of the importance of improving evacuation operation, and since there has been increased emergency evacuation research and planning in the USA (e.g. Fu & Wilmot 2004), although the experiences from Hurricane Katrina suggested that much remains to be done (e.g. Litman 2006; Lindell & Prater 2007). Research on transport implications remains limited.

Wolshon and Meehan (2003) summarised some of the practices that can be applied to traffic systems to increase evacuation efficiency:

- contraflow strategies, where lanes and shoulders are reversed to increase conveyance in the dominant direction, have been shown to potentially increase the outbound volume by approximately 70 per cent. Similar strategies can also be applied to assist in maximising evacuation flow including coordination of traffic signals on parallel arterial roads, use of public transport systems especially to assist low mobility community members, and limiting interruptions to flow at rail crossings and drawbridges
- deployment of intelligent transportation systems in urban areas, and supplementary advisory services to assist rural areas in order to inform drivers of the most efficient evacuation routes as conditions change
- removing any limitations imposed in road work areas to minimise delays

4. Developing adaptation responses

In developing adaptation strategies it is critical to understand what the fundamental objective of adaptation is, not only for transportation infrastructure and systems, but for the population as a whole. The concept of resilience has been growing in momentum as the desired overall outcome for climate change adaptation of human systems. Resilience is a concept borrowed from ecological systems, and has been defined in the context of urban systems as the capacity to accommodate, or successfully adapt to external threats such as the impacts of enhanced climate change (Hamin & Gurran 2009). Adaptation strategies are one of the tools required to reduce the vulnerability of urban systems to external threats, thereby limiting the impacts of climate change. For land based transportation systems, vulnerability must consider 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 (Sohn 2006; Taylor 2008; Freeman et al. 2009).

The implications of climate change for transportation systems discussed in this paper are provided in the general Australian context. The actual impacts of climate change are likely to have considerable variation on a regional and local scale. Adaptation measures will have to take this spatial variation into account with localised approaches. This however requires an understanding of localised impacts which in turn requires a framework for risk assessment of land based transportation infrastructure under climate change. Decision support tools are needed that allow planners and policy makers to assess the threats to infrastructure, the consequences of network degradation and failure at various locations and under different circumstances, and what to do about these (Taylor & D'Este 2005). Vulnerability assessments are proposed to provide the information necessary to make practical decisions for adapting transport infrastructure to climate change at the appropriate spatial scale. The origin of vulnerability assessments lies in impact assessments and hazard research, and has been recently applied to map potential climate change impacts and to develop strategies to facilitate adaptation (Fussel & Klein 2006; Naess et al. 2006). Assessment and prioritisation of adaptation strategies should be conducted considering both the costs and benefits of the economic investment required, with respect to the consequences arising from accessibility restrictions imposed by loss of transport links (ATSE 2008).

As discussed in Section 3.4, it is the ultimate owner of any piece of infrastructure who must ensure that it is designed to operate effectively for its design life, since they will bear the primary liability in the event of failure (CSIRO 2006). Responsibility for transport infrastructure in Australia is decentralised and shared between the public and private sectors. The control and expertise required for making decisions regarding climate change adaptation measures for land based transportation infrastructure are therefore dispersed among multiple levels of government, various authorities and interest groups. These factors raise governance issues with respect to the development of adaptation strategies. Governance is the term used here to refer to the political and legal structures and mechanisms used to manage and coordinate transport systems, how they interrelate, how resources are allocated and outcomes are achieved. The current governance structures that exist in Australia with implications for transport infrastructure can be summarised as (CoA 2010a, 2010b):

- the Australian Federal Government has stewardship of the national economy and broad interests. As climate change will impact on virtually every sector of the economy and society, the federal government must perform a leadership role in adapting Australia to the climate change impacts with direct implications for the economy and Australia's security. With respect to transportation systems, the federal government has specific interests in major land transport networks in relation to their contribution to the productivity of the nation. Input required will be a combination of direct actions, including the management of federal transportation assets, and indirect efforts through the coordination of national reform effort. State, territory and local governments deliver more direct services and manage more assets than the federal government, and as such will have to play a bigger role in direct adaptation actions
- State and Territory Governments are responsible for the majority of legislation related to climate change adaptation measures for land based transportation infrastructure. Metropolitan land use planning, the importance of which is discussed in Sections 3.3 and 3.4, and urban roads and transport have largely been the responsibility of state and territory governments. States and territories fund infrastructure mainly through transfers from the federal government but also from state taxes such as stamp duty
- Local Governments will be key actors in adapting to the local impacts of climate change and engaging in ground level works. Local governments generally have planning authority over land use zoning. Funds for local government to provide infrastructure are sourced from local land rates, and through levies and grants from the other two higher levels of government.

