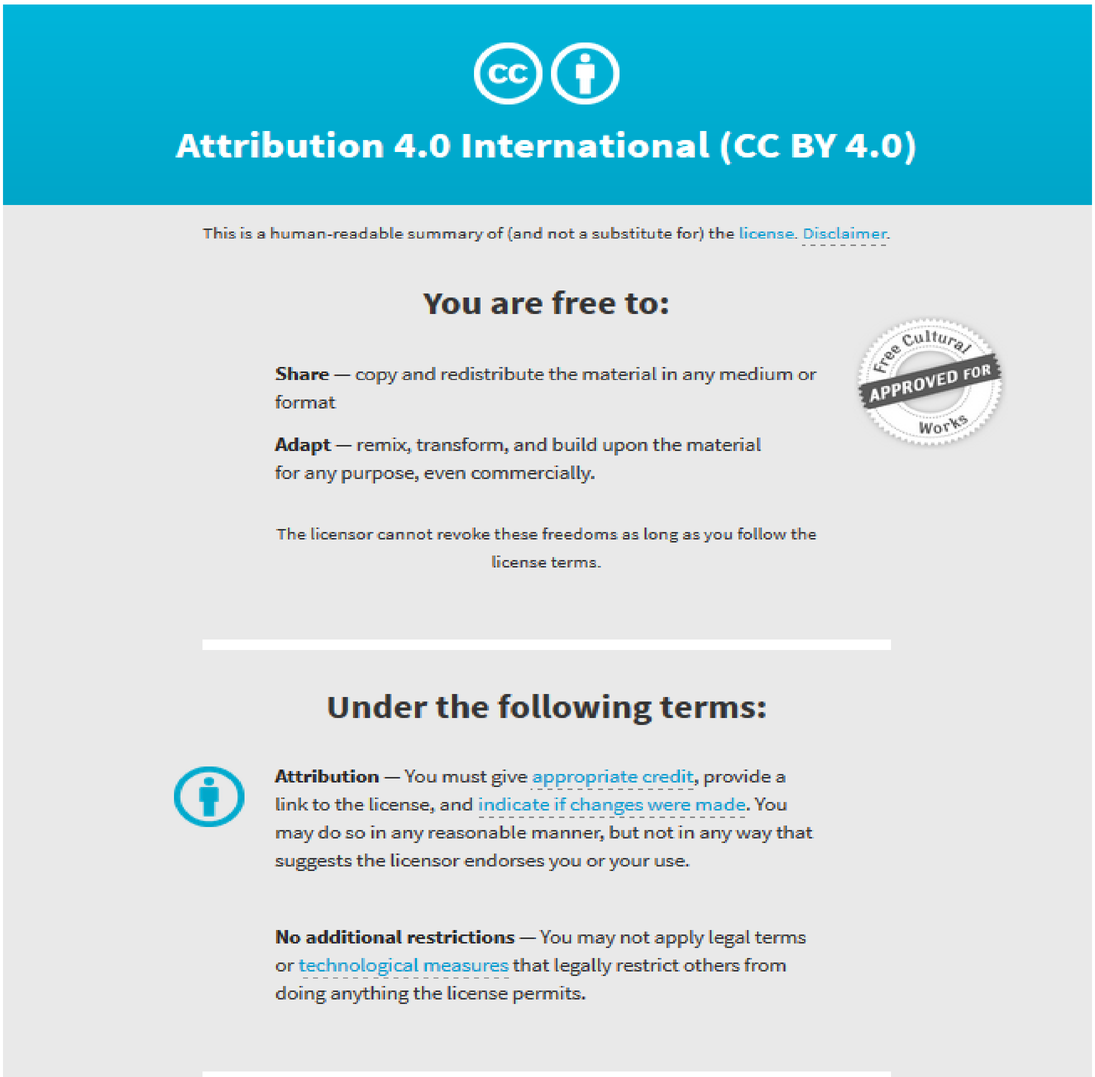
Jacqueline Balston, Steven Li, Ivan Iankov, Jon Kellett and Geoff Wells
Quantifying the financial impact of climate change on Australian local government roads
Infrastructures, 2017; 2(1):2-1-2-16

Originally published at:
http://doi.org/10.3390/infrastructures2010002



infrastructures

MDPI

Article

Quantifying the Financial Impact of Climate Change on Australian Local Government Roads

Jacqueline Balston [1], Steven Li [2], Ivan Iankov [1], Jon Kellett [3,*] and Geoff Wells [4]

[1] School of Natural and Built Environments, University South Australia, Adelaide, SA 5001, Australia; jacqueline.balston@jbalston.com (J.B.); ivan.iankov@mymail.unisa.edu.au (I.I.)
[2] Graduate School of Business and Law, RMIT University, Melbourne, VIC 3000, Australia; steven.li@rmit.edu.au
[3] School of Architecture and Built Environment, University of Adelaide, Adelaide, SA 5005, Australia
[4] Consultant, Robe, Adelaide, SA 5276, Australia; geoff@geoffwells.com
* Correspondence: jon.kellett@adelaide.edu.au; Tel.: +61-8-8313-0683

Academic Editor: Boulent Imam
Received: 7 November 2016; Accepted: 21 December 2016; Published: 11 January 2017

Abstract: Australia's 560 Councils are responsible for assets worth approximately $270 billion, many of which have a life span >50 years and so will be affected by climate change. Maintenance and replacement of Council infrastructure is guided by principles, models and tools in the International Infrastructure Management Manual that currently do not allow for climate change impacts or the likely flow-on effects to asset and financial management. This paper describes a financial simulation model developed to calculate the financial impacts of climate change on three major asset classes of importance to Australian Councils: hotmix sealed, spray sealed and unsealed roads. The research goes beyond previous studies of climate change impacts on roads in that it provides a location specific toolkit that is designed to assist councils in their asset management and planned maintenance programmes. Two categories of inputs are required for the model: climate inputs, relating specifically to baseline temperature and rainfall distributions and climate change parameters for temperature and rainfall; and engineering inputs, relating specifically to the three road types and the key parameters of their performance and useful lives over the scenario period. The baseline distributions are then shifted mathematically within the model by the mean change as projected by a selected Global Climate Model (GCM) scenario. Outputs of the model are the historical baseline climate variable distributions and the climate change (CC) impacts on road performance are in the form of changes to the useful life of the asset and associated changes in asset resurfacing and rehabilitation costs. Ten case study local councils in southern Australia are examined. Using IPCC AR4 scenarios, the results suggest that the incremental impact of climate change on all three types of road infrastructure modelled will be generally low. There are small cost reductions over the period for all road types as a result of the expected drying and warming trends in the climate.

Keywords: local government; asset management; climate change impacts; financial modeling

---

1. Introduction

The Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report (AR4) [1] states that the warming of the climate system is now "unequivocal", and it is likely that, despite current mitigation policies, the level of greenhouse gases in the atmosphere will continue to increase over the next few decades. As a result, the global climate system will very likely see climate changes that exceed those observed over the past century.

