Adaptation of Melbourne's Metropolitan Rail Network in Response to Climate Change

Department of Climate Change and Energy Efficiency
30 August 2011
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Prepared for
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Acronyms

AGO	Australian Greenhouse Office
AGCM	Atmospheric Global Circulation Models
AWAP	Australian Water Availability Project
BoM	Bureau of Meteorology
CBA	Cost Benefit Analysis
CBD	Central Business District
CoM	City of Melbourne
CSIRO	Commonwealth Scientific and Industrial Research Organisation
DCCEE	Department of Climate Change and Energy Efficiency
DoT	Department of Transport (Victorian Government)
DSE	Department of Sustainability and Environment (Victorian Government)
GCM	Global Climate Models
GHG	Greenhouse gas
IPCC	Intergovernmental Panel on Climate Change
LOS	Level of Service
OGCM	Oceanic Global Circulation Model
PV	Present Value
PWDM	Passenger Weighted Delayed Minutes
NPV	Net Present Value
UHIE	Urban Heat Island Effect
SRES	Special Report on Emission Scenarios

Glossary

Adaptation

The process, or outcome of a process, that leads to a reduction in harm or risk of harm associated with climate variability and climate change - UK Climate Impact Programme (UKCIP, 2003).

Economic benefits

A benefit to a person, business, or society that can be measured in financial terms.

Greenhouse gas emission scenarios

Estimations of the future quantity of greenhouse gases that may be released into the atmosphere, based on global changes to society, economy, population and technology over time.

Net Present Value

Compares the value of a dollar today to the value of that same dollar in the future.

Passenger Weighted Delayed Minutes (PWDM)

The number of minutes delay multiplied by number of passengers affected by the delay. For example, 100 passengers delayed by 2 minutes implies 200 PWDM

Projections

Model-derived estimates of the future climate (IPCC, 2010).

Scenario

A plausible description of a possible future state of the world. A set of scenarios is often adopted to reflect the range of uncertainty in projections (IPCC, 2010).

Urban Heat Island Effect

The increase in urban air temperature relative to surrounding rural temperatures is referred to as the urban heat island effect (CSIRO, 2007).

Willingness to pay

The amount of money that individuals are prepared to pay to avoid the loss of a service.

At a Glance

The study focussed on the cost benefit analysis of commuter rail adaptation to climate change and particularly the delays from increased hot days impacting the Melbourne metropolitan rail network. Commuter delays are a strong indicator of network performance and reliability. The costs and benefits of reducing these delays through a range of climate adaptation options was assessed.

The cost benefit analysis of adaptation options showed that only two options produced an economic result: regenerative braking (Option 3) and changing cabling and tension in power lines (Option 4).

Adaptation by increasing use of regenerative braking produced the best economic results, with a Net Present Value of approximately $107 M and a benefit cost ratio of 1.70 (under both greenhouse gas (GHG) scenarios). It should be recognised that the vast majority of the benefits of this option result from energy savings from the regenerative braking system rather than reductions in commuter delays.

Adaptation by changing tension and cabling in overhead lines provides considerable value for money in reducing commuter delays. The benefit cost ratio for this option is approximately 1.27 under the low GHG scenario with an NPV of $1.2M, and benefit cost ratio of 1.78 under a high GHG scenario with an NPV of $3.5 M. This option is also significantly cheaper than the other options.

The remainder of the adaptation options were shown to be uneconomic in this analysis with regard to reducing commuter delays. This outcome was unchanged under different assumptions about discount rates, the value of commuter time, and implementation timing, as shown in the sensitivity testing.

In general, lower discount rates and higher values of time produced better outcomes. Altering the timing of implementation produced mixed results. The uneconomic outcomes (Options 1, 2, 5 and 6) tended to become less economic the longer they were delayed. Option 3 also became less economic the longer its implementation was delayed, and delaying this option beyond about 20 years resulted in the option becoming uneconomic. Interestingly, Option 4 produced better economic outcomes as a result of delaying the implementation for 40 years, but beyond this became less economic.

The cost benefit analysis revealed that the remainder of the adaptation options are prohibitively expensive ways to address risks of increased commuter delays. However, it is important to recognise that many of these options produce benefits other than reduced delays that have not been assessed. For example, concrete sleepers are expected to be more durable and long-living than the current timber sleepers which would significantly reduce the costs involved in maintenance of sleepers and increase the replacement intervals. Improved air conditioning provides comfort benefits to passengers in addition to reducing the potential for train cancellations and delays.

Behaviour change programs may increase awareness of climate change resulting in benefits that extend far beyond the impacts on commuter delays. Inclusion of these other factors within the scope of the study and the analysis would provide significantly better results for some of the options, and the results shown here should be viewed with this in mind. The take home message from the analysis here is that there are adaptation measures that result in net benefits for the community and drive a range of other positive outcomes. This analysis is likely true across other rail network systems in Australia and worldwide. There would be value in seeing whether the lessons learned in this project can be applied more widely.

Summary of Benefit-Cost Analysis Results

A summary of the Net Present Value and Benefit Cost Ratio of each adaptation option is presented in Table 14.

Table 1 **Summary of BCA Results for all Adaptation Options**

ADAPTATION OPTION	LOW GHG SCENARIO (A1B)		HIGH GHG SCENARIO (A1FI)	
	Net Present Value ($M)	Benefit Cost Ratio	Net Present Value ($M)	Benefit Cost Ratio
Option 1 - Concrete sleepers	-$120	0.09	-$115	0.12
Option 2 - Replace air con.	-$80	0.13	-$75	0.18
Option 3 - Regen. braking	$107	1.70	$107	1.70
Option 4 - Cabling	$1	1.27	$4	1.78
Option 5 - Protect equipment	-$295	0.01	-$242	0.01
Option 6 - Behaviour change program	-$29	0.04	-$28	0.05

1.0 Introduction

Infrastructure investors, owners, managers and governments need to understand the physical impacts of climate change. They also need information on adaptation options, to inform decision making on which to implement and when.

Effective adaptation will reduce the economic impacts to the community resulting from an increased risk of infrastructure failure due to climate change. This is recognised by the Australian Government and is reflected in adaptation being one of the three pillars of the Australian Government's climate change strategy. To appropriately guide adaptation, the Government needs to understand the:

- likely community impacts of climate change
- impediments for infrastructure owners to implement adaptation options
- optimal timing of this adaptation implementation
- costs and benefits of adaptation options.

AECOM was engaged by the Australian Department of Climate Change and Energy Efficiency (DCCEE) to undertake a series of case studies analysing the economic case for adaptation in response to risks of climate change impacts on infrastructure.

This case study analysed the benefits and costs of possible measures to adapt Melbourne's metropolitan rail network to climate change impacts. It did so in terms of the measures' modelled impacts on the number of minutes passengers would wait for the arrival of scheduled train services following delays as a result of changed weather impacts.

This project will inform the Australian Government on policy responses to the risk that climate change might increase infrastructure investment and maintenance costs.

1.1 Project objectives

The objectives of this project were to:

- explore the optimal climate change adaptation options for maintaining the operational performance of the metropolitan rail network
- determine the optimal timing for implementing adaptation options.

1.2 Nature and benefits of analysis undertaken

Climate change is increasing severity and frequency of future weather and climate events. The uncertainty of the timing of these increased impacts on infrastructure can be partially reduced through effective adaptation, such as additional flood protection or increasing the tolerance of overhead structures to increased wind speeds. However, even when an ostensibly effective adaptation option is identified, there is currently little indication regarding the specific benefits it will deliver, when it should be built, or to what standard. This case study responds to this concern by identifying viable adaptation options, costing these options and analysing their benefits and the optimal timing for their implementation.

AECOM has used an expected benefit-cost methodology to rank and select preferred adaptation options for Melbourne's metropolitan rail network. Using this approach, economic benefits are estimated in terms of the willingness of consumers or other beneficiaries to pay for a good or service. The use of a benefit-cost analysis approach allows an assessment of the relative social merits of potential adaptation options in monetary terms.

Benefit-cost analysis is a methodology that enables the analysis of all costs and benefits in monetary units that reflect our preferences for, and use of, resources. Its scope therefore encompasses the value placed by society as a whole on the costs and benefits of a proposed course of action, rather than just using financial or commercial values. Costs are measured as both losses and implementation costs, and benefits reflect the willingness to pay of those who consume or otherwise benefit from an action or project.

1.3 Report outline

This report is structured into seven chapters:

- **Chapter 1** describes the objectives of the project, the nature of the analysis undertaken, and the benefits of the approach adopted.
- **Chapter 2** provides the background on Melbourne's metropolitan rail network.
- **Chapter 3** provides an overview of climate change and how future changes in weather events were determined.
- **Chapter 4** describes the methodology that was used for the case study.
- **Chapter 5** presents the inputs developed for the economic model, including the value of time, expected passenger delays and the projected change in climate.
- **Chapter 6** discusses adaptation options to mitigate the impacts of climate change and presents the modelling results for each adaptation option in terms of the benefits and costs.
- **Chapter 7** describes the findings in terms of the preferred adaptation options and discusses lessons learnt for adaptation of infrastructure and rail networks.

1.4 Acknowledgements

AECOM received significant input into this study from the following organisations and individuals, and acknowledges their support:

- Department of Transport (DoT)
- Metro Trains Melbourne (Metro)
- Commonwealth Scientific and Industrial Research Organisation (CSIRO)
- Bureau of Meteorology (BoM)
- Dr Leo Dobes, Crawford School of Economics and Government, Australian National University.

