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1 **Evaluating the effects of climate change on road maintenance intervention**
2 **strategies and Life-Cycle Costs**

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1 **Abstract**

2 Climate change has the potential to impact long-term road pavement performance. Consequently, to
3 maintain pavements within the same ranges of serviceability as before, current pavement maintenance
4 strategies need to be re-assessed and, if necessary, changed. Changes in maintenance may lead to
5 different agency costs and user costs as a consequence. This paper commences by defining an
6 assessment procedure, showing how maintenance intervention strategies and Life-Cycle Costs (LCC)
7 may be affected by future climate. A typical Virginia flexible pavement structure and anticipated
8 climate change was used as an example. This example is believed to be representative for a great
9 number of localities in the United States. A method using historical climatic data and climate change
10 projections to predict pavement performance using Mechanistic-Empirical Pavement Design Guide
11 (MEPDG) under current or future climate was introduced. Based on pavement performance prediction,
12 maintenance interventions were planned and optimized. The maintenance effects of three treatments
13 (thin overlay, thin overlay with an intermediate layer, and mill & fill) were considered. A Life-Cycle
14 Cost analysis is reported that used binary non-linear programming to minimize the costs (either
15 agency costs or total costs) by optimizing intervention strategies in terms of type and application time.
16 By these means, the differences in maintenance planning and LCC under current and future climate
17 can be derived. It was found, that for this simplified case study, pavement maintenance and LCC may
18 be affected by climate change. Optimized maintenance may improve resilience to climate change in
19 terms of intervention strategy and LCC, compared to responsive maintenance.

20 **Keywords:** Flexible pavement; performance modelling; maintenance effect; maintenance optimization;
21 Life-cycle cost; climate change

22

1. INTRODUCTION

Global average surface temperature has increased 1.3 °F (0.74 °C) since 1850. Moreover, the warming rate has been increasing, with global average surface temperature increasing in the last 50 years twice as fast as in the last 100 years (IPCC, 2007). This presents many challenges for conventional infrastructures, which are usually designed and managed on the basis of historical climate data. Thus there is a need to rethink the design of infrastructures for future climate (Austroads, 2004; Meyer, 2006; TRB, 2008; Willway et al., 2008).

Assuming that local changes mirror global changes, researchers found by pavement performance modelling that rutting of flexible pavements may be aggravated by climate change, due to temperature increasing or seasonal hot/cold extreme temperatures (Qiao et al., 2013b; Tighe et al., 2008). Pavement cracking may be affected by climate change, including longitudinal and fatigue cracking (Kim et al., 2005). Pavement roughness was found to be affected by climate change (Graves and Mahboub, 2006), although the impact may sometimes be negligible (Kim et al., 2005; Qiao et al., 2013b).

If pavement performance will be affected by climate change, it is important to know how pavement maintenance and Life-Cycle Costs (LCC) may change as a consequence. Australian researchers (Austroads, 2004) estimated that a small budget decrease between 0 to -3% would be necessary to maintain the same level of performance based solely on climate factors because a predicted generally drier climate leads to a slower pavement deterioration rate nationally (Cechet, 2007). However, this budget reduction may not be applicable elsewhere with different climate conditions. This paper proposes a method for assessing the necessary changes to pavement maintenance procedure(s) and the LCC consequent of climate change and to illustrate this with a case study.

2. METHODOLOGY AND ASSUMPTIONS

A methodological framework to compute the LCC for a particular pavement & climate is presented in Figure 1. This section of the paper considers each part of the methodology (each box in Figure 1) in turn. By using this framework twice, once with historic climate and current optimized maintenance interventions and once with an anticipated climate, the effects of climate change may be assessed and maintenance can be adjusted in the second use to minimize the LCC.

