Framework to Address the Climate Change Impacts on Road Infrastructure Assets and Operations

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Abstract

The road transport sector is a key area that contributes to climate change (CC) by way of greenhouse gas emissions. However, the transport sector is in turn itself affected by CC. Whilst, transport systems and infrastructure are designed to withstand typical weather patterns, CC impacts arising in the near and longer-term can have an impact on the efficiency of transport operations and ability of infrastructure to withstand extreme events outside the 'typical' threshold.

The purpose of this paper is to summarise the findings of a study undertaken for Queensland Department of Main Roads (QDMR) in 2008. This paper highlights the possible impacts of CC on road transport with specific reference to the Queensland, Australia context. It provides an overview of the impacts of CC on the Queensland road network. In particular, the effects of CC on operations and infrastructure due to temperature changes, changes in precipitation, rising sea levels, and increased storm activity. Additionally, the short- and long-term impacts of CC as they may affect Queensland and the implications of these for road infrastructure assets, are then considered.

The paper also provides a framework that will assist road agencies in the formulation of an appropriate response to these changes in the immediate future that is urgently required, especially in terms of how they manage their road networks. A Climate Change Framework (CCF) is presented, which is designed to assist road authorities in determining appropriate investment priorities, and to enable efficient development of CC mitigation and adaptation responses for transport decision makers. It is argued in the paper that CC impacts should be incorporated as a key component in road authorities' planning processes.

1 Introduction

Considerable research has been conducted at the international, national and jurisdictional level on the effects of CC in relation to transport. This research suggests that significant changes in climate have been emerging and are expected to become more pronounced in the future. As a result, a wide range of impacts across sectors and regions are expected to lead to varying economic, social and environmental costs (Watkiss *et al.,* 2007).

Anticipated CC and accompanying implications are significantly raising the level of uncertainty surrounding existing man-made systems. Road networks are no exception. The Environment and Heritage Directorate of Main Roads, Queensland acknowledges that CC is a significant issue, and sought to ascertain what this challenge means for the Department, and to identify its obligations. ARRB Group was engaged to assist in this task by developing a report detailing a Climate Change Framework (CCF) exploring issues and implications. The CCF was developed as a 'guide' of principles and techniques for the practitioner dealing with the impacts of climate change on road transport, and can be used in the planning and implementation of road infrastructure works. This paper summarises the findings of this study and the key elements of the developed CCF (Evans *et al.,* 2008).

The road transport sector is a key area that not only contributes to CC by way of greenhouse gas emissions, but is in turn predicted itself to be increasingly affected by CC. Whilst it is acknowledged that CC is global in nature, its effects can be local and unique to a region.

In the context of Queensland, its climate is highly variable, experiencing more extreme weather events such as temperature changes, variations in rainfall (both reductions and increases), flooding, rising sea levels, storm surges, and increase in cyclone frequency and intensity. These events can vary from location to location and year to year. Their impacts are further defined in this paper in terms of how they affect road transport infrastructure and operations. For example, increases in Queensland's temperature are associated with impacts on infrastructure such as thermal expansion on bridge joints and paved surfaces. Additionally, in terms of operations and maintenance, the increased incidence of storms can result in disruptions to network operations when roads are flooded, causing route delays, disruptions to transit services, freight and car travel, and greater need for emergency services.

2 Impacts of climate change on the Queensland road network

It is acknowledged that the impacts of CC on transport systems and infrastructure differ depending on the particular mode of transport, its geographical location, and its condition. A key challenge of CC developments is to determine the magnitude and direction of these changes at a local level. The major climatic events to mostly affect Queensland are as follows:

- temperature changes (increases in very hot days in the majority of Queensland's regions)
- variations in rainfall (both reductions and increases) and flooding
- rising sea levels, added to storm surges
- increase in cyclone frequency and intensity.

In terms of effects on operations and infrastructure, Table 1 provides a summary of potential CC events in Queensland that cause environmental conditions to extend outside the range for which the current system was designed.