2.0 Background on Melbourne's metropolitan rail network

Heavy rail is a mainstream mode of transport in cities across the world. It is widely favoured as a transportation mode due to its relative speed, capacity and comfort. The Central City Users Survey identified rail as the predominant transportation mode used to access Melbourne's Central Business District (City of Melbourne, 2009). As governments seek to relieve road congestion and encourage less carbon intensive forms of transport, investment in rail is likely to increase. Climate change poses a risk to the operational performance of rail, which needs to be quantified and managed.

2.1 Background

Victoria's heavy rail network consists of four parts, the metropolitan network, the country passenger network, interstate lines and freight. The scope of this study is limited to the Melbourne metropolitan rail network.

The Melbourne metropolitan network is operated under a franchise agreement with the Government of Victoria by Metro Trains Melbourne (Metro). The current agreement has been in place since November 2009, and runs until November 2017.

The metropolitan rail network is based on a commuter rail model centred on the Melbourne CBD and Flinders Street Station. Primarily built at ground level, the network includes a number of level crossings and consists of mostly electrified lines.

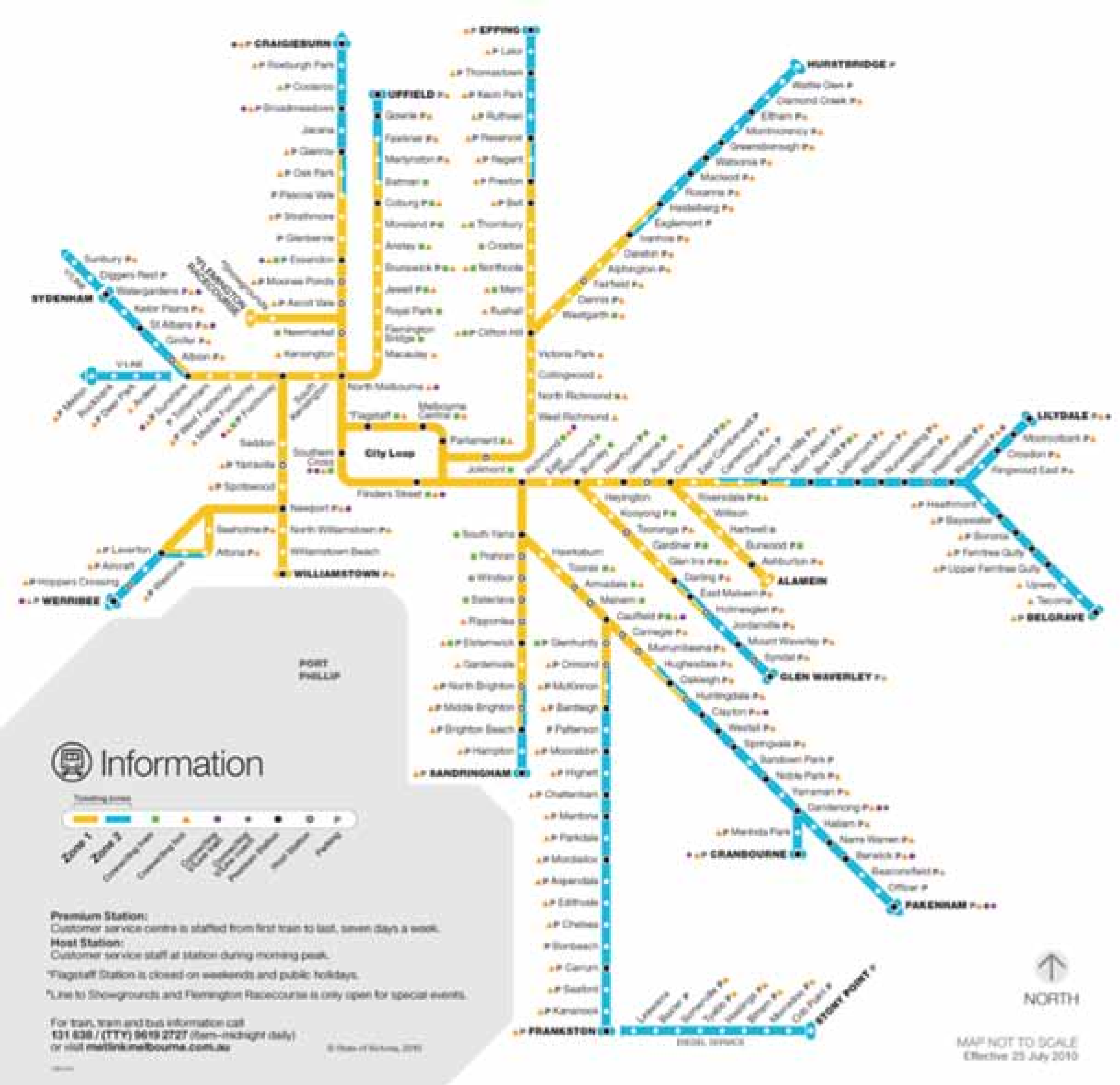
Key features of the network include:

- the central City Loop underground railway
- 211 stations
- 830 km of electrified track
- around 170 level crossings
- track sharing with freight trains and V/Line regional services
- 69 power stations and 51 high voltage supply points
- Rolling stock (i.e. trains) manufactured by 4 different suppliers, including:
    - Hitachi, representing 4% of all operating trains, built in 1970's and operating without air conditioning

- Comeng, representing 56% of all operating trains and built in the 1980's
- X'trapolis, representing 18% of all operating trains and built after 2000
- Siemens, representing 22% of all operating trains and built after 2000.

A map showing the layout of the Melbourne metropolitan network is provided in Figure 1.

Figure 1 **Map of Melbourne's metropolitan rail network (Source: Metro Trains Melbourne, 2010)**



2.2 Performance

Punctuality targets are set as part of Metro's franchise agreement to monitor and measure its operational performance. Over the past decade the performance of the metropolitan network has declined (Parliament of Victoria, 2010). The main factors nominated as the sources of decline include increased patronage, a deterioration of the network and increases in the frequency and severity of extreme weather events.

The Melbourne rail network has experienced an 80% increase in patronage since 1999 (Connex Melbourne, 2009). This has placed an unprecedented demand on the network which in turn has affected the reliability and performance of services (Parliament of Victoria, 2010). Other service failures have been attributed to V/Line trains' use of the metropolitan network, signal failures, uncooperative passengers, network congestion and a driver shortage (Connex Melbourne, 2009). Although it is recognised that these factors have significantly affected the performance of the rail network, this study's scope is limited to considering the impact of extreme weather events.

A number of extreme temperature days in 2009 and 2010 highlighted problems with the performance of the metropolitan network. For example, on 28 January 2009 the temperature in Melbourne reached 43°C, which led to the cancellation of at least 58 train services due to a range of track and operational problems. Two days later, the temperature exceeded 45°C, leading to 730 train cancellations (Parliament of Victoria, 2010).

Air conditioning on some trains becomes unreliable when the temperature rises to 35°C requiring these trains to withdrawal from service. On 11 January 2010, when temperatures reached 43.6°C, approximately 40% of all train cancellations were attributed to faulty air conditioners (Parliament of Victoria, 2010).

In March 2009, the Victorian Legislative Council appointed a Select Committee to investigate the causes of the inadequate performance of the metropolitan train service (Parliament of Victoria, 2010). The investigation found the main causes for cancellations and delays were train and infrastructure faults and issues regarding passenger interchange (Parliament of Victoria, 2010). The committee found that the influence of weather conditions on these causes included:

- extremely hot temperatures causing tracks built using wooden sleepers to buckle
- extremely hot temperatures causing signal and power failures
- extreme weather events causing network operations to fail – this impact has also been influenced by a lack of network maintenance
- extreme weather conditions causing air conditioners on the Comeng train fleet to fail.

Based on the findings from the Select Committee, the Victorian Government is embarking on a program of operational change and capital investment to improve the performance of the metropolitan rail network. To enhance network reliability, Metro is currently:

- undertaking a program to replace all timber sleepers with concrete sleepers to reduce incidences of track buckling (this should also reduce long term maintenance costs)
- replacing the air conditioning system on all trains manufactured by Comeng, so they are able to operate in temperatures of up to 45ºC (DoT, 2009).

2.3 Climate Change

Future climate change poses significant risks to the Melbourne metropolitan rail network, including:

- an increased number and extent of disruptions from extreme wind, heat, flash flooding, and intense storms
- power failures from wind, heat and storms affecting operations (e.g. signalling)
- flooding of train tracks

- increased risk of derailment due to tracks buckling in intense heat, also causing trains to run slower during these periods
- increased incidence of illness on public transport, resulting in service disruption, contributed to by intense heat and congestion.

These expected impacts have been noted in various studies, including the City of Melbourne's Climate Change Risk Report (City of Melbourne, 2008) and those released by the Select Committee discussed above.

This study will explore climate change adaptation options for maintaining the operational performance of the metropolitan rail network in the face of these anticipated impacts.