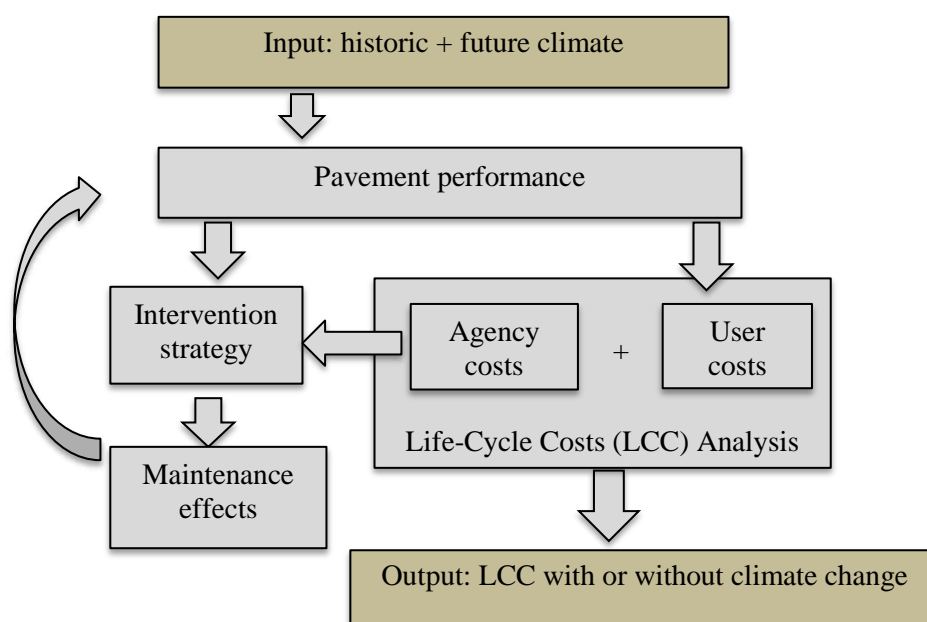


FIGURE 1 Methodological sequence.

1 The impact of climate change on flexible pavements can be direct and indirect (Austroads,
2 2004). Direct impacts are due to environmental effects e.g. temperature, precipitation, solar radiation,
3 wind speed and groundwater level. Indirect impacts refer to changes in traffic loading caused by
4 demographic changes due to climate change (Koetse and Rietveld, 2009). Due to the significant
5 uncertainties in likely demographic changes, the indirect impact of climate change is excluded in this
6 study. When traffic demand prediction is available, the methodology of this study should be updated
7 by integrating this indirect impact.

8 Pavement maintenance intervention strategies can be classified into several categories
9 according to the frequency of maintenance, maintenance intensity, costs, and time for maintenance. In
10 this paper, the mentioned maintenance treatments are categorized as follows:

- 11 • Crack sealing and filling: routine maintenance.
- 12 • Chip seal, slurry seal, microsurfacing, and thin overlays: preventive maintenance.
- 13 • Thin overlay with intermediate layer, and mill & fill (inlays): corrective maintenance.

14 Routine maintenance is applied periodically and is less determined by pavement performance,
15 compared to preventive and corrective maintenance. Preventive maintenance is most cost-beneficially
16 applied before a pavement starts to exhibit visible deterioration (Hicks et al., 2000) and is usually
17 used to improve the functional condition of the road without substantial improvement in structural
18 capacity. It has also been observed that some preventive maintenance will deliver reduction in
19 pavement roughness and rutting (ISOHDM, 1995; Odoki and Kerali, 1999). Corrective maintenance
20 is planned according to the pavement performance level. For instance, many road authorities initiate a
21 certain intervention when a performance threshold is triggered. Triggers may occur when one of the
22 pavement performance indices reaches a critical level or when a combination of conditions is reached.
23 Early application of corrective maintenance can often be applied to achieve greater cost-benefit,
24 becoming, in effect, a form of preventive maintenance. Major corrective maintenance removes the
25 pavement surface distress, and has the greatest maintenance effect. Pavement performance prediction
26 aids decision making concerning the time and type of preventive maintenance or early corrective
27 maintenance.