Table 1 — Climate Change Impacts on Land Transport Operations and Infrastructure

	Impacts on Land Transport: Roads, Rail and Pipelines	
Potential climate change	**Operations and interruptions**	**Infrastructure**
Temperature: Increases in very hot days and heat waves	Limitations on periods of construction activity, and frequent detours, traffic disruptions resulting from thermal expansion of bridges Vehicle overheating and tyre deterioration Impacts on wetland and biodiversity management	Impacts on pavement and concrete construction practices, including thermal expansion on bridge expansion joints Concerns regarding pavement integrity, e.g, softening, traffic related rutting, migration of liquid asphalt Changes to landscape/biodiversity
Precipitation: Increase in intense precipitation events	Infrastructure deterioration e.g. concrete deterioration, impacts on water quality, loss of property, increased hazardous cargo accidents Increases in weather-related delays e.g. traffic disruptions, increased flooding of evacuation routes Disruption of construction activities e.g. changes in rain and seasonal flooding that impact safety and maintenance operations	Overloading of drainage systems, causing backups and street flooding Increases in road washout, damages to rail-bed support structures, landslides and mudslides that damage roadways and tracks, and increases in scouring of pipeline roadbeds and damage to pipelines Impacts on soil moisture levels, affecting structural integrity of roads, bridges, and tunnels
Precipitation: Increases in drought conditions for some regions	Increased susceptibility to wildfires, causing road closures due to fire threat or reduced visibility Less rain to dilute surface salt may cause steel reinforcing in concrete structures to corrode	Increased susceptibility to wildfires that threaten transportation infrastructure directly Increased susceptibility to mudslides in areas deforested by wildfires
Precipitation: Changes in seasonal precipitation and river flow patterns	Increased interruptions in travel and transport demand if rainfall patterns intensify, depending on terrain	Increased risk of floods from runoff, landslides, slope failures, and damage to roads if rainfall increases
Sea level rise, added to storm surge: Increased risk of inundation of coastal infrastructure	More frequent interruptions in travel on coastal and low-lying roadways and rail service due to storm surges and road closures More severe storm surges, requiring evacuation and increased search and rescue operations	Inundation of roads and rail lines in coastal areas, and more frequent or severe flooding of underground tunnels and low-lying infrastructure Erosion of road base and bridge supports, bridge scour, reduced clearance under bridges Loss of coastal wetlands and barrier shoreline, and land subsidence
Storms: More frequent strong cyclones	More debris on roads and rail lines, reduced visibility, interrupting travel and shipping Increased frequency of road accidents, route delays, disruption to transit services/closures, freight and standard motorists More frequent and potentially more extensive emergency evacuations	Increased road flooding Greater probability of infrastructure failures e.g. increased damage to signs, lighting, bridges, signs, overhead cables, railroad signals, tall structures Decreased expected lifetime of highways exposed to storm surge

Source: Adapted from TRB (2008a; 2008b).

2.1 Short-term impacts of climate change

CC impacts arising in the near- and longer-term can have an impact on the efficiency of transport operations and ability of infrastructure to withstand extreme events outside the typical threshold. These impacts are separated into direct and indirect impacts. Often when an impact is direct, it will have immediate impact on the physical infrastructure and hence the existing transport system and network (TRB, 2008b). In the context of this paper, these direct impacts are discussed in terms of short-term impacts on the road network. These include:

- diversion of freight routes resulting from immediate environmental events, such as storms, flooding, or cyclones
- road closures or damage caused to the road as a result of flooding
- damage to roads caused by weather events e.g. debris on roads or damage to road bridges
- restrictions of access by vehicles to ensure safety and rehabilitation of roads.

These short-term impacts and implications on the transport system were manifested in 2006 when Cyclone Larry in Northern Queensland caused severe damage to road infrastructure and crops, e.g. banana plantations. This had flow-on effects to the economy, where government expenditure was required to 'get communities back on their feet'. Other impacts included the increase in price of bananas for consumers for example, and implications for the freight industry in terms of reduced freight demand due to lost production. Additionally, the Queensland road network is also susceptible to short-term flooding events where in 2008/09 many state owned roads were limited to 80% carrying capacity in order to prevent long-term damage to the road. This also had the effect of reducing the efficiency of the road transport industry by 20% (QDMR, 2008).

