

Garnaut Climate Change Review

Impact of climate change on Australia's roads and bridge infrastructure

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1 Introduction

On 30 April 2007 Professor Ross Garnaut was commissioned by Australia's State and Territory Governments to undertake an independent study titled the Garnaut Climate Change Review (GCCR).

This review examines the impacts of climate change on the Australian economy and recommends medium to long-term policies to achieve sustainable prosperity and address key climate change issues.

The Terms of Reference provided by the States and Territories require the GCCR to report on:

- 1) The likely effect of human induced climate change on Australia's economy, environment and water resources in the absence of effective national and international efforts to substantially cut greenhouse gas emissions;
- 2) The possible ameliorating effects of international policy reform on climate change and the costs and benefits of various international and Australian policy interventions on Australian economic activity.

To achieve this, the GCCR Secretariat, established to facilitate the review, proposes to undertake an assessment of the impacts of climate change on a range of infrastructure types. Maunsell Australia Pty Ltd (Maunsell) was engaged by the Secretariat to identify and assess the impacts of climate change on road and bridge infrastructure in Australia.

The purpose of this report is to qualitatively describe the impacts of climate change on Australian road and bridge infrastructure and to provide further technical information relating to assumptions made while developing the matrix of impacts.

2 Australian road and bridge infrastructure

The road network is critical to Australia's economic and social needs. An efficient and reliable national road network has been critical for the strong economic performance in recent years. The national road network is 812,000 kilometres in length and used by over 14.7 million registered motor vehicles and 420,000 motor cycles (Austroads 2008). Approximately 2.3 billion tonnes of freight were transported in Australia in 2004–05, the bulk of which was carried via the road system (BTRE 2006). Australia has higher road lengths and road freight (tonne km) per person or per \$GDP than most other countries (Austroads 2005). There are more than 37,000 bridges in Australia which also make up an important component of the road network (Austroads 2005).

The three tiers of government in Australia share responsibility for funding the road network. The Federal government provided all funding for the 18,500 km interstate National Highway from 1974 to 2004, and subsequently started to contribute funding to a more extensive strategic road network, which forms part of the AusLink National Network. AusLink provides a national planning framework as well as funding for Federal Government investment in land transport infrastructure (AusLink 2008). Maintenance occurs with assistance from local governments. Maintaining and improving the total road network cost all governments \$7.6 billion in 2001–2002 (Austroads 2008). In 2008–09 the Federal Government has committed \$3.2 billion to investment in road and rail projects (Albanese, 2008).

Increasingly more roads are operated by the private sector, such as Citylink and Eastlink in Victoria. These assets are geared to be handed back to government after a nominal operating period e.g. 20 to 30 years.

3 Climate change information

Seven climate change scenarios were used to assess the impacts on roads and bridges. The climate scenarios are as follows:

3.1 'Business as usual' scenarios

- **Unmitigated Scenario 1 (U1).** Hot, dry business as usual scenario, using A1FI emission path, 10th percentile rainfall and relative humidity surface for Australia (dry extreme), 90th percentile temperature surface. Mean global warming reaches ~4.5°C in 2100.
- **Unmitigated Scenario 2 (U2).** Best estimate (median) business as usual scenario using A1FI emissions path, 50th percentile rainfall and relative humidity surface for Australia, 50th percentile temperature surface. Mean global warming reaches ~4.5°C in 2100.
- **Unmitigated Scenario 3 (U3).** Warm, wet business as usual scenario under A1FI emissions path, 90th percentile rainfall and relative humidity surface for Australia (wet extreme), 50th percentile temperature surface. Mean global warming reaches ~4.5°C in 2100.

