# Quantifying the effect of climate change on the deterioration of a flexible pavement

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Abstract: Climate change raises challenges for conventional pavement design. With climate projections, deteriorations of a pavement can be analysed using the Mechanistic-Empirical Pavement Design Guide (MEPDG), under various global warming trends. The result exhibits to what extent climate change will have an impact on deteriorations of a flexible pavement. An alternative binder for the asphalt layers was considered in the simulation to investigate if a binder upgrade can mitigate the impact of possible climate change. The pavement is found to deteriorate more quickly due to temperature increase, although not very significantly. Moreover, a binder upgrade in the pavement design proved to be a possible mitigation against the effects of climate change on the chosen pavement.

KEY WORDS: Flexible pavement, deterioration, climate change, MEPDG, alternative binder

### 1. INTRODUCTION

As an environmentally sensitive infrastructure, a flexible pavement is influenced by the environment which it is exposed to, including temperature, solar radiation, wind, precipitation, and ground water level. Environmental considerations are indispensable for pavement design and practices. Nevertheless, the deterioration of a pavement due to the environment is inevitable and sometimes significant. In conventional pavement design and analysis, the pavement environment is usually considered to change over the year around an average value that is static from year to year. The values of the average and variation are obtained from experience (i.e. local climate records). Thus a question arises: will the current design method and assumptions remain suitable for the future climate?

As an observation from the historical climate, the global average surface temperature has increased 0.74 °C since 1850. Moreover, the growth of the temperature has become faster during the past 50 years. Meanwhile, precipitation is found to have increased in the Eastern American continent, North Europe and Central Asia. In addition, extreme weather events seem to appear more often in some locales (IPCC, 2007). As the climate change is a global issue, substantial road networks can be affected. Thus even if the impact on each pavement is small, the budget to mitigate the impact of climate change on pavements may be considerable on a municipal or national scale. For instance, an Australian study estimated that the

rehabilitation budget of a road project may increase by as much as 30% as a result of climate change (Cechet, 2007). Demographic change due to climate change was considered in Cechet's (2007) study, consequently causing significant increasing in the traffic demand. Thus the budget purely from increasing temperature and other environmental factors may be less. The impact of climate change on the demographic change is excluded in this study due to uncertainties.

Many studies have been performed to investigate the impact of environmental factors on flexible pavements. Zuo et al. (2007) studied the effect of temperature and moisture on the service life of pavements based on temperature and moisture observations in pavements from Tennessee and found that the effect of the subgrade water content is normally not as critical as the effect of temperature. Similar conclusions have been reached by Byram et al. (2012) and Qiao et al. (2013) by examining the sensitivities of the MEDPG environmental factors. Given a pavement under a specific environmental condition, the impact of increasing temperature may be so significant that the impact from other factors is negligible. In this paper the state-of-the-art climate projections and pavement performance prediction are linked. A mitigation method to deal with the impact of climate change on a flexible pavement is proposed and examined.

# 2. IPCC EMISSION SCENARIOS

The global climate system is balanced with solar radiation as inputs, through absorption, and outward radiation and reflection of the rest of the energy into space. The balance may be disturbed by any interruption of these processes. As one of the reasons for climate change, it is believed that greater concentration of 'greenhouse gases' (GHG) can retain more energy in the atmosphere, thus increases the global temperature (IPCC, 2007). Human industrial activities provide abundant sources of GHG, thus the future GHG emissions and temperature increase are correlated to societal development in climate projection estimates. The projected future emission of GHG based on alternative development pathways was reported in the IPCC Special Report on Emission Scenarios (SRES) (IPCC, 2007).

The SRES includes four emission scenarios which are projected under three general societal characteristics including economic, technical and demographic conditions, respectively named as A1, A2, B1 and B2 (IPCC, 2007). Among them, the scenario A1(FI), A1(B) and B1 may be referred to elsewhere as high emissions, medium emissions and low emissions scenarios respectively (Murphy et al., 2009). Climate projections under the low, medium and high scenarios are believed to represents the likely upper and lower limits of future climate change.

#### 3. MAGICC/SCENGEN

MAGICC/SCENGEN is a tool which is used by IPCC to access the global and local projections of future climate. MAGICC/SCENGEN includes two separate tools: MAGICC (Model for the Assessment of Greenhouse-gas Induced Climate Change) and SCENGEN (SCENario GENerator). MAGICC/SCENGEN can provide projections of temperature, precipitation and the sea level change for a given location. Thus it can provide useful environmental inputs for this study. In the study reported here, MAGICC/SCENGEN version 5.3 is utilised.