Within this changing climate, Local Government in Australia is responsible for a significant range and extent of infrastructure assets with a total value of approximately $270 billion including

650,000 km of local roads and other fixed assets worth more than $180 billion [2]. Many of these assets (buildings, roads, footpaths, coastal retaining walls, water infrastructure, etc.) have a life span greater than 50 years and so will be affected by long-term shifts in climate. Historically, maintenance and replacement of hard infrastructure in Councils has been guided by the principles, models and tools provided in the International Infrastructure Management Manual (IMM), developed by the Institute of Public Works and Engineering Australia (IPWEA) in collaboration with Councils, engineers and manufacturers of various components and materials. However, due to limited information on the potential impacts of climate change on infrastructure, these tools have not allowed for the assessment of likely flow-on effects to asset and financial management. As a result, the impacts of climate change on existing Council assets have not been effectively incorporated into Local Government planning processes.

This paper outlines an approach to address these gaps in current knowledge and practice. Specifically, it aims to: identify key Council infrastructure assets vulnerable to climate change; determine the likely impacts of climate change on Council assets; undertake a financial risk modelling exercise to quantify in monetary terms climate change asset risk; and develop the necessary modifications to existing infrastructure asset management and financial sustainability tools so that Councils may evaluate various climate change action scenarios at the management and planning levels. This research represents a level of detailed analysis that goes beyond most recently published work. There have been numerous papers that examine the potential impacts of climate change on transportation. Koetse and Rievald [3] provide an extensive review of the literature, which tends to focus on analyzing the threat of changing climate in two respects. Firstly, there is a body of work that seeks to identify the vulnerability of different types of transport infrastructure such as ports, public transit systems and road networks in different regions around the world; and secondly, other commentators have examined behavioural response to changing weather conditions by network users. Most of this literature takes a relatively broad brush approach, starting from established predictive climate models. For example, Petersen et al. [4] provide a wide-ranging review of the potential impacts on US transportation systems at sea, in the air, and on land. The overall aim is to focus on the avoidance of future costly infrastructure investment and disruption to transport operations with a clear emphasis on the impact of extreme weather events. Focusing on road networks, Chinowsky and Arndt [5] comment on Mozambique. They estimate the total national network length, and, using generalized classification data on road type, which ignores detailed construction data, estimate the scale of potential impact of changing precipitation, temperature, storm frequency and intensity and wind speeds. Our approach differs in that it seeks to address the problem of climate change and roads at a finer level of detail than the studies noted above. It addresses the awkward question of how gradually shifting climate zones and conditions might impact day-to-day management of road infrastructure, rather than emphasizing the effects and response to intermittent extreme events.

We begin by introducing the ten case study local government areas in southern Australia used to test our model and follow this with a discussion of the range of vulnerable assets that they control. Next, we outline climate predictions for southern Australia based on currently available modelling. A discussion of engineering literature follows, focusing on different approaches to road surface construction and the impact of traffic over time. A modelling approach using engineering and climate inputs is then developed to predict the physical impacts of changing temperature and rainfall patterns on roads as well as the cost implications for maintenance. Finally, using data provided by the collaborating case study councils, the model is tested in a range of locations across southern Australia, and the results are summarised in the discussion and conclusions.

Uncertainty is a central reality of climate change projections and a central technical challenge in modelling its impact on infrastructure assets [6]. It is important to realise that, in any climate change assessment such as this, there is a cascade of uncertainties in the process [7] (p. 203). Our lack of perfect knowledge in understanding how the climate system works, how individual systems will respond to the impacts of climate change, how dependent systems will respond to primary changes [8], the level of future greenhouse gas mitigation [9], and the complexities of economic repercussions all contribute to the uncertainty when attempting to quantify climate change impacts. This has meant a shift to risk-based assessments of climate change effects and responses by local authorities, prior to decisions being made in the interests of long-term sustainability.

2. Materials and Methods

2.1. Case Study Councils

Ten collaborating Local Government jurisdictions representing coastal, inland, metropolitan, rural and regional areas were selected from across southern Australia to be involved in the project to ensure a spread of population, asset and geography (Figure 1). Councils provided the necessary data to support the analysis and guided the development of outputs to ensure relevance for their business. The Councils that collaborated in the study were: South Australia: Port Adelaide Enfield (metro coastal), Campbelltown (metro inland), Barossa (regional inland), Wattle Range (regional coastal), Onkaparinga (metro mixed) and Tumby Bay (regional coastal); Victoria: Hume City (metro inland), Bass Coast (regional coastal); Western Australia: Esperance (regional, coastal); and Tasmania: Brighton (regional mixed).

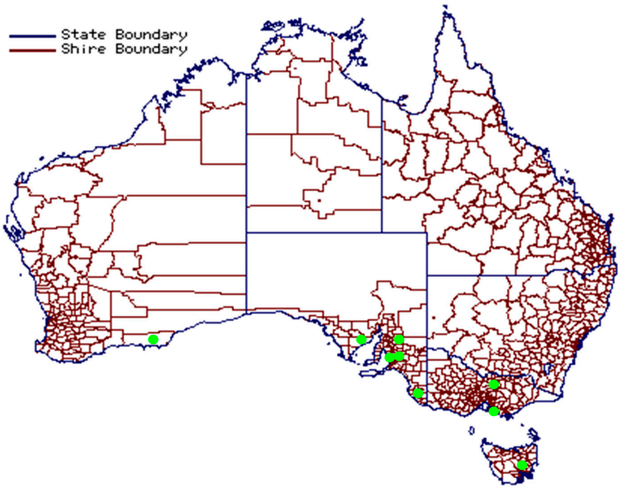


Figure 1. Map of the Australian Local Government areas. Collaborating Councils in this National Climate Change Adaptation Research Facility (NCCARF) settlements and infrastructure project are highlighted in **green** [10].

2.1.1. Council Asset Climate Vulnerability

Key Council infrastructure assets that are likely to be affected by changes to the climate were identified on the basis of an extensive literature review, data provided by IPWEA, and engineering assessments of collaborating Councils. Infrastructure are generally defined as stationary (or fixed) systems that serve defined communities where the system as a whole is intended to be maintained indefinitely to a specified level of service by the continued replacement and refurbishment of its components [11]. Infrastructure assets are typically found in: transport networks (roads, rail, ports, airports); energy supply systems (gas electricity generation and transmission); parks and recreation (tennis courts); water utilities (water supply, sewer); storm water management (flood detention systems, pipes); community facilities (libraries, community halls); and telecommunication networks. The largest proportion of Council assets (by dollar value) in Australia is long-lived infrastructure, and roads are usually by far the largest category (Figure 2).

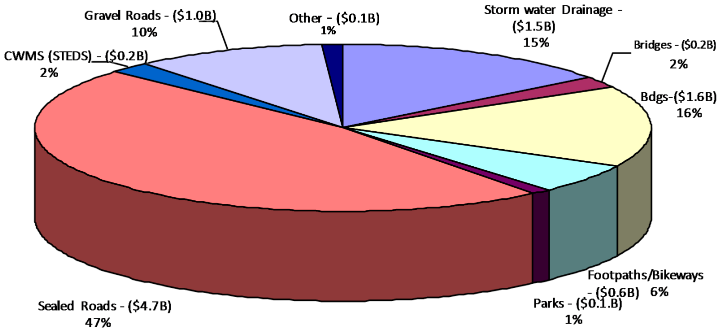


Figure 2. South Australian Local Government infrastructure asset stock 2006 [12].