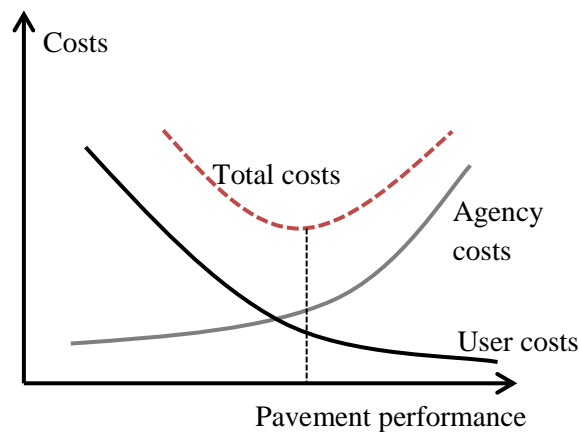
28 The effects of maintenance may include two parts in general, which are:

- 29 (1) Immediate improvement of pavement performance level after the treatment; and
- 30 (2) Reduction in the future deterioration rates.

31 Many studies concern the former, including the maintenance effects models used in HDM-4
32 (ISOHDM, 1995). However, there is little quantitative study on the latter part, in terms of modelling
33 methods. Therefore, it is assumed that interventions will not reduce deterioration rates, but have an
34 immediate improvement on pavement performance level. In the future, it is necessary for the latter
35 part to be included for a better understanding of maintenance effects and for beneficial pavement
36 management.

37 Generally, major corrective maintenance costs more than preventive maintenance, and routine
38 maintenance usually costs much less. Road agencies aim to select maintenance interventions with the
39 best cost-benefit although their ability to achieve this may be limited by yearly budget constraints.
40 Life-Cycle Cost Analysis (LCCA) is used to help to find the most cost-effective maintenance
41 strategies. Commonly, the LCC of a pavement incorporates discounted long-term agency costs, the
42 road user costs, and the environmental costs (Huang, 2004). Agency costs are costs incurred directly
43 by the agency over the life time of a pavement, such as the construction costs and maintenance costs
44 (Huang, 2004). Road user costs usually consist of Vehicle Operating Costs (VOC), delay costs and
45 accident costs (Daniels et al., 1999). Environmental costs are incurred by the emission of
46 environmental hazards, for instance air pollutants and noise. It is usually difficult to quantify the
47 environmental costs, although the impact to environment and human health may be significant.

1 Road roughness has been found to have a significant impact on fuel economy (Zaniewski,
 2 1989). Furthermore, road accident costs are believed to be affected by road surface condition,
 3 including skid resistance (Parry and Viner, 2005) and roughness (Cenek and Davies, 2004). In
 4 practice, road user costs are commonly associated with roughness as measured by the International
 5 Roughness Index (IRI) (Chatti and Zabaar, 2012; Paterson, 1985). As road user costs increase as the
 6 pavement is rougher, road agencies need to invest more on maintenance to make the pavement
 7 smoother. Therefore, the most appropriate intervention strategies can be found when the total costs
 8 are minimum (see Figure 2) and this will be achieved by an optimal (cost-based) mix of routine,
 9 preventive and corrective maintenance.



10
 11 **FIGURE 2 Road life cycle costs.**

12 As the aim of this paper is to compare the additional costs or changes to maintenance practice
 13 caused by climate change, the LCC components that are not relevant or sensitive to the climate can be
 14 neglected, because LCCA needs only to consider differential costs between alternatives (Huang,
 15 2004).