3.0 Projecting changes in climate

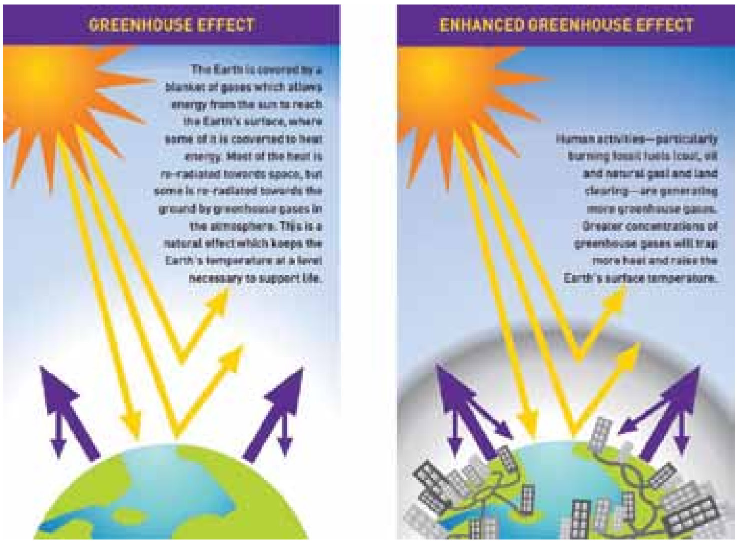
This chapter outlines why the climate is changing and describes currently observed and projected future climatic changes. The methods used to project these future changes are also discussed.

3.1 The greenhouse effect

The greenhouse effect is the natural process that maintains the Earth's habitable temperature. Energy from the sun passes through the atmosphere and hits the Earth's surface. Some of this energy warms the land and oceans, whilst most of it is radiated back into the atmosphere. A blanket of greenhouse gases then re-radiates some of this energy back towards the Earth's surface, whilst most escapes into space. Greenhouse gases (GHG) include water vapour, carbon dioxide, methane and a range of other gases. The greenhouse effect keeps the planet warm enough to sustain life, maintaining an average global temperature of approximately 15°C. Without the greenhouse effect the average global surface temperature would be approximately -18°C (Holper, 2002).

Human activity, mostly in the last 200 years, has increased the concentration of GHGs in the atmosphere, with key contributors including the burning of fossils fuels (e.g. coal and oil) and the clearing of vegetation. From 1800 to 2009, the atmospheric concentration of carbon dioxide has increased from 280 parts per million (ppm) to 386 ppm – a 38% increase. This has caused more energy to be trapped in the atmosphere, creating the enhanced greenhouse effect (see Figure 2).

Figure 2 **The Natural Greenhouse Effect and Enhanced Greenhouse Effect (AGO, 2006)**



3.2 Observed and projected changes

In 2007 the Intergovernmental Panel on Climate Change (IPCC) released their fourth assessment report, concluding that:

- warming of the climate system is unequivocal
- humans are very likely to be causing most of the warming that has been experienced since 1950
- it is very likely that climatic changes will continue well into the future, and that they will be larger than those seen in the recent past (IPCC, 2007).

The Earth's average temperature increased by approximately 0.7°C over the past century (CSIRO, 2011), whilst Australia's average temperature increased by just under 1°C between 1910 and 2009 (CSIRO, 2011). Most of this increase occurred after 1950 (approximately 0.7oC) and the past decade (2000 – 2009) was the warmest on record (CSIRO, 2011). In Victoria the average temperature increased by just under 0.6ºC from 1950 to 2005 (CSIRO, 2007).

In the future, Victoria is expected to warm at a slightly faster rate than the global average (CSRIO, 2007). Climate change projections prepared by CSIRO and BoM (2007) suggest that the future climate of Victoria is likely to be characterised by:

- lower average rainfall
- more intense extreme rainfall events
- higher average temperatures
- a more frequent occurrence of extreme temperatures
- more frequent very high and extreme fire danger days
- higher storm surge events
- higher average sea levels.

The degree of climate change which we will experience, and the timeframe over which these changes occur, will be significantly influenced by the volume and timing of future GHG emissions.

3.3 Greenhouse gas emission scenarios

The IPCC has agreed to six GHG emission scenarios, which each provide a different estimate of the future trajectory of GHG emissions. Each scenario has been built based on a range of different demographic, economic and technological assumptions. For this study, GHG emission scenarios from the 'A1' family have been adopted (refer to Box 1). This set of scenarios assume a future of rapid economic growth, a global population that peaks in the middle of the 21st century, and the rapid introduction of new technologies.

The 'A1' family of GHG emission scenarios represent a 'high emissions' future. Selection of these scenarios for this study therefore ensures that a cautious, conservative approach has been taken. Additionally, the current global GHG emissions trajectory is tracking in line with this 'high emissions' future; choosing a set of scenarios which represent a lower emissions future (such as the 'B1' family) would be unduly optimistic (Rahmstorf et al,, 2007).

The following specific scenarios were used for this study:

- **The A1FI scenario** describes a future with the highest concentrations of GHGs, and therefore the greatest climate change, of the IPCC's emission scenarios.
- **The A1B scenario** describes a lower emissions future than the A1FI scenario, particularly in the latter half of the 21st Century.

Box 1: Emission Scenarios

Emission scenarios are estimates of the future quantity of greenhouse gases that may be released into the atmosphere. These are based on assumptions about future demographic changes, and the implementation and efficiency of energy policies.

The Intergovernmental Panel on Climate Change (IPCC) developed scenarios in 1990, 1992 and 2000 and released a Special Report on Emission Scenarios (SRES). The SRES is used for input data for climate models. To reflect the latest rapid changes in societies since 2000, new emission scenarios are currently under development.

The IPCC emission scenarios are divided into four families: A1, A2, B1 and B2. A description of each scenario is provided in Table 2. Potential future temperature changes associated with each of the two SRES that have been modelled are presented in Figure 3, for low medium and high rates of global warming.

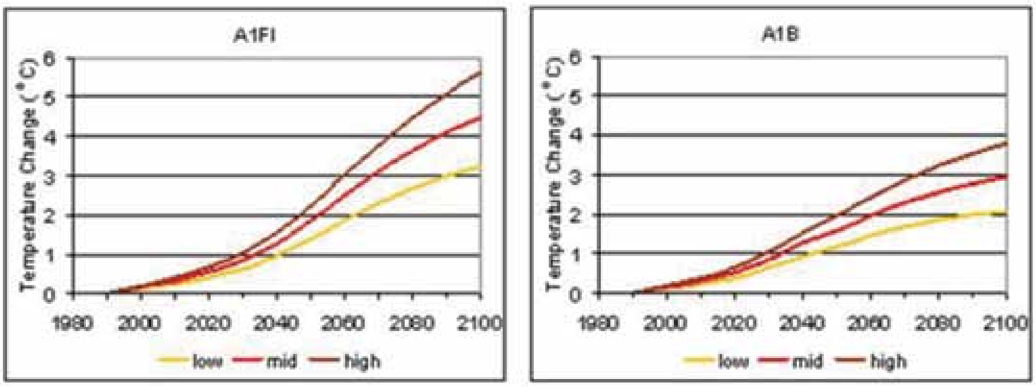
Table 2 **SRES Scenarios (Nakićenović & Swart, 2000)**

SRES SCENARIO	DESCRIPTION OF SCENARIO	
A1FI	Rapid economic growth, a global population that peaks mid 21st century and rapid introduction of new technologies	Intensive reliance on fossil fuel energy resources
A1T		Increased reliance on non-fossil fuel energy resources
A1B		Balance across all energy sources
A2	Very heterogeneous world with high population growth, slow economic development and slow technological change	
B1	Convergent world, same global population as A1 but with more rapid changes in economic structures toward a service and information economy	
B2	Intermediate population and economic growth, emphasis on development of solutions to economic, social and environmental sustainability	

The modelled GHG emission scenarios suggest the following potential future temperature changes:

- a 5.5oC increase in global average temperatures by 2100, compared with 1990 levels, for the A1FI GHG emissions scenario
- a 2oC increase in global average temperatures by 2100, compared with 1990 levels, for the A1B GHG emissions scenario.

Figure 3 **Global-average temperature change for low (yellow), mid (red) and high (brown) rate of global warming for the two SRES emission scenarios used in this study (Source: SRES 2000 in CSIRO 2010).**



3.4 Global Climate Models

In addition to the uncertainty regarding which GHG emission scenario will most accurately predict actual future emissions, twenty-three different Global Climate Models (GCMs) have been developed by researchers, to project the likely influence of these scenarios on the future climate. These GCMs use Atmospheric and Oceanic Global Circulation Models (AGCMs and OGCMs), in addition to other modelling inputs, to develop these climate change projections, and improve our understanding of climatological processes.

AGCMs and OGCMs rely on mathematical models of atmospheric and oceanic circulation to project changes in climate variables (CSIRO, 2011). Although the results from individual climate models can differ significantly, each one produces a plausible future climate for a given emissions scenario. Typically, projections are created for individual climate variables, for selected years and emission scenarios.

For the purposes of this study, we needed to identify which GCMs would be most relevant and appropriate. This task was done in consultation with CSIRO, in consideration of:

- our ability to access their outputs, in the format required for our study
- their anticipated accuracy for projecting changes to Melbourne's climate.

Based on this process, all but six models were excluded. The following GCMs were used for the purposes of this study:

- CSIRO-Mk3.0 (developed by CSIRO)
- CSIRO-Mk3.5 (developed by CSIRO)
- GFDL-CM2.0 (developed by the National Oceanic and Atmospheric Administration's Geophysical Fluid Dynamics Laboratory)
- GFDL-CM2.1 (developed by the National Oceanic and Atmospheric Administration's Geophysical Fluid Dynamics Laboratory)

- MIROC3.2(medres) (developed by the Center for Climate System Research at The University of Tokyo, the Japanese National Institute for Environmental Studies, and the Frontier Research Center for Global Change
- ECHAM5/MPI-OM (developed by the Max Planck Institute for Meteorology).

