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ANNUAL SUMMARY REPORT

Project Title: P91: Improved pavement temperature prediction model for asphalt pavement design in Queensland (Year 1 - 2018/19)

Project No: PRP18035

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SUMMARY

At present, asphalt pavements in Australia are designed through a simplified procedure, which results in a single annual design temperature value, the Weighted Mean Annual Pavement Temperature (WMAPT), representing the range of temperatures in the pavement. Queensland faces extreme heat, both in terms of the incidence of consecutive hot and sunny days in summer, and in the relatively mild winters. With thick asphalt pavements increasingly being selected ahead of alternative treatments in the west and north of Queensland, there is potential for large thickness reductions without compromising performance in areas where the listed WMAPT is above 30 °C.

The objective of this project was to develop an initial pavement design model that could be customised to Queensland locations and conditions while aligning with the Queensland Department of Transport and Main Roads pavement design procedures.

This report summarises the outcomes of temperature data collected through to the end of 2018 to update an hourly pavement temperature model. Key findings include:

- By analysing four case studies at three locations in Queensland, the model indicates that thick asphalt pavements are being constructed with WMAPT values above 30 °C, and these pavements may be overdesigned.
- The model was also used to estimate the temperature at depth in three locations in Queensland, with each location returning average pavement temperatures lower than the WMAPT values for that location – particularly for the locations with WMAPT values over 30 °C.

Recommendations to improve the design of asphalt pavements in Queensland, and for further research include:

1. For major projects and where very thick pavements are specified by the current method, there would be value in implementing simple modifications to the WMAPT calculation. This may include updating the WMAPT value based on local weather stations and recent climatic data and adjusting WMAPT values for thicker pavements in line with the original research in the *Shell Pavement Design Manual*.
2. High temperatures at the surface contributing to the urban heat island effect may persist for a large part of the year in Brisbane and other parts of Queensland. Further investigation into reducing surface (and layer) temperatures may contribute to improved pavement performance as well as improving public amenity benefits.
3. Further developing the initial design tool to improve the user interface, making it more user-friendly and customisable, thus facilitating its use on a wider range of projects.
4. The pavement temperature and loading rate model developed to date assumes the applied traffic loading is the same for each hour in each 24-hour period. This model could be enhanced by allowing for the hourly distribution of truck axle loads.

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1 INTRODUCTION

As a viscoelastic material, the temperature of asphalt has a significant impact on pavement performance. In hot climates like Queensland, the assumptions in the Austroads design methodology predict low moduli values for thick asphalt, resulting in significantly shorter predicted fatigue lives compared to the same pavement in a cooler climate.

At present, asphalt pavements in Australia are designed through a simplified procedure, which results in a single annual design temperature value, the Weighted Mean Annual Pavement Temperature (WMAPT), representing the range of temperatures in the pavement.

There is ongoing work underway to enhance this process, including mix-specific design measures. Another step in this process will be to develop location-specific designs which are able to model pavement temperatures at depth and for various traffic loading scenarios.

Between 2014 and 2018, four thick asphalt pavements around Australia were instrumented with temperature sensors and a linked weather station – in Eagle Farm (Brisbane), South Gippsland (Victoria), Perth and Karratha (WA) – with the data analysed and presented in a report under the WA Road Research & Innovation Program (WARRIP). The report indicated that for deep (300+ mm) asphalt pavements, significant improvements can be made to the current design methodology through potential amendments to how WMAPT is calculated.

Queensland faces the same extreme heat that is experienced in Western Australia, both in terms of the incidence of consecutive hot and sunny days in summer, and in the relatively mild winters. With thick asphalt pavements increasingly being selected ahead of alternative treatments in the west and north of Queensland, there is potential for large thickness reductions without compromising performance in areas where the listed WMAPT is above 30 °C.

1.1 Anticipated Benefits

This project aims to deliver benefits in several areas, including:

1. improved calculation of pavement damage over time due to a better understanding of the relationship between pavement temperature at depth and pavement performance, leading to more accurate predictions of resilient response and fatigue life of pavements
2. reduced cost of pavements – reduced uncertainties will (in many cases) allow for reduced pavement thickness, particularly in areas with deep asphalt pavements and relatively high typical pavement temperatures, with thinner asphalt pavement designs saving money due to:
   (a) reduced material costs
   (b) reduced haulage and personnel costs
   (c) reduced paving runs and reduced paving time
3. preliminary modelling may be developed in the future into a more complete design tool for asphalt pavements, incorporating the findings of this and other completed and concurrent projects.

1.2 Project Scope

This project included adopting the work undertaken to date for WARRIP to Queensland temperatures and climate, and it includes a series of case studies based on real pavement designs used on Queensland projects. Preliminary design tools are to be released which will enable an optimised design of asphalt pavements based on localised climate and traffic.

It is envisaged that in the future, this tool can be integrated with mix-specific asphalt testing and performance predictions to build a model that is tailored to a specific location and mix design.

The project scope involved the following key tasks:

1. Update model and customise for Queensland:
   The initial model was to be updated based on data through to the end of 2018 and customised to Queensland locations and conditions, and was to align with Queensland Department of Transport and Main Roads (TMR) pavement design procedures.
2. Annual summary report:
   A report with case studies and methodology for applying the model in Queensland, and the final version of the model to be trialed within TMR.

A potential second year for the project may include development of guidance to implement changes to asphalt pavement design in Queensland, through a Technical Note and/or an update to the TMR Pavement Design Supplement. The introduction of this guidance will also require a tool to facilitate implementation, either through a simple spreadsheet or customised software. These new developments would be accompanied by consultation and knowledge transfer activities.

1.3 Report Outline

Firstly, the report documents background information that has led to this study, and highlights the challenges that have been faced in developing improved design procedures for asphalt pavements in Australia (refer to Section 2). The pavement temperature prediction model is also introduced, which has been developed through a series of research projects under NACoE, WARRIP and Austroads.

Climate and pavement temperature data through mid-2019 is reported in Section 3, with the updated asphalt pavement temperature model presented. This section also includes a comparison of predicted temperatures and actual measured data at the Eagle Farm location. A series of 'typical' full-depth asphalt pavement designs are presented with existing WMAPT values and predictions under the new model for select Queensland locations.

Section 4outlines key conclusions and recommendations for further work to implement the outcomes into TMR pavement design practices.

2 BACKGROUND

2.1 Design of Asphalt Pavements

There is a well-established relationship between temperature and asphalt modulus, with a series of studies over the last several decades confirming that asphalt moduli decrease as the asphalt temperature increases. To account for this behaviour in pavement design, the Austroads *Guide to Pavement Technology* (AGPT) (Austroads 2017a) includes a single temperature for design purposes for each city or major town in Australia, known as the Weighted Mean Annual Pavement Temperature (WMAPT).

The original WMAPT concept was developed with reference to the *Shell Pavement Design Manual* (Shell 1978), which itself was based on a small range of materials and pavement configurations. The background work contributing to the WMAPT concept in Australia is based upon work by Dickinson (1981) with pavement temperature profiles and a series of back-calculated asphalt moduli from falling weight deflectometer (FWD) tests (Jameson 2013; Jameson, Sharp & Vertessy 1992).

Over time, the single value WMAPT approach has proven to be a reasonable approximation for the effects of temperature within the overall asphalt pavement design process, but it oversimplifies the input to a point where subtleties in climatic effects across different parts of the country are not well captured. This indicates that although weighted for seasonal fluctuations, WMAPT values do not adequately distinguish between parts of the country with extreme temperature ranges (big difference between summer and winter maximums, or locations with hot days and cold nights) and those with more consistent annual and diurnal temperature profiles.

For example, a thick asphalt pavement that is heavily loaded in the morning peak would experience proportionately less loading at hotter times of the day. Locations with heavy traffic in the evening peak would subsequently be subjected to more rapid fatigue than predicted. The WMAPT model also fails to account for factors such as solar radiation, relative humidity and rainfall. Given relatively easy access to this data through the Bureau of Meteorology, and the availability of more affordable instrumentation and hourly traffic distributions, it is clear that there is scope to improve our design procedures.

Austroads (2013) demonstrated that there are several avenues to improve the design of asphalt pavements for temperature, including models that are capable of predicting the temperature at any time and depth with only basic weather input data, which was further explored in a recent report under WARRIP (Beecroft 2019). The research efforts through Austroads, NACoE and WARRIP have contributed to building a large and geographically diverse database of pavement temperature data.