MAGICC is a coupled gas-cycle/climate model and is used to predict global average temperature and sea level rise, depending on the assumed SRES emission scenarios. It has been the primary climatic model used by IPCC for assessing temperature change and sea level rise. Presumed in MAGICC as a main driving force for temperature and sea level rise, the emission of GHGs plays an important role in the projection of future climate and thus different emission scenarios were included to account for possible variations. Furthermore, a

carbon cycle model has been integrated to predict  $CO_2$  concentration in the atmosphere. Meanwhile, the stabilisation of  $CO_2$  in the atmosphere can be analysed in this model by the effect of climate feedback. If the feedback effect is ignored, overestimation of  $CO_2$  concentration, and hence an overestimated temperature, may be predicted (Wigley, 2008). Aerosol forcing, which can affect energy balance of the earth by absorbing and reflecting solar radiation and have indirect impact on the radiative forcing from other factors (e.g. clouds), is taken into consideration. In addition, climate sensitivity (3°C (Wigley, 2008)) and melting of ice sheets are considered by the model.

SCENGEN provides projections of local temperature, precipitation and pressure on a  $5^{\circ}$  (latitude) and  $5^{\circ}$  (longitude) grid (Wigley, 2008). The projections are based on an extensive database of Atmosphere/Ocean General Circulation Model (AOGCM) data. Several AOGCM models are believed to be well suited for North America according to Meyer et al. (2009), and were made use of in this study. Accordingly, the selected climatic models include:

- National Center for Atmospheric Research (NCAR CCSM3.0), USA.
- Geophysical Fluid Dynamics Laboratory (GFDL CM2.0 and CM2.1), USA.
- Institute Pierre Simon Laplace (IPSL\_CM4), France.
- Center for Climate System Research (MIROC 3.2 Medium), Japan.
- Meteorology Research Institute (MRI-CGCM 2.3.2A), Japan.
- Max Planck Institute for Meteorology (MPIECH-5), Germany.
- Hadley Centre for Climate Prediction and Research (HadCM3 and HadGEM1), United Kingdom.

In MAGICC/SCENGEN, the results from each model remain unweighted and are normalized to an average value, which is then scaled up using an independent estimation of global-mean temperature change. The same process is also applied with precipitation.

# 4. LOCATION AND ROAD STRUCTURE SELECTION

The chosen location for this study is Southern Virginia (VA), USA. This choice is made because a middle range of climate change is expected in this region, which makes the study indicative for many other regions in the U.S. (Meyer et al., 2009). Historical climate records (of approximately 10 years duration) measured from Richmond (37° 32' N 77° 25' W, VA) International Airport are used in this study to provide a climatic baseline, while noting that the suburban location of the airport may lead to an underestimation on the temperature in urban areas due to the heat island effect. The urban area, which is approximately 47 m above sea level, can be excluded from the risk of flooding due to rising of the sea level which is much lower (see Table 1). Figure 1 and 2 are the MAGICC/SCENGEN predictions for temperature and precipitation in 2050 under A1FI scenario (Wigley, 2008).



Figure 1: MAGICC/SCENGEN result on change in annual temperature.



Figure 2: MAGICC/SCENGEN result on change in annual precipitation.

Given coordinates, predictions for change in annual temperature, precipitation and the sea level rise can be provided by the programme. Those predictions are made for the chosen SRES emission scenarios A1FI, A1B and B1. The high and low emission scenarios predicted a high and low climatic change, for the year 2050. The predicted results are listed in Table 1.

Tuble 1. Childre und Seu le ver predictions for Ademinond, vir in 2000.							
Projection years and		Annual temperature	Annual precipitation	Sea level			
SRES s	cenarios	increase (°C)	increase (%)	rise (cm)			
	A1FI	2.02	5.3	16			
2050	A1B	1.72	4.5	15			
	B1	1.26	3.3	13			

Table 1: Climate and sea level predictions for Richmond, VA in 2050.

However, future temperature and precipitation will change not only in terms of their annual average values, of the form given in Table 1, but also in respect of their extremes (IPCC, 2007). The extreme events, although they may only last for a short period, may cause great damage to the pavement due to the non-linearity of deterioration relative to the value of the damaging condition. The increase in extreme events is not intentionally considered in this study due to the insufficient prediction methodology. As the damage from the increase in extreme weather events are neglected, the studied effect of climate change on the flexible pavement reflects the long-term and minimum additional pavement distresses to occur.