In September 2009 a workshop was conducted in the USA, bringing together transportation industry stakeholders from the states of California, Florida, Maryland, Missouri and Washington to discuss climate change adaptation and mitigation from a transportation perspective (AASHTO 2009). Discussions at the workshop revealed that regardless of jurisdiction, all transportation stakeholders were experiencing the same barriers to climate change adaptation and mitigation which were summarised as (AASHTO 2009):

- general lack of knowledge on the need to adapt infrastructure for climate change impacts and which adaptation methods should be applied
- governance and communication barriers that prevented cooperation between stakeholders and were in some cases causing agencies to work at cross purposes
- limited funding for planning and implementing adaptation measures

The generic nature of these barriers and the comparative nature in the governance, urban form and social structures between the United States and Australia suggest that these barriers are also likely to be present in the adaptation of Australian transport infrastructure to climate change (Luten 2006; Philp & Taylor 2010 *in prep*). The AASHTO workshop participants determined the following set of general approaches that were required to facilitate adapting transportation for climate change (AASHTO 2009):

- educate the transportation community about the importance of addressing climate change
- top level leadership is needed to provide clarity in policy direction

- climate change focussed partnerships should be developed across all governance levels and include private industry
- increased assistance and guidance is required to grow institutional capacity to deal with climate change
- synergies should be identified among goals and projects being undertaken across all governance levels and private industry
- develop new funding strategies

These approaches provide insight into the needs of the Australian transportation community in facilitating adaptation of land based transportation systems and infrastructure.

Each level of government has different responsibilities and therefore will play different roles in adapting Australian transport infrastructure to the impacts of climate change. Preparation to deal with climate change impacts will require a whole of government approach to adaptation planning, engaging all levels from federal to local according to the resources and capacity available and to empower private industry and individuals to facilitate the adaptation process (Monash 2008). The Council of Australia Governments (COAG) may be the appropriate governance pathway for facilitating climate change adaptation where a number of governments must act or for issues where national leadership is required. In December 2009 COAG agreed to a set of reforms for national criteria for capital city strategic planning with the aim to ensure there are long term plans in place to address issues such as climate change. The federal government intends to assess funding for future infrastructure decisions according to whether the criteria have been met in the jurisdiction in question.

5. Adaptation planning - defining a decision support system for evacuation planning

As discussed previously, the uncertainty of climate change acts as one of the barriers to long term adaptation. Decision support systems are designed to assist in planning decisions where future conditions are uncertain or can change rapidly. As such decision support systems can prove useful in adaptation planning, as shown in the following discussion with respect to evacuation planning.

A specification for a decision support system for emergency management and evacuation planning can be written as follows. For a simple macroscopic model that can provide planning guidance for the evacuation of people from threatened areas to safe designated shelters outside or inside the threatened area, the following model features are required:

- the simplicity of the model should not be achieved at the expense of reliable results and appropriate detail
- the model should be dynamic in updating both the state of the emergency and the levels of road access, traffic conditions, volumes, travel times and (if appropriate) queuing
- the model needs to include and provide realistic measures of intersection, link and network capacities. This must include specific realisation of the capacity and characteristics of traffic flow on two-way two-lane roads with restricted sight distances
- the model requires the capability to evaluate the impacts of future land use plans and population distribution and intensity on evacuation times and rates
- the model must include good representation of the behaviour of individuals

- the major application of the model is for strategic planning, based on scenario studies for different natural disasters (including intensity and location) under a range of environmental and meteorological conditions
- the model's outputs will be used to inform and assist the strategic planning processes in a locality, in conjunction with local knowledge and available professional expertise
- the model should be developed in a dynamic GIS software platform, including and integrating accurate road network, terrain and topography, land use and population, and vegetation, environmental and meteorological databases.