While it is not the primary intention of this project and the associated Austroads and WARRIP research projects to propose comprehensive models to immediately replace the current Austroads design methodology, it is believed that the data captured and models proposed in this research can provide road agencies with a stronger understanding of the impact of climate on asphalt pavements and allow for optimisation of pavement designs. It is expected that further work, particularly in other components of the Austroads methodology, would be required before wholesale changes to the design method could be justified.

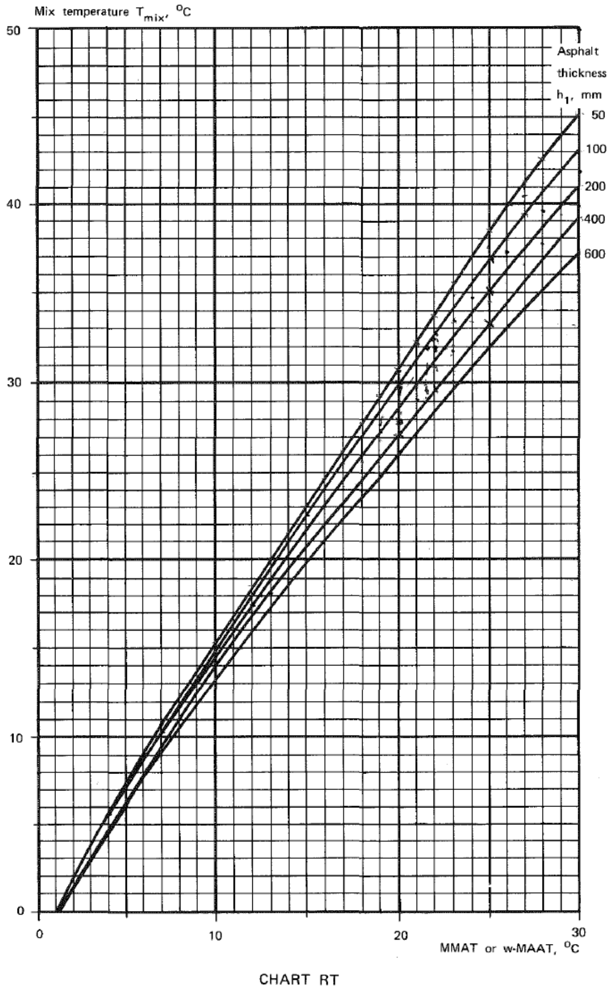
2.2 Weighted Mean Annual Pavement Temperature (WMAPT)

2.2.1 History of WMAPT

WMAPT values were developed in accordance with the methodology and tables in the *Shell Pavement Design Manual* (Shell 1978) and used air temperatures at local weather stations over 30+ years. Austroads (2008) outlines the history behind the adoption of WMAPT in the current design methodology used in Australia.

The values in Shell take into account daily and monthly variations in air and pavement temperature through the Weighted Mean Annual Air Temperature (WMAAT) and WMAPT, with the formula for WMAPT in Austroads (2017a) being an approximation of the 100 mm asphalt thickness curve in Chart RT (see Figure 2.1).

Figure 2.1: WMAAT and corresponding WMAPT at five depths – Chart RT



Source: Shell (1978).

While the chart in Shell (1978) does acknowledge that thicker pavements would likely have lower average pavement temperatures over the course of a year, this was not adopted in the Austroads methodology, as it was considered the effect was offset to some extent by reduction in loading rate with depth. In recent decades, pavements have been constructed at increasing thicknesses in order to handle heavier freight loads and greater traffic volumes, and these pavements are often expected to last for 40+ years.

Whether considered over a single day or across different periods of the year, the simplified WMAPT approach that has been adopted may not sufficiently account for the wide fluctuations in climatic conditions and subsequently in asphalt moduli (Austroads 2013).

Preliminary models developed in Austroads (2013) were not sufficiently validated against pavement temperature data to publish a proposed update to the WMAPT approach. However, the availability of at least a full year of data from three sites in Eagle Farm, South Gippsland and on the Kwinana Freeway allowed for the adoption of a more sophisticated pavement temperature prediction model. This was a key outcome of the 2016–18 research under WARRIP (Beecroft 2019).

2.3 Temperature Monitoring Instrumentation

There are at least seven sites around Australia with pavement temperature sensors installed at depth, including four sites instrumented through recent Austroads, NACoE and WARRIP research which are managed by ARRB as well as several other sites that maintained by external stakeholders, as summarised in Table 2.1. Data from sites managed by external stakeholders has been made available for the purposes of ongoing research and has therefore contributed to the models developed to date.

Each instrumented location

Table 2.1: Pavement instrumentation sites – summary data

Location	Managed by	Date started	Depth of sensors (mm)	Data interval	Air temp	Solar radiation	Wind	Rain
Great Eastern Highway, Perth, WA	Curtin University	28/3/2013	40, 80, 150, 220, 290 & 360	5 min	No	No	No	No
Sippy Downs, Queensland	University of the Sunshine Coast	13/9/2013	Surface & approx. 75 mm	1 min	Yes	Yes	No	No
Eagle Farm, Brisbane, Queensland	ARRB	20/2/2014	50, 70, 110, 190, 290 & 390	10 min	Yes	Yes	Yes	Yes
South Gippsland Highway, Victoria	ARRB	26/6/2015	55, 75, 120, 185, 235 & 325	10 min	Yes	Yes	Yes	Yes
Kwinana Freeway, Jandakot, WA	ARRB	21/9/2016	45, 85, 120, 160, 200 & 320	10 min	Yes	Yes	Yes	Yes
Coolalinga, Darwin, NT	NT DIPL	14/8/2017	50 shoulder, 50 wheelpath, 150, 250	15 min	No	No	No	No
Karratha, WA	ARRB	26/6/2018	45, 85, 120, 160, 200 & 260	10 min	Yes	Yes	Yes	Yes

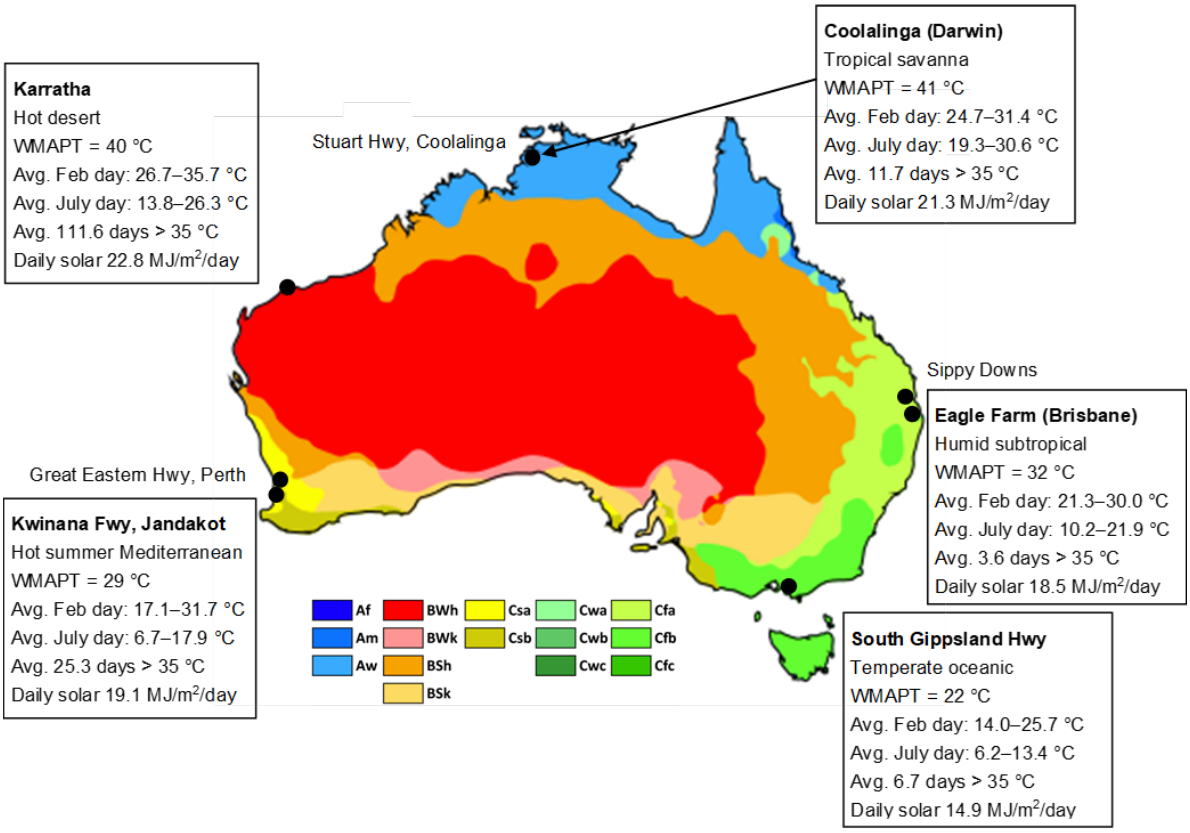
These instrumented sites represent a broad range of locations and climates, and this has contributed to a robust dataset, which can be utilised in modelling and used across much of the country with a relatively high degree of confidence. The locations for the four ARRB-managed sites are summarised in Table 2.2 and presented on a Köppen climate classification map in . However, there were some issues associated with the Eagle Farm instrumentation as discussed in Section 2.3.1.