An overview of how these climate models have been used to generate climate change projections for this study is provided in Section 4.

4.0 Methodology

This study developed a model that can be used by decision makers to evaluate climate change adaptation options for Melbourne's metropolitan rail network. To do this, we have assessed the projected socio-economic costs from climatic changes and identified the optimal timing to implement a number of costed adaptation solutions. The six stages involved in delivering this study are discussed below (Figure 4).

Figure 4 **Methodology for the study**

	Key outcomes from each stage
1. **Scope the study**	• Project parameters were set • The study boundary was established • Modelling relationships were identified
2. **Quantify historic weather events**	• Temperature thresholds causing delays were identified • Historic dates when thresholds were exceeded, and their associated passenger delays, were identified • The relationship between a weather event and passenger delays was determined
3. **Quantify future weather events**	• The number of projected yearly events triggering thresholds were identified under the different climate change scenarios
4. **Modelling climate change without adaptation**	• The assumptions and economic parameters governing the model were established • The model was designed, built and tested • The relationship between economic costs and frequency of extreme temperature events was determined
5. **Modelling climate change with adaptation**	• Adaptation options were identified and prioritised • Costs and benefits for the prioritised adaptation options were developed • Benefits and costs were averaged across climate models for each climate scenario used
6. **Analysis and communicate the findings**	• A draft report was developed and issued to DCCEE for review • Report was updated and finalised to incorporate DCCEE's feedback

4.1 Scoping the study

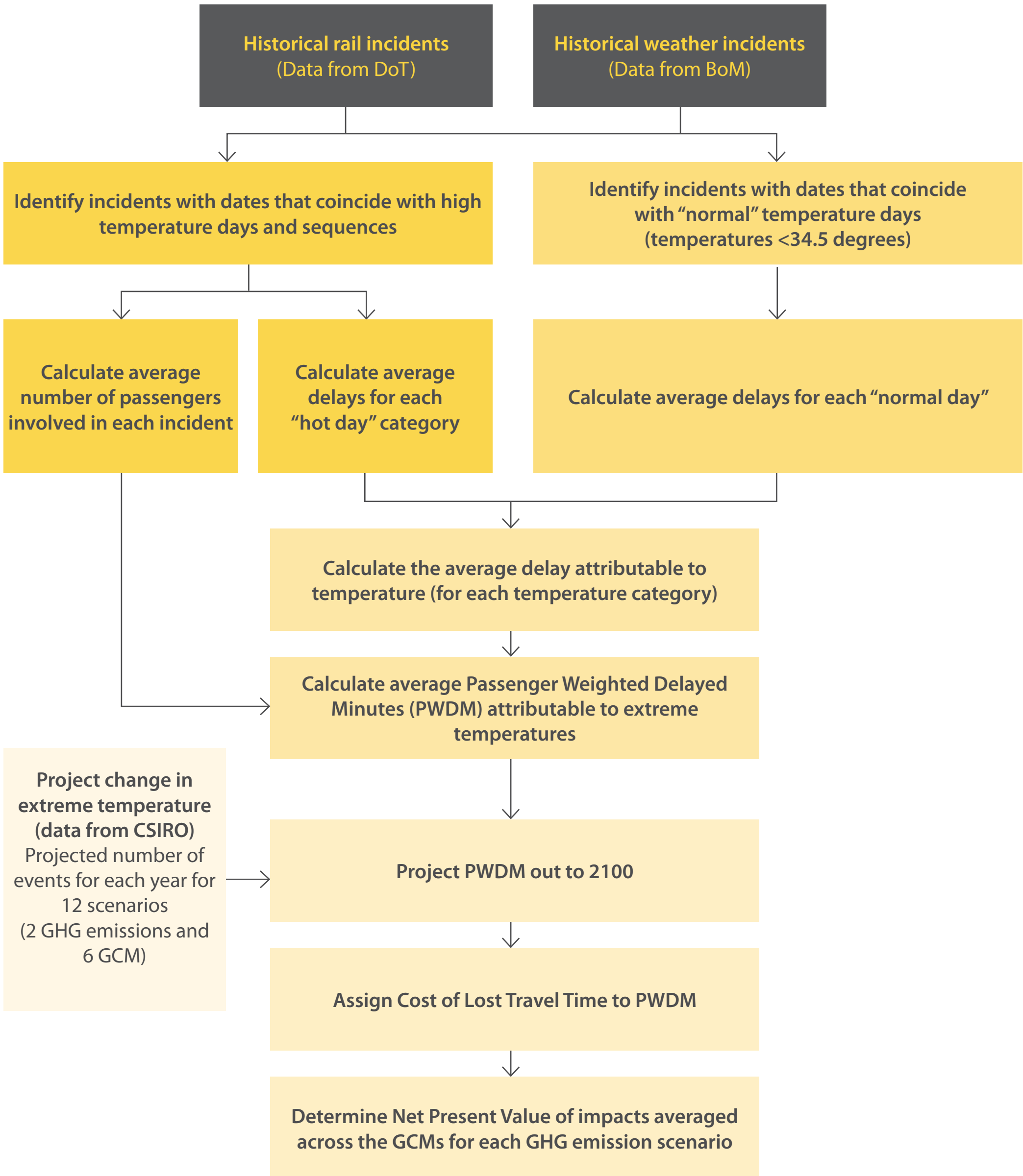
AECOM identified and confirmed key project parameters in consultation with DCCEE, Metro and DoT, namely:

- the region under investigation (refer to Figure 1 for a map of the Melbourne metropolitan rail network)
- the climate variables to be initially considered for inclusion (extreme wind, extreme rainfall and temperate)

- the greenhouse gas emission scenarios to be modelled (A1FI and A1B)
- the global climate models to be utilised (as discussed above)
- a measurement indicator of network performance
- historic weather events which affected the reliability of the metropolitan commuter rail network
- costs associated with the impacts of climate change
- adaptation options for the metropolitan network, including their associated costs
- projected changes in the number of extreme weather events as yearly time series, from 2011 to 2100
- the detailed economic model specifications.

The way in which these project parameters were used in the study is outlined in Figure 5.

Figure 5 **Process flow of the relationships for modelling the economic impact to rail network from climate change induced hot weather events**



4.2 Quantifying impacts of historic weather events

AECOM worked with DoT to understand the possible relationships between historic weather events and the performance of train services. One of the key purposes of this was to identify a performance indicator which would enable the modelling of the likely impact of future weather events on the train network. This work concluded that the most appropriate measure would be an existing performance measurement indicator, given the access to robust and meaningful data. Passenger Weighted Delayed Minutes (PWDM) was the chosen indicator for recorded network delays.

To determine PWDM for the Melbourne metropolitan train network, any service failures (such as delays or cancellations) are recorded and rounded to the nearest minute. They are then weighted to account for the number of people estimated to be travelling on that specific train during the measured time period, day of week and direction of travel. The DoT provided AECOM with records of PWDM for the past 10 years from the ToPS database, factoring in growth in passenger numbers over that period.

AECOM's rail network specialists then identified the weather conditions which are likely to affect network performance, in the form of specific thresholds being exceeded. AECOM identified the dates on which these thresholds were exceeded by analysing historic weather data obtained from the BoM.

AECOM reviewed the PWDM for days in which these weather thresholds were exceeded. There was a clear increase in PWMD for days that exceeded these weather event thresholds compared to the annual average PWDM. The last 10 years of PWDM data was analysed to determine:

- The average PWDM for each category of weather thresholds exceeded (for example, the average PWDM on a single day with temperatures reaching between 37 and 40 degrees was 1,139,482 minutes delay across the network)
- The average PWDM for a 'normal day' (i.e. a day in which none of the temperature thresholds were exceeded).

This 'normal-day' figure represents the average delay that would be expected to occur on any given day, regardless of temperature. This normal-day PWDM was then deducted from the temperature related PWDM for each of the threshold categories to estimate the average PWDM in each category attributable to temperature.

The outputs of this process were then used as the basis for estimating expected delays (as measured by PWDM) in the future on any given high-temperature day, or sequence of high-temperature days. By assessing the number of such days expected in the future, the expected impacts of delay under climate change could then be assessed.

4.3 Quantifying future weather events

AECOM consulted CSIRO to establish the projected number of days when the thresholds established during the previous project stage might be exceeded due to future climate change. All climate variables were considered for this analysis. However, all variables except extreme temperature were excluded due to a lack of appropriate, available data, or a lack of anticipated impact on the rail network.

Climate induced changes to average and extreme wind speed and rainfall could significantly affect the rail network. However, both of these variables were not able to be assessed in this study due to a lack of yearly data (i.e. data was available for time slices such as 2030 or 2050, but not for every year between 2020 and 2100, as required by this study).

Other climate variables such as bushfires, hail, dust, sea level rise and storm surge are not considered significant risks to the metropolitan rail network relative to extreme temperature.

To enable an analysis of the likely number of days exceeding extreme temperature thresholds within the rail network, CSIRO generated projections for the probable annual number of days where the temperature is likely to exceed 34.5°C, 37.0°C and 40.0°C, for each GHG emission scenario (i.e. A1FI and A1B), from 2020 to 2099. In other words, CSIRO modelled how the right hand tail of the temperature duration curve might change under different climate models. The Australian Water Availability Project was used to model these results. To provide a baseline for comparison with this projected data, the historic period 1970 to 2009 was used.