16 **2.1. Case study location and road section**

17 A typical flexible pavement from Southern Virginia (USA) is used to illustrate the methodology. The
 18 pavement was created by experience from the Long Term Pavement Performance (LTPP) database.
 19 The road consists of two lanes each approximately 11.5 feet, assumed to be 60 miles long for
 20 calculation of the LCC. The traffic is assumed to be 38000 Annual Average Daily Traffic (AADT),
 21 which is common on Virginia Interstate routes according to the LTPP database. The percentage of
 22 trucks is 10%. Traffic growth rate is assumed to be 0 % to exclude the effects of change in traffic
 23 demand, so that the effects of climate change can be isolated. The groundwater level is assumed to be
 24 approximately 4.5 feet below ground surface, which is a common water level judging from recorded
 25 groundwater levels (USGS, 2012). The structure and material of the pavement can be found in Table 1.
 26 SM-12.5 is a dense-graded surface mix of asphalt (PG 70-22) and aggregates (maximum size 0.5
 27 inch). BM-25.0 consists of aggregates with a maximum size of 1 inch and asphalt (PG 64-22)
 28 (Apeageyi and Diefenderfer, 2011). Granular materials are standard to AASHTO and Unified Soil
 29 Classification definitions (AASHTO, 2009). A-1-a is a granular material with a typical resilient
 30 modulus of 40,000 psi at optimum moisture content. A-7-6 is a silt-clay material with a typical
 31 resilient modulus between 5,000 and 13,500 psi.

32 **TABLE 1 Layer Information of the Studied Pavement (Qiao et al., 2013a)**

Layers	Material	Design Binder Grade	Thickness (in)
Surface course	SM-12.5D	PG 70-22	2
Bituminous base course	BM-25.0D	PG 64-22	2.5
Bituminous base course	BM-25.0D	PG 64-22	3

Granular Base	A-1-a	-	5
Sub-base	A-7-6	-	6
Subgrade	A-7-6	-	-

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The reason why a pavement in Virginia is chosen is because:

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- Southern Virginia is in the southeast climatic region of USA, which was found to have a middle range climate change and, therefore, may be broadly representative of the average case nationally (Meyer et al., 2009).

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- The grade of asphalt binder PG 64-22 is widely used and covers a great number of pavements in mid-southern USA (see Figure 3).

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- The frequent and detailed pavement management system (PMS) data from Virginia Department of Transportation (VDOT) makes it possible to validate the maintenance effects of various intervention strategies, which is one of the key elements for decision-making.

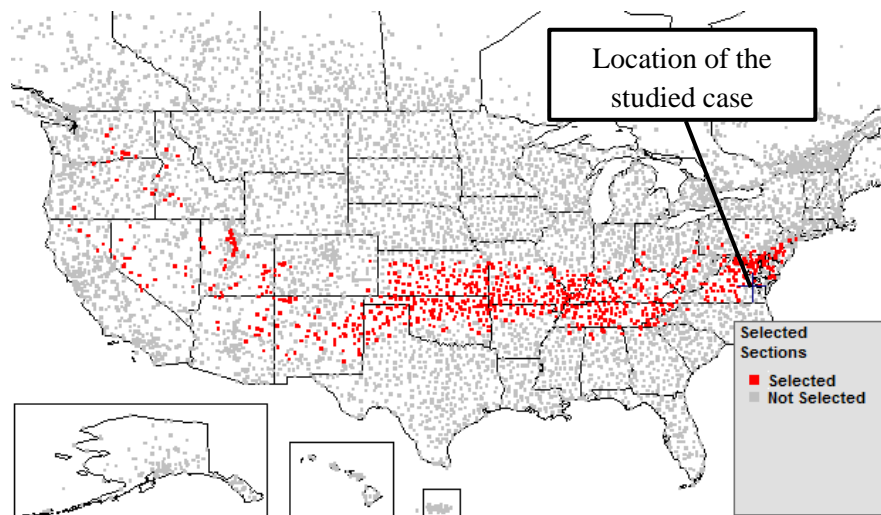
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- It has been estimated from previous study that the case study pavement service life may be significantly reduced (if maintenance does not adapt) due to climate change (Qiao et al., 2013b), thus it provides an effective site for assessing pavement maintenance and LCC as a consequence of climate change.



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FIGURE 3 Flexible pavements recorded with binder PG 70-22 and PG 64-22 were shown by the red dots (with 98% reliability, LTPPBIND, version 3.1 Beta, (FHWA, 2009)).