The vital position of dynamic GIS as the underlying software platform support for the model has already been identified, e.g. Ahola et al. (2007). Given the existence of comprehensive and accurate data on physical characteristics (e.g. terrain, topography, vegetation and environment), demographics and land use, infrastructure and facilities (e.g. road networks, water supply and electricity distribution), the GIS platform provides the means to integrate the databases and to host the different computational models. In addition, the road network model attached to the GIS is used to determine both shortest paths from inhabited zones to shelters and also 'second-best' paths. Similar path calculations would be made for use by emergency services when seeking to reach any specified locations. Path determination is done initially for the normal, full and intact network as the base case.

Disaster scenarios may then be simulated for different scenarios, using (in the case of bushfires) a model such as Phoenix (Tolhurst et al. 2008), to be run with different meteorological conditions and fire ignition points. The paths and impacts of the simulated fires can then be used to determine the likely consequences for the road network. Sohn (2006) has, for instance, used a similar approach to establish vulnerable links in a regional road network subject to flooding. In the case of bushfire modelling, the analysis would be undertaken from two perspectives. First would be the identification of likely 'weak spots' in the road network, being links and road sections most likely to be affected (i.e. degraded or closed) by fires. Second would be the identification of resilient links and road sections, being those parts of the network least likely to be affected by fires. That is, both network vulnerability and network resilience are important considerations. Outputs from the model would include *qualified* advice about most reliable evacuation routes – and access routes for emergency services. Qualification of the advice is necessary because of the significant stochastic variations in circumstances inherent in the natural disaster scenarios, e.g. Yuan et al. (2006), Murray-Tuite (2007).

A similar analysis approach could be adopted for flood scenarios. The NSW SES (Opper et al. 2009) has developed a conceptual model for flood evacuation assessment and planning. The estimation of evacuation timing and duration using this model would benefit greatly from a better understanding of the influence of human behaviour and of realistic road traffic capacity under flood conditions.

Traffic movements on rural road networks need to be studied and modelled with care, because of the unique nature of traffic flows on such roads. On this score, recent developments in traffic flow modelling for two-way, two-lane roads should prove useful in providing the necessary macroscopic traffic modelling capability. In particular the recent research in France (Laval 2006) and in The Netherlands (Hoogendorn 2005) is most useful.

The identification of vulnerable links in a network can be undertaken using the recently developed methods for network vulnerability analysis and the determination of critical locations, as described in Jenelius et al. (2006), Taylor (2008) and Susilawati and Taylor (2008). Modifications to the approach can be made to identify the most resilient links as well as the most vulnerable ones. It is likely that a combination of the criticality and importance metrics introduced by Jenelius et al. (2006) and the area-accessibility-based vulnerability analysis method described by Susilawati and Taylor (2008) – which is firmly embedded in a

GIS framework – should produce a valid and practical assessment methodology for network assessment.

Figure 1 outlines a decision support system designed to assist in planning for emergency management and evacuations in the face of a given hazard or natural disaster, based on the availability of models for predicting the intensity and trajectory of a given disaster[2] (e.g. the Phoenix model for bushfires, Tolhurst et al. 2008).