4.4 Modelling climate change without adaptation

During this project stage, we developed a model that would calculate the projected increase in PWDM due to extreme temperature events as shown in the right hand tail of the temperature duration curve, for each climate change scenario and GCM. This was done without consideration of the effect of any future implementation of adaptation options.

All model inputs, excluding adaptation options, were developed and the model was tested. A key aspect of this testing involved designing the model to analyse the relationships identified in Section 4.1, by drawing on the modelling inputs developed in Section 4.2 and 4.3.

Assumptions

An assumption that was made for this stage was that the majority of PWDMs result from extreme temperature events. While in reality there are a range of other factors that may contribute to passenger delays, for the purposes of this study it is assumed that they are insignificant. Another critical assumption is that all network parameters remain constant, while in reality the performance of the network will change over time.

For the three day sequences only the delay on the third day is considered; or longer sequences are considered multiples of three day events. For example a four day sequence of high temperatures is classified as two events, with the events occurring on the third and fourth day.

As the analysis has been undertaken at the Metro level, only the highest of each of the weather station outputs for any one day has been used.

Economic parameters

The model we developed has been designed to be consistent with standard economic appraisal guidelines, including the Australian Transport Council National Guidelines for Transportation System Management. The economic parameters used in this study are based on those that have been established in previous case studies, as outlined in Table 3.

Table 3 **Economic parameters used in the model**

PARAMETER	VALUE	COMMENT
Appraisal period	2011 to 2100	To align with previous case studies
Time series	Yearly	Projected increase in the number of hot days has been determined for each year
Discount rate	3%, with sensitivity testing of discount rates of 1.5% and 6%	Refer to discussion below
Discount and base pricing periods	2011	To match the year the case study commences

Discounting is a standard method to add and compare costs and benefits that occur at different points in time, allowing a comparison of future costs and benefits against today's costs and benefits (Garnaut, 2010). Discounting takes into account the time value of costs and benefits, and opportunity costs of diverting current investment into something that may accrue benefits in the future but are worth less to society in today's terms.

The choice of discount rate for climate adaptation projects is important. Standard infrastructure projects use a discount rate between 6% and 7%, the Victorian State Government typically uses 6.5%, while Infrastructure Australia uses a 7% discount rate. However, it is common for projects with long term social and environmental impacts, such as those relating to climate change, to adopt a lower discount rate. For example, in the Garnaut Climate Change review, Garnaut argues for adoption of a social discount rate between 1.4% and 2.7%. The Stern Review on the Economics of Climate Change (2006) adopted a discount rate of between 1.4% and 1.7%.

This study has utilised a 'middle-ground' discount rate of 3%, with sensitivity testing of results using 1.5% and 6% discount rates to assist decision making.

4.5 Modelling climate change with adaptation

A set of adaptation options that might reduce the impact of projected changes in extreme temperature events was identified in collaboration with DCCEE, DoT and Metro. A workshop was then held with key stakeholders to establish a set of adaptation options and implementation pathways to determine the costs and benefits of each option.

AECOM worked with DoT and Metro to collect data on the adaptation costs and possible benefits. This drew from the capital and operational costs of measures that have been implemented in response to the 2009 heatwave. Once identified, this data was translated into economic modelling inputs and the model was run.

Economic model

The economic model developed for this project operates with a range of inputs in a Microsoft Excel spreadsheet. The model simulates each climate change scenario and each adaptation option and considers differing timing for implementation. This correlates to the year the NPV for an adaptation option is at its maximum over the appraisal period (2011 to 2100).

For each time step in the appraisal period, the model:

1. determined the passenger delay due to the extreme temperature events (with and without adaptation options) for each year between 2011 and 2100
2. determined the cost impact of these passenger delays on commuters (with and without adaptation options).

Once the impacts and costs were generated for each extreme temperature event, the model:

1. discounted the extreme temperature event's impact costs for each year of appraisal
2. discounted adaptation capital and ongoing operation and maintenance costs
3. summed all discounted costs across the entire appraisal period and recorded the results
4. averaged across all GCMs but not emission scenarios.

Sensitivity analysis was then undertaken to assess the impacts of altering the implementation timing, as well as other key assumptions such as discount rates and value of delayed time.

4.6 Reporting results on the modelling outputs

The economic modelling results were then analysed to consider different timing for implementing adaptation options for the metropolitan rail network. A report was then developed that captured and communicated the findings, including reporting the NPV of the adaptation options and providing an evaluation of the methodology used.

5.0 Modelling inputs for assessing climate change adaptation

This chapter presents the modelling inputs that were developed and used to assess the climate change adaptation options. The inputs that were developed include the critical temperature thresholds when network performance is likely to be affected, the average time delay incurred when these temperature thresholds are exceeded, the projected changes in the number of future events and the economic benefits of both time and adaptation options. This section provides a discussion of each of these modelling elements.

5.1 Temperature thresholds

At certain temperature thresholds the operation of the metropolitan network will be affected. The type of impact relates to the temperature and the component of the network that is under stress. Thresholds have been identified for the key components of the metropolitan network including rail track, rolling stock and signalling.

Rail tracks are designed for tension or 'neutral stress' at temperatures of 37ºC. This means that rail track neither expands nor contracts at this temperature. When the temperatures exceeds 37ºC, the risk of the rail track not performing to its required level of service or, in the worst case, failing, increases. The actual threshold or trigger point for when the rail track starts buckling is unknown and depends on many other factors.

At certain temperatures some trains' air conditioning units will fail, and the train cannot be used. The temperature at which the failure occurs depends on the type of rolling stock:

- Comeng trains comprise over 50% of the rolling stock, and their air conditioning units are designed to operate up to ambient temperatures of 34.5°C
- X'Trapolis and Siemens each comprise approximately 20% of the rolling stock, and their air conditioning units are designed to operate up to ambient temperatures of 42°C.

Signalling faults can expect to double on high temperature days due to:

- sag in overhead lines
- overheating and unstable behaviour of electric components in trackside cabinets
- problems with insulated joints causing track circuit failures

- expansion of the blade rail that moves across the track transferring a train from one track to another
- loss of power supply leading to trains being unable to operate (Connex Melbourne, 2009).

As an input to the modelling, this information assisted in identifying the number of occasions temperature thresholds are likely to be exceeded over the period of investigation (2010 to 2100). Operational performance of the network may be further compromised on consecutive days of high temperatures. For example, if residual heat is retained in the rail overnight and not dispersed by cooler temperatures, the rail will be more prone to buckling (Connex Melbourne, 2009). As such, the impacts of three consecutive days at the temperature thresholds were also investigated.

The temperature thresholds that were identified to enable this analysis were 34.5°C, 37°C and 40°C.

5.2 Average delay per event

The historic PWDM for each high temperature event was assessed based on historic records of temperatures in Melbourne, and PWDM records over the previous decade, after allowing for PWDM that would be expected to occur on any given day regardless of temperature.

This exercise showed that PWDM increased significantly above the annual average PWDM as the temperature thresholds were exceeded.

Climate change is likely to result in an even more significant increase in the number of events projected to trigger the temperature thresholds. Two climate change scenarios are presented in Table 4 along with a summary of the number of historical average delays per event and the average number of triggered events per year for the scenarios discussed above.

Table 4 **Historic PWDM per incident and average number of triggered events per year for a given scenario**

TEMPERATURE THRESHOLDS		PWDM per event (minutes per day) (historic)	AVERAGE NUMBER OF EVENTS PER YEAR FOR A GIVEN SCENARIO			
			1970 - 2009 (historic)	2009 (historic)	2100 (A1FI mpi_echam5)	2100 (A1B miroc3_2_medres)
Single days	>34.5ºC to <37ºC	91,702	7	14	48	27
	>37ºC to <40ºC	277,313	3	7	33	16
	>40ºC	490,092	0	4	20	7
Three consecutive days	>34.5ºC to <37ºC	507,463	0	2	16	7
	>37ºC to <40ºC	1,021,273	0	1	8	2
	>40ºC	3,599,598	0	1	3	1

5.3 Climate change projections

The probability of exceedence for a temperature event has been modelled by CSIRO, in consultation with AECOM. Projections were run for the two identified GHG emission scenarios (A1FI and A1B), the six identified GCMs and for single and consecutive day events for three temperature thresholds (34.5°C, 37°C and 40°C). This represents 72 different combinations of weather events. What follows is a discussion of the projected changes in the probability of exceedence of extreme temperature events.

The GHG emission scenarios projections for a single day event and a consecutive event show an upward trend. The number of events under all scenarios increases over time in comparison to historic events. The number of 37°C events is greater than the number of 40°C events.

CSIRO were not able to generate climate projections prior to 2020. Instead, it was assumed that for the years 2010 to 2019 the same number of extreme temperature days would be experienced as the years 2000 to 2009.

Observational data for the last 40 years (historic period 1970 to 2009) was used to generate the projections. This historic data was used to replicate natural variability to the future projections. To calculate the full 80 years of projections, 2020 to 2099, the last 40 years of variability was used twice.