Table 2.2: Climate data across the four ARRB installation locations

City	Perth, WA(1)			Karratha, WA(2)			Brisbane, Queensland(3)			South Gippsland, Victoria(4)		
Köppen climate classification	*Hot-summer Mediterranean*			*Hot desert*			*Humid subtropical*			*Temperate oceanic*		
	Feb	Jul	Year	Feb	Jul	Year	Feb	Jul	Year	Feb	Jul	Year
Record high (°C)	46.6	25.9	46.6	47.7	34.0	48.2	41.7	29.1	41.7	46.0	22.5	46.0
Average high (°C)	31.7	17.9	24.5	35.7	26.3	32.4	30.0	21.9	26.5	25.7	13.4	19.4
Mean days ≥ 35 °C	6.7	0.0	25.3	16.0	0.0	111.6	0.6	0.0	3.6	1.7	0.0	6.7
Average low (°C)	17.1	6.7	11.5	26.7	13.8	20.8	21.3	10.2	16.3	14.0	6.2	9.7
Record low (°C)	6.5	−2.8	−3.4	19.4	6.9	6.9	16.5	2.6	2.6	6.7	-0.7	-2.5
Mean days ≤ 2 °C	0.0	5.9	15.8	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.6	4.6
Mean 3 pm temperature (°C)	29.7	16.7	22.9	33.7	25.0	30.6	28.2	20.8	24.8			
Mean 3 pm rel. humidity (%)	36	58	47	55	40	43	59	44	52			
Rainfall (mm)	16.0	173.1	824.3	77.1	14.0	300.4	142.5	24.0	1021.6	49.5	71.1	819.9
Average precipitation (days)	2.3	17.6	108.8	5.3	2.0	27.4	13.3	7.3	124.7	8.6	19.9	183.4
Mean daily solar exposure (MJ/m^2)	26.0	9.7	19.1	25.4	16.9	22.8	21.1	13.0	18.5	21.3	6.7	14.9

1 1989–2016 at Jandakot Airport – BoM site number 009172.
2 1993–2018 at Karratha Aero – BoM site number 004083.
3 1999–2016 at Brisbane – BoM site number 040913.
4 1990–2016 at Cranbourne – BoM site number 086375.

Figure 2.2: World Köppen Climate Classification map (Australia)



Source: Adapted from Peel, Finlayson and McMahon (2007), Commonwealth of Australia (2019).

2.3.1 Eagle Farm Pavement Temperatures

As a part of the introduction of the French Enrobés à Module Elevé Class 2 (EME2) high modulus asphalt technology to Australia, a trial took place in Eagle Farm, Brisbane in February 2014. To allow for pavement temperature monitoring at this location, a section of pavement 400 mm in depth was profiled out and sensors were installed. The instrumentation process and early observations are documented in Austroads (2014) and Beecroft, Denneman and Petho (2015).

Unfortunately, there were some issues with the first set of sensors which required replacement in mid-2015. The sensors performed relatively well through 2018, with only one major failure, although as of mid-2019 there are now only two sensors consistently returning usable data.

Table 2.3 presents maximum, minimum and average air temperatures, daily solar radiation, rainfall, and pavement temperatures at six depths. Cells are noted where there was total sensor failure or data was unavailable for a significant portion of the month.

Table 2.3: Eagle Farm pavement temperatures and weather from 2015 to 2018

		2015–16	2016–17	2017–18	2018–19
Air temperature (°C)	Max	36.2	35.5	37.5	36.9
	Avg	21.6	22.0	21.7	21.7
	Min	7.3	8.6	7.9	6.7
Daily solar exposure (MJ/m^2)	Max	25.1	27.7	26.3	26.3
	Avg	14.1	15.5	14.4	14.0
	Min	1.7	1.4	1.9	2.0
Total rainfall (mm)		698.8	984.6	1045.2	773.4
Sensor 1 (°C) 50 mm	Max	59.2	56.7	56.3	55.2
	Avg	30.4	Sensor failure	Sensor failure	Sensor failure
	Min	11.0	13.0	13.3	Sensor failure
Sensor 2 (°C) 70 mm	Max	54.6	Sensor failure	Sensor failure	Sensor failure
	Avg	30.2			
	Min	12.0			
Sensor 3 (°C) 110 mm	Max	50.3	51.4	50.9	49.7
	Avg	30.3	30.7	30.1	29.9
	Min	13.0	14.7	14.7	14.1
Sensor 4 (°C) 190 mm	Max	45.9	47.3	46.4	Sensor failure
	Avg	29.8	29.9	30.0	
	Min	15.7	18.2	16.6	
Sensor 5 (°C) 290 mm	Max	42.9	44.4	43.6	42.6
	Avg	30.2	30.6	30.0	29.9
	Min	17.0	17.9	18.3	18.0
Sensor 6 (°C) 390 mm	Max	40.6	42.2	41.4	Sensor failure
	Avg	29.9	30.3	28.8	
	Min	18.1	18.9	20.3	

Note: Year taken from 1 July through 30 June.

Notable observations include:

- Average air temperatures have been very consistent year on year, and even the extreme values appear to be consistent and predictable.
- Extreme pavement temperatures at 50 mm below the surface reached as high as 59.2 °C, with actual surface temperatures likely closer to 65 °C.
- The pavement does not reach such extreme temperatures deeper in the pavement; however, the average across the year is very similar at any depth, and the pavement temperature rarely drops below 20 °C near the base, even in the middle of winter.
- In November 2015 there was around a week of pavement temperatures that were consistently 5–15 °C lower than would be expected based on the air temperature and solar radiation recorded. It is possible that over this time there was a vehicle or other obstruction covering the instrumented section of pavement, which would have had no effect on the solar radiation or air temperature sensors. This data was removed when used for calibrating the model.
- Additionally, in March 2017 the solar radiation sensor failed but was fixed by a technician by April 2017. Once again, this data was removed from the dataset.
- Several other instances of failed sensors or clearly erroneous data were removed.

2.4 Alternative Approaches to WMAPT

A range of methods for calculating asphalt surface or layer temperature are summarised in Austroads (2013) and Beecroft (2019). This includes using the energy balance concept for heat transfer equation to predict the surface temperature of a pavement. By using relationships developed in literature the pavement surface temperature can be used to calculate temperatures for the underlying asphalt layers at various depths below the surface. This can further be broken down into discrete segments by day or year to enhance accuracy.

Beecroft (2019) also compared five different approaches using single pavement temperature values, including the WMAPT as currently followed, three alternative approaches and the actual measured pavement temperature values from instrumented sites. This analysis has been updated to include data at Eagle Farm for a total of five years as summarised in Table 2.4.

The five analysis cases with different WMAPT values are defined as:

1. actual pavement temperature data from the sensor closest to 100 mm, found through averaging and interpolating between the sensors closest above and below 100 mm for the entire year
2. WMAPT referenced from the closest site listed in Appendix B in Austroads (2017a)
3. WMAPT value calculated from weather station data at the instrumented site over the time period as relevant
4. WMAPT calculated from Chart RT in the *Shell Pavement Design Manual* (Shell 1978), taking into account the five lines in the chart (Figure 2.1) representing different depths (and interpolating between lines when necessary)
5. as above in Case 4, except using a Weighted Mean Average Air Temperature (WMAAT) calculated using only the weather station data from the actual site for that year.