A typical pavement structure in the Virginia area is determined by experience from the Long Term Pavement Performance (LTPP) database (see Table 2). The asphalt mixtures for the surface course and base mix are common in Virginia (Apeagyei & Diefenderfer, 2011). SM-12.5 is a dense-graded surface mix of aggregates (with a nominal maximum aggregate size of 12.5 mm) and asphalt binder (PG grade: 70-22). The nominal maximum aggregate size in BM-25.0 is 25 mm and the PG grade for the binder is 66-24.

Lavora	Matarial	Design Binder	Thickness				
Layers	wrateriai	Grade	(mm)				
Surface course	SM-12.5D	SM-12.5D PG 70-22					
Bituminous base course	BM-25.0D	PG 64-22	63				
Bituminous base course	BM-25.0D	PG 64-22	75				
Granular Base	A-1-a	-	125				
Subbase	A-7-6	-	150				
Subgrade	A-7-6	-	-				

Table 2: A typical pavement structure in Virginia, USA.

The ground water level is assumed to be 5 feet below the pavement surface. The increase of ground water level is assumed to be in accordance with the increase in the sea level.

The local traffic volume is assumed to be 3800 AADTT (Annual Average Daily Truck Traffic), which is common on Virginia interstate routes. Traffic is considered without annual growth for two reasons. Firstly, due to the long analysis period (40 years), the traffic may be magnified to an unrealistic volume in the end even with a small traffic growth rate. Secondly, the purpose of this paper is to make a comparison of the consequences of climate change on which growth rate is not likely to have a major influence.

# 5. MODELLING CLIMATE EFFECT ON FLEXIBLE PAVEMENTS

Pavement performance modelling was performed by the MEPDG (Version 1.100). Taking advantage of its Enhanced Integrated Climatic Model (EICM), the temperature and moisture can be considered through the entire depth of the pavement. Thus change in temperature and moisture profiles in a pavement structure, as a consequence of climate change, can be assessed.

Environmental factors can have different impacts on specific pavements. Therefore, examining the sensitivities to environmental factors is necessary. Meanwhile, different pavement structures and material designs may have better resistance to any environmental factors. Even for the same pavement, the effect of climatic factors is sometimes non-linear. For instance, the permanent deformation in asphalt layers accumulates much faster under extreme high temperature than at normal temperatures. Therefore, the sensitivities of environmental factors need to be tested for the chosen pavement structure under its local climate condition. Generally, the sensitivity can be formulated as:

Sensitivity = 
$$\frac{\Delta F(t)/F(t)}{\Delta t/t}$$

Where,

F(t) = function where t is involved;

 $\Delta F$  = increment in the function;

t =parameter; and

 $\Delta t$  = increment in the parameter.

The sensitivity of the same pavement structure with the same climate condition has been tested by Qiao et al. (2013). The study was performed by increasing all the climatic factors including temperature, precipitation, wind speed, solar radiation and the ground water level by 5% and calculating the relative sensitivity according to Eq. 1. The historical climate records, with a 5% increase, provide a simple but reasonable estimation of the climate change in 2050 under a medium emissions scenario. Given that the variation in climate predictions under different emission scenarios for the chosen location is rather small (see Table 1) and the pavement does not seem to show dramatic response due to such variation, it can be assumed that the calculated sensitivities under A1B are almost identical to those under A1F and B1. It was found from the study that temperature is the most sensitive environmental factor for almost for all predicted distresses (see Figure 3).



Figure 3: Sensitivity of the MEPDG environmental factors.

Therefore it can be inferred that under high, medium and low emission scenarios, temperature is the most influential environmental factor for the analysed pavement, and that temperature has the greatest impact on longitudinal cracking, (asphalt) rutting and alligator cracking. The importance of temperature sensitivity has also been reported by Byram et al. (2012) and Zuo et al. (2007). Roughness (expressed as IRI) is found to be insensitive to temperature, which has been reported by Kim et al. (2005). Permanent deformation accumulated from unbound materials and subgrade is found to be almost unaffected by temperature changes.