Typically in Australia, highways and major roads (arterials and main roads) are managed by state transport authorities, and the dominant cause of deterioration of these assets is traffic volumes. Councils, on the other hand, generally manage roads that have lower traffic volumes—collector and local roads. These roads are generally either sealed (sprayed seal or hotmix asphalt) or unsealed (gravel) roads and can be constructed using a variety of techniques. A study by the Commonwealth Scientific and Industrial Research Organisation (CSIRO) [13] identified three primary risks for roads from climate change, with associated implications for management:

1. Asphalt degradation (increased solar radiation; increased temperature and heat waves) causes: increased maintenance and renewal of road and pavement surfaces in localised regions; increase in short-term loss of public access or increased congestion to sections of road and highway during repair and replacement; increase in road replacement costs due to greater rate of degradation; and likely financial impact to local Councils.
2. Road foundations degradation (increased variation in wet/dry spells, decrease in available moisture) causes: degradation, failure and replacement of road structures due to increases in ground and foundation movement, shrinkage and changes in groundwater; increased maintenance and replacement costs of road infrastructure; short-term loss of public access or increased congestion to sections of road and highway due to increased maintenance and replacement regime; and regional cost to Councils and state.
3. Flood damage (increase in extreme daily rainfall, increase in frequency and intensity of storms) causes: degradation, failure and replacement of road structures due to increased damage from flooding, inundation of foundations and changes in groundwater; increased maintenance and replacement costs of road infrastructure; short term loss of public access or increased congestion to sections of road and highway due to increase maintenance and replacement regime; and regional cost to Councils and state.

2.1.2. Climate Change and Southern Australia

As the likely climate impacts to roads will be from changes to rainfall and temperature (including extreme events such as floods and heatwaves), a review of the observed and likely future climate across southern Australia was undertaken. From 1950 to 2007, the average temperature of Australia increased by 0.9 °C. The frequency of hot days and nights and heatwaves increased and the frequency of cold nights decreased [14]. Southern Australia has recorded a drying trend since the early 1990s [15,16]. In the future, an increase in average annual temperature of between 0.6 °C and 2.0 °C by 2030 and 1.0 °C to 5 °C by 2070 compared to 1990 levels is projected for southern Australia. By 2070 in Adelaide, under a high greenhouse gas emissions scenario, there may be twice as many extreme hot days as are experienced now [15]. Cold events and frost will decrease [15]. The majority of models simulate a future that is drier for southern Australia than was experienced from 1900 to 2000 [15].

Despite the material relevance of extreme events to the impacts of climate change on infrastructure, they present complex challenges to modelling in the case of localised studies such as this. Debate exists about the thresholds that define an extreme event and, even if there were agreement, a climatological threshold (e.g., a one in 100 year event) is not necessarily one that will cause damage to a road. Extreme precipitation is the major issue here. These events are typically short temporal episodes and their irregular occurrence makes them difficult to capture and record. In addition, precipitation linked to thunderstorm or frontal activity can be quite spatially localised even within a Council area and its impacts can be similarly localized. The same rainfall event in the same general location may cause only localized damage to a road, depending on specific local conditions such as soils and drainage.

In projecting the likely future occurrence of an extreme event, the difficulties increase further. Because of the rare nature of extreme events, there are by definition very few recorded events and so in the climate data extreme events are at the extreme tail of the distribution. When modelling future climate projections, these tails in the distribution are not well estimated by the Global Climate Models (GCMs) and there is currently little confidence in the accuracy of projections for an event that has never occurred in recorded history. For the next round of AR5 global climate models Coupled Model Intercomparison Project phase 5 (CMIP 5 GCMs) some models will be run at the hourly and half hourly time step. However, they will be limited in number, will provide a small number of scenarios, and will not be available for a number of years yet. In addition, the output from these types of models is huge (60 petabytes) and would not be readily available to the public [17].

It is also worth noting that extreme events are not usually included in the financial budget of Australian Councils. Instead, money to cover damage from extreme events is sourced from extraordinary or contingency funds, existing projects that are postponed, disaster relief funding from the state and possibly federal governments in the case that the event was declared to be a disaster under State Emergency legislation. Alternatively, low priority assets may be left unrepaired or repaired at a later stage. In addition, it was agreed by the research stakeholder group that extreme events only affect a small proportion of the total asset (e.g., 1 or 2 km of a 500 km road) and are by nature infrequent in occurrence. It was also suggested that future changes in design specifications will take in to account the increased frequency of extreme rainfall events and so will reduce the exposure to the risk over time.

All these limitations make defining, recording, analysing and projecting the impacts of extreme weather events accurately in either the past or the future impossible at the level of specific locations. For these reasons, extreme events are not included in the formal simulation modeling reported below. However, an input field to allow for the inclusion of an extreme events budget allocation is included in the spreadsheet input page of the model in case the data is available at the Local Government Area (LGA) level. We note that addressing extreme events at the local level is an important topic in the field, and presents an opportunity for critical future research.

2.2. Modelling Climate Impacts on Roads

Engineering models that would allow for quantitative calculations of the impact of these climate changes on road degradation rates were then reviewed.

2.2.1. Sealed Roads

Sealed roads are a complex construction of a variety of components made from different materials. The surface of the pavement is subject to the highest level of climatic stress, while the sub-base and subgrade are sealed from climate impacts by a weather proof binder applied to the surface layer as either a sprayed seal, or mixed hot with an aggregate to create asphalt. Bitumen is the most commonly used binder in Australia and is used to hold together the aggregate to create the weatherproof surface layer (asphalt/tarmac) of the pavement [18].

The maximum service life of a sealed road surface is primarily dependent on the service life of the binder. With time, the bitumen binder hardens and loses its flexibility and in turn makes the road surface vulnerable to cracking and loss of aggregate material due to the traffic stress. The key factor influencing the duration of the service life of bitumen in the field is its durability. The better the durability, the more resilient it is to hardening. Bitumen durability is typically measured in laboratory testing programs. In Australia, the Australian Road Research Board (ARRB) Transport Research Pty. Ltd. (Melbourne, Australia) tests are used to determine the durability of different bitumen types (see [19]) and bitumen hardening models developed by ARRB research for their road management program [20–24] have air temperature, bitumen durability and road pavement seal surface thickness as their key input parameters. The second factor affecting bitumen service life is its distress viscosity—that is the viscosity at which the bitumen no longer has the necessary flexibility to ensure that the road surface can sustain the stress generated from traffic. Bitumen distress viscosity levels have been shown to depend on the climate at a specific site, specifically average minimum annual air temperature [22].