The actual pavement temperatures, at all three sites, were consistently lower than the WMAPT values adopted for those locations in accordance Austroads (2017a), as noted in Table 2.4. As noted in Section 2.2, the fact that the WMAPT is weighted for variation of fatigue damage with temperature means that there is likely to be some difference in any case. It is also possible that some of this variation is owing to yearly fluctuations, but when the WMAPT is recalculated using local weather station data and weighted appropriately (Scenario 3 above), the difference is actually even larger (average just over 3 °C higher than actual pavement temperature).

Table 2.4: Comparison of current and alternative WMAPT calculation methodologies

			Kwinana Fwy		South Gippsland		Eagle Farm				
		Closest WMAPT site	Perth		Warragul		Brisbane				
		Year	2016–17	2017–18	2015–16	2016–17	2014–15	2015–16	2016–17	2017–18	2018–19
1	Average annual pavement temperature at 100 mm (°C)		25.3	*25.5*	20.2	19.3	30.3	30.4	31.0	29.7	29.9
2	Austroads WMAPT[1] (2017a)	WMAPT (°C)	29		22		32				
		Offset to actual (°C)	3.7	*3.5*	1.8	2.7	1.7	1.6	1.0	2.3	2.1
3	Calculate WMAPT[1] from single-year weather station data	WMAPT (°C)	28.2	*28.9*	24.0	22.7	33.0	33.4	33.8	33.3	33.4
		Offset to actual (°C)	2.9	*3.4*	3.8	3.4	2.7	3.0	2.8	3.6	3.5
4	Shell PDM Chart RT[1] (correcting for depth)	WMAPT (°C)	26.8		20.6		29.0				
		Offset to actual (°C)	1.5	1.3	0.4	1.3	–1.3	–1.4	–2.0	–0.7	–0.9
5	Shell PDM Chart RT[1] (2016–17 weather station data)	WMAPT (°C)	26.0	*26.6*	22.4	21.3	29.8	30.2	30.6	30.2	30.2
		Offset to actual (°C)	0.7	*1.1*	2.2	2.0	–0.5	–0.2	–0.4	0.5	0.3

1 In calculating the WMAPT values, consideration is given to the increase in fatigue damage with increasing temperature: it is an average temperature weighted for the fatigue damage. The effect of these weightings varies: For the South Gippsland Highway and Eagle Farm, the WMAPT is 0.8 °C higher than the average monthly pavement temperature, whereas for Kwinana Freeway the WMAPT is 1.4 °C higher.

The instrumented pavements from the locations in Table 2.4 are all over 300 mm in depth. While the average annual temperature in a thick layer near the surface is near identical to the average annual temperature in a deeper layer, it is not clear that thick and thin pavements in the same location would have similar average annual temperatures. A thin pavement may heat more rapidly in hot, sunny conditions but would also lose heat more rapidly overnight, while a thick pavement takes longer to reach maximum temperature but retains heat longer into the night and early morning due to the significant latent heat deep in the pavement. Chart RT in the *Shell Pavement Design Manual* predicts that thicker pavements would have lower average pavement temperatures, but it is not incorporated into the WMAPT calculation in Austroads (2017a as it was considered the temperature variation with depth was offset to some extent by reduction in loading rate with depth.

Scenario 4 interpolates this value for the thickness of pavements in the three instrumented locations and finds that this reduces the average error significantly. Scenario 5 uses this value but updates for the local weather in the year analysed. This scenario returned the lowest average error with all five years at the Eagle Farm site being within 0.5 °C of the actual pavement temperature (Table 2.5).

Table 2.5: Accuracy of four alternative WMAPT calculation methodologies

Case	Methodology	Mean squared error
2	WMAPT (Appendix B, Austroads 2017)	5.85
3	Calculate WMAPT (with actual weather station data)	10.59
4	Shell PDM Chart RT (correcting for depth)	1.64
5	Shell PDM Chart RT (with actual weather station data)	1.26

2.4.1 Climate Change Impacts

The initial work to develop WMAPT values for Australia and New Zealand was based on temperature records from the mid-late 20th century, which only incorporates the early stages of what has proven to be a consistent warming trend in most Australian locations. The expected increase of up to 2 °C in global temperatures over the next 30–50 years is not currently accounted for in pavement design. This is particularly relevant to heavy-duty pavements which are often designed for lives of 40+ years.

Beecroft (2019) outlined the impact of increasing temperatures on a range of WA locations, which found that hypothetically thick asphalt pavements with a 40-year design life would have a theoretical reduction in design life of up to 10% for each 1 °C increase in the WMAPT used in design.

3 UPDATED QUEENSLAND PAVEMENT TEMPERATURE MODELLING

3.1 Development of New Model

As a part of the 2016–19 WARRIP research presented in Beecroft (2019), an asphalt pavement temperature prediction model was developed, that can predict pavement temperatures at any Australian location for any time of day or time of year.

The model required an analysis of the key factors influencing pavement temperatures (summarised in Section 3.1.1), and a range of approaches were tested. The general form of the model for maximum and minimum pavement temperatures, and a tool for predicting the hourly temperature at any depth are presented in Section 3.1.2 and Section 3.1.3, respectively. This can then be combined with traffic data and assumed material properties to estimate the pavement fatigue life using a mechanistic pavement design tool, with examples drawn from several typical Queensland pavement designs (see Section 3.2).

3.1.1 Key Considerations

Beecroft (2019) outlines key factors that influence pavement temperatures, and thus were considered in the development of the model. These factors included:

- the daily distribution (by hour) of temperatures near the surface and at depth
  - what impact does the depth have on maximum and minimum temperatures?
  - when are the maximum and minimum temperatures reached, and how does it change for various depths?
  - what 'shape' does the temperature function take over the course of the day?
- the impact of solar radiation, independent of the air temperature
  - what is the practical difference between a warm but overcast day and a day with the same temperature but full sunlight?
  - how does shading from trees and buildings etc. impact pavement temperature and is it practical to include these factors in the modelling?
- the impact of moderate-to-heavy rainfall on temperatures at the surface
  - is the impact of rapid surface temperature decreases caused by moderate-to-heavy rainfall significant enough to factor this in for all locations, or just in locations with more regular rainfall, or ignore it completely?
- surface temperature calculations and the relationship between the actual surface temperature and the near-surface temperature (e.g. at around 50 mm)
- the effect of vehicle movements in terms of shading and/or wind draught as vehicles pass
  - can we differentiate between the shading/wind effect of trucks and light vehicles?
- the impact of the material type – different types of asphalt and other (e.g. foamed bitumen)
- the effect of climate trends on air temperatures over time
  - can the impact of increasing air temperatures over time be incorporated into our proposed model and design tools, and is there benefit in accounting for this in design for long-life pavements?
- whether specific data is readily available for use in the proposed model.

3.1.2 Proposed General Model

The proposed general form of the model is based on work by Diefenderfer et al. (2002), and is presented below in Equation 1:

$$T_{p\ max\ (at\ depth\ D)} = \alpha + \beta * (T_a \max) + \gamma * \frac{SR}{1000} + \delta * (D) \qquad 1$$

$$T_{p\ min\ (at\ depth\ D)} = \alpha + \beta * (T_a \min) + \gamma * \frac{SR}{1000} + \delta * (D)$$

where

$T_p \max$	=	daily maximum pavement temperature in °C at depth D
$T_p \min$	=	daily minimum pavement temperature in °C at depth D
$T_a \max$	=	daily maximum air temperature in °C
$T_a \min$	=	daily minimum air temperature in °C
SR	=	daily total solar exposure in kJ/m^2/day
α	=	intercept coefficient
β	=	ambient temperature coefficient
γ	=	solar radiation coefficient
δ	=	pavement depth coefficient to adjust for temperature at depth

The following input variables were used in calibration of the model, and as such these inputs are required for any analysis (all climate variables are readily available from the Bureau of Meteorology):

- daily maximum air temperature
- daily minimum air temperature
- daily total solar exposure
- four constants for calculating maximum and minimum pavement temperatures from climate data (set of four values for each of maximum and minimum calculations):
  - an intercept coefficient (α)
  - an ambient temperature coefficient (β)
  - solar radiation coefficient (γ)
  - pavement depth coefficient (δ) to adjust for temperature at depth = D metres.