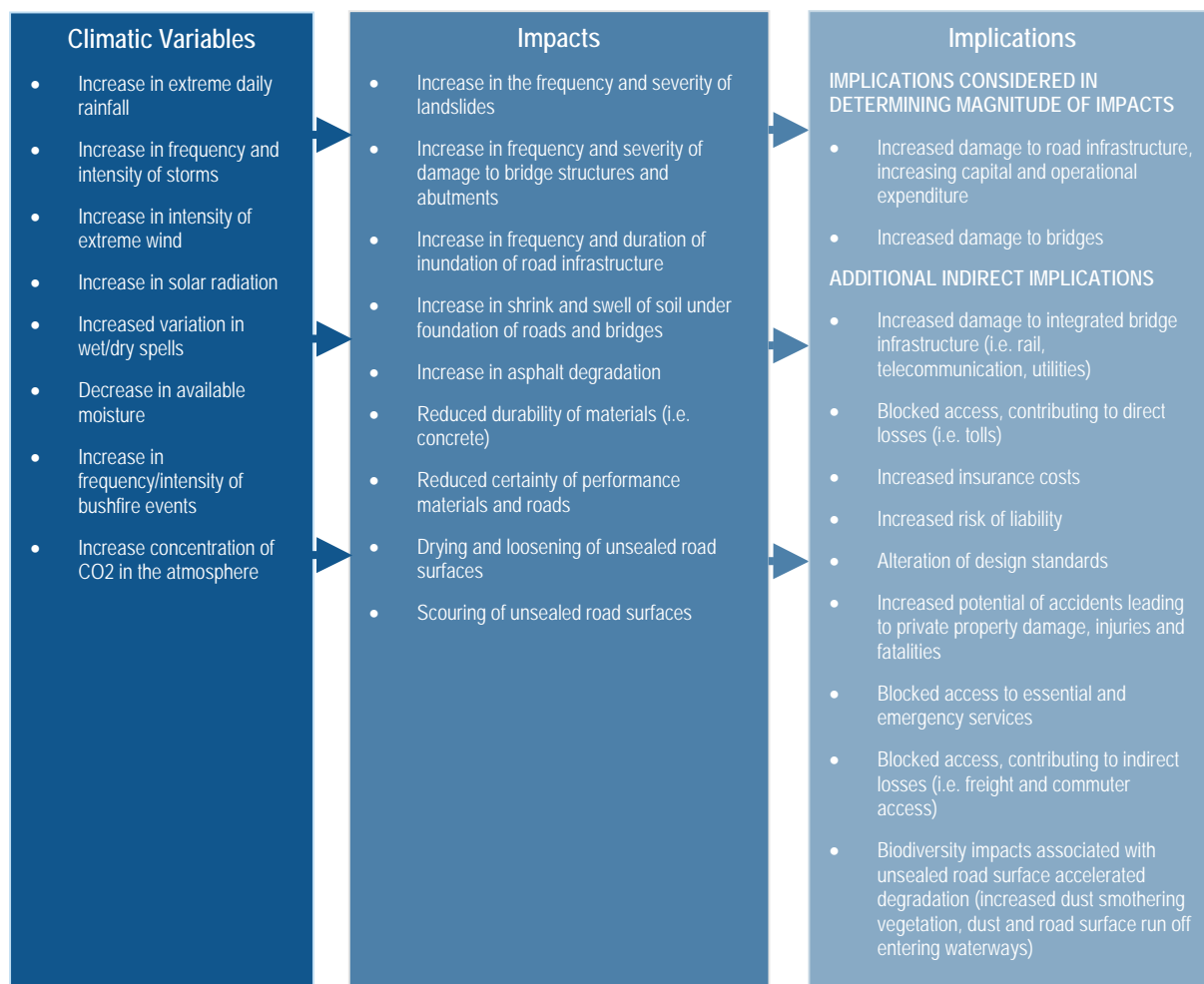
3.2 Strong mitigation scenarios

- **Mitigation Scenario 1 (M1).** Dry mitigation scenario where stabilisation of 550ppm CO₂ equivalent (CO₂ stabilised at 500ppm) is reached by 2100, 10th percentile rainfall and relative humidity surface for Australia (dry extreme), 90th percentile temperature surface. Mean global warming reaches ~2.0°C in 2100.
- **Mitigation Scenario 2 (M2).** Best estimate (median) mitigation scenario where stabilisation of 550ppm CO₂ equivalent (CO₂ stabilised at 500ppm) is reached by 2100, 50th percentile rainfall and relative humidity surface for Australia, 50th percentile temperature surface. Mean global warming reaches ~2.0°C in 2100.
- **Mitigation Scenario 3 (M3).** Wet mitigation scenario where stabilisation of 550ppm CO₂ equivalent (CO₂ stabilised at 500ppm) is reached by 2100, 90th percentile rainfall and relative humidity surface for Australia (wet extreme), 50th percentile temperature surface. Mean global warming reaches ~2.0°C in 2100.
- **Mitigation Scenario 4 (M4).** Best estimate (median) strong mitigation scenario where stabilisation of 450ppm CO₂ equivalent (CO₂ stabilised at 420ppm) is reached by 2100, 50th percentile rainfall and relative humidity surface for Australia, 50th percentile temperature surface. Mean global warming reaches ~1.5°C in 2100.

4 Summary of climate change impacts

Figure 1 outlines the impact storyline identified for road and bridge infrastructure. This storyline was assessed against climate conditions considered in the seven climate scenarios U1, U2, U3, M1, M2, M3 and M4 to develop the matrix of impacts for each coastal state and territory.

Figure 1 Impact storyline for road and bridge infrastructure



The impacts on road and bridge infrastructure are anticipated to increase overtime varying in severity from state to state. Table 1 provides a summary of the impacts for each climate scenario across the three time scales assessed; 2030, 2070 and 2100. The most significant impacts are anticipated to occur under the U1 and U3 climate scenarios in the 2071–2100 timeframe. Under the U1 scenario, the high and extreme impacts are principally due to the increased drying and associated ground movement weakening the foundations of road and bridge infrastructure, combined with increased extreme storm events. The high and extreme impacts in the U3 climate scenario are principally related to the effects of an increasing magnitude of storm events and increased moisture contributing to an increase in landslides.

Table 1 Summary of magnitude of impacts on road and bridge infrastructure for seven climate scenarios

	2008–2030	2031–2070	2071–2100
U1	Low to Moderate	Low to High	Moderate to Extreme
U2	Low to Moderate	Low to Moderate	Low to High
U3	Low to Moderate	Moderate to High	High to Extreme
M1	Low to Moderate	Low to Moderate	Low to Moderate
M2	Low to Moderate	Low to Moderate	Low to Moderate
M3	Low to Moderate	Low to Moderate	Low to Moderate
M4	Low to Moderate	Low to Moderate	Low to Moderate

5 Climate change impact storyline

The impact storyline identified for road and bridge infrastructure as described in Figure 1 consequently causes impacts which are a combination of road and bridge capital expenditure and operational expenditure impacts over the given time period. Table 2 outlines the magnitude of impacts on roads and bridges for the seven climate scenarios for each state. Table 3 outlines the scale used to assess the magnitude of impacts.