2.2 Long-term impacts of climate change

Climate Change not only has immediate implications resulting from storms or flooding, but also has long-term impacts which can in turn have implications for the Queensland freight task. Some of these longer-term effects are referred to as indirect impacts. These may affect the location of economic activities or levels of pollution, and as such are linked to the effects of human activity altering the demand for roads (Austroads, 2004). Specific examples include:

- changes in population and demographics
- long-term impacts for freight routes due to changes in production locations
- effect of regulating GHG emissions from freight vehicles, resulting in shifts to energy efficient options and modes
- ability of infrastructure and networks to cope with increased (decreased) freight flows, and movement of people to seek employment in new locations.

Additionally, climate-induced shifts in the distribution of agricultural production may in turn have implications for road usage and other transport patterns between emerging economic centres and urban areas (TRB, 2008b).

3 A Climate Change Framework (CCF)

Due to the uncertain nature of CC, there are difficulties in planning and designing infrastructure that can accommodate CC impacts. This is due to factors such as the lack of available data on the various CC hazards (particularly for the transport sector) and their economic consequences. Additionally, there is uncertainty in the data that is available e.g. the rate of CC and extent of its impacts, and the reliability of future CC projections. This makes it difficult to distinguish between the occurrence in the future of a storm with a frequency of '1-in- 100-years' from that of '1-in-500-years'. Historical evidence may also not be a reliable predictor of future CC conditions, and CC impacts are likely to change over time. Therefore designing more robust infrastructure to cope with CC events may incur more costly designs and be difficult to implement given budget constraints (TRB, 2008b). These challenges in turn influence the way in which CC is addressed and accommodated within policy initiatives both in the short- and long-term.

Owing to the long life of road assets, future transport managers may therefore take steps that can reduce or unintentionally increase the consequences of future CCs and their impacts (TRB, 2008b). Mitigation of these impacts can involve the need for decision makers to consider planning frameworks that incorporate appropriate assessment of risk and uncertainty associated with future CC.

3.1 The decision framework

In spite of the challenges, it is necessary to implement actions today to evaluate and protect vulnerable infrastructure from CC events occurring in the future. These measures may include operational decisions that are focussed on near-term changes in weather and CC conditions.

A decision-making framework should accommodate uncertainty, incorporate probabilistic approaches to assessing risk and make appropriate investment choices as much as possible. In assessing how CC may affect transportation assets and to enable efficient development of mitigation and adoption responses within the decision-making process, the following questions may be asked (TRB, 2008b):

- Which projected CC events are most relevant for a particular region?
- How are CC hazards likely to be manifested (e.g. flooding, storm surge coupled with sea level rise)?
- Which transportation assets may be affected?
- How severe must a hazard be before it becomes relevant and what action is required? Can thresholds be identified?
- How likely is it (what is the probability) that a projected hazard will exceed the threshold, when, and where?
- How much risk can be tolerated, or in other words, what infrastructure performance level is tolerable?
- What level of investment (capital and operating) is needed to maintain different levels of service? Can acceptable performance standards for all modes of transportation be established?
- Are there critical levels of service needed to protect health and safety?
- Who is responsible for making these judgments and decisions?

- What are the risks of adverse impacts or consequences if no action is taken?
- If action is necessary, how will investment priorities be determined?
- Who will make the necessary investments, and how will they be funded?

In order to address these questions and assist in determining appropriate investment priorities for transport decision makers to apply, a decision framework for practitioners to address the impacts of climate change on Queensland's road infrastructure was developed and is detailed below. This framework is based on TRB (2008a; 2008b). It identifies a number of key concepts with regards to road transport networks and this project has expanded and adapted these to the Queensland context. This climate change framework is divided into the following four phases also illustrated in Figure 1.

- Potential climate change effects
- Impacts on Queensland's transport infrastructure
- Possible adaptation strategies
- Planning and project evaluation.

3.2 Potential climate change effects

As indicated in the Framework, it is important to identify the CC effects which have the potential to threaten a road infrastructure system, its operations and performance. This entails determining CC impacts at the regional and local level and the time frame over which these impacts unfold. Potential CC effects can include:

- the effects of greatest relevance for transportation
- geographic scale at which effects can be projected with confidence
- degree of certainty with which effect is known
- timeframes of effects (TRB, 2008b).