Asphalt/Hotmix Sealed Roads (AHR)

Asphalt/hotmix sealed roads (AHR) are constructed as a mixture of bituminous binder and aggregate with or without mineral filler that is produced hot in a mixing plant, and then delivered, spread and compacted while hot onto the road base [20] (p. 12). AHR account for over 70% of the roads in Australian City Councils. Equation (1) is the recommended model developed by the Australian Road Research Board (ARRB) and is the most relevant model for Australian roads. It predicts the useful life in years (Y) of an asphalt/hotmix road surface [25]:

$$Y = \left(0.323T_{min} - 0.169T - 0.848\sqrt{A_v} + 5.217\right)^2, \tag{1}$$

where:

- T_{min} (T_{max}) = the yearly mean of the daily minimum (maximum) air temperature (°C),
- T = the mean temperature of the site (°C), calculated as $T = (T_{min} + T_{max})/2$,
- A_v = air voids of the asphalt surfacing at the time of sampling (%, usually 4% to 6%).

All of the independent variables in this equation were statistically significant (Student 't' $p < 0.05$). The equation does not include a variable to allow for different traffic levels or other climatic impacts apart from temperature. The equation is not recommended for use where the asphalt thickness is greater than 40 mm.

Sprayed Sealed Roads (SSR)

Sprayed-sealed roads (SSR) are comprised of a thin layer of bitumen binder sprayed onto a pavement surface that has a layer of aggregate incorporated onto it [20] (p. 132). SSR are found mostly in rural Councils, as they are cheaper and easier to construct than AHR. For these roads, the climate variable is included in the model by first calculating the Thornthwaite Moisture Index (TI) as described by Gentilli [26]—a function of monthly rainfall and mean monthly temperature (Equation (2)):

$$TI \approx 1.25\, P_e - 60, \tag{2}$$

where:

$$P_e = \sum_{m=1}^{12} P_{em},$$

$$P_{em} = 1.65 \frac{P_{Tm}}{(M_m + 12.2)^{1.1111}},$$

where P_{Tm} is total monthly rainfall and M_m is mean monthly temperature. Following Gentilli P_e is effective annual rainfall and P_{em} effective monthly rainfall.

TI is then included into road engineering equations developed by the ARRB [25]. Equation (3) determines relative performance factors (*rpf*) for an SSR based on *TI*. These *rpf* are used in Equation (4) to determine performance of the road against baseline scenario:

$$rpf_{miri}unckdss\left(\frac{TI}{d}\right) = 1.073 + 0.00147TI, \tag{3}$$

where $rpf_{miri}unckdss\left(\frac{TI}{d}\right)$ = *rpf* for roughness at a specific Thornthwaite Moisture Index (*TI*) for an uncracked single sealed road relative to dry conditions (*d*)

$$d_i(TI_i) = \frac{rpf_m unckdss\left(\frac{TI_i}{d}\right)}{rpf_m unckdss\left(\frac{TI}{d}\right)} \times \Delta d, \tag{4}$$

where:

- Δd is the cumulative deterioration (rutting and roughness) relevant to baseline scenario,
- $\Delta d_i(TI_i)$ is the cumulative deterioration (rutting and roughness) relevant to scenario i,
- *TI* is the Thornthwaite Moisture Index relevant to baseline scenario,
- TI_i is the Thornthwaite Moisture Index relevant to scenario i.

Note:

$rpf_m unckdss\left(\frac{TI_i}{d}\right)$ = relative performance factor (*rpf*) for rutting and roughness at a specific Thornthwaite Moisture Index TI_i for an uncracked single sealed road relative to dry conditions (*d*).

$rpf_m unckdss\left(\frac{TI}{d}\right)$ = relative performance factor (*rpf*) for rutting and roughness at a specific Thornthwaite Moisture Index TI for an uncracked single sealed road relative to dry conditions (*d*).

ARRB has developed models for the deterioration of local sealed roads by analysing data from experimental sites located across Australia. Equations (3) and (4) above are the result of rigorous methodological research by ARRB. They are derived by utilization of road deterioration models for various climates and road surfaces. The deterioration models were developed by linear regression on sufficient and robust experimental data obtained at a sophisticated accelerated load testing facility. All regression models have a highly significant f-statistic value and a highly significant t-statistic for included regression co-efficients. Most importantly the r-square values are around 0.8. This suggests small variation in the data around the predicted expected values giving high confidence in the estimation of road surface deterioration using *rpf*. We note that the future research agenda of the ARRB includes verification of predicted road deterioration using these models against real world observed data, and we suggest that the results of this research could strengthen the approach suggested here. At the moment, however, we are confident that the approach to modeling road deterioration used here represents the best currently available science.

2.2.2. Unsealed Roads

Because of the large distances involved, many communities in rural Australia depend on unsealed Council roads to access vital services. Unsealed roads (also known as gravelled roads) are those constructed with a layer of imported compacted gravel and are designed and built to engineering principles that satisfy standards for alignment, drainage, etc. We did not consider dirt roads that do not have imported high quality added gravel. The two most common maintenance works for repairing unsealed roads are blading and re-gravelling. Blading with a grader smooths the surface by taking a thin top layer off the top and collects loose material from the windrows and then spreads and compacts it onto the road surface. Re-gravelling is the importation of additional gravel material to compensate for losses. A number of engineering models that include climate variables have been developed to calculate gravel loss from a USR [27,28]. Analysis of the different USR engineering models identified the Australian ARRB model [20] road deterioration model as superior in terms of its relevance to current Australian USR (Equation (5)):

$$GL = D(\alpha ADT + \beta MMP + \gamma PF), \tag{5}$$

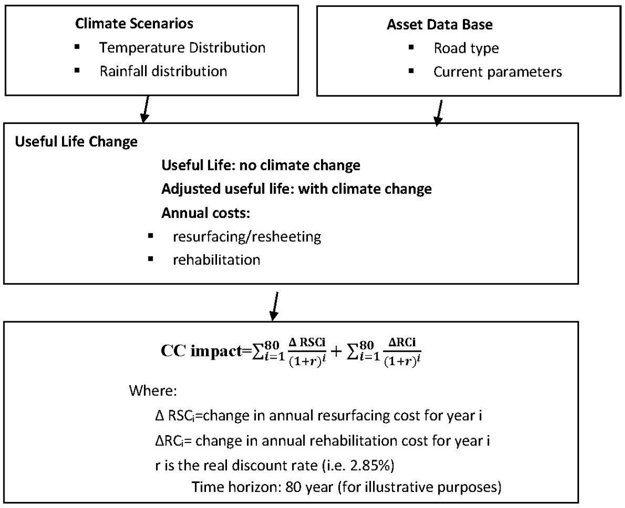
where:

- GL is the average gravel thickness loss (mm) across roadway,
- D is the time period in hundreds of days (days/100),
- ADT is the average daily vehicular traffic in both directions, in vehicle/day,
- MMP is the mean monthly precipitation, in mm/month,
- PF is the plasticity factor,
- $P075$ is the amount of material passing the 0.075 mm sieve, in per cent by mass,
- PI is the plasticity index,
- PF is the plasticity factor ($PI \times P075$),
- α, β, γ are model coefficients.