The model has been built in an Excel spreadsheet, which allows for calibration and analysis of the output. A calibration process was undertaken as a part of the WARRIP research, and was repeated after a full year of data was available at the Karratha instrumented site. The calibrated data was checked against a dataset from the Northern Territory Department of Infrastructure, Planning and Logistics (DIPL), with average errors of 3.1 °C for maximum daily pavement temperatures and 2.7 °C for minimum daily pavement temperatures.

Using these maximum and minimum daily pavement temperatures, a separate linked spreadsheet is used for calculating the hourly pavement temperatures and performing CIRCLY pavement design iterations for each hour of the year.

3.1.3 Hourly Pavement Temperature Model

The daily maximum and minimum pavement temperatures calculated using the calibrated general model, along with some location data, can be used to predict the pavement temperature at any depth over the course of a day.

The hourly temperature model consists of two parts, a day model and a night model, which the model moves between based on the local sunrise and sunset times for the day of the year in question. The day function utilised a sine function to move up to the maximum daily value at any depth, while the night function calculates a proportionate drop-off in temperature from the current temperature down to the daily minimum at any depth. Both functions and the transition function to move between day and night are explained in more detail in Beecroft (2019).

The following input data is required for the hourly temperature model:

- latitude and longitude for the location
- time zone for the location, entered as the offset from Coordinated Universal Time (UTC)
- sunrise and sunset times, as determined through a US National Oceanic and Atmospheric Administration (NOAA) solar calculation spreadsheet
- layer depths for calculation (generally mid-depth of the asphalt layer of interest)
- model coefficients to produce curves and shift between day/night mode
  - two curve shift coefficients as a part of the day function
  - a depth delay coefficient to shift the time of maximum temperature based on the calculation depth
  - a time delay coefficient to delay shifting the mode between day and night based on sunrise and sunset times
  - a drop-off coefficient for proportional temperature loss at night.

The day model can be represented as in Equation 2:

$$T_{p\,(at\;depth\;D)} = \frac{(T_p\max + T_p\min)}{2} + \frac{(T_p\max - T_p\min)}{2} * \sin[x_1 * t + x_2 - (D * x_3)] \quad (2)$$

where

T_p	=	temperature at the given depth, calculated for each hour for 1 year
$T_p\max$	=	daily maximum pavement temperature in °C at depth D from Equation 1
$T_p\min$	=	daily minimum pavement temperature in °C at depth D from Equation 1
D	=	depth at which pavement temperature is required (in metres)
x_1	=	sine curve shift coefficient 1
x_2	=	sine curve shift coefficient 2
x_3	=	sine curve depth delay coefficient for depth = D

The night model can be represented as in Equation 3:

$$T_{p\,(at\ depth\ D)} = T_{p\,(t-1)} - x_4 * T_p \min \tag{3}$$

where

T_p = pavement temperature at depth = D and time = t

$T_{p\,(t-1)}$ = pavement temperature at depth = D and time = $t-1$ (i.e. 1 hour previous)

x_4 = drop-off coefficient for proportional temperature loss at night

$T_p \min$ = daily minimum pavement temperature in °C at depth D from Equation 1

The transition function can be represented as in Equation 4:

$$Day\ model\ active\ IF\text{:}\ \ t > (t_{sunrise} + x_5 * D)\ AND\ \ t < (t_{sunset} + x_5 * D) \tag{4}$$

where

t = time (hourly increments, measured in days and fractions of days)

$t_{sunrise}$ = time of sunrise at location

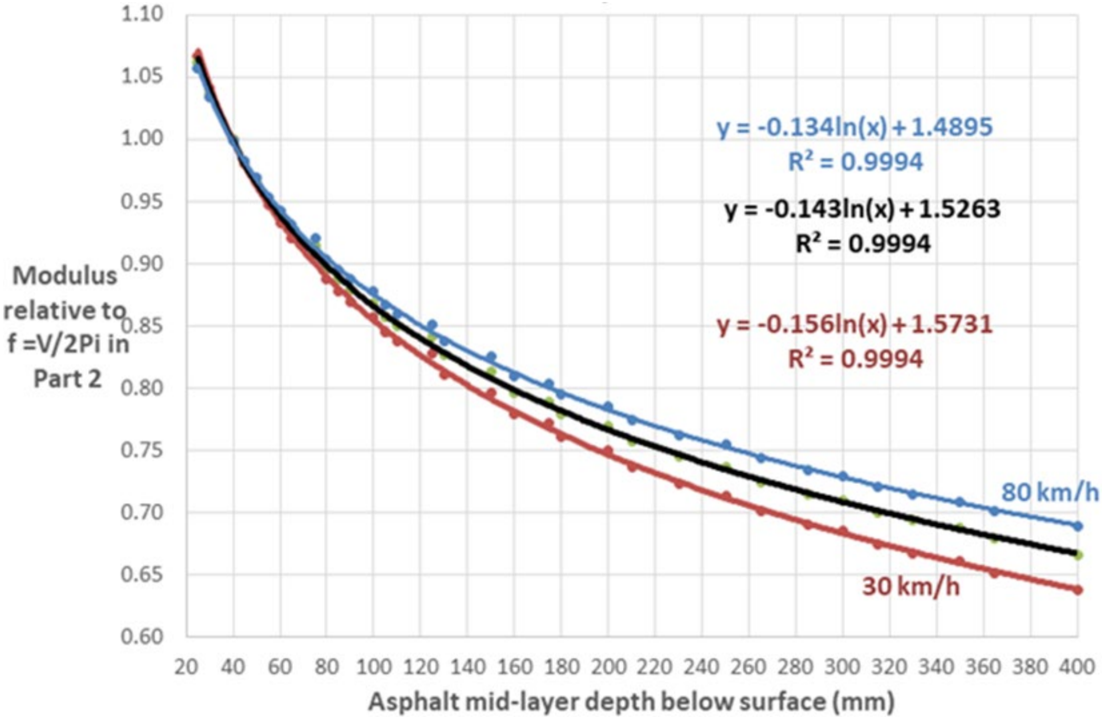
t_{sunset} = time of sunset at location

x_5 = depth delay coefficient for shifting mode between day and night

D = depth at which pavement temperature is required (in metres)

Additionally, the asphalt design moduli for the hourly model were adjusted by loading rate and depth below the surface in accordance with Figure 3.1.

Figure 3.1: Modulus adjustment by loading rate and depth below surface



Source: Adapted from Jameson and Hopman (2000).

3.2 Queensland Case Studies

In order to test the model under some realistic scenarios, a series of 'typical' full-depth asphalt pavement designs have been developed for three locations in Queensland as summarised in Table 3.1. These were run through the standard process (WMAPT with CIRCLY pavement design) and then run through the pavement temperature model and a modified hourly CIRCLY simulation. The resultant fatigue lives were then compared, both across the various seasons and over the 20–30 year design life.

3.2.1 Actual Pavement Temperatures in Queensland Locations

One component of the analysis was to assess whether actual pavement temperatures, as determined by the model, aligned with WMAPT values. As shown earlier in Table 2.4, the average pavement temperature appears to be lower than the WMAPT for thicker pavements. As shown in Table 3.1, this trend holds for the four theoretical pavement designs explored in this project. The difference is larger for the hotter locations of Brisbane and Townsville, although only one cooler Queensland location (Toowoomba) was included in this study.