This phase also includes an overall assessment of the economic, social and environmental effects of CC discussed later in this paper.

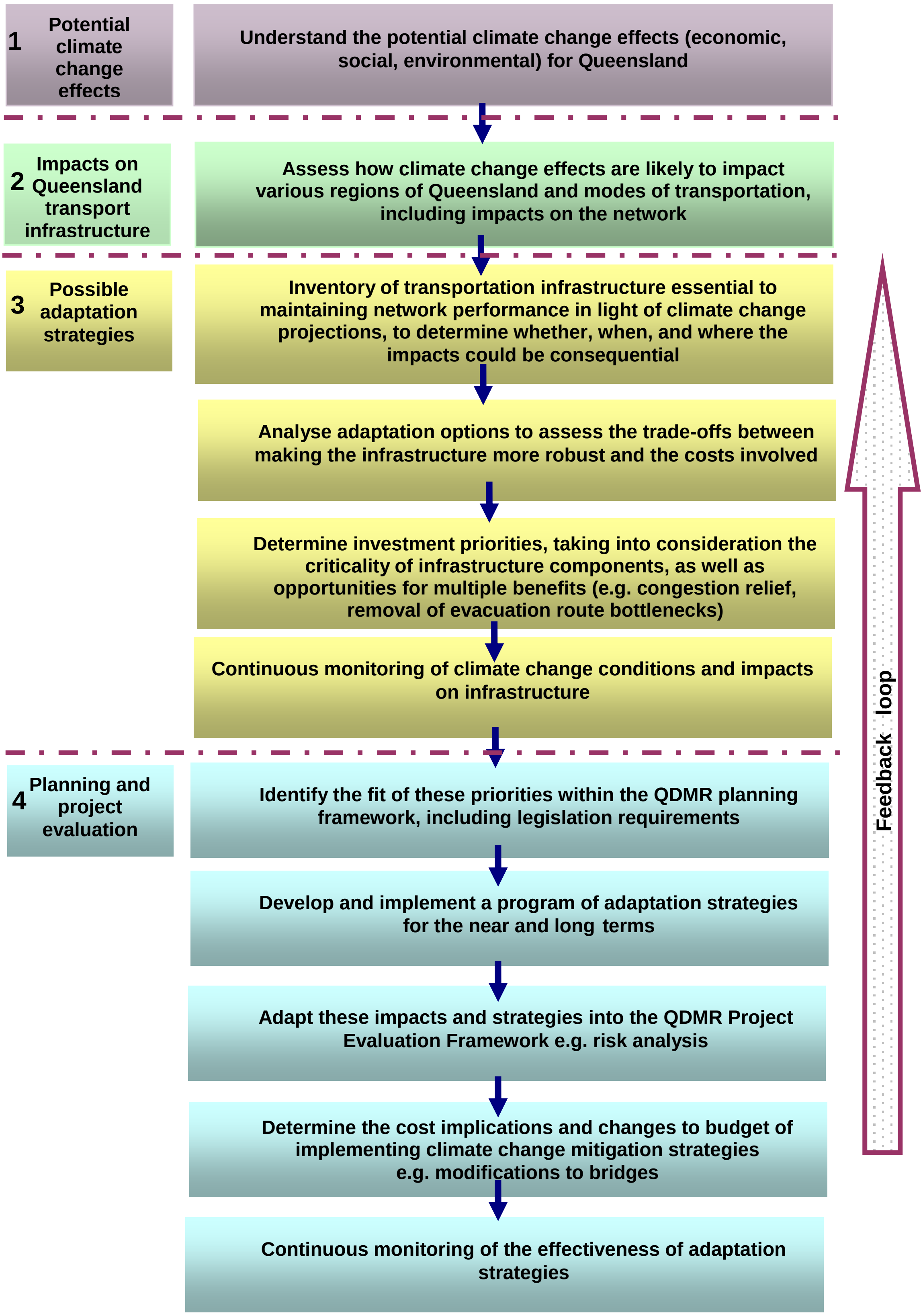

Figure 1 — Decision framework for practitioners for addressing impacts of climate change on Queensland's road infrastructure

Source: ARRB Group Ltd; adapted from TRB (2008a; 2008b).