2.3. Development of the Financial Model

Given the uncertainty associated with climate change projections, a standard approach to value the impacts of climate change is to use a Monte Carlo simulation. To do this, we used the software @Risk ™ in Excel® (Version 7.5, Palisade, Ithaca, NY, USA) and considered each of the three asset classes of roads above: SSR, AHR and USR. The service or useful life of each road type was quantified using the engineering models described and relevant climate variables: for AHR, annual mean monthly minimum temperature (T_{min}) and annual mean monthly temperature (T); for SSR, the Thornthwaite Moisture Index (TI), which, in turn, requires mean monthly temperature (T) and total monthly precipitation (P); and, for USR, mean monthly precipitation (MMP).

The structure of the financial model is displayed in Figure 3. As shown, two categories of inputs are required for the model: climate inputs, relating specifically to temperature and rainfall distributions across the scenario period; and engineering inputs, relating specifically to the three road types and the key parameters of their performance and useful lives over the scenario period. Outputs of the model are the historical baseline climate variable distributions and the climate change (CC) impacts on road performance are in the form of changes to the useful life of the asset and associated changes in asset resurfacing and rehabilitation costs.



$$\text{CC impact} = \sum_{i=1}^{80} \frac{\Delta\,\text{RSCi}}{(1+r)^i} + \sum_{i=1}^{80} \frac{\Delta\text{RCi}}{(1+r)^i}$$

Where:
Δ RSC$_i$=change in annual resurfacing cost for year i
ΔRC$_i$= change in annual rehabilitation cost for year i
r is the real discount rate (i.e. 2.85%)
Time horizon: 80 year (for illustrative purposes)

Figure 3. Structure and flow of the financial model.

2.4. Climate Inputs to the Model

High quality gridded baseline (historical) datasets averaged over each case study Council area were included in the model at a monthly resolution to generate baseline climate distributions for the variables required. The baseline distributions are then shifted mathematically within the model by the mean change as projected by a selected GCM scenario. There are both advantages and limitations to this approach. Advantages are first, that the historic baseline data set will not change and so it does not need to be updated in the future regardless of change in the IPCC scenarios or GCM projection outputs, and so requirements for maintaining the model are minimal; secondly, there is no need to house substantial GCM output data for the nation in the financial model; thirdly, users are not limited to a single set of GCM outputs but can select those at a spatial resolution and scenario that are appropriate to their needs and location; and, finally, users can undertake sensitivity testing for various future temperature and rainfall scenarios without having to have access to GCM output data and can select scenarios not usually modeled by GCMs for policy decisions.

The limitations of the approach are twofold: first, because climate changes will not be linear, calculations of climate impacts over long time periods (e.g., out to 2100) will overestimate early changes and underestimate later ones because of the linear relationship used; secondly, the shifted baseline climate variable distribution may not accurately represent the distribution that would have been generated by the GCM as not only the mean of the distribution will change but possibly also the shape of the distribution. Advice from the Bureau of Meteorology climate staff indicated that shifting the mean of a temperature distribution by the median projected value is unlikely to introduce significant errors, but that the shape of the rainfall distribution may change into the future and so may not be accurately depicted by a shift in the baseline mean alone [29]. The complexity attached to rainfall predictions is noted by the IPCC as follows, "A range of GCM and regional modelling studies in recent years have identified a tendency for daily rainfall extremes to increase under enhanced greenhouse conditions in the Australian region . . . Commonly, return periods of extreme rainfall events halve in late 21st-century simulations. This tendency can apply even when average rainfall is simulated to decrease, but not necessarily when this decrease is marked" [1] (para. 11.7.3.5).

To minimise these errors, two modifications to the financial model were made. First, the user is able to select an end point for the projections of climate change impacts at a five-year resolution so that calculations can be undertaken for short through to long time frames. This option provides two benefits: first, the user is able to easily update the calculations in the future, and secondly, by selecting shorter steps for the projection of climate changes, the overestimation of near-term scenarios is removed and yet long-term scenarios can still be calculated if required; secondly, to minimise errors introduced by shifting the rainfall distributions by a projected annual mean, changes to rainfall were made at the monthly scale prior to calculating annual values to take into account the uneven distribution of rainfall throughout the year.

Historical monthly baseline data were taken from the Bureau of Meteorology High Quality National Real Time Monitoring (RTM) gridded data set (previously known as the Australian Water Availability Project data set (AWAP)) at a 0.05° × 0.05° grid (~5 km by ~5 km) resolution [30]. The boundaries of each of the ten case study Councils were sourced from the Australia Digital Administrative Boundaries Database and used to develop a mask in ArcInfo® (Version 10, Esri, Redlands, CA, USA). All data points on the 0.05° × 0.05° grid within the boundaries of the Council area mask were extracted from the RTM dataset and averaged to create an area-averaged time series for P, T_{min} and T_{max} from 1911 to 2010 [31]. Calculations were then made by the financial model to generate monthly distributions for MMP and T to calculate annual baseline climate distributions for each of the required variables. These historical baseline distributions are used by the financial model to simulate baseline useful life and annual costs for each road type (no climate change).

The model then allows for the calculation of any future climate change scenario with the input of a projected change in the mean annual temperature and rainfall. As current increases in greenhouse gasses are within or higher than the worst case scenario predicted in the IPCC AR4, the high emissions scenarios as described by the IPCC Special Report in Emissions Scenarios (SRES) were used to calculate the long term projections in this study. To demonstrate the outputs of the model and provide an estimate of climate change impacts for each of the ten case study Councils, projections of the expected change in mean temperature and rainfall for the business as usual A1FI scenario in the years 2050 and 2100 as projected by the ECHAM Atmospheric General Circulation Model with a high climate sensitivity were extracted from the publically available OZCLIM [32] climate change scenario generator developed by CSIRO. This high emissions and high sensitivity emissions scenario was selected on purpose to represent a 'worst case scenario' for road deterioration in the financial model. The projected change in annual temperature and rainfall were recorded for each of the ten case study areas and are summarised in Table 1.

Table 1. Projected changes in average annual temperature and annual total rainfall for each of the case study Council sites as determined from the CSIRO OZCLIM climate generator for the years 2050 and 2100. These values are entered into the financial model developed to run the trial results presented.

State	**Case Study Area**	**2050**				**2100**			
		Change in Average Annual Temperature (°C)		**Change in Total Annual Rainfall (mm)**		**Change in Average Annual Temperature (°C)**		**Change in Total Annual Rainfall (mm)**	
		Range	**Mean**	**Range**	**Mean**	**Range**	**Mean**	**Range**	**Mean**
WA	Esperance	1 to 2	1.5	−50 to −150	−100	3 to 5	4	−150 to −250	−200
SA	Tumby Bay	1 to 2	1.5	−50 to −100	−75	3 to 4	3.5	−50 to −150	−100
	Cambelltown	1 to 2	1.5	−50 to −100	−75	3 to 4	3.5	−150 to −200	−175
	Barossa	1 to 2	1.5	−50 to −100	−75	3 to 4	3.5	−100 to −150	−125
	Port Adelaide/ Enfield	1 to 2	1.5	−50 to −100	−75	3 to 4	3.5	−150 to −200	−175
	Onkaparinga	1 to 2	1.5	−50 to −100	−75	3 to 4	3.5	−100 to −150	−125
	Wattle Range	1 to 2	1.5	−100 to −150	−125	2 to 3	2.5	−200 to −250	−225
VIC	Hume	1 to 2	1.5	−50 to −100	−75	4 to 5	4.5	−150 to −200	−175
	Bass Coast	1 to 2	1.5	−50 to −100	−75	4 to 5	4.5	−200 to −250	−225
TAS	Brighton	1 to 2	1.5	0 to +25	+12.5	4 to 5	4.5	+25 to +50	+75

CSIRO is the Commonwealth Scientific and Industrial Research Organisation.