Graphs of the number of single day events over 37°C per year for the historic, high and low scenarios are provided in Figure 6. Graphs of the number of consecutive day events over 37°C per year for the historic, high and low scenarios are provided in Figure 7. The modelling uses probability of exceedence rather than projected numbers of events in any particular year. The benefit-cost modelling is linear in impacts within particular bands, therefore Monte Carlo simulation is not required.

Figure 6 **Historic and projected single day events over 37°C per year (1970 to 2100)**

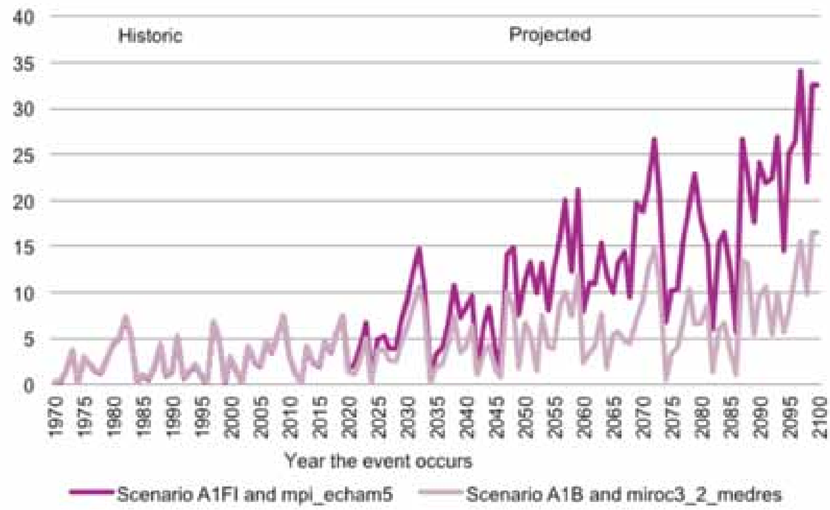
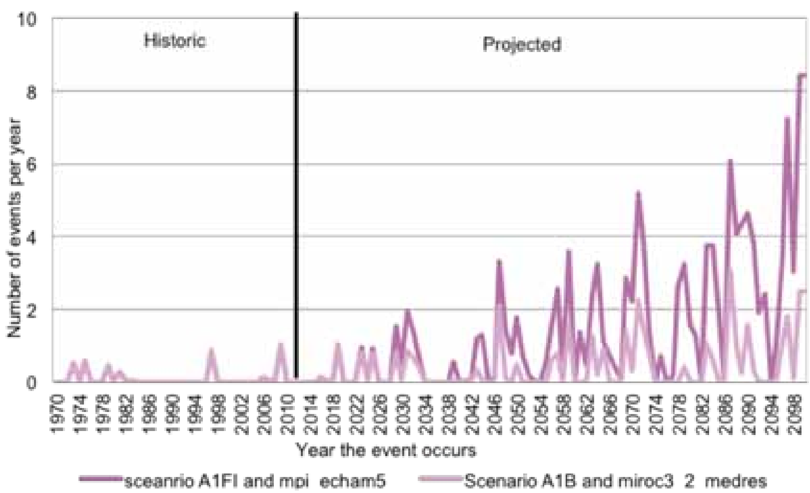


Figure 7 **Historic and projected consecutive three day events over 37°C per year (1970 to 2100)**



5.4 Public transport growth

The number of passengers using the commuter rail network over the period 2000-2010 is presented in Table 5 (source: Department of Transport). These figures have been factored into the calculation of PWDM for the past decade.

Table 5 **Rail patronage over the period 2000-2010**

YEAR	MILLION OF PEOPLE	ANNUAL CHANGE
2000-01	130.3	-
2001-02	131.8	1.2%
2002-03	133.8	1.5%
2003-04	134.9	0.8%
2004-05	145.1	7.6%
2005-06	159.1	9.6%
2006-07	178.6	12.3%
2007-08	201.2	12.7%
2008-09	213.9	6.3%
2009-10	219.3	2.5%

Forecasts for growth in patronage of rail transport are presented in Table 6.

Table 6 **Patronage Growth Rate (Average Weekday AM Peak and Train Cordon), (source: pers comm. 16 March 2011)**

YEAR	ALL DAY	AM PEAK	AM PEAK AT CORDON (INBOUND)
2009/10	8.9%	8.6%	7.2%
2010/11*	10.5%	9.6%	6.9%
2011/12	8.1%	7.4%	6.6%
2012/13	7.8%	7.1%	6.1%
2013/14	7.6%	6.8%	5.7%
2014/15	7.4%	6.5%	5.5%
2015/16	7.2%	6.3%	5.3%
2016/17	7.5%	6.0%	5.1%
2017/18**	7.4%	5.8%	4.3%
2018/19	5.9%	4.2%	3.5%
2019/20	4.6%	3.4%	2.7%
2020/21	3.3%	2.7%	2.0%
2021+	2.0%	2.0%	1.3%

Note: * reflects proposed carbon tax

**reflects movement towards a growth rate – marginally ahead of population growth

5.5 Value of commuter time

A number of studies have identified the value of time lost due to unexpected delays. Hensher (1994) found that the value of lost time due to delay ranged between 44% and 88% of the commuter's wage rate for the period of delay. Miller (1996) undertook a similar study, finding that commuter's willingness to pay to avoid unexpected delays ranged between 55% and 75% of the commuter's wage rate for the period of delay.

Based on this, AECOM has assumed a value of 60% of the average wage rate. The average wage rate in Victoria in 2010 was $62,748 (ABS, 2010). Based on a 40 hour week, this equates to a rate of approximately $0.50 per minute.

The value of delayed time adopted for this study has therefore been assumed to be 60% of this value, or approximately $0.30 per minute. Sensitivity testing has been undertaken in the cost benefit analysis at 45% of the wage rate ($0.23 per minute) and 75% of wage rate ($0.38 per minute).

5.6 Adaptation strategies

This study considered a range of adaptation responses, including infrastructural and non-infrastructural options. The adaptation strategies explored include:

- concrete sleeper replacement;
- replacement of air conditioners in all rolling stock to ensure they operate up to at least 45°C;
- installation of regenerative braking;
- changing the cabling in the power lines and/or tensioning of the lines;
- signalling equipment replacement and installing backups for their electronics;
- behaviour change mechanisms to influence commuter travel behaviour (i.e. phone-based early-warning systems);
- heatwave behaviour change program (i.e. messages, issuing water and providing shade);
- providing alternative modes of transport (i.e. buses).

Each adaptation strategy has a benefit and a cost. Benefits are derived from avoiding network delays, asset failure and operational response cost. Costs will be incurred to implement the strategy and derive the benefits from the preventative measures.

A summary of the selected adaptation strategies and the modelling inputs developed for each option is provided in Table 7.

Following the table (in Section 6.0) is a discussion of the modelled adaptation options to determine the costs and benefits for implementation to mitigate the likely impacts of climate change induced extreme temperatures on the metropolitan rail network. As discussed in Section 4.5, these modelling inputs were developed in consultation with DoT, MMT and DCCEE.

Table 7 **Summary of the adaptation options and the modelling data inputs**

ADAPTATION OPTION	LIFE OF BENEFIT (YEARS)	REDUCED DELAYS (%?)	CAPITAL COST ($)	ADDITIONAL OPERATIONAL COST ($/YEAR)	TIME TO IMPLEMENT ADAPTATION OPTION (YEARS)
Concrete sleeper replacement	60 (100+)	20%	$122.4M	Some minor reduction in replacement of timber sleepers	5
Replace air conditioners in all rolling stock to 45°C	20	20%	$23.2M	$4M every 6 years	1
Regenerative braking	15	5%	$65M	$10M saving in energy per year	6
Change the cabling in the power lines and/or tensioning of the lines	60	10%	$1.2M	$0.12M (cost to inspect and keep the pits clean assumed to be 10% of capital)	4
Signalling equipment protection of the electronics	30	5%	$200M	Nil	3
Heatwave behaviour change program	Ongoing program	Less than 5%	Nil capital cost yet requires $1M annual operational cost	$10,000 per event	1

6.0 Potential adaptation strategies

The results of the cost benefit analysis of each of the six adaptation options is presented in the subsequent section. Results have been reported under low and high GHG scenarios (A1FI and A1B respectively), and are averages of the results of the six climate models.

Note all assumptions relating to reduced delays under each of the options have been developed in consultation with the DoT and DCCEE. All costs of adaptation options have been provided by DoT.

All results are based on a discount rate of 3%.

6.1 Adaptation Option 1: Concrete sleeper replacement

6.1.1 Description

Adaptation Option 1 assumes a full replacement across the entire network of wooden rail sleepers to concrete rail sleepers. This option seeks to reduce rail buckling in extreme temperatures. By introducing concrete sleepers the strength of the track is increased. The connection of the concrete sleepers to the steel rails holds the track in place assisting to reduce heat related buckling.

The Victorian Government commenced a sleeper replacement program in 2010. This option assumes the program is extended to a full replacement of all sleepers across the entire network and may take five years to implement.

6.1.2 Cost and benefits

The key costs associated with this option are:

- implementing a concrete sleeper replacement program at a total capital cost of $122.4M
- There are significant GHG emissions associated with the production of concrete sleepers. This was not quantified for this assessment.

Key benefits are:

- avoided passenger delays, based on an assumed 20% reduction in delays per triggered event
- a slight reduction in operating costs, although the value of this benefit has been taken as insignificant.

6.1.3 Results

The results of Adaptation Option 1 are presented in Table 8.