Table 3.1: WMAPT compared to actual recorded values in 2018, three Queensland locations

	WMAPT (°C)	Surfacing layer (°C) (at 50 mm depth)	Base layer (°C) (at approx. 200 mm depth)
Brisbane (motorway)	32	28.9	28.2
Brisbane (arterial)	32	28.9	28.2
Townsville	37	33.4	32.6
Toowoomba	27	26.1	25.3

3.2.2 Assumptions and Calculation Process

The analysis presented in Section 3.2.3 followed several key assumptions:

- Pavement design has been prepared using the following technical documents and software:
  - using the strain based multiple-axle method in AGPT Part 2 (Austroads 2017a), together with CIRCLY 7.
  - using the standard axle method in AGPT Part 2 (Austroads 2012), together with CIRCLY 6.
  - TMR Pavement Design Supplement (TMR 2018).
- Two scenarios were provided by TMR Engineering and Technology in March 2019, with a base case design (WMAPT) and alternative case design (hourly model) calculated for each:
  - Case 1 – an urban motorway at 75 000 AADT and a 30-year design life, which is relevant to the south-east Queensland area only, with input parameters as follows:

Input	Value/details
Road description	Typical urban motorway in south-east Queensland
Pavement type	Full depth asphalt
Annual average daily traffic (AADT)	75 000
Proportion heavy vehicles	10%
Heavy vehicle yearly growth rate	3%
Pavement design period	30 years
Traffic load distribution and load parameters	Queensland presumptive (2013–16)
Pavement design traffic (Austrroads 2012)	NHVAG = 2.85, ESA/HVAG = 0.94, ESA/HV = 2.68, SAR5/ESA = 1.18, SAR7/ESA = 1.86, SAR12/ESA = 10.17
Pavement design traffic (Austroads 2017)	1.20×10^8 heavy vehicle axle groups (HVAG) 1.13×10^8 equivalent standard axles (ESA)
Reliability	95% – asphalt fatigue reliability factor 6.0
Heavy vehicle design speed	80 km/h

The pavement design has been prepared with the following input values:

	Base CASE 1
Course	Brisbane WMAPT 32 °C
Surfacing	50 mm stone mastic asphalt (SMA14) E_v (presumptive*) = 1300 MPa
Intermediate	50 mm dense graded asphalt (AC14H(A15E)) E_v (presumptive*) = 1500 MPa
Base[1]	260/295 mm dense graded asphalt (AC20H(C600)) E_v (presumptive[2]) = 3100 MPa
Prime and seal	AMC0 prime and sprayed seal (10 mm cover aggregate with C170 bitumen)
Improved layer	150 mm lightly bound (cementitious) Type 2.3 unbound granular material $E_{v(max)}$ 210 MPa (with unbound granular sub-layering)

	Base CASE 1
Course	Brisbane WMAPT 32 °C
Select fill	170 mm CBR 7% select fill $E_{v(max)}$ 70 MPa (with selected subgrade sub-layering)
Natural subgrade	CBR 3% E_v = 30 MPa

1 Presumptive moduli in accordance with TMR (2018).
2 The two thicknesses shown are for AGPT02-2017 (CIRCLY 7) and AGPT02-2012 (CIRCLY 5/6).

— Case 2 – an urban arterial road with 20 000 AADT and a 20-year design life, which is relevant to south-east Queensland, Toowoomba and north/far north Queensland, with input parameters as follows:

Input	Value/details
Road description	Typical urban arterial, various locations
Pavement type	Full depth asphalt
Annual average daily traffic (AADT)	20 000
Proportion heavy vehicles	10%
Heavy vehicle yearly growth rate	3%
Pavement design period	20 years
Traffic load distribution and load parameters	Qld presumptive (2013–16)
Pavement design traffic (Austroads 2012)	NHVAG = 2.85, ESA/HVAG = 0.94, ESA/HV = 2.68, SAR5/ESA = 1.18, SAR7/ESA = 1.86, SAR12/ESA = 10.17
Pavement design traffic (Austroads 2017)	2.79×10^7 heavy vehicle axle groups (HVAG) 2.62×10^7 equivalent standard axles (ESA)
Reliability	90% – asphalt fatigue reliability factor 3.9
Heavy vehicle design speed	50 km/h

The pavement design has been prepared with the following input values for Toowoomba, Brisbane/Gympie and Townsville/Cairns:

	Base CASE 2A	Base CASE 2B	Base CASE 2C
Course	Toowoomba WMAPT 27 °C	Brisbane/Gympie WMAPT 32 °C	Townsville/Cairns WMAPT 37 °C
Surfacing	50 mm dense graded asphalt (AC14H(A15E)) E_v (presumptive*) = 1900 MPa	50 mm dense graded asphalt (AC14H(A15E)) E_v (presumptive*) = 1300 MPa	50 mm dense graded asphalt (AC14H(A15E)) E_v (presumptive*) = 1000 MPa
Intermediate	50 mm dense graded asphalt (AC14H(A15E)) E_v (presumptive*) = 1900 MPa	50 mm dense graded asphalt (AC14H(A15E)) E_v (presumptive*) = 1300 MPa	50 mm dense graded asphalt (AC14H(A15E)) E_v (presumptive*) = 1000 MPa
Base[1]	170/190 mm dense graded asphalt (AC20H(C600)) E_v (presumptive[2]) = 3900 MPa	195/220 mm dense graded asphalt (AC20H(C600)) E_v (presumptive*) = 2600 MPa	215/245 mm dense graded asphalt (AC20H(C600)) E_v (presumptive*) = 1700 MPa
Prime and seal	AMC0 prime and sprayed seal (10 mm cover aggregate with C170 bitumen)		

	Base CASE 2A	Base CASE 2B	Base CASE 2C
Course	Toowoomba WMAPT 27 °C	Brisbane/Gympie WMAPT 32 °C	Townsville/Cairns WMAPT 37 °C
Improved layer	150 mm lightly bound (cementitious) Type 2.3 unbound granular material $E_{v(max)}$ 210 MPa (with unbound granular sub-layering)		
Select fill	170 mm CBR 7% select fill $E_{v(max)}$ 70 MPa (with selected subgrade sub-layering)		
Natural subgrade	CBR 3% E_v = 30 MPa		

1 Presumptive moduli in accordance with TMR (2018).
2 The two thicknesses shown are for AGPT02-2017 (CIRCLY 7) and AGPT02-2012 (CIRCLY 5/6).

- Asphalt design moduli in the above-mentioned base cases have been determined using the WMAPT for the selected location as listed in Austroads (2017) and the presumptive asphalt design moduli in accordance with TMR (2018).
- Assumed heavy vehicle speeds in each scenario are considered typical and appropriate for the case as described. In accordance with TMR (2018), in calculating the base case asphalt moduli, no allowance has been made for the variation in loading rate with depth in accordance with TMR (2018).
- All designs are listed with 10 mm construction tolerance as a part of the design, as is common practice in real designs.
- Alternative case designs were prepared using the model, which used CIRCLY 5 for calculations (hence may produce slightly different results to any designs using more recent versions of CIRCLY).
  - The alternative case design moduli determined using the collected temperature data were also adjusted for loading rate and depth (in accordance with Figure 3.1).
  - A minimum modulus of 1000 MPa was applied for the hourly model – without this restriction, some modulus values during very hot days were returned as being unrealistically low. The minimum modulus adopted in the model can be adjusted to any value.
- The model for the alternative case used temperature and solar radiation data from the Bureau of Meteorology for the 2018 calendar year at the Brisbane (BoM site number 040913), Toowoomba Airport (BoM site number 041529) and Townsville Aero (BoM site number 032040).
- Location data was taken from the Bureau of Meteorology weather station location, in lieu of exact project location details. This was used for the sunrise/sunset calculations.
- Base case designs were directly compared to the alternative case using the same spreadsheet but with a single design with identical parameters used for the entire year.