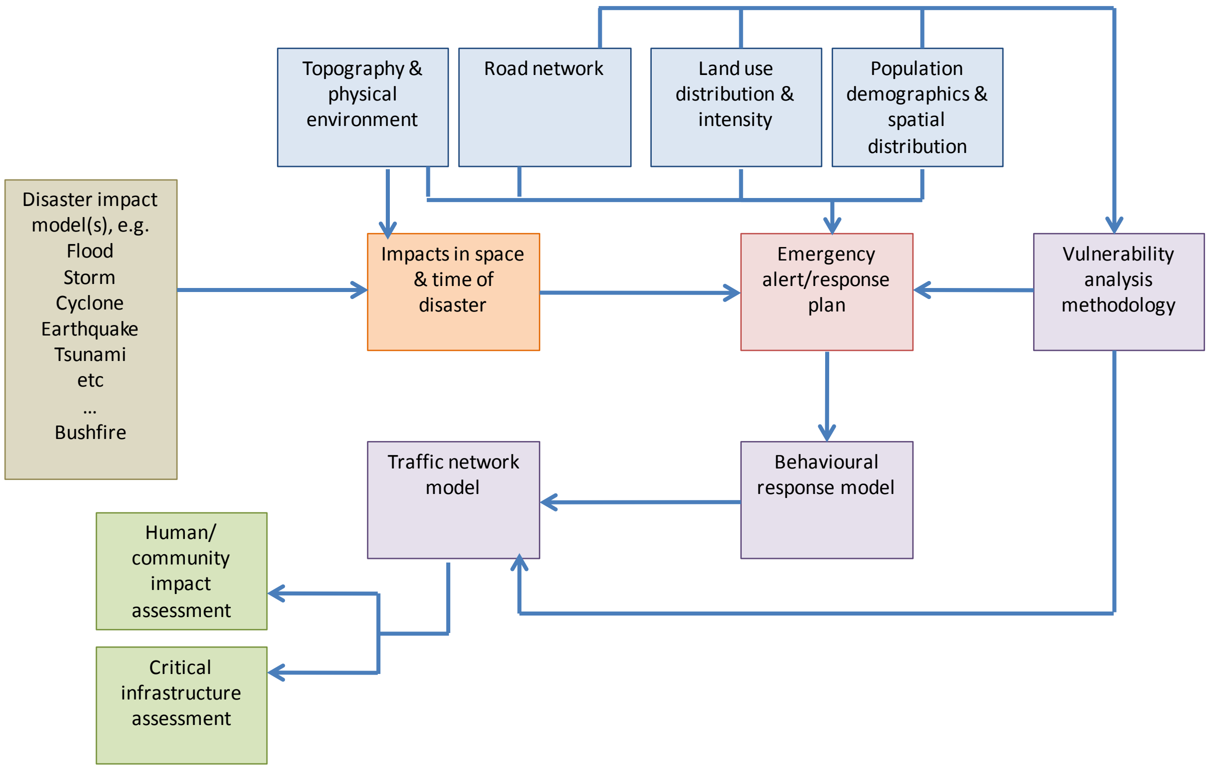

Figure 1: Proposed decision support system for transport aspects of emergency management and evacuation planning

6. Conclusions

This paper has outlined the observed and predicted impacts of climate change in Australia. These impacts have then been considered with respect to their implications for land based transportation infrastructure, systems and travel behaviour. Despite the number of assumptions used to estimate future climate trends, the indicative results clearly indicate a predominantly negative impact on transportation. Climate change will have transport specific implications related to design, material selection, operations and management; economic costs; planning systems; liability and insurance; user behaviour; and emergency evacuation, transport network and vehicle efficiencies.

The concept of resilience is proposed as the basis for the development of transport adaptation strategies for climate change. A vulnerability assessment approach is proposed as the method for considering 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, in order to plan and prioritise

[2] Noting that not all of the potential natural disasters are attributable to poor influenced by climate change. The decision support system could also be used to consider manmade interventions and disasters, such as terrorist attacks or explosions.

adaptation. Climate change is a global problem, with global impacts. However, climate change impacts with respect to land based transport infrastructure should be investigated at the local or regional scale for a number of reasons including the observations that climate change impacts will vary spatially and the uniqueness of transport infrastructure in each locality.

The decentralised nature of transportation infrastructure ownership, operations and maintenance, and the current governance structures may induce barriers to climate change adaptation. A unified approach is required to develop and implement effective adaptation strategies for Australian transportation infrastructure. This is surely an interest for COAG.

7. Acronyms

AASHTO	American Association of State Highway and Transportation Officials
ATSE	Australian Academy of Technological Sciences and Engineering
BOM	Bureau of Meterology
CoA	Commonwealth of Australia
COAG	Council of Australian Governments
CSIRO	Commonwealth Scientific and Industrial Research Organisation
IPCC	Intergovernmental Panel on Climate Change
TRB	Transportation Research Board
USDOT	United States Department of Transportation

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