2.5. Engineering Inputs to the Model

To assess the climate impact on each road type a range of engineering inputs are required for each road type. These include current maintenance and rehabilitation costs as well as projected life as provided by the Councils undertaking the analysis.

Model Processes

The first model runs provide a distribution of the asset useful life using historic climate data (i.e., baseline useful life with no climate change) and then the useful life using historic climate data shifted to account for project climate changes relating to the chosen scenario (i.e., adjusted useful life) as described in the previous section. In parallel, cost impacts expressed as a standard Net Present Value (NPV) with climate change are simulated for maintenance, resurfacing and rehabilitation, as appropriate to the road type in the Council area.

An example of the model process and outputs for an SSR are provided here. The first step was to generate distributions for the 'baseline' climate *TI* using historic climate data. To quantify *TI* with climate change, we accessed the projected change for temperature and rainfall at the selected location and then shifted the historical distributions at a monthly scale for each climate parameter. From these new climate change distributions we calculated the *TI* distribution for the terminal year (e.g., 2100). The distribution for each year in the time horizon was then obtained by interpolation using the *TI* values of the current and the terminal year. The model is designed to automatically update the fitted distribution for *TI* (or any other climate variable) when a different Council area is selected or a different scenario is run.

Given the simulated values of *TI* over the time horizon (e.g., 80 years), we calculated the change in useful life over each year relative to the previous year using the engineering equations identified.

The calculation was then translated into the change of annual cost via the equivalent annual cost (*EAC*) method. For example, let *TC* be the total cost of resurfacing. The equivalent annual cost can be calculated via the following annuity formula:

$$TC = \frac{EAC}{r}[1 - \frac{1}{(1+r)^{UL}}], \tag{6}$$

where r is the discount rate and *UL* denotes the useful life. Therefore, if the useful life changes from *UL*1 to *UL*2, then the *EAC* changes from *EAC*1 to *EAC*2 to satisfy the following relationship:

$$\frac{EAC2}{EAC1} = \frac{1 - \frac{1}{(1+r)^{UL1}}}{1 - \frac{1}{(1+r)^{UL2}}} \tag{7}$$

One important underlying assumption here is that the total cost of resurfacing over the time horizon remains constant in real terms over time. In this way, we were able to calculate the annual cost based on the previous year's cost and the total cost over the time horizon by summing all the annual costs. The total costs with/without climate change can be calculated similarly. The difference between them is the dollar impact of climate change. By running the simulation repeatedly, we obtained a distribution of the cost impact as a result of changes in the climate.

Similarly, when we know the total cost over the 80-year period, we can calculate the equivalent annual cost figure *EAC*. On the other hand, the given annual resurfacing cost (RSC) and expected useful life (*UL*) can give us a total cost for each resurfacing. Combining the *TC* and *EAC*, we can calculate the useful life from the above annuity formula. In this way, the average useful life with/without climate change can then be obtained. Furthermore, the climate change impact on the useful life can be calculated and the distribution determined. For each road type, we then proceeded in the financial model as shown in Figure 3.

As all the financial analyses are undertaken in real terms, maintenance costs (MC) are also assumed to be constant in real terms regardless of climate change. Councils can opt to change the MC if deemed appropriate, but as we believe that the change is not likely to be significant, the default MC growth rate is set as zero.

3. Results

The financial model was run for each of the ten collaborating Councils across southern Australia using road asset and cost data that they provided and the IPCC A1FI SRES climate change scenario for the years 2050 and 2100 as shown in Table 1. Example model outputs of the change in real-time costs and road useful life in years for an unsealed road in Hume Council in Victoria are shown in Figure 4 for 2100 as compared to the 1911–2010 baseline climate and using 2010 costs.

The upper graph shows the impact of climate change in costs (% change) and the lower graph shows the impact of climate change in useful life (resurfacing) (% change in UL-RS). In both graphs, the vertical axis represents frequency, and the horizontal axis represents the values of climate change impact with the statistics in the legend on the right-hand side.

A summary of the financial model results for all the case study Councils and road types (except Tumby Bay, which did not have sufficient data for the analysis) is provided in Table 2 for the IPCC SRES A1FI 2100 scenario as projected by the ECHAM GCM outputs.

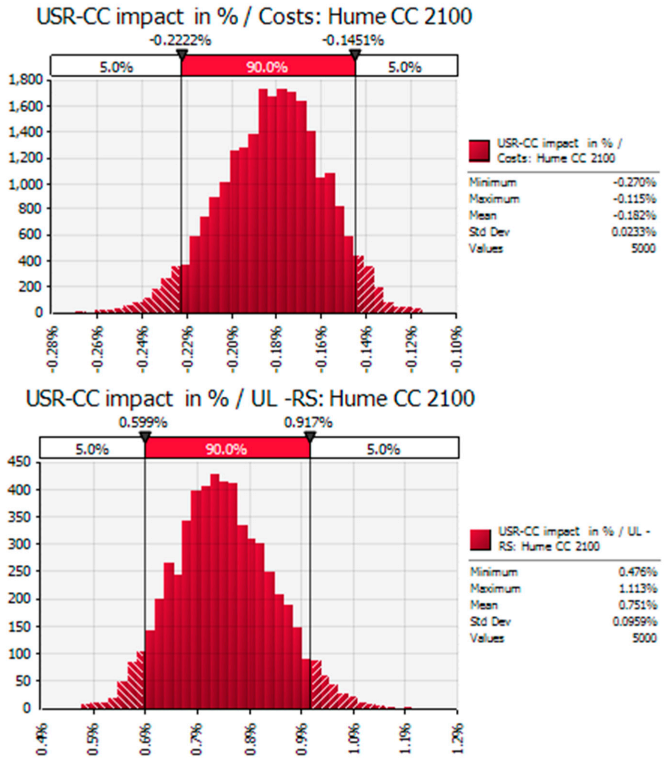


Figure 4. Hume Council Scenarios.

Table 2. Summary of financial results for all case study councils.