The sensitivities of pavement distresses to other environmental factors are, comparatively, small and may even cancel the effect of one another. Consequently, their changes are considered to be insignificant and are neglected for the chosen pavement under the given climate condition. However, this decision may not be applicable for another pavement under another environmental change.

(Eq. 1)

It will be observed that the sensitivity of longitudinal cracking to temperature is surprisingly high, which is also observed by other researchers (Kim et al., 2005; Hoff & Lalague, 2010). However this tendency is not expected for thin asphalt pavements in a warm climate (Hoff & Lalague, 2010). This raises questions about the longitudinal cracking model in MEPDG (Hoff & Lalague, 2010) that cannot be answered here. In addition, it has been found that the layer thickness and modulus of the base has a significant influence on longitudinal cracking in the MEPDG (Graves & Mahboub, 2006; Masad & Little, 2004). Thus the sensitivity of longitudinal cracking to temperature change in another pavement structure may be significantly different.

# 6. RESULT AND CONCLUSION

Temperature records were modified to represent the expected temperature increase by 2050 under A1FI, A1B and B1 emission scenarios. With the modified climate, the performance of the chosen pavement was evaluated by the MEPDG. Therefore the results should not be considered to show the predicted pavement performance in the future but, rather, as how the pavement would deteriorate if the present climate were to become, and remain, that expected in 2050.

As a way to mitigate the temperature increase in the future, the asphalt binder used in all the asphalt layers in the structure is substituted for another binder (PG grade: 76-16), which is generally utilised for pavements in hotter regions.

The pavement performance predictions for the chosen pavement is thus analysed under four different temperature levels: Baseline (historical climate), A1FI, A1B and B1. Under A1FI scenario, which is the likely to be the upper boundary of warming in 2050, simulation is run with substituted binder to demonstrate if a binder upgrade in the pavement design can address the impact of climate change.

The pavement performance prediction results at the end of the design life (40 years) are expressed in Table 3 below:

		,			
	Baseline	+2.02 °	+1.72 °C	+1.26 °C	+2.02 °C with binder
		C			upgrade
Longitudinal	0.26	0.41	0.38	0.34	0.10
cracking (m/km)					
Alligator	4.16	4.42	4.37	4.32	3.82
cracking (%)					
Rutting (mm)	18.7	20.1	19.9	19.6	17.9

Table 3: Distress prediction by the MEPDG.

The discussed distresses include longitudinal cracking, alligator cracking and rutting (permanent deformation). The others distresses are excluded because of two reasons: 1) No distress is predicted in the chosen pavement (transverse cracking); 2) The predicted stresses exhibit negligible variation with temperature, including IRI and permanent deformation accumulated in unbound layers and subgrade.

The following conclusions can be drawn for the chosen pavement under Richmond climate:

1. An increase in temperature tends to accelerate pavement deterioration. The higher the temperature is, the worse the deterioration will become. Nevertheless, the impact seems to be rather small for the chosen road. For instance, the additional rutting over 40 years under the high emission scenario is predicted to be only 1.4 mm. However, this seemingly small increase may lead to a significant reduction in service life and earlier intervention strategies (Qiao et al., 2013). This typically occurs on pavements experiencing low stress level, which

have low rate of rutting after initial compaction by trafficking (Werkmeister, 2003). Thus, a small increase in rutting may trigger maintenance threshold considerably earlier.

2. Considering the substantial network at a national level, this increase may necessitate a significant budget increase for maintenance. Furthermore, additional road user costs (particularly fuel consumption due to higher rolling resistance) may occur as a consequence.

3. The distresses that are most influenced by temperature increase are longitudinal cracking, alligator cracking and (asphalt) rutting, while IRI and permanent deformation in unbound granular materials and subgrade are less affected. However, this is based on an overall sensitivity which is calculated using overall climate change and total distresses at the end of its design life. Thus this sensitivity may not apply for a specific season/month/day.

4. Upgrading the binder in pavement design can address the additional deterioration, even under a high warming hypothesis (A1FI). Nevertheless, the costs associated with the binder upgrade may be rather high. Even if the unit change in cost of binder is low, the total costs for upgrading a road network can be high, considering the large areas involved.

5. The accuracy and precision of the climate models (MAGICC/SCENGEN and its submodels), the EICM and pavement performance models in the utilized MEPDG should be reviewed because their reliability is crucial for this study. Also, the impact of extreme events – particularly high temperature and high solar radiation days – should be studied to increase the reliability of estimates of climate change in general and temperature in particular.

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