Table 2 Magnitude of impacts on roads and bridges for seven climate scenarios as a national outlook

Timeframe 2008 - 2030							
Climate Scenario	U1	U2	U3	M1	M2	M3	M4
VIC	M	M	M	M	M	M	M
NSW	M	M	M	M	M	M	M
WA	L	L	M	L	L	M	L
NT	L	L	M	L	L	M	L
SA	M	M	M	M	M	M	M
QLD	M	M	M	M	M	M	M
ACT	L	L	L	L	L	L	L
Tas	L	L	L	L	L	L	L

Timeframe 2031 - 2070							
Climate Scenario	U1	U2	U3	M1	M2	M3	M4
VIC	H	M	H	M	M	M	M
NSW	H	M	H	M	M	M	L
WA	M	M	H	M	L	M	M
NT	M	L	H	L	L	M	L
SA	H	M	M	M	M	M	M
QLD	H	M	H	M	M	M	M
ACT	L	L	M	L	L	L	L
Tas	L	L	M	L	L	L	L

Timeframe 2071 - 2100							
Climate Scenario	U1	U2	U3	M1	M2	M3	M4
VIC	H	M	H	M	M	M	L
NSW	H	M	E	M	M	M	L
WA	H	H	H	M	M	L	L
NT	H	M	E	L	L	M	L
SA	H	M	H	M	M	L	M
QLD	E	H	E	M	M	M	M
ACT	M	L	H	L	L	L	L
Tas	M	L	E	L	L	M	L

Table 3 Scale of impacts

	Magnitude of net impact	Description of impact
N	Neutral	No change in, capital expenditure, operational expenditure.
L	Low	Minor increase in capital expenditure and operational costs but no significant change to cost structure of industry. For example, minor increase in operational costs associated with repairing/restoring road or bridge assets.
M	Moderate	Moderate increase in capital and operational expenditure with a minor change to cost structure of industry. For example, moderate increase in capital and operational expenditure for road or bridge infrastructure due to increased design standards, maintenance regimes and damage from extreme events.
H	High	Major increase in capital and operational expenditure with a significant change to cost structure of industry. For example, major increase in capital expenditure for increased design standards for new and existing road or bridge assets.
E	Extreme	Extreme increase and major change to cost structure of industry with an extreme increase in operational and maintenance expenditure. For example, extreme increase in capital expenditure from significant investment in new or replacement of existing road or bridge infrastructure.

5.1 Business as usual scenarios

The business as usual climate change scenarios provided by the CSIRO on behalf of the Garnaut Climate Change Review Secretariat and considered in the roads and bridges storyline are discussed in turn below.

U1: Hot, dry reference scenario—A1FI emissions path, 3°C climate sensitivity, 10th percentile rainfall and relative humidity surface for Australia (dry extreme), 90th percentile temperature surface. Mean global warming reaches 4.5°C in 2100.

This 'hot and dry' scenario adopts a 'business-as-usual' approach to greenhouse gas emissions and therefore assumes the highest level of temperature increase, along with the greatest decline in rainfall and relative humidity. With this level of emissions, mainland Australia experiences a 1 degree temperature increase by 2030 and generally exceeds 5 degrees by 2100. Varying in different regions, rainfall decreases across the country, particularly in the southern areas.

The A1FI emissions scenario, upon which U1 is based, describes a 'future world of very rapid economic growth, global population that peaks in mid-century and declines thereafter, and the rapid introduction of new and more efficient technologies. Major underlying themes include convergence among regions, capacity building and increased cultural and social interactions, with a substantial reduction in regional differences in per capita income' (IPCC SPM 2007). A1FI has a fossil fuel-intensive technological emphasis. It is with this guide that these 'business-as-usual' developments are based. This scenario is expected to result in low to moderate economic impacts by 2030, low to high impacts by 2070 and moderate to extreme impacts by 2100.

The climatic characteristics associated with U1 do not have as significant an impact as those experienced under U3. Although U1 results in higher temperatures with lower humidity, this does not impact roads and bridges as severely as an increase in extreme rainfall events.

It is indicated in Austroads (2004) that pavement deterioration may slow, in theory, as rainfall decreases. This could in turn lead to a reduction in the design thickness of road surfaces, reducing maintenance costs. However, increased solar radiation associated with hotter days is likely to increase the required maintenance of road surfaces as asphalt degrades at a faster rate. Austroads (2004) indicates that increased temperature can increase the embrittlement of road surfaces, causing

bitumen surfaces to crack. This reduces the waterproofing allowing water infiltration that can further degrade the road surface causing potholes and quickening the degradation process. Surface cracking would be compounded by occurrences of increased flash flooding in areas experiencing a decrease in annual rainfall and whole of catchment flooding in areas that are likely to experience minimal change in rainfall.