Terminal Year = 2100	Asphalt/Hotmix Sealed Roads			Spray Sealed Roads			Unsealed Roads	
% Change	**Costs**	**UL-RS**	**UL-RH**	**Costs**	**UL-RS**	**UL-RH**	**Costs**	**UL-RS**
Esperance SC	−4.70	8.61	9.34	−0.34	0.62	0.65	−0.83	2.16
Barossa							−5.20	16.4
Campbelltown City	−3.61	6.89	7.90					
Port Adelaide Enfield CC	−4.5	6.94	7.80					
Onkaparinga CC	−3.60	7.40	8.27	−0.36	0.76	0.89	−0.13	1.02
Bass Coast SC	−3.76	8.84	9.23	−0.39	1.10	1.25	−2.50	13.4
Hume CC	−5.90	8.74	9.01	−0.60	0.82	0.89	−0.18	0.75
Brighton	−4.40	8.98	9.03	−0.21	0.47	0.59	−0.45	1.50
Means	−4.35	8.06	8.65	−0.38	0.75	0.85	−1.55	5.87

Note that the above simulation results are based on a real discount rate of 2.85%, which is slightly lower than the average real rate of return on the 10-year government bonds over the period from 1971 to 2008. Of course, the discount rate for different Councils can be slightly different, and it can also vary over time for the same Council. Discount rate can never be precise and can be a contentious issue. For these reasons, the discount rate can be entered into the model as a variable and if necessary, a sensitivity analysis can be carried out. CC is City Council. UL-RS is Useful Life–Resurfacing; UL-RH is Useful Life–Rehabilitation.

4. Discussion

For the climate change scenarios used, the incremental impact of climate change on all three types of road infrastructure modelled appears to be generally low. There are small cost reductions over the period for all road types (higher for AHR) as a result of the expected drying and warming trend in the climate. The useful life for resurfacing increases significantly more for AHR and USR than for SSR. The useful life for rehabilitation increases significantly more for AHR than for SSR. For AHR and SSR, the range of results across Councils is narrow, clustering closely around the mean, while for USR, although the range for costs is reasonably narrow (Barossa is an outlier), there is a significant range for useful life, with both Barossa and Bass Coast returning much higher results. In all cases, the 2100 scenario maintains the direction of the 2050 results although at greater magnitudes.

As the engineering formulas show, an increase in temperature and decrease of precipitation is likely to improve road surface performance. This result is indicated by small reductions in total cost and small increases in the useful life of all three road types. The range of effects is largest for USR: this may reflect, in part, different methods of USR construction and different methods of data collection, both of which were variable for USR. The impacts of climate change, though small, are greatest for USR because mean monthly precipitation is a direct driver of gravel loss and hence reductions in precipitation would decrease gravel loss, as would be expected. AHR ranks second in the size of effect, followed by SSR. This result may reflect the differential binding of aggregates, sands and fillers under a warming temperature regime.

It should be noted that the results of the analysis would obviously be different if projected changes to the climate indicated that it will get wetter—as might be the case in northern Australia. For this reason, the results provided here are relevant only to southern Australia and the climate scenarios tested although the model is considered robust for use in other areas of the country if supported by the correct climate data.

Like all financial models, the model developed here is based on inputs—in this case from climate data and engineering road performance equations—and is therefore subject to the theoretical assumptions, data structures, and empirical testing of those areas. In addition, important assumptions have been made in the financial model for the way climate inputs are configured and the way the simulations are conducted. Furthermore, there are other factors that affect the useful life and costs associated with road maintenance and rehabilitation that have been identified as important, but that have not been incorporated fully into the model. For example, the changes to climate variables in the engineering equations only represent a small proportion of the changes to useful life of the asset—traffic volumes, for example, are expected to increase over time and outstrip the likely impacts of climate change on roads. In addition, the impacts of extreme events are not well documented and not well captured in the monthly climate data, and so are not included in the financial model except as a fixed amount entered by the user rather than as part of the simulation. It is important to note that the cumulative effect of assumptions across the disciplines as included in the financial model should not be underestimated. This study does, however, provide a first empirical test of these assumptions using real data.

Subject to those caveats, we conclude that the approach taken in the project has proven to be reliable and consistent. The financial modelling is based on a sound theoretical and empirical foundation, in both engineering and climate science. The main achievement of this work, we believe, is to show that climate data can be effectively captured and configured as inputs to the engineering performance equations, and that the implications of this work can be taken as inputs to financial modelling to generate coherent asset cost and useful life projections. These costs can then become valuable inputs into Local Government management instruments. This integrated outcome, we believe, represents a practical and well-founded contribution to international work in the science and practice of climate change adaptation and management.

We note that we have considered three asset road classes as part of this study: AHR, SSR and USR. Together they account for nearly all the roads owned by Local Governments across Southern Australia, and so it is expected that the financial model outputs can provide a guide to Councils developing climate change policy, particularly in terms of capital budgeting. The financial model developed is compatible with any other Excel® based financial or asset management system but does require the @RISK software add-in to run the simulations. Currently, the existing Australian NAMS.PLUS asset management templates (Version 2, Institute of Public Works Engineering Australasia (IPWEA), New South Wales, Australia) developed by the IPWEA were identified as the only national asset management planning software framework that is supported by a standardised methodology for use by Local Governments. The templates include projections for asset renewal requirements based on useful service life. Outputs from the financial model developed in this project are easily included in the NAMS.PLUS templates by using the expected change in useful life of the asset as a result of climate change, and the likely associated renewal costs. The NAMS.PLUS output can then provide a forward prediction of renewal costs that incorporate the climate change impacts. Currently, NAMS.PLUS is undergoing an upgrade process and IPWEA are considering the inclusion of the financial model developed here in the next version of the software.

5. Conclusions

The research reported in this paper aimed to identify key Council infrastructure assets vulnerable to climate change, determine the likely impacts of climate change on Council assets, undertake a financial risk modelling exercise to quantify in monetary terms climate change asset risk, and develop the necessary modifications to existing infrastructure asset management and financial sustainability tools so that Councils may evaluate various climate change action scenarios at the management and planning levels.

A review of Local Government asset values and likely impacts from the climate identified roads as a priority. Engineering models to describe the degradation of three classes of roads as a result of climate were identified—sprayed sealed roads, asphalt/hotmix sealed roads and unsealed roads. These engineering models were taken as the basis for constructing a financial model that provides a cost analysis of the likely impacts of climate changes on each of three road asset classes. Outputs from the financial model include likely changes to asset useful life and maintenance costs in response to changes in temperature and rainfall as defined by a user selected climate change scenario and include the dimensions of risk and uncertainty. Outputs from the model will allow Local Governments anywhere in Australia to input their climate specific, site specific and infrastructure specific variables and calculate the likely impacts of climate change on the road types currently included in the model. The results described in this paper used data from ten collaborating case study Local Governments across southern Australia and indicated that the impact of median changes in temperature and rainfall, as can be expected to the year 2100 under a high greenhouse gas emissions scenario, will result in only small changes in the useful life or maintenance and rehabilitation costs of the roads modeled. This result is a function of the warming and drying trends expected in the climate for the region, and results may be different in other areas of the county. Modelled outputs can be used as input data to other Local Government financial and asset management tools such as the NAMS.PLUS software developed by the IPWEA.

In summary, this study has demonstrated the viability of quantifying the financial impact of climate change on Council roads by combining the expertise and knowledge across a number of disciplines. Furthermore, the case studies have revealed that our financial model can yield sensible and useful results of practical value to Councils.

Acknowledgments: This project was funded by the National Climate Change Adaptation Research Facility (NCCARF) and Local Government Association of South Australia (LGASA) and was a collaboration of the LGASA, University of South Australia (UniSA), the Institute of Public Works and Engineers Australia (IPWEA), the Municipal Association Victoria (MAV) and the Western Australian Local Government Association (WALGA), and had support and input from ten case study Councils across southern Australia. The authors would like to thank Adam Gray, Rohan Hamden, Darren Ray, Alex Evans, John Comrie, Murray Townsend, Leon Patterson and other collaborating Council and industry representatives that were involved in the project. A full report of the project has been published by the NCCARF [33].