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2.2. Pavement performance under climate change

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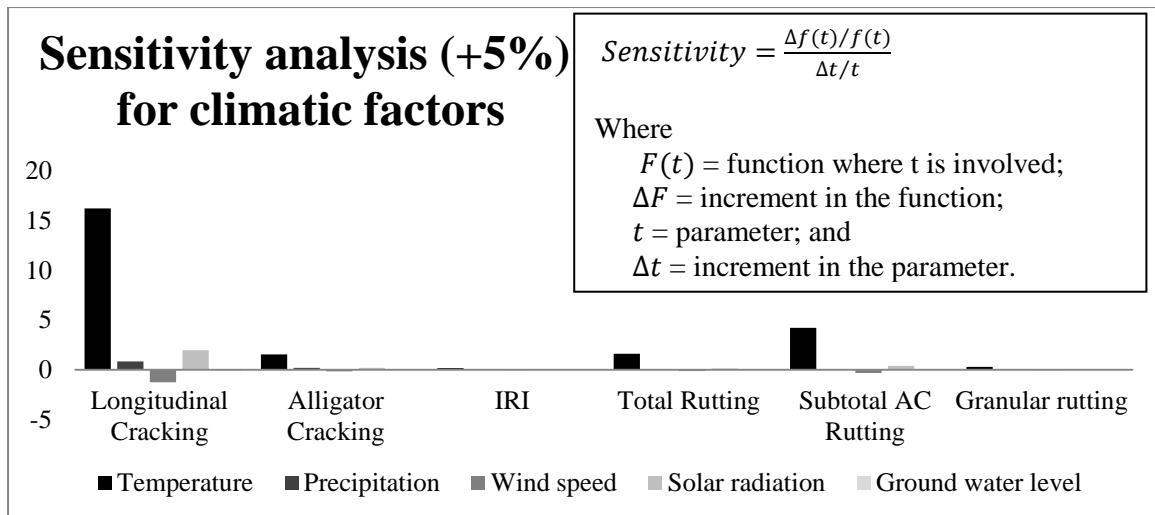
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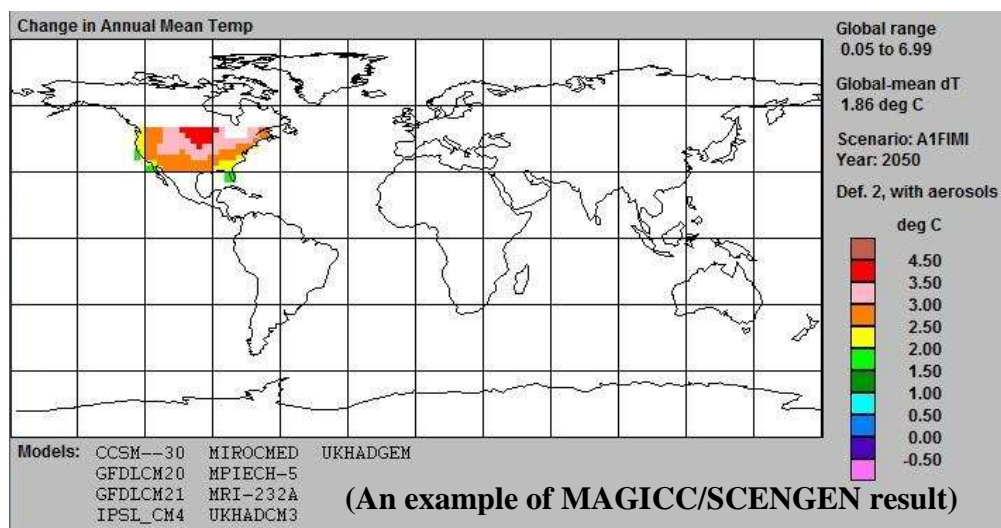
The impact of climate change on the performance of this pavement has been evaluated in previous research (Qiao et al., 2013a). The Mechanistic-Empirical Pavement Design Guide (MEPDG, version 1.1) was used to model pavement performance because its sub-model, the Enhanced Integrated Climatic Model (EICM) is capable of taking consideration of climate factors. The sensitivity (+5%) of climatic factors including temperature, precipitation, solar radiation, wind speed, and groundwater level to pavement performance was examined (Qiao et al., 2013a). It was estimated that the performance of the studied road in Virginia, is most sensitive to temperature and the impact of the other factors is negligible (see Figure 4).