3.3 Determining the impacts on the Queensland transportation system

The second phase of the framework involves describing the impacts of the effects of CC on transport. The first step within this phase includes determining the relevant impacts on transport according to the:

- type of CC effect e.g. flooding, cyclone
- transportation mode affected, and network implications
- type of impact direct, indirect, infrastructure, operations
- geographic area where infrastructure is located (TRB, 2008b).

Within this phase, the direct and indirect impacts are determined. It is important for these impacts to be included within a CC framework, as these events can vary according to the type, mode, network and location of the particular infrastructure impacted. When assessing the geographic area, this may also include identifying how CC effects are likely to impact various regions of Queensland, e.g. coastal regions.

3.4 Possible adaptation and mitigation strategies

The third phase involves developing possible adaptation and mitigation strategies to address CC. Potential adaptations can be identified which may necessitate a response in terms of changes in operations for near-term impacts, or changes in infrastructure design and materials. Within the proposed framework, it is noted that it is essential to conduct an inventory of ‘vulnerable’ transport infrastructure to maintain expected network performance. In developing this inventory, consideration of a risk-based approach would be required in order to determine:

- whether, when and where potential impacts may occur
- whether changes in operation and maintenance practices are required
- whether relocation of vulnerable infrastructure is required.

Transport infrastructure is vulnerable to conditions such as temperature, duration and intensity of precipitation. According to the TRB (2008b), most of these conditions are accounted for in the design of transport infrastructure such as in the sub-surface and foundation design, choice of materials, and drainage capacity. However, due to the uncertainty of CC effects, TRB (ibid) suggests that it is important to ask questions such as: Will the drainage capacity be adequate for expected increases in precipitation events? What critical infrastructure is potentially at risk? What new materials may be needed when very hot temperatures and heatwaves become more frequent? It is therefore important to analyse adaptation options to assess the trade-offs between making the infrastructure more robust and the cost implications of doing so. This leads to the final steps within phase three of the framework which is to determine investment priorities, taking into consideration the criticality of infrastructure components, as well as opportunities for multiple benefits (e.g. congestion relief, removal of evacuation route bottlenecks).

According to TRB (2008a), four key factors that characterise the ability of a system to adjust to CC are:

1. exposure – the manner and degree to which a system is exposed to significant climate variations

2. vulnerability – the potential for loss, or the degree to which a system is susceptible to or unable to cope with adverse effects of CC

3. resilience – the restorative or regeneration capacity of a system when faced with change

4. adaptation – the adjustment made to a system in response to actual or expected CC impacts to moderate harm or exploit beneficial opportunities.

In order to address and mitigate CC events on transport, it is necessary to monitor the conditions and impacts on infrastructure and operations, and to consider these factors in planning. For example, in the identification of strategies for adaptation and planning, more work may be required on incorporation of CC into the long-term strategic planning process. Appendix A further details a series of findings and recommendations for governments and the private sector to consider as ways to adapt systems and infrastructure to future events. These findings have been reviewed and modified from TRB (2008a; 2008b).

3.5 Planning and project evaluation

This final phase of the framework provides a link between phases 1-3 and the need for effective planning and evaluation of projects involving the redesign or establishment of new plans and initiatives to adapt to CC implications. Proceeding with these steps is dependent on the current procedures and guidelines in place for strategic planning and project appraisal. It is important for the outcomes of each stage of the Framework to be communicated to decision makers, and to conduct each step with the understanding that CC is uncertain and requires a longer-term perspective. This also involves consideration of the life-cycles of infrastructure design and planning, and allocation of budgets in the context of both immediate CC events and longer-term impacts.

Included in this phase of the Framework is the need to undertake a risk analysis and to incorporate this into the project evaluation process. Incorporating CC factors has significant implications for the evaluation of road projects. Construction (including rehabilitation) and maintenance activities accounting for CC will alter the costs and benefits involved in projects, directly affecting project evaluation outcomes.