A rise in temperature may cause additional stress on infrastructure as materials expand, such as concrete, protective cladding, coatings, sealant and steel reinforcement (CSIRO, 2007). This is likely to have a greater impact on pavement and road surfaces than bridges; as design solutions (i.e. expansion joints) are more applicable to bridges. However, given the shorter design life of roads compared to bridges, the former will be more adaptable to hotter, drier conditions.

The hot dry scenario is likely to lead to a reduction in soil moisture and therefore greater ground movement, particularly in areas with clay based soils such as Adelaide, Melbourne and Brisbane (CSIRO, 2007). These three states consequently are likely to experience relatively greater impacts from a warmer, drier climate. New South Wales is also more sensitive to ground movement due to the older age of much its infrastructure. The 'shrinking' of the ground will place additional stress on road and bridge foundations making them more vulnerable to extreme weather events. Brisbane therefore is likely to experience extreme impacts from 2071–2100 due to the effects of increased extreme weather events damaging infrastructure already weakened by ground movement of the clay soil.

Austrroads (2004) noted that less rain limits the dilution of surface salt, causing any surface water run-off to have higher salt concentration. This increases the corrosion rate of steel reinforcements in concrete structures, including bridges which could have impacts on the cost of applying additional protection measures from salt exposure, as well as maintenance.

While limited research has been conducted, it could be reasonably foreseen that hot dry conditions are likely to increase drying and loosening of unsealed road surfaces also leading to additional maintenance costs. When combined with increased wind, a drier, loose road surface could lead to an increase in dust storms impacting usability of the road. Environmental impacts (smothering vegetation) and social impacts (dust infiltration of residential properties) may also follow, leading to increased clean up costs and potential public relations issues for responsible road authorities.

For U1, sea level rise is expected to be approximately 17cm by 2030, 50cm by 2070 (CSIRO 2007, Hennessy et al, 2006) and 70cm by 2100 (Weller 2005). Towards the end of the century, coastal roads and bridges could be affected by inundation and likely to require relocation or increased coastal protection investment. This would lead to some level of impact for all state and territory capital cities (except for the ACT) which are situated in proximity to the coast. Erosion is likely to be further accelerated when sea level rise combines with extreme rainfall events and storm surge.

U2: *Best estimate (median) business as usual scenario using A1FI emissions path, 50th percentile rainfall and relative humidity surface for Australia, 50th percentile temperature surface. Mean global warming reaches ~4.5°C in 2100.*

This scenario is most closely related to U1 due to the modelled reduction in rainfall. However, the drying and humidity is less extreme than U1 as is the temperature increase. The temperature increase and evaporation is the same as U3.

Compared to the projected impacts under the U1 scenario, the impacts projected under the U2 storyline are similar up to 2030. During the remainder of the century the spread of the impacts is anticipated to be similar to U1 although the magnitude and severity is anticipated to be less than U1. This scenario is expected to result in low to moderate economic impacts up to 2070, and low to high impacts by 2100.

Under the U2 scenario mainland Australia experiences a gradual increase in temperature. Between 2030 and 2070 all capital cities exceed are modelled to experience a 2°C increase in temperature. Rainfall is anticipated to decrease across most of the country, with the exception of Greater Hobart and Darwin. The greatest reductions in rainfall are anticipated to be in Perth and Adelaide.

As with U1, this scenario is likely to lead to a reduction in soil moisture and therefore ground movement, particularly in areas with clay based soils such as Adelaide, Melbourne and Brisbane (CSIRO, 2007). These three states consequently feel relatively greater impacts from a warmer, drier climate. New South Wales is also more sensitive to ground movement due to the older age of much its infrastructure. The effects of U2 are similar to U1 up until 2030, after which the effects become of lesser magnitude. Brisbane and Perth may experience a relatively higher impact from 2071–2100 due to the effects of increased extreme weather events damaging infrastructure already weakened by ground movement.

Sea level rise is expected to be gradual up to 2100. Coastal roads and bridges could be affected by inundation and likely to require relocation in line with settlement retreat or require increased coastal protection investment.