Author Contributions: Jacqueline Balston is a climatologist and was the project manager of this research. She was responsible for the climate prediction work. Ivan Iankov and Jon Kellett were responsible for literature review and engineering analysis. Steven Li is a mathematician, and Geoff Wells is a business analyst. Together, they designed the financial model and managed the local council survey and analysis work.

Conflicts of Interest: The funding sponsors had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript, and in the decision to publish the results.

References and Notes

1. Intergovernmental Panel on Climate Change (IPCC). *Climate Change 2007: The Physical Science Basis*; Intergovernmental Panel on Climate Change: Geneva, Switzerland, 2007.

2. Department of Regional Australia, Local Government, Arts and Sport. *2008–2009 Local Government National Report*; Department of Regional Australia, Local Government, Arts and Sport: Canberra, Australia, 2012.
3. Koetse, M.J.; Rietveld, P. The impact of climate change and weather on transport: An overview of empirical findings. *Transp. Res. D* **2009**, *14*, 205–221. [CrossRef]
4. Petersen, T.C.; McGuirk, M.; Houston, T.; Horvotz, A.; Wehner, M. *Climate Variability and Change with Implications for Transportation*; NOAA National Climatic Data Centre: Asheville, NC, USA, 2006.
5. Chinowsky, P.; Arndt, C. Climate change and roads: A dynamic stressor-response model. *Rev. Dev. Econ.* **2012**, *16*, 448–462. [CrossRef]
6. Patt, A.; Klein, R.; Delavegaleinert, A. Taking the uncertainty in climate-change vulnerability assessment seriously. *C. R. Geosci.* **2005**, *337*, 411–424. [CrossRef]
7. New, M.; Hulme, M. Representing uncertainty in climate change scenarios: A Monte-Carlo approach. *Integr. Assess.* **2000**, *1*, 203–213. [CrossRef]
8. Wise, R.; Fazey, I.; Stafford Smith, M.; Park, S.; Eakin, H.; Archer Van Garderen, E.; Campbell, B. Reconceptualising adaptation to climate change as part of pathways of change and response. *Glob. Environ. Chang.* **2014**, *28*, 325–336. [CrossRef]
9. Rogelj, J.; McCollum, D.; Reisinger, A.; Meinshausen, M.; Riahi, K. Probabilistic cost estimates for climate change mitigation. *Nature* **2013**, *493*, 79–83. [CrossRef] [PubMed]
10. Sourced from Australian Local Government Areas Map, Annotated by Authors. Available online: https://commons.wikimedia.org/wiki/File:Australian_local_government_areas.png (accessed on 9 January 2017).
11. Association of Local Government Engineering New Zealand Inc.; National Asset Management Steering (NAMS) Group. *International Infrastructure Management Manual*; Association of Local Government Engineering New Zealand Inc.: Wellington, New Zealand, 2011.
12. Information provided by Local Government Association of South Australia, November 2011.
13. Commonwealth Scientific and Industrial Research Organisation (CSIRO). *Infrastructure and Climate Change Risk Assessment for Victoria: Report to the Victorian Government*; CSIRO: Aspendale, Australia, 2006.
14. Commonwealth Scientific and Industrial Research Organisation and Bureau of Meteorology. *Climate Change in Australia Technical Report*; Commonwealth Scientific and Industrial Research Organisation and Bureau of Meteorology: Canberra, Australia, 2007.
15. Garnaut, R. *Updated Paper Five—The Science of Climate Change*; The Garnaut Climate Change Review—Update 2011; Commonwealth of Australia: Canberra, Australia, 2011.
16. Steffen, W. *Climate Change 2009: Faster Change and More Serious Risks*; Australian Department of Climate Change: Canberra Australia, 2009.
17. Ray, D. (Senior Meteorologist, South Australian Climate Section, Bureau of Meteorology, Adelaide, Australia). Personal communication, October 2011.
18. Austroads. *Austroads Glossary of Terms*, 4th ed.; Austroads: Sydney, Australia, 2010.
19. Standards Australia AS/NZS 2341.13. *Methods of Testing Bitumen and Related Roadmaking Products, Method 13, Long Term Exposure to Heat and Air*; Standards Australia: Sydney, Australia, 1997.
20. Giummarra, G.; Martin, T.; Hoque, Z.; Roper, R. Establishing deterioration models for local roads in Australia. *Transp. Res. Rec. J. Transp. Res. Board* **2007**. [CrossRef]
21. Martin, T.C. Experimental estimation of the relative deterioration of surface maintenance treatments. *J. Transp. Eng.* **2010**, *136*, 1–10. [CrossRef]
22. Martin, T.C.; Toole, T.; Oliver, J.W.H. The development of HDM-4 technology road deterioration models for Australia's sealed granular pavements. In Proceedings of the 6th International Conference on Managing Pavements, Brisbane, Australia, 19–24 October 2004.
23. Oliver, J. *Australian Road Research Board (ARRB) Research Report 326—The Performance of Sprayed Seals*; Australian Road Research Board: Vermont South, Australia, 1999.
24. Oliver, J. *AP-R270/05—Improved Distress Viscosity Model for Reseal Intervention*; Austroads: Sydney, Australia, 2005.
25. Choi, Y. *Development of Asphalt Crack Initiation Model Based on Binder Hardening—Contract Report*; Austroads Project AT1479; Austroads: Sydney, Australia; ARRB Group: Vermont South, Australia, 2009.
26. Gentilli, J. *Australian Climate Patterns*; Thomas Nelson: Melbourne, Australia, 1972.
27. Visser, A.T. *An Evaluation of Unpaved Road Performance and Maintenance*; University of Texas: Austin, TX, USA, 1981.

28. Jones, T. *The Kenya Maintenance Study on Unpaved Roads: Research on Deterioration*; Transport and Road Research Laboratory (TRRL) Laboratory Report 1111. TRRL; Department of the Environment, Department of Transport: Crowthorne, Berkshire, UK, 1984.
29. Timbal, B. (Climate Forecasting Group, Bureau of Meteorology, Melbourne Australia). Personal communication, October 2011.
30. Jones, D.A.; Wang, W.; Fawcett, R. High-quality spatial data-sets for Australia. *Aust. Meteorol. Oceanogr. J.* **2009**, *58*, 233–248.
31. Evans, A. (Climatologist, Bureau of Meteorology Climate Group, Kent Town, Adelaide, Australia). Personal communication, October 2011.
32. CSIRO Climate Change Scenario Generator. Available online: http://www.csiro.au/ozclim/home.do (accessed on 12 October 2011).
33. Balston, J.M.; Kellett, J.; Wells, G.; Li, S.; Gray, A.; Iankov, I. *Quantifying the Cost of Climate Change Impacts on Local Government Assets*; National Climate Change Adaptation Research Facility: Griffith University Gold Coast Campus, Southport, Australia, 2012.