4 Benefits of the Climate Change Framework

The proposed CCF provides an approach for decision makers to apply in order to plan and address CC. It has been developed to assist Queensland Government in determining appropriate investment priorities and enable efficient development of climate change planning and mitigation responses. The CCF has the additional benefit in that it can be easily applied to planning and decision-making processes within each Australian state/territory.

This CCF also enables key economic, social and environmental implications associated with CC in the context of land transport, to be identified and addressed. These include:

- Economic impacts arising from climate change in Queensland such as increased costs of providing road and bridge infrastructure that can cope with extreme weather. This may require authorities to adopt a risk-based approach that takes into account probabilities of failure of the assets and the economic costs of this occurring.

- Identifying the social impacts of CC, such as, increasing numbers of people displaced due to temperature changes and rising sea levels e.g. rural-urban migration, ‘coastal-urban’ migration, regional migration, inter-state migration. This may result in increased populations in some urban centres, reduced land available, increased land values and an altered urban form (with changes in infrastructure requirements and the need to integrate land-use, transport planning and multi-modal transport requirements).
- Identifying and addressing environmental impacts of CC. In Queensland, these include stresses to water supply due to increased demand, declines in annual rainfall and subsequent increased incidence of drought, and extreme storm events causing more cyclone damage and flash flooding. Additionally, in the coastal zones, storms may combine with a rise in the sea level to worsen coastal erosion. However, in some areas of Queensland, agricultural or forestry activities may benefit from slight temperature increases and higher carbon dioxide concentrations.

A key feature of this CCF is that it proposes a series of steps required to tackle uncertainties posed by CC. It can be used to identify the economic, social and environmental impacts and can assist in developing possible adaptation strategies for these. It also identifies road assets and operations affected and a project evaluation process in which risk analysis is a standard element for assessing these assets and operations.

5 Risk planning for the future

CC raises the possibility of significant, long-lasting impacts on transport infrastructure and systems performance that are likely to be widespread and costly in human and economic terms (TRB, 2008b). As noted in phase 3 and 4 of the proposed CCF, risk identification and analysis is an important aspect of project evaluation and can assist in determining better decision making responses to CC.

According to Austroads (2005), the assessment of risk often includes the assumption that input data are deterministic, that is, their values are known with certainty. In practice, however, there is a need to distinguish between risk and uncertainty of CC, whereby risk is often referred to as future events that can be well characterised by probability distributions, whereas uncertainty is the state of imperfect knowledge whereby values are less defined in a statistical or probabilistic sense (Austroads, 2005).

It is noted that there are uncertainties in all stages of the project development cycle including uncertainty in the costs involved in planning, designing, constructing and operating transport infrastructure. These uncertainties represent project risks that may result in outcomes different from those intended (Patrick *et al.,* 2004). In the context of this paper, environmental issues can be a significant source of uncertainty in the process of evaluating benefits of road investment decisions (Austroads, 2004).

TRB (2008b) defines risk as the product of the magnitude of adverse consequences and the probability that those consequences will occur. This concept can be broadly adopted for a range of CC related events (e.g. a storm surge damaging a road or bridge) and can be expressed as follows:

$$\text{Total Risk} = \sum_{\text{All Assets, All Hazards}} \text{Prob[Hazard]} \times \text{Prob[Consequence]}$$

5.1 Assessment of risks for road infrastructure

During the planning and design stages of road infrastructure a number of uncertainties have to be considered in relation to CC, e.g. the risk of flooding, changes in the level of the watertable, traffic volume, volume of freight and axle loads. In the case of flooding, this is usually expressed as a flood magnitude of a frequency of once in so many years. For bridges, this may be an increase from 1 in 200 years event, to 1, in say, 100 years. These frequencies of climatic events represent a probability of 0.005 and 0.01, respectively, of a flood of that magnitude occurring in the next year.

As there are significant costs associated with redesigning, retrofitting, protecting and potentially relocating road infrastructure from extreme CC weather events, there is a need for more strategic, risk-based approaches to decision making and infrastructure design. It is also necessary to clearly present the trade-offs between the costs of investments to make the infrastructure more robust and the likelihood and costs of facility failures or major disruptions to the system. A decision therefore exists as to whether to invest in infrastructure changes to mitigate potential CC events in the future, or to adopt a 'do-nothing' approach.