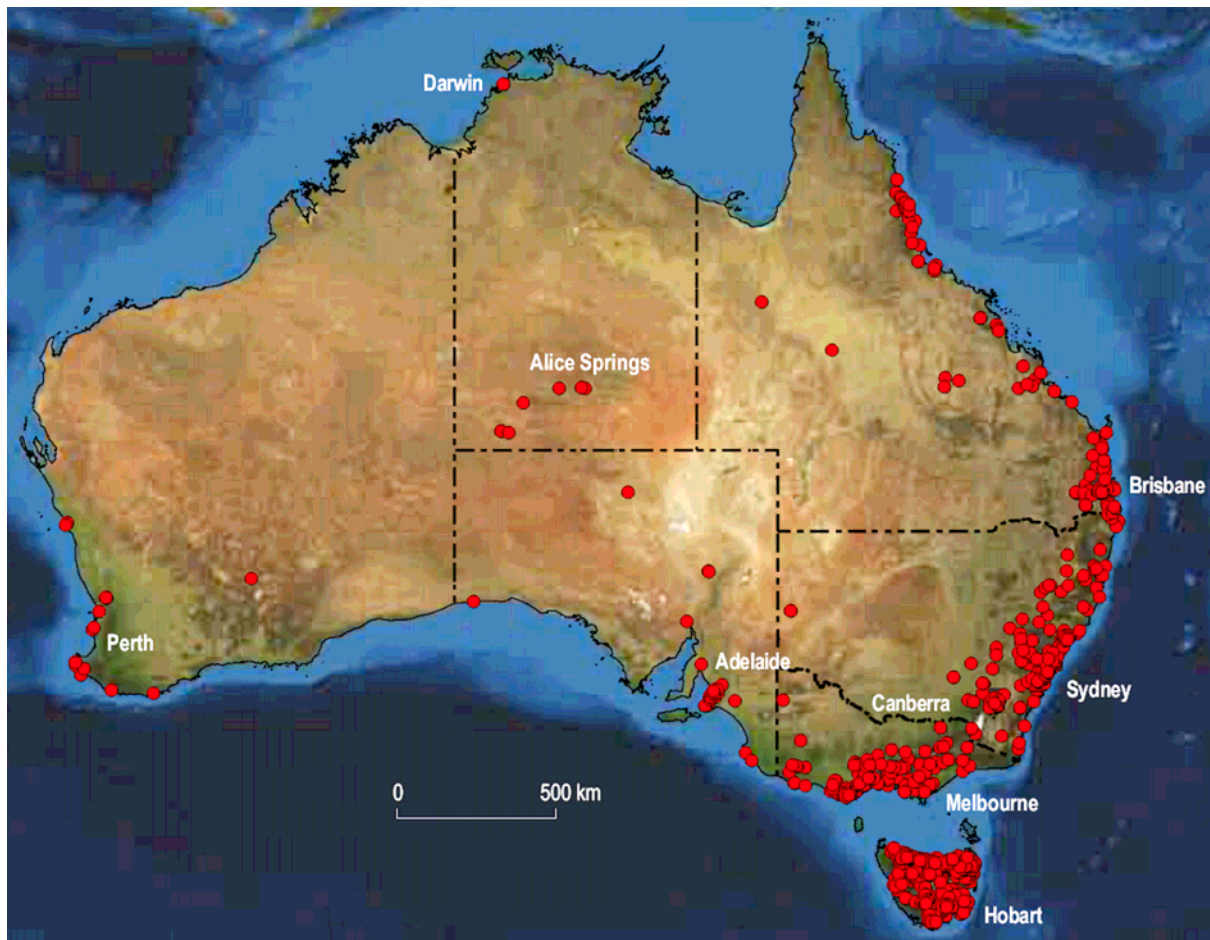
U3: Warm, wet reference scenario—A1FI emissions path, 3°C climate sensitivity, 90th percentile rainfall and relative humidity surface for Australia (wet extreme), 50th percentile temperature surface. Mean global warming reaches 4.5°C in 2100.

This scenario adopts a ‘business as usual’ approach to greenhouse gas emissions and assumes the statistically most likely level of temperature increase, along with the greatest increase in rainfall and relative humidity.

This scenario results in the most significant impacts on road and bridge infrastructure out of the seven scenarios discussed in this paper, predominantly due to increased levels of rainfall and catchment flooding. However, all states do not experience these impacts. Rainfall is projected to increase at the greatest rate in the Northern Territory, Tasmania and New South Wales, with rainfall in Darwin modelled to increase by over 30% towards the end of the century. Conversely, Victoria, Western Australia and South Australia are likely to experience little or no increase in annual rainfall. This scenario is expected to result in low to moderate economic impacts by 2030, moderate to high impacts by 2070 and moderate to extreme impacts by 2100.

The U3 scenario results in the most significant impacts on road and bridge infrastructure out of the seven scenarios discussed in this paper, predominantly due to the increased rainfall and magnitude of extreme rainfall events. Although landslides can occur for many reasons, Middelmann (2007) indicates increased rainfall is a dominant trigger factor. As such, it can be reasonably concluded that the frequency and severity of landslides are likely to increase under the U3 scenario as rainfall increases. Topography is also a predicting factor relating to landslides, with mountainous or steep terrain most at risk. Landslides occur regularly in Australia as indicated in Figure 2. Middelmann (2007) indicates that while the individual costs of each landslide are low; the costs associated with cumulative landslides are high.

Figure 2 Recorded landslide events in Australia (Source: Middelmann, 2007)



The greatest public costs resulting from landslides relate to disaster assistance, road maintenance, relocation and repair (Middelmann 2007). The flow on costs associated with landslides include emergency service and essential services access being blocked. This can be critical particularly in situations when landslides are caused by storm events that trigger other incidents requiring emergency service responses, including clean up and repair responses. Economic losses can also be associated with the landslides including direct losses from toll roads, and indirect losses for example freight supply interruption and commuter interruption. As the likelihood of landslides increases so too does the risk of potential accidents involving injuries and fatalities. This will in turn increase the potential liability to road and rail authorities, operators and owners.

Due to the combination of a likely increase in intensity and frequency of storms, high density and age of road and bridge infrastructure, and topography (including the Great Dividing Range), Queensland, New South Wales and Victoria are likely to be at the highest risk of landslides.