Table 8 **Option 1 Cost Benefit Analysis Results**

ITEM	LOW GHG SCENARIO (A1B) ('000)	HIGH GHG SCENARIO (A1FI) ('000)
Cost of Delays	$47,163	$65,683
Benefits (avoided delay)	$11,336	$15,966
Adaptation Costs	$131,140	$131,140
Net Present Value	**-$119,804**	**-$115,174**
Benefit Cost Ratio	**0.09**	**0.12**

6.2 Adaptation Option 2: Replace air conditioners in all rolling stock

6.2.1 Description

Adaptation Option 2 assumes replacement of air conditioners in all rolling stock to ensure they operate up to at least 45oC. This adaptation reduces the chance of air conditioner failure and the potential risks to passenger health. This adaptation response is likely to increase energy demand by trains and increase the GHG emissions of the metro rail network. The expected benefit has a life of 20 years while the duration to implement is 1 year.

6.2.2 Cost and benefits

The key costs associated with this option are:

- Capital cost of $23.2M
- Additional operational cost of $4M every 6 years.

Key benefits assessed are:

- 20% reduction in delays per event

6.2.3 Results

The results of Adaptation Option 2 are presented in Table 9.

Table 9 **Option 2 Cost Benefit Analysis Results**

ITEM	LOW GHG SCENARIO (A1B) ('000)	HIGH GHG SCENARIO (A1FI) ('000)
Cost of Delays	$46,867	$65,387
Benefits (avoided delay)	$11,632	$16,262
Adaptation Costs	$91,251	$91,251
Net Present Value	**-$79,619**	**-$74,989**
Benefit Cost Ratio	**0.13**	**0.18**

6.3 Adaptation Option 3: Regenerative braking

6.3.1 Description

Adaptation Option 3 assumes the use of regenerative braking to convert friction generated during braking into energy. High temperature events reduce the braking performance of existing brake mechanisms while increasing the chance of brake failure. Regenerative braking will reduce brake wear and tear, and potential failure. Trials will be required to validate and refine the most suitable technology, as such, implementation could take six years or more. Most of the new current rolling stock already has regenerative braking technology installed but not activated or utilised.

6.3.2 Cost and benefits

The key costs associated with this option are:

- implementing a regenerative braking program ($65M)
- avoiding passenger delays, which assumes avoiding a 5% reduction in delays per triggered event
- operational saving in energy of $10M per year.

6.3.3 Results

The results of Adaptation Option 3 are presented in Table 10.

Table 10 **Option 3 Cost Benefit Analysis Results**

ITEM	LOW GHG SCENARIO (A1B) ('000)	HIGH GHG SCENARIO (A1FI) ('000)
Cost of Delays	$54,611	$77,706
Benefits (avoided delays + energy savings)	$259,041	$259,095
Adaptation Costs	$152,406	$152,406
Net Present Value	**$106,635**	**$106,689**
Benefit Cost Ratio	**1.70**	**1.70**

6.4 Adaptation Option 4: Change the cabling in the power lines and/or tensioning of the lines

6.4.1 Description

Adaptation Option 4 assumes the replacement of the cabling in the power lines and/or tensioning of the lines across the network. The existing tensioning mechanisms for most of the lines were not sufficiently designed to operate at extreme temperatures. Improved materials would also be used in the power lines to increase extreme tolerance and reduce potential sagging. The expected benefit has a life of 60 years while the duration to implement is 4 years.

6.4.2 Cost and benefits

The key costs associated with this option are:

- Capital cost of $1.2M
- 10% reduction in delays per triggered event
- Operational cost of $0.12M based on assuming the cost to inspect and keep the pits clean is 10% of capital

6.4.3 Results

The results of Adaptation Option 4 are presented in Table 11.

Table 11 **Option 4 Cost Benefit Analysis Results**

ITEM	LOW GHG SCENARIO (A1B) ('000)	HIGH GHG SCENARIO (A1FI) ('000)
Cost of Delays	$52,791	$73,626
Benefits (avoided delay)	$5,708	$8,023
Adaptation Costs	$4,503	$4,503
Net Present Value	**$1,205**	**$3,520**
Benefit Cost Ratio	**1.27**	**1.78**

6.5 Adaptation Option 5: Protection of signalling equipment

6.5.1 Description

Adaptation Option 5 assumes increased temperature protection of heat exposed signalling equipment such as in trackside cabinets. Overheating of the signalling equipment leads to temporary or permanent failure of electric components. Failed or faulty signals can cause extensive train delays if the location of failure in the circuit is not known. Protection measures include insulating equipment and cabling, providing shade protection or relocating signalling equipment to less heat exposed areas (this may also have a co-benefit of preventing flood damage).

This option assumes a signalling protection program may take three years to implement.

6.5.2 Cost and benefits

The key costs associated with this option are:

- implementing a signalling protection program ($200M)
- avoiding passenger delays, which assumes avoiding a 5% reduction in delays per triggered event
- no additional operating costs are incurred.

6.5.3 Results

The results of Adaptation Option 5 are presented in Table 12.

Table 12 **Option 5 Cost Benefit Analysis Results**

ITEM	LOW GHG SCENARIO (A1B) ('000)	HIGH GHG SCENARIO (A1FI) ('000)
Cost of Delays	$55,628	$77,620
Benefits (avoided delay)	$2,871	$4,029
Adaptation Costs	$298,271	$298,271
Net Present Value	**-$295,400**	**-$241,808**
Benefit Cost Ratio	**0.01**	**0.01**

6.6 Adaptation option 6: Heatwave behaviour change program

6.6.1 Description

Adaptation Option 6 assumes development and ongoing delivery of a heatwave behaviour change program. The program would be designed to target elderly or potentially sick passengers to influence behavior to minimise potential health risks and to reduce train delays from ill passengers. Successful behaviour change programs are structured with a range of communication campaigns, prompts, supportive infrastructure or equipment (e.g. shade protection for station platforms, issuing water to passengers or have first aid support on hand for stations with higher track record of health incidents), and aim to create a social/cultural expectation around appropriate behaviour and actions during heat waves.

Behaviour change programs require continual renewal of messages, expectations and target audiences to maintain effectiveness. The Transport Accident Commission or WorkSafe have a long history of effective and relevant behaviour change programs to protect the community from health risks. There is an expected annual benefit while the program is maintained. It is assumed that the program will be maintained up to 2100. The duration to implement is 1 year.

6.6.2 Cost and benefits

The key costs associated with this option are:

- No capital cost but requires an annual operational cost to maintain effectiveness ($1M)
- Less than 5% reduction in delays per triggered event
- Additional operating cost of $10,000 per event.

6.6.3 Results

The results of Adaptation Option 6 are presented in Table 13.

Table 13 **Option 6 Cost Benefit Analysis Results**

ITEM	LOW GHG SCENARIO (A1B) ('000)	HIGH GHG SCENARIO (A1FI) ('000)
Cost of Delays	$57,336	$80,023
Benefits (avoided delay)	$1,163	$1,626
Adaptation Costs	$30,031	$30,031
Net Present Value	**-$28,868**	**-$28,405**
Benefit Cost Ratio	**0.04**	**0.05**

6.7 Summary of Cost Benefit Analysis Results

A summary of the Net Present Value and Benefit Cost Ratio of each of the Adaptation Options is presented in Table 14. The results clearly indicate that Option 3 Regenerative braking and Option 4 Cabling have a benefit to implement immediately.

Regenerative braking was the only option that had additional co-benefits applied to the assessment beyond commuter delays from energy savings and reduced GHG emissions. There are other co-benefits for Options 1, 2, 4, 5 and 6 that are noted in this report but were not quantified for this assessment such as values of comfort, loss of life and mode transfer as these benefits were not available at the time of the study. However, for this assessment, Options 1, 2, 5 and 6 do not provide a net benefit to implement in 2011.

The sensitivity analysis in Section 7 indicates that Option 4 Cabling is significantly more beneficial to implement later in the century, around 2050, as the increase in high temperature events increases considerably from the changing climate. The sensitivity analysis for different discount rates also indicates that the results do not change dramatically in terms of which options are considered beneficial. The cost benefit analysis results would only change if co-benefits were appropriately identified and quantified to increase the benefits or the cost of implementing adaptation was significantly reduced.

Table 14 **Summary of CBA Results for all Adaptation Options**

ADAPTATION OPTION	LOW GHG SCENARIO (A1B)		HIGH GHG SCENARIO (A1FI)	
	Net Present Value ($M)	Benefit Cost Ratio	Net Present Value ($M)	Benefit Cost Ratio
Option 1 - Concrete sleepers	-$120	0.09	-$115	0.12
Option 2 - Replace air con.	-$80	0.13	-$75	0.18
Option 3 - Regen. braking	$107	1.70	$107	1.70
Option 4 - Cabling	$1	1.27	$4	1.78
Option 5 - Protect equipment	-$295	0.01	-$242	0.01
Option 6 - Behaviour change program	-$29	0.04	-$28	0.05

7.0 Sensitivity Analysis

The sensitivity of results to the changes in the following assumptions and inputs has been tested:

- Discount rate.
- Value of time.
- Implementation timing.

These are presented below.

7.1 Discount Rate

As discussed in Section 4.4, the appropriate discount rate is a matter of some debate when analysis is to be undertaken over the length of periods necessary to evaluate climate change impacts. Sensitivity of results to these assumptions has therefore been tested by applying lower (1.5%) and higher (6.0%) discount rates.