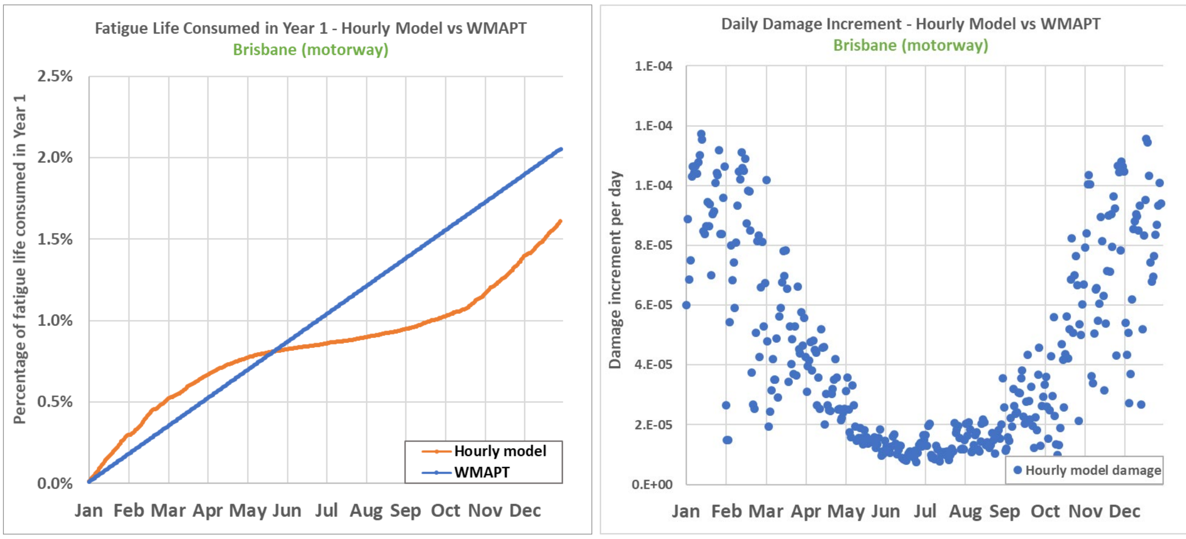
3.2.3 CIRCLY Analysis

The four cases analysed with the pavement temperature model have been run through an automated CIRCLY spreadsheet, which uses the pavement temperature taken from the hourly pavement temperature model to calculate the pavement modulus for each hour of the day for every day of a single year. The CIRCLY calculation for each hour returns a maximum strain value, which is used within the Austroads (2017) fatigue equation to calculate the allowable traffic loading. This is then used to calculate the relative damage increment incurred per ESA in that hour which is then multiplied by a sample daily traffic distribution, to output a total damage value for that day.

Under the WMAPT approach, this is relatively simple as the maximum strain and all other parameters are constant throughout the pavement life (shown as a straight line in Figure 3.2 to Figure 3.5). Under the hourly model, the current pavement temperature has a major influence on the damage incurred by each ESA, and as such, the damage in summer is proportionately much higher than in winter.

Over the course of the year, the net effect can vary. For the Brisbane high traffic motorway case, the net effect is that accelerated fatigue damage in summer was offset by slower fatigue progression in winter resulting in an accumulated fatigue damage after year one that is 21% lower than under WMAPT assumptions, as shown in Figure 3.2. This lower damage translates to a reduction in total asphalt thickness of approximately 10 mm.

Figure 3.2: Case 1: Brisbane (motorway) – WMAPT vs hourly model



In the three arterial road cases, the hourly model returns accumulated fatigue damage after year one varies. The Toowoomba arterial model (Figure 3.3) shows that the hourly model fatigue was 2% greater than for the WMAPT assumptions, where the accelerated fatigue in summer was offset by the slower fatigue progression in winter, resulting in approximately the same damage as the WMAPT model. However, in both the Brisbane and Townsville arterial cases, the fatigue damage after one year was approximately 30% and 25% lower than under WMAPT assumptions, respectively. For Brisbane and Townsville, this could mean that thick asphalt pavements are currently being overdesigned and thickness reductions could be achieved without reducing the pavement design life. The total asphalt thickness of the Brisbane and Townsville arterial cases could be reduced by approximately 15 mm and 10 mm, respectively, with the same pavement design life using the hourly model.

Figure 3.3: Case 2A: Toowoomba – WMAPT vs hourly model

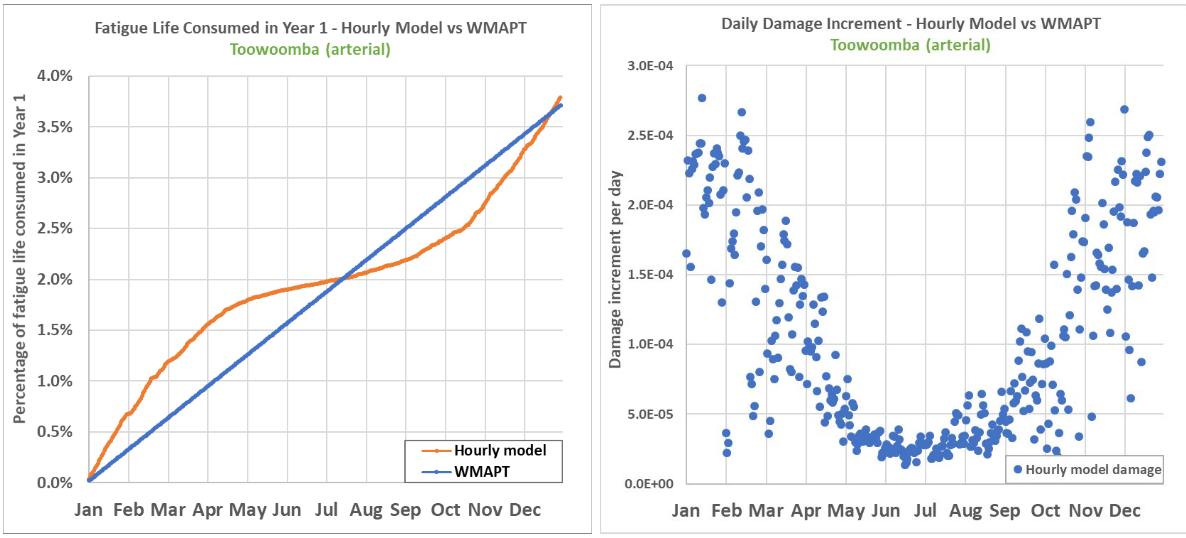


Figure 3.4: Case 2B: Brisbane/Gympie – WMAPT vs hourly model

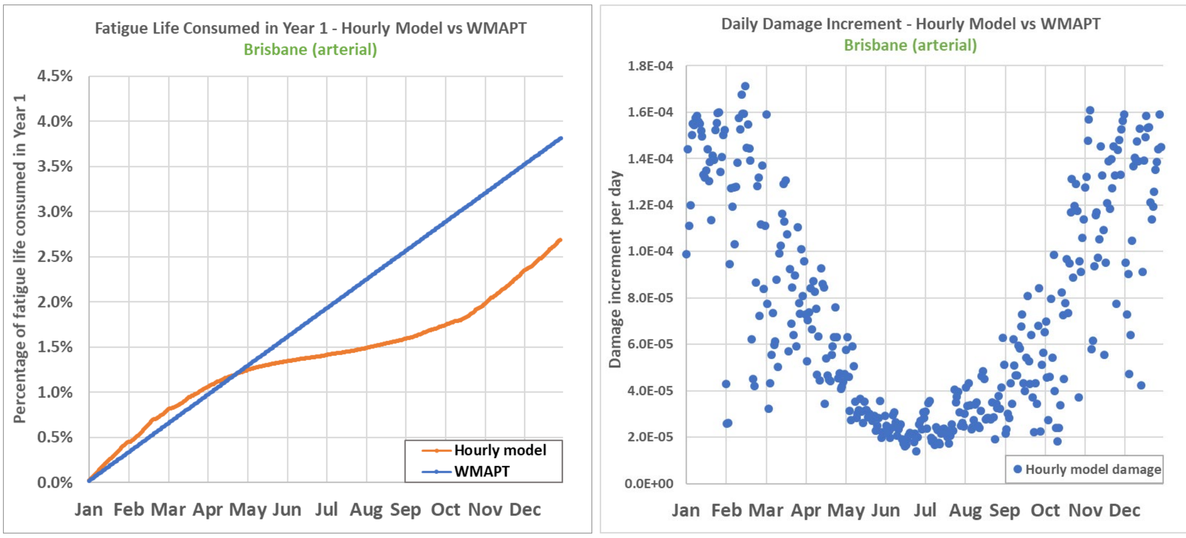
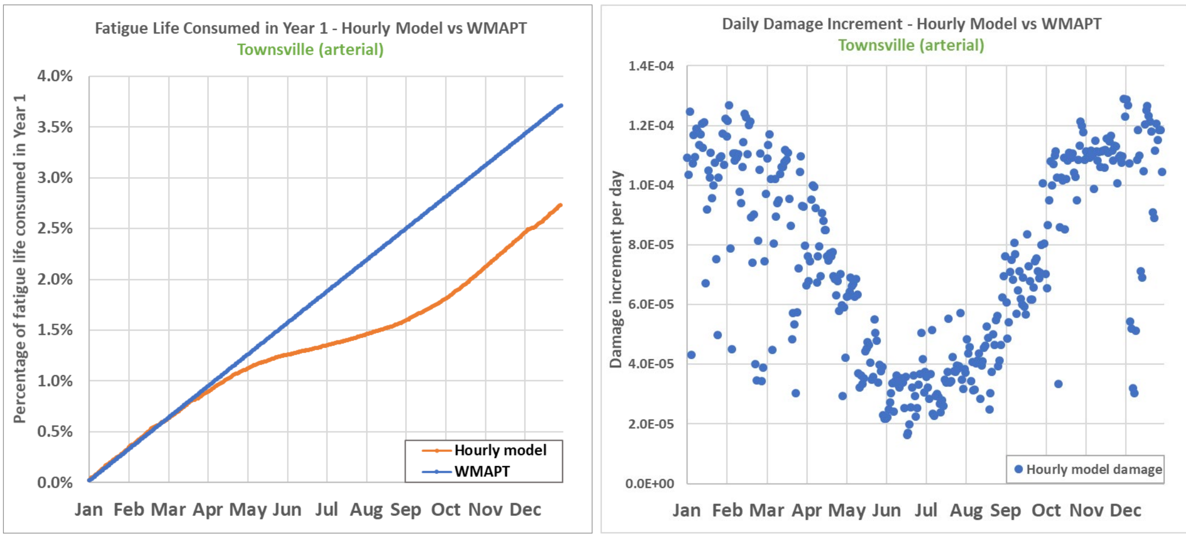