Increased rainfall can amplify the deterioration of pavements, particularly as higher temperatures worsen cracking impacts (Austrroads, 2004). Higher water tables (caused by greater rainfall) can speed up the deterioration of road pavements as the moisture content of pavements increase. This may be compounded as salt rusts the steel reinforcement in pavements and bridge foundations (Austrroads 2004).

Storm related damage and flooding have the potential to cause significant damage to roads and bridges. While bridge foundations and supports may withstand storm events and flooding, failing abutments may isolate a bridge rendering it useless. The failure or isolation of a bridge may lead to a community's access to emergency and essential services being blocked. This would be compounded by the often significant cost and timeframe involved in repairing or rebuilding a failed bridge or bridge abutments.

An increased number of extreme weather events would lead to a greater proportion of bridge and road infrastructure being vulnerable to storm damage. Areas at most risk are in Queensland but impacts may also be felt in Northern Territory and northern Western Australia. Due to the density of assets the economic impacts associated with extreme weather events are likely to be greatest in Queensland towards the end of the century. However New South Wales and Tasmania are also likely to experience extreme impacts by 2100 due to the combination of increased rainfall, topography and age of infrastructure.

Extreme rainfall and an increase in intensity and frequency of storms under the U3 scenario are likely to increase the scouring of unsealed roads surfaces. An increase in maintenance is likely to be the most significant direct economic impact. Associated impacts are likely to include environmental impacts including turbidity of local water ways, and social and economic costs associated with an increase in accidents potentially causing injury or death.

As with U1, sea level rise is expected to be approximately 17cm by 2030, 50cm by 2070 (CSIRO 2007, Hennessy et al, 2006) and 70cm by 2100 (Weller 2005). The consequences for roads and bridges would be significant if coastal assets become affected by inundation, and similar to those listed for U1.

5.2 Strong mitigation scenarios

The four climate change scenarios with mitigation provided by CSIRO, on behalf of the Garnaut Climate Change Review Secretariat and considered in the roads and bridges storyline are discussed in turn below.

M1: *Dry mitigation scenario where stabilisation of 550ppm CO₂ equivalent (CO₂ stabilised at 500ppm) is reached by 2100, 10th percentile rainfall and relative humidity surface for Australia (dry extreme), 90th percentile temperature surface. Mean global warming reaches ~2.0°C in 2100.*

This scenario adopts a policy intervention that leads to a greenhouse gas emissions trajectory that stabilises atmospheric greenhouse gas concentrations at a level that constrains the temperature increase to 2.0°C in 2100; as compared to 4.5°C in 2100 under the reference scenario U1.

Under this scenario, the changes in rainfall (decline), humidity (decline), temperature (increase) and evaporation (increase) are similar to U1 until around 2030. From the middle of the century the M1 temperature and rainfall changes begin to level out. The temperature and rainfall changes modelled in U1 significantly outpace the M1 scenario after this time period. The M1 temperature increases at 2100 are reached in the middle of the century under the U1 scenario. The temperature and rainfall changes for M1 are approximately 55% of the U1 changes at 2070 and 40% of U1 at 2100. This scenario is expected to result in low to moderate economic impacts throughout the three time periods.

The reduced rate and level of temperature increase relative to the U1 scenario has the impact of lessening the impact of increased extreme rainfall and flash flooding with less additional temperature driven storm energy in the climate system relative to U1. This would see similar impacts due to storms, bushfires and heatwaves during this period. However, there would be some difference in responses, as greater capital investment is likely in 2070 scenario U1 to minimise future operating expenditure.

Similar to U1, increased ground movement of clay soils in combination with extreme weather events is likely to cause moderate impacts. Western Australia is also likely to experience moderate impacts as reductions in rainfall are likely to be greater there than in other regions.

A decrease in annual rainfall and increase in temperature and evaporation will lead to less ground movement damage and asphalt embrittlement than under the reference scenario U1. Sea level rise is expected to be gradual up to 2100 in a similar trajectory as U1.

M2: Best estimate (median) mitigation scenario where stabilisation of 550ppm CO₂ equivalent (CO₂ stabilised at 500ppm) is reached by 2100, 50th percentile rainfall and relative humidity surface for Australia, 50th percentile temperature surface. Mean global warming reaches ~2.0°C in 2100.

The modelled M2 climate changes are similar to the U2 climate changes. For the M2 scenario, the changes in rainfall (decline), humidity (decline), temperature (increase) and evaporation (increase) are anticipated to be greater than U2 at 2030. From the middle of the century the M2 temperature and rainfall changes begin to level out. However the temperature and rainfall changes modelled in U2 significantly outpace the M2 scenario after this time period. The M2 temperature increases at 2100 are reached in the middle of the century under the U2 scenario. The temperature and rainfall changes for M2 are approximately 55% of the U2 changes at 2070 and 40% of U2 at 2100. This scenario is expected to result in neutral to low economic impacts by 2030, neutral to moderate impacts by 2070 and neutral to low impacts between 2071 and 2100.