7.1.1 Discount Rate of 1.5%

The results of the CBA using a discount rate of 1.5% are presented in Table 15.

Table 15 **CBA Results with discount rate at 1.5%**

ADAPTATION OPTION	LOW GHG SCENARIO (A1B)		HIGH GHG SCENARIO (A1FI)	
	Net Present Value ('000)	Benefit Cost Ratio	Net Present Value ('000)	Benefit Cost Ratio
Option 1 - Concrete sleepers	-$139,287	0.16	-$127,117	0.23
Option 2 - Replace air con	-$112,076	0.19	-$99,907	0.28
Option 3 - Regen. braking	$213,756	1.94	$214,304	1.94
Option 4 - Cabling	$6,016	1.87	$12,101	2.76
Option 5 - Protect equipment	-$391,350	0.02	-$293,865	0.02
Option 6 - Behaviour change program	-$45,622	0.05	-$44,405	0.08

7.1.2 Discount Rate of 6.0%

The results of the CBA using a discount rate of 6.0% are presented in Table 15.

Table 16 **CBA Results with discount rate at 6.0%**

ADAPTATION OPTION	LOW GHG SCENARIO (A1B)		HIGH GHG SCENARIO (A1FI)	
	Net Present Value ('000)	Benefit Cost Ratio	Net Present Value ('000)	Benefit Cost Ratio
Option 1 - Concrete sleepers	-$102,830	0.03	-$101,914	0.04
Option 2 - Replace air con.	-$50,846	0.07	-$49,931	0.08
Option 3 - Regen. braking	$26,768	1.29	$26,669	1.29
Option 4 - Cabling	-$890	0.66	-$433	0.84
Option 5 - Protect equipment	-$213,743	0.00	-$190,990	0.01
Option 6 - Behaviour change program	-$15,267	0.02	-$15,176	0.03

7.2 Value of Commuter Time

As discussed in Section 5.5, the value of commuter time used in the CBA was based on a number of studies that quoted a range of values. The sensitivity of the CBA results to changes in this input to values at higher and lower parts of the quoted ranges has been tested here.

7.2.1 Value of commuter time = 45% of Wage Rate ($0.23 per minute)

The results of the CBA using a lower value of commuter time of 45% of the wage rate ($0.23 per minute) are presented in Table 17.

Table 17 **CBA Results: value of time = $0.23 per minute**

ADAPTATION OPTION	LOW GHG SCENARIO (A1B)		HIGH GHG SCENARIO (A1FI)	
	Net Present Value ('000)	Benefit Cost Ratio	Net Present Value ('000)	Benefit Cost Ratio
Option 1 - Concrete sleepers	-$122,638	0.06	-$119,166	0.09
Option 2 - Replace air con.	-$82,528	0.10	-$79,056	0.13
Option 3 - Regen. braking	$105,663	1.69	$105,704	1.69
Option 4 - Cabling	-$222	0.95	$1,514	1.34
Option 5 - Protect equipment	-$296,118	0.01	-$245,294	0.01
Option 6 - Behaviour change program	-$29,159	0.03	-$28,812	0.04

7.2.2 Value of commuter time = 75% of Real Wage ($0.38 per minute)

The results of the CBA using a higher value of commuter time of 75% of the wage rate ($0.38 per minute) are presented in Table 18.

Table 18 **CBA Results: value of time = $0.38 per minute**

ADAPTATION OPTION	LOW GHG SCENARIO (A1B)		HIGH GHG SCENARIO (A1FI)	
	Net Present Value ('000)	Benefit Cost Ratio	Net Present Value ('000)	Benefit Cost Ratio
Option 1 - Concrete sleepers	-$116,970	0.11	-$111,182	0.15
Option 2 - Replace air con	-$76,713	0.16	-$70,926	0.22
Option 3 - Regen. braking	$107,607	1.71	$107,675	1.71
Option 4 - Cabling	$2,632	1.58	$5,526	2.23
Option 5 - Protect equipment	-$294,682	0.01	-$238,326	0.02
Option 6 - Behaviour change program	-$28,578	0.05	-$27,999	0.07

7.3 Timing of implementation of adaptation option

The CBA undertaken thus far has assumed that all capital works programs begin immediately. The sensitivity of results to changing this assumption has been tested here using periods of implementation beginning in 20 years, 40 years, and 60 years.

7.3.1 Implement in 20 years

The outcomes of the cost benefit analysis assuming implementation of options in 20 years is presented in Table 19.

Table 19 **CBA Results with implementation of options in 20 years**

ADAPTATION OPTION	LOW GHG SCENARIO (A1B)		HIGH GHG SCENARIO (A1FI)	
	Net Present Value ('000)	Benefit Cost Ratio	Net Present Value ('000)	Benefit Cost Ratio
Option 1 - Concrete sleepers	-$63,790	0.12	-$59,447	0.18
Option 2 - Replace air con.	-$81,965	0.10	-$77,539	0.15
Option 3 - Regen. braking	$2,211	1.02	$2,367	1.02
Option 4 - Cabling	$2,067	1.87	$4,249	2.79
Option 5 - Protect equipment	-$162,926	0.01	-$130,056	0.02
Option 6 - Behaviour change program	-$14,659	0.06	-$14,216	0.09

7.3.2 Implement in 40 years

The outcomes of the cost benefit analysis assuming implementation of options in 40 years is presented in Table 20.

Table 20 **CBA Results with implementation of options in 40 years**

ADAPTATION OPTION	LOW GHG SCENARIO (A1B)		HIGH GHG SCENARIO (A1FI)	
	Net Present Value ('000)	Benefit Cost Ratio	Net Present Value ('000)	Benefit Cost Ratio
Option 1 - Concrete sleepers	-$27,541	0.20	-$23,842	0.31
Option 2 - Replace air con.	-$84,081	0.08	-$80,243	0.12
Option 3 - Regen. braking	-$59,269	0.52	-$59,046	0.52
Option 4 - Cabling	$2,309	3.01	$4,178	4.63
Option 5 - Protect equipment	-$220,195	0.01	-$198,891	0.01
Option 6 - Behaviour change program	-$6,873	0.09	-$6,489	0.15

7.3.3 Implement in 60 years

The outcomes of the cost benefit analysis assuming implementation of options in 60 years is presented in Table 21.

Table 21 **CBA Results with implementation of options in 60 years**

ADAPTATION OPTION	LOW GHG SCENARIO (A1B)		HIGH GHG SCENARIO (A1FI)	
	Net Present Value ('000)	Benefit Cost Ratio	Net Present Value ('000)	Benefit Cost Ratio
Option 1 - Concrete sleepers	-$127,357	0.03	-$125,032	0.05
Option 2 - Replace air con.	-$86,903	0.05	-$84,313	0.08
Option 3 - Regen. braking	-$127,660	0.16	-$127,527	0.16
Option 4 - Cabling	-$2,567	0.43	-$1,374	0.69
Option 5 - Protect equipment	-$297,297	0.00	-$282,559	0.01
Option 6 - Behaviour change program	-$2,727	0.14	-$2,468	0.22

8.0 Findings and outcomes

This study has focussed on the impacts of commuter delays due to the increasing heat stresses that are expected to be placed on the rail network on hot days due to climate change. It has also assessed the relative benefits and costs of reducing these delays through a range of adaptation options.

The cost benefit analysis of adaptation options showed that only two options produced an economic result, regenerative braking (Option 3) and changing cabling and tension in power lines (Option 4).

Regenerative braking (Option 3) produced the best economic results, with a Net Present Value of approximately $107 M and a benefit cost ratio of 1.70 (under both GHG scenarios). The vast majority of the benefits of this option result from energy savings from the regenerative braking system rather than reductions in commuter delays.

Changing cabling and tension in power lines (Option 4) provides considerable value for money in reducing commuter delays. The benefit cost ratio for this option is approximately 1.27 under the low GHG scenario with an NPV of $1.2M, and a benefit cost ratio of 1.78 under a high GHG scenario with an NPV of $3.5 M. This option is also significantly cheaper than the other options.

The remainder of the options were shown to be uneconomic in this analysis with regard to reducing commuter delays. This outcome was unchanged under different assumptions about discount rates, the value of commuter time, and implementation timing, as shown in the sensitivity testing.

In general, lower discount rates and higher values of time produced better outcomes. Altering the timing of implementation produced mixed results. The uneconomic outcomes (Options 1, 2, 5 and 6) tended to become even less economic the longer their implementation was delayed. Option 3 also became less economic the longer its implementation was delayed, and delaying this option beyond approximately 20 years would result in the option becoming uneconomic. Interestingly, Option 4 produced better economic outcomes as a result of delaying the implementation for 40 years, but beyond this time it became less economic.

The cost benefit analysis revealed that the remainder of the adaptation options are prohibitively expensive in reducing commuter delays. However, it is important to recognise that many of these options produce benefits other than reduced delays that have not been assessed. For example, concrete sleepers are expected to be more durable and long-living that the current timber sleepers which would significantly reduce the costs involved in maintenance of sleepers and increase their replacement intervals. Improved air conditioning provides comfort benefits to passengers in addition to reducing the potential for train cancellations and delays. Behaviour change programs may increase awareness of climate change resulting in benefits that extend far beyond the impacts on commuter delays. Inclusion of these other factors within the scope of the study and the analysis would provide significantly better results for some of the options, and the results shown here should be viewed with this in mind.

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