and businesses function.
Climate change needs to be addressed using a combination of mitigation and adaptation measures along with technological

2007a, 2007b, 2007c;
imate change and the actions required to adapt
iduals, communities

The National Climate Change Adaptation Research Facility (NCCARF) is leading the research community in a 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 following 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; Lynch et al. 2008; Maunsell 2008; Nicholls, 2008; Koetse & Rietveld 2009; CSIRO & BOM 2010):

Changes in temperature and frequency of other extreme events

Climate models are predicting an increase in the severity and frequency of extreme events. Lynch et al. (2008) in a study on the effect of climate change on extreme events 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, heavy rainfall, drought, floods, hail, thunderstorms, tropical cyclones, bushfires, and extreme winds.

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 (Lynch et al. 2008; Nicholls 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 (Lynch et al. 2008).

By 2030 average temperatures are predicted to increase from 0.6 to 1.5^{o}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. There is an associated increase in the frequency and length of drought periods especially over southern Australia.

The predicted weather conditions result in a substantially higher fire weather risk, culminating with increased frequency of bushfires over a wider area.

Corresponding to warmer temperatures, evaporation is predicted to increase. Solar radiation is predicted to increase moderately in southern Australia especially in winter and spring. Combined with reduced precipitation it is expected that soil moisture is likely to decline over southern Australia.

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

Changes in precipitation

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.

Changes in sea level

Changes in temperature and frequency of other extreme events

Temperature extremes increase the expansion stress and movement experienced on steel bridges and rail tracks, and also cause the expansion of maintenance schemes. Longer term impacts may require changes in culvert design and the design and materials specifications of road subgrade.

Changes in sea level

Sea level rise and the increased potential for storm surge may affect transport infrastructure in coastal areas. Sea level rise in response to climate change is proposed to increase extreme water levels and wave heights, thereby increasing the potential for wave overtopping and flooding.

Port infrastructure as well as tunnels and culverts are particularly prone to damage due to increased tidal and salt gradients, ground water pressure and corrosion of materials. Sea level with respect to dock level is an important consideration for clearance of dock cranes and other structures. As such, any changes due to sea level rise could require some retrofitting of port infrastructure. As a result of climate change it is also predicted that the navigability of shipping channels is also likely to change. Some channels may be more accessible to shipping farther inland because of sea level rise others however, could be adversely affected by changes in sedimentation rates and the location of shoals.

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.

Changes in coastal winds

Airports, ports and bridges are highly susceptible to the predicted increase in coastal winds.

decade 1999 to 2008 insured losses almost doubled the losses recorded for the previous two decades (Munich Re 2009).

Climate change has been identified as one of the contributing factors to increasing event costs, along with (Auld et al. 2006; Lynch et al. 2008; Munich Re 2010):

- 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
- global networking e.g. tourism

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. Climate change adaptation measures must include planning to reduce vulnerability and/or increase resilience with respect to climate change through the development, analysis and revision of planning systems and practices. Land use planning can provide a powerful tool to help reduce the loss of life, property, and assets. Burch (2010) suggests that land use zoning is the single most powerful regulatory instrument, however the effectiveness of this tool is severely restricted through a lack of coordination between interdependent groups.

Aside from the effects of climate change, Section 3.2 identified the causes of increased costs due to natural disaster damages which included increased urbanisation and the expansion of urban areas into vulnerable regions with a likelihood of increasing exposure to risk (Auld et al. 2006; COAG 2007; Lynch et al. 2008; Munich Re 2010). The eventual impacts of climate change will vary depending on the form of the settlement, geographic considerations and the nature of the local economy (COAG 2007). 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 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 transport infrastructure and systems 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.

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. Climate change poses new challenges for these markets by widening the probability distribution of possible losses and increasing the severity of damages and payouts (Garnaut 2008).

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 transport infrastructure, inclusive of those listed in Section 3.1, are covered under existing insurance arrangements. 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).

Conventional insurance is of limited value when there are similar impacts over wide areas (e.g. sea level rise) or when uncertainty involves the timing rather than the extent of an impact. There may be a requirement for developing new insurance products using the principles of traditional life insurance i.e. life insurance covers the risk of timing of death, although the fact of eventual death is itself certain (Garnaut 2008). Land use planning mechanisms, as described in Section 3.3, may act to improve insurability and minimise pressure on the insurance sector. Insurance companies may also opt to provide adjustments to insurance premiums for risk reducing behaviour as incentive for households and businesses to actively take adaptation measures.

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, and tourism markets, 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.

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.

Emergency evacuations in Australia generally take place in response to natural disasters, most commonly for bush fires, floods, and occasionally cyclones (Taylor & Freeman 2009). Travel during evacuations is very different from the day to day travel used in conventional urban transportation planning due to a combination of factors, including long travel times, high levels of extended congestion, uncertainty of road conditions, and the possibility that destinations may change in response to conditions on route (Fu & Wilmot 2004). Evacuation rates are influenced by official orders as well as personal evaluations of a wide variety of risk factors including, but not limited to, demographic characteristics, risk sensitivity, social ties, information and perceived threat (Dow & Cutter 2002; Fu & Wilmot 2004; Taylor & Freeman 2009). Traffic flow during evacuations can be less than the normal daily commuting conditions with highway flow reduced because of evacuees' tendency to heavily load vehicles or to

- develop the ability to prioritise transport system resources when necessary to give priority to emergency and service vehicles
- design critical components of the transportation system to be fail safe, self correcting, repairable, redundant, and autonomous

Important research is required in emergency planning, management, response and recovery regarding cultural considerations associated with communicating warnings and response advice, governance

infrastructure projects (www.agic.net.au) in Australia may suggest a shift from the bottom up approach to an intermediate governance framework.

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.

Garnaut (2008) proposes that there should be direct government intervention by developing a national policy response in order to:

- facilitate understanding with respect to climate change, its impacts and the options available to respond
- develop capacity in the community to use this information to address climate change
- deal with events that are beyond the community's capacity to address
- use a market approach to create options for individuals and businesses to manage climate change risk

The

5 Developing adaptation responses for transport infrastructure

Garnaut (2008) states that one of the most significant adaptation challenges for the Australian community is to respond to the immense potential impacts of climate change on the basis of imperfect information. The total impact, distribution and damage due to climate change and its distribution strongly depends on the adaptive policy

5.2 Framework for adaptation planning

The implications of climate change for transportation infrastructure and 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 transport 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).

There

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 (Hoogendoorn 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

6 Conclusions and research requirements

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 transportation infrastructure, systems and travel behaviour. Despite the number of assumptions used to estimate future climate trends, the results clearly indicate a predominantly negative impact on transportation systems and infrastructure. 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 adaptation. Climate change is a global problem with global impacts. However, climate change impacts with respect to transport systems and infrastructure should be investigated at the local or regional scale for a number of reasons including the fact that climate change impacts

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