As with U2, this scenario leads to a reduction in soil moisture and therefore ground movement, particularly in areas with clay based soils such as Adelaide, Melbourne and Brisbane (CSIRO, 2007). These three states consequently feel relatively greater impacts from a warmer, drier climate. New South Wales is also more sensitive to ground movement due to the older age of much its infrastructure. These regions suffer moderate shocks up to 2100. Due to its significant reduction in rainfall, Western Australia is anticipated to experience moderate impacts between 2071 and 2100. The impacts for the other states are likely to remain constant across the time periods as changes in temperature and rainfall levelling off and investment in asset protection and improved design standards better addressing the 'new' climate conditions.

M3: Wet mitigation scenario where stabilisation of 550ppm CO₂ equivalent (CO₂ stabilised at 500ppm) is reached by 2100, 90th percentile rainfall and relative humidity surface for Australia (wet extreme), 50th percentile temperature surface. Mean global warming reaches ~2.0°C in 2100.

This scenario adopts a policy intervention that leads to a greenhouse gas emissions trajectory that stabilises atmospheric greenhouse gas concentrations at a level that constrains the temperature increase to 2.0°C in 2100; as compared to 4.5°C in 2100 under the reference scenario U3. The scenario assumes an increase in temperature, along with an increase in rainfall and relative humidity.

Under this scenario, the changes in rainfall (increase), humidity (increase), temperature (increase) and evaporation (increase) are anticipated to be greater than U3 at 2030. From the middle of the century the M3 temperature and rainfall changes begin to level out. However, the temperature and rainfall changes modelled in U3 significantly outpace the M3 scenario after this time period. The M3 temperature and rainfall increases at 2100 are reached in the middle of the century under the U3 scenario. The temperature and rainfall changes for M3 are approximately 55% of the U3 changes at 2070 and 40% of U3 at 2100. This scenario is expected to result in low to moderate impacts across all three time periods.

The extreme rainfall events causing flooding and landslides are likely to increase but to a lesser extent than U3, as the expected increase in temperature that drives extreme storm, wind and rainfall events is lower. The more moderate temperature increase post 2050 would also comparatively reduce the likelihood of pavement deterioration occurring. The impacts under this scenario are anticipated to soften in the 2071–2100 time period as the changes in rainfall and temperature reduce and investment in asset protection and improved design standards better address the 'new' climate.

M4: Best estimate (median) strong mitigation scenario where stabilisation of 450ppm CO₂ equivalent (CO₂ stabilised at 420ppm) is reached by 2100, 50th percentile rainfall and relative humidity surface for Australia, 50th percentile temperature surface. Mean global warming reaches ~1.5°C in 2100.

This scenario is the 'best-case' of the group of scenarios assessed. The temperature and rainfall changes are modelled to stabilise around 2080 and begin to reverse toward 2100 therefore reducing the pressures generating increased storm related impacts. Of the scenarios that result in a decline in

rainfall and relative humidity (scenarios U1, U2, M1, M2 and M4), this scenario would have the least impact of climate change induced storm, wind and bushfire impacts. This scenario is expected to result in low to moderate impacts across all three time periods.

This scenario would result in the lowest level of climate change impacts and hence would result in the lowest level of economic impact to roads and bridges. Impacts are likely to be greatest in the areas with clay soils (Adelaide, Melbourne and Brisbane) and those experiencing the greatest amount of rainfall reduction (Western Australia).

6 Opportunities for adaptation

Up to 2030, it is anticipated that adaptation is likely to be in the form of maintenance of road infrastructure.

There is scope to use bridge and road design standards as a mechanism for building in adaptation responses. The design changes may relate to the materials used in construction to improve resilience to solar radiation, to cope with shrinking or swelling soils under the foundation, and to withstand greater exposure to rain and salinity.

The design life of different assets will impact on the effectiveness of this adaptation response. The design life of road surfaces is typically 10 years and bridges 100 years. Although it is noted that recently, a 300-year life span has been considered for bridge development in Queensland (Fenwick (2003), which, in light of a rapidly changing climate, raises a number of design issues. In fact the trend may reverse and be that shorter design life spans may be required for some infrastructure as the climate may change so significantly that it is no longer feasible to design infrastructure for any longer.

The design of new bridge infrastructure is likely to benefit from consideration of likely changes in flood design levels (i.e. 1:50 year, 1:100 year levels). In coastal regions consideration should also be given to the likely sea level rise and storm surge.

7 Conclusion

The greatest magnitude of climate change impacts on road and bridge infrastructure are anticipated to occur under the U3 climate scenario. The effect of increased magnitude of extreme rainfall events is anticipated to contribute to increased landslide and flooding (flash and catchment) causing damage to assets and flow on costs i.e. private property damage, injury, death and blocked access to communities. Queensland, Victoria and New South Wales are likely to be more dramatically impacted due to the combined factors of infrastructure age and density, increased magnitude of extreme rainfall events and topography. Tasmania has the lowest magnitude of impacts across most scenarios due to its relative lower increase in temperature, a key driver of extreme storm events.

Under the mitigation scenarios it is anticipated that existing infrastructure is likely to be impacted greatest over the next 20 years, as the adaptation response in the form of adapted design standards (including materials and flood levels) is likely to reduce the impact of newly designed and refurbished infrastructure. However, as climate predictions are refined it may become evident that certain infrastructure may be 'abandoned' as it no longer becomes feasible to maintain assets in certain locations due to their vulnerability to climate conditions.