A good example of where these trade-offs have been considered and where clear benefits are displayed for implementing CC mitigation measures today, is in the development of the new Houghton Highway Bridge in Queensland. This bridge is considered to be an investment in the region's future by providing a CC proof bridge that will withstand waves generated by a severe 1-in-400 years storm event. It will also provide additional immediate benefits to the users such as reducing traffic delays caused by vehicle breakdowns or crashes, including a 4.5 m wide pedestrian and cycle path connecting with existing cycle networks, improving safety for mariners in terms of navigation clearance, whilst also maintaining the environmental and cultural heritage features of the area.

In order to assist in identifying, assessing and analysing risks related to uncertain CC factors, an option exists for the use of a software exploration tool – *Risk Explorer.* This tutorial tool (used for exploration of risks only) is discussed in Austroads (2005), and applies an illustrative Excel based model and the use of third-party software from Palisade called *@Risk.*

Risk Explorer provides a tool to identify, assess and analyse risks. It enables the user to identify variables of interest, and is prompted by a list of common variables affecting transport project benefits and costs. Additional variables may also be identified by the user which may be climate change specific, or relate to potential benefits, economic opportunities, social inclusion opportunities and other benefits/opportunities identified. This tool also enables the user to assess (qualitatively) and rank variables as low, medium and high as to their potential impact on the project benefits and costs; and quantify the nature of the uncertainty through distribution functions. Finally, the user can generate the probability distributions for selected output variables e.g. uncertain variables used in project evaluation (Patrick *et al.,* 2004).

6 Conclusion

The challenge in addressing CC is complicated by the uncertain nature of when, how frequent and how severe its impacts will be. This paper emphasises that CC should be incorporated as a key component in road authorities' planning processes. The Climate Change Framework developed directly achieves this by providing an effective analytical approach to identify and understand possible impacts/implications of CC, and assists government in determining its obligations and responsibilities to CC across Queensland's transport (road) system.

As outlined in this paper, CC impacts on transport can be short-term with immediate, temporary and intensive repercussions (e.g. spending on emergency repairs). They can also be longer-term in nature: changes in the size and type of economic activity, population movement and thus changing demand for transport and usage of roads. Also climate impacts directly affect road infrastructure design requirements, e.g. increased temperatures affecting pavements and flooding risks to roads and bridges.

In these situations, different responses are urgently required in order to prepare communities, and adapt procedures or infrastructure designs to mitigate future CC events (e.g. realignment of roads and bridges). Significant costs are, however, associated with these undertakings, and therefore require careful consideration of the trade-off between adapting infrastructure to improve the robustness of such infrastructure and the costs involved. The CCF therefore forms a critical element to enable such risk analysis to be undertaken, and also enables the efficient development of CC mitigation and adaptation responses for transport decision makers both today and in future years.

References

Austroads 2004, Impact of climate change on road infrastructure: appendices, AP-R243A/04, Austroads, Sydney, NSW.

Austroads 2005, Guide to project evaluation: part 2: project evaluation methodology, by N Rockliffe, S Patrick & D Tsolakis, AGPE02/05, Austroads, Sydney, NSW.

Evans, C, Tsolakis, D, Naudé, C & Lloyd, B 2008, 'Climate change framework', contract report VC74303, ARRB Group, Vermont South, Vic.

Patrick, S, Tsolakis, D & Houghton, N 2004, 'Risk analysis in the evaluation of transport proposals', Australasian Transport Research Forum (ATRF), 27th, Adelaide, South Australia, University of South Australia, Transport Systems Centre, Adelaide, SA., vol. 27, 14pp.

Queensland Department of Main Roads 2008, Connecting industry: Queensland floods special edition, QDMR, Brisbane, Qld.

Transportation Research Board 2008a, Impacts of climate change and variability on transportation systems and infrastructure: Gulf Coast study: phase I, Synthesis and assessment product 4-7, TRB, Washington, DC.

Transportation Research Board 2008b, Potential impacts of climate change on U.S. transportation, special report no. 290, TRB, Washington, DC.

Watkiss, P & European Environment Agency 2007, Climate change: the cost of inaction and the cost of adaptation, EEA, Copenhagen, Denmark.