Figure 3.5: Case 2C: Townsville/Cairns – WMAPT vs hourly model



3.2.4 *Practicality of Modelling*

The process of running a full year of analysis and fatigue life prediction for a pavement takes approximately 45 minutes of processing and computation time, with 1–2 hours likely required for inputting climate information, site data and pavement characteristics. This analysis process can likely be streamlined with some relatively simple programming; however, the approach described here is considered appropriate for the purposes of this initial research work and to provide a relatively simple design tool in the interim.

4 CONCLUSIONS AND RECOMMENDATIONS

Despite the importance of temperature on the design of asphalt pavements, the temperature input used in the design of asphalt pavements is relatively simplistic. As such, it stands out as an area for continued research and refinement. There have been previous efforts to enhance this part of the asphalt pavement design process; however, it was necessary to gather real pavement temperature data from a range of representative locations.

Building upon over five years of research through Austroads, NACoE and WARRIP, and with a total of four instrumented asphalt pavements across the country, a model has now been developed to calculate location-specific temperature profiles for asphalt pavements. This can be combined with traffic data and material properties to predict the fatigue life of an asphalt pavement and can account for a wide range of factors that the WMAPT value cannot. The input data required for this model is relatively basic and easily accessible, and there is capacity to make the model more user-friendly in the future.

Observations at the instrumented site in Eagle Farm included that near-surface temperatures peaked at close to 60 °C, while the surface temperature may have been closer to 65 °C. Additionally, because of the ability for thick pavements to hold heat through the night, the pavement rarely cools below 20 °C in winter for lower layers.

This report explored some implications that may stem from this model, including how adopting an hourly pavement temperature model compared to using the WMAPT for four full-depth asphalt design scenarios. Thick asphalt pavements are being constructed with WMAPT values above 30 °C, and the case studies selected show that these pavements may be overdesigned when following the current design methodology. Further research is required to assess the impact of considering the hourly distribution of applied traffic to complete the hourly distributions in allowable traffic loadings.

The calibrated model was also used to estimate the temperature at depth in three locations in Queensland, with each location returning average pavement temperatures lower than the WMAPT values for that location – particularly for the locations with WMAPT values over 30 °C. The measured data at the Eagle Farm location was also approximately 2 °C lower than the Brisbane WMAPT of 32 °C. However, part of the reason for the WMAPT being higher is that it is a weighted mean temperature that allows for the increase in fatigue damage with temperature.

4.1 Recommendations

A series of recommendations to improve the design of asphalt pavements in Queensland, and for further research, are provided below:

1. For major projects and where very thick pavements are specified by the current method, there would be value in implementing simple modifications to the WMAPT calculation. This could include updating the WMAPT value based on local weather stations and recent climatic data, and adjusting WMAPT values for thicker pavements in line with the original research in the *Shell Pavement Design Manual*.
2. Extreme temperatures at the surface contribute to the urban heat island effect and may also reduce road user comfort (particularly for pedestrians and cyclists). This research has highlighted that these high temperatures persist for a large part of the year in Brisbane and other parts of Queensland. Further investigation into reducing surface (and layer) temperatures may contribute to improved pavement performance and would also have additional public amenity benefits.

3. The pavement temperature and loading rate model, and the linked design tools are in Excel spreadsheet format, which has the potential to be used for major projects or for locations where a high WMAPT value is pointing towards extreme asphalt thicknesses. In order to use these tools more widely, and to facilitate their use on a wider range of projects, it is necessary to develop this tool further with additional funding into making it more user-friendly and more easily customisable.
4. The pavement temperature and loading rate model developed to date assumes the applied traffic loading is the same for each hour in each 24-hour period. This model could be enhanced by allowing for the hourly distribution of truck axle loads.

REFERENCES

Austroads 2008, T*echnical basis of Austroads guide to pavement technology part 2: pavement structural design*, AP-T98-08, Austroads, Sydney.

Austroads 2012, *Guide to pavement technology part 2: pavement structural design,* AGPT02-12, Austroads, Sydney, NSW.

Austroads 2013, *Improved design procedures for asphalt pavements: pavement temperature and load frequency estimation*, AP-T248-13, Austroads, Sydney, NSW.

Austroads 2014, *High modulus high fatigue resistance asphalt (eme2) technology transfer*, AP-T283-14, Austroads, Sydney, NSW.

Austroads 2017a, *Guide to pavement technology part 2: pavement structural design*, AGPT02-17, Austroads, Sydney, NSW.

Austroads 2017b, *High modulus high fatigue resistance asphalt (EME2) technology transfer,* AP-T323-17, Austroads, Sydney, NSW.

Beecroft, A, Denneman, E & Petho, L 2015, 'Analysis of the temperature profile for an asphalt pavement over one-year in Brisbane', AAPA International Flexible Pavements Conference, 16th, AAPA, vol.

Beecroft, A 2019*, Investigation of asphalt pavement temperatures in WA*, WARRIP 2016-010, Report 2.

Commonwealth of Australia 2018a, Climate Data Online, Bureau of Meteorology, viewed 22/3/2019, <http://www.bom.gov.au/climate/data/index.shtml>.

Diefenderfer, BK, Al-Qadi, IL, Reubush, SD & Freeman, E 2002, 'Development and Validation of a Model to Predict Pavement Temperature Profile', TRB Annual Meeting, Washington DC, USA, Transportation Research Board, vol.132, no. 2, pp. 162-167.

Dickinson, EJ 1981, *Pavement temperature regimes in Australia, their effect on the performance of bituminous constructions and their relationship with average climate indicators*, report, Australian Road Research Board, Vermont South, Vic.

Jameson, GW 2013, *Technical basis of Austroads Guide to Pavement Technology Part 2: Pavement Structural Design*, report ARR 384, ARRB Group Ltd, Vermont South, Vic.

Jameson, GW & Hopman, PC 2000, ‘Development of Austroads pavement design reliability guidelines’, APRG Document 00/17, Australian Pavement Research Group, Sydney, NSW.

Jameson, GW, Sharp, KG & Vertessy, NJ 1992, *Full depth asphalt pavement fatigue under accelerated loading: the Mulgrave (Victoria) ALF trial, 1989/1991*, report ARR 224, ARRB Group Ltd, Vermont South, Vic.

Peel, MC, Finlayson, BL & McMahon TA 2007, ‘Updated world map of the Köppen-Geiger climate classification’, *Hydrology and Earth System Sciences,* vol. 11, no. 5, pp. 1633-1644.

Queensland Department of Transport and Main Roads (TMR) 2018, *Supplement to ‘part 2: pavement structural design’ of the Austroads guide to pavement technology,* Pavement Design Supplement, TMR, Brisbane, Qld.

Shell 1978, *Shell pavement design manual – asphalt pavements and overlays for road traffic* Shell International Petroleum Co Ltd, London, UK.