8 Key assumptions

- The investment in road and bridge infrastructure is likely to be inline with the expansion of population across Australia over the 100 year timescale.
- Up to 2030 the greatest response is likely to be in the form of maintenance expenditure.
- Due to the life cycle of rail bridges, adaptation in design standards will be incorporated around 2030.
- The majority of roads and bridges will have been replaced or refurbished to include consideration of new design standards, and climate conditions.
- Lesser used roads and bridges and lower hierarchy bridges and roads (typically under local government jurisdiction) are likely to be effected more greatly due to less frequent maintenance.
- Frequency of storms, wind intensity, lightning, rainfall, storm surges and increased temperature variations can all contribute to increased failure of road and bridge infrastructure.
- As extreme events increase in frequency and severity it is anticipated stronger materials and techniques will eventually be utilised to increase infrastructure resilience. This will reduce vulnerability to future events presuming the increased standards can respond to the further increasing climatic pressures.
- The economic impacts associated with climate impacts on unsealed roads are likely to be substantially less than sealed roads due to the economic value of the traffic associated with each road type.

9 Future research

- The environmental and social impacts associated with climate change impacts on unsealed roads (i.e. dust, road surface scouring and run-off) as well as the impacts of isolation and restriction of emergency and essential service access.
- The future use or demand of road freight transport versus rail. The impact of freight demand on the wear and tear of road surface, and therefore design standards. Some work has been done in Austroads (2004)
- Potential risks associated with bushfires followed by extreme rainfall—additional and or more severe landslides.
- The number of roads and bridges at risk under a scenario of a one metre sea level rise.

10 Case studies

Case study 1: Flood causes road collapse

This case study demonstrates how climate related events can have devastating effects for road users. Councils are likely to require more money in future years to maintain roads to adequate standards given that rates of road obsolescence are likely to increase. There are also major liability costs associated with accidents such as the June 2007 event in New South Wales which cause death, injury and infrastructure damage. Due to the inquest, repairs on the road have been delayed for ten months adding additional stress to the F3 road-way for which it typically provides relief (ABC, 2008).

Government (sic) to probe NSW highways after fatal flood collapse

ABC Online, 13 June 2007

'The Federal Government wants to examine the issue of funding for road maintenance after the deaths of five people in a road collapse on the New South Wales Central Coast during Friday's severe weather.

The two adults and three children were in a car that fell into the collapsed section of the Old Pacific Highway and was washed downstream by floodwaters.

Police have now closed a second section of road about two kilometres away because it is in a dangerous state, with cracks on the surface and chunks of bitumen crumbling away at the side.

'To be frank, it looks like it's about to suffer some severe damage,' said Detective Chief Inspector Darren Bennett.

Police say the section is of concern to the investigation into Friday's deaths. The Deputy Mayor of Gosford City Council, Craig Doyle, has told The Australian newspaper that the council has not been adequately funded to maintain the highway since it assumed responsibility from the State Government in 1996.

Councillor Doyle says half of the area's roads were dumped on the council in 1996 but it has been impossible to maintain them properly.

He estimates the roads need at least \$4 million but the council has only been given just under \$1 million.

State Opposition local government spokesman and Central Coast MP Chris Hartcher says the NSW Government has abandoned the highway.

'It's walked away from the responsibility and now we have what can only be described as the most tragic consequences,' he said.

A spokesman for federal Roads Minister Jim Lloyd says his Government is looking to address the issue of cost shifting between governments but will not comment further until the completion of a coronial inquest into the deaths.'

Case study 2: Cost of landslides

'The total direct cost of landslides in Australia for the period from 1967 to 1999 is estimated at \$40 million. This can be solely attributed to the 1997 Thredbo landslide as only landslides costing \$10 million or over were included in the BTE (2001) estimate. However, for the period from 1900 to 1999 the total socioeconomic cost of landslides was estimated at \$500 million in 1998 dollars (EMA 1999).

Most damage is the result of many small landslide events, and it is believed they have a significant cumulative cost. Few insurance policies in Australia cover landslides, and it is understood that the majority of landslide costs are absorbed directly by individual property owners as well as by infrastructure authorities.

Costs associated with disaster assistance and road maintenance, relocation and repair are among the greatest public costs resulting from landslides. For example, the Australian Landslide Database indicates that the construction cost of diverting the Lawrence Hargrave Drive coastal route around a cliff face subject to rockfalls was \$49 million in 2006 dollars, and it is estimated that from 1989 to 1996 the cost of repairs to railway infrastructure in Wollongong amounted to \$175 million. Reconstruction of the Alpine Way after the Thredbo landslide cost \$24 million (BTE 2001).'

(Middelmann 2007, p120)

Case study 3: Climate change and the need for adaptation

'There is now considerable evidence emerging in Europe, America and Japan that the construction and transportation sectors are paying attention to climate change impacts and the need for adaptation. As one example, the US\$1 billion 12.9 km Confederation Bridge between New Brunswick and Prince Edward Island in Canada, which opened in 1997, was built one meter higher to accommodate anticipated sea-level rise over its 100-year lifespan.'

(IPCC 2007, p379)

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