Appendix A

This Appendix details a series of findings and recommendations for governments and the private sector to consider as ways to adapt systems and infrastructure to future events.

Findings and recommendations for addressing climate change

Findings	**Recommendations**
Assessing significance of risks involved in climate change	More work may be required to not only identify the risks involved in climate change but to quantify them as well.
Developing a methodological approach for assessment	A general methodology to assessing the impacts of climate change on transport may be required, which can be used across regions.
Identifying strategies for adaptation and planning	Although there is good understanding of the differences between short-term and long-term effects of climate change, more work may be required on incorporation of climate change into the long-term strategic planning process.
Public authorities and officials at various governmental levels and executives of private companies make short- and long-term investment decisions that often have implications for how the transportation system will respond to climate change in the near and long-terms.	Governments and private infrastructure providers could incorporate climate change into their long-term capital improvement plans, facility designs, maintenance practices, operations, and emergency response plans.
The significant costs of redesigning and retrofitting transportation infrastructure to adapt to potential impacts of climate change suggest the need for strategic, risk-based approaches to investment decisions.	Transportation planners and engineers could use more risk (probabilistic) investment analyses and design approaches that incorporate techniques for trading off the costs of making the infrastructure more robust against the economic costs of failure. At a more general level, these techniques could also be used to communicate these trade-offs to policy makers who make investment decisions and authorise funding.
Transportation professionals often lack sufficiently detailed information about expected climate changes and their timing to take appropriate action.	Agencies could work together to institute a process for better communication among transportation professionals, climate scientists, and other relevant scientific disciplines, and establish a clearing-house for transportation-relevant climate change information.
Better decision support tools may also be needed to assist transportation decision makers.	More work may be required to develop decision support tools for transport practitioners that enable them to include planning for climate change impacts. Ongoing and planned research at federal and state agencies and universities that provide climate data and decision-support tools could include the needs of transportation decision makers.
Projected increases in extreme weather and climate underscore the importance of emergency response plans in vulnerable locations, and require that transportation providers work more closely with weather forecasters and emergency planners and assume a greater role in	Transportation agencies and service providers could build on the experience in those locations where transportation is well integrated into emergency response and evacuation plans.

Findings	Recommendations
evacuation planning and emergency response.	
Greater use of technology may enable infrastructure providers to monitor climate changes and receive advance warning of potential failures due to water levels and currents, wave action, winds, and temperatures exceeding what the infrastructure was designed to withstand.	Government and academic research programs could encourage the development and implementation of monitoring technologies that could provide advance warning of pending failures due to the effects of weather and climate extremes on major transportation facilities.
The geographic extent of different state regions—and the diversity of weather and climate conditions—can provide a laboratory for identifying best practices and sharing information as the effects of climate change develop.	Relevant transportation professional and research organisations could develop a mechanism to encourage sharing of best practices for addressing the potential impacts of climate change.
Re-evaluating, developing, and regularly updating design standards for transportation infrastructure to address the impacts of climate change may require a broad-based research and testing program and a substantial implementation effort.	Departments could take a leadership role, along with those professional organisations in the forefront of civil engineering practice across all modes, to initiate immediately a federally funded, multi-agency research program for ongoing re-evaluation of existing and development of new design standards as progress is made in understanding future climate conditions and the options available for addressing them.
Governments could increase focus on adaptation in addressing climate change.	Departments could take the lead in developing an inter-agency working group focused on adaptation.
Transportation planners may not be required to consider climate change impacts and their effects on infrastructure investments, particularly in vulnerable locations.	Government planning regulations could require that climate change be included as a factor in the development of public-sector, long-range transportation plans; eliminate any perception that such plans should be limited to 20–30 years; and require collaboration in plan development with agencies responsible for land use, environmental protection, and natural resource management to foster more integrated transportation and land–use decision making.
Current institutional arrangements for transportation planning and operations could be organised to address climate change and should be adequate for the purpose.	Incentives incorporated in federal and state legislation could be considered as a means of addressing and mitigating the impacts of climate change through regional and multi-state efforts.

Source: TRB (2008a; 2008b)