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FIGURE 4 Sensitivity analysis (Qiao et al., 2013a).

The temperature projections were investigated with MAGICC/SCENGEN, a climate change projection tool used by the Intergovernmental Panel on Climate Change (IPCC, 2007). MAGICC/SCENGEN can predict future local temperature on a 5° grid (See Figure 5). The future emissions of greenhouse gases were estimated using three emission scenarios, A1FI (high emission), A1B (medium emission), and B1 (low emission). The A1FI and B1 scenarios provided an upper/lower estimates between which the future greenhouse gas emissions are likely to fall. Thus the projected temperature under A1FI and B1 can represent future upper and lower temperature boundaries. The future temperature projections for 2050 under three scenarios are presented in Figure 5.



Projection year and emission scenarios	Increase of Annual Average Temperature Increase 2000s – 2050s (°F)
2050 A1FI	3.64
2050 A1B	3.10
2050 B1	2.27

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FIGURE 5 Temperature Projections for 2050 and an example of MAGICC/SCENGEN result.

1 Ten years of recent historical temperature records were used to represent the current climate.
 2 The records were then modified by climate projections to represent the possible climate in 2050 by
 3 adding the predicted increase in temperature to the hourly temperature records. As a consequence of
 4 the modification, the average temperature was increased, with more hot hours but fewer cold hours.
 5 Under current and future climate, pavement performance indicators including longitudinal cracking,
 6 transverse cracking, fatigue cracking, IRI and rutting were evaluated over the service life of the
 7 pavement (40 years). It was estimated that the development of longitudinal and fatigue cracking
 8 would develop faster under future climate, although the cumulative amounts were considerably lower
 9 than maintenance thresholds, so the data were not presented here. IRI was estimated to increase with
 10 temperature; however the increase was not significant (as will be show later in Figure 7a). Permanent
 11 deformation in unbound granular materials and subgrade did not show any impact from temperature
 12 increase. The total rutting increased as temperature increased (see later in Figure 7b), because the drop
 13 in viscosity of the asphalt binder at higher temperatures allows greater permanent deformation.

14 Pavement service life, defined by the time until the maintenance threshold of performance
 15 indices are triggered, may be significantly affected by the temperature increase. For instance, if the
 16 threshold for rutting is 0.75 inch, the service life calculated by rutting under AIFI reduces
 17 approximately 6 years compared to the baseline (see later in Figure 7b). Therefore, it is interesting to
 18 assess if climate may have an impact on the pavement maintenance and the LCC as a consequence.

19 **2.3. Maintenance effects modelling**

20 Maintenance effects including crack sealing, single/double surface treatment, slurry seal, and
 21 cape seal can be modelled in a linear form (Djarf, 1995; ISOHDM, 1995; NDLI, 1991) as adopted in
 22 this study (Equation 1, 2). The relationships may, thus, be formulated as:

$$23 \quad \Delta IRI = a * IRI_0 + b \quad (1)$$

24 Where,

25 ΔIRI = reduction in roughness due to maintenance

26 Subscript "0" indicates original condition before maintenance

27 a, b = model coefficients

28 The maintenance effect on rutting was modelled using the same approach:

$$29 \quad \Delta Rut = c * Rut_0 + d \quad (2)$$

30 Where,

31 ΔRut = reduction in rutting due to maintenance

32 c, d = model coefficients

33 The models were calibrated with in-situ measurements of IRI and rutting from three districts
 34 in Virginia (Bristol, Salem and Richmond) where intensive maintenance works have been performed.
 35 The data was provided by VDOT and included records of pavement construction and performance
 36 data over several years. The pavement performance indices in and after the year of intervention within
 37 or matching the intervention section were used to compute the change in pavement performance
 38 indices as a result of interventions. Although various different types of maintenance treatment
 39 including slurry seal, chip seal, microsurfacing, overlays, and mill and fill (M&F) can be found in the
 40 investigated data, only three treatment types have sufficient data for the validation. These treatments
 41 are as follows:

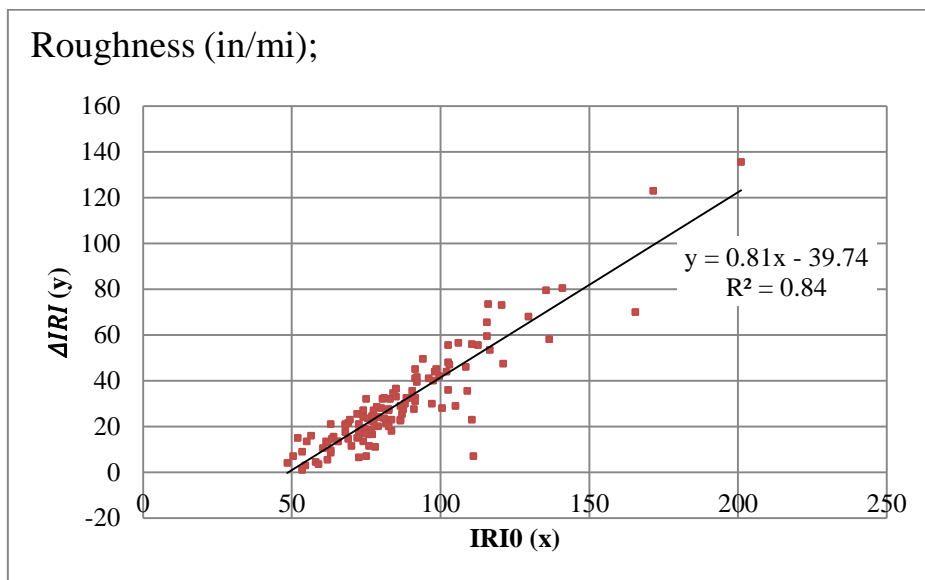
42 Op 1) Thin overlay with SM12.5D or SM12.5E, thickness 1.5 or 2 inch;

43 Op 2) The same thin overlay with a 2 inch intermediate layer (IM) BM25; and

44 Op 3) Mill of 2 or 4 inch and fill with SM12.5E (Diefenderfer, 2008).

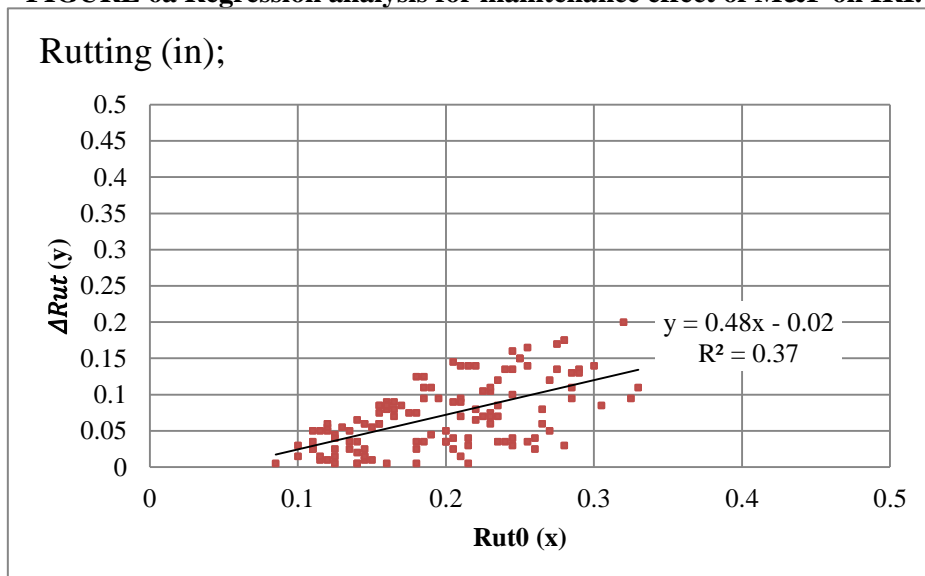
1 As no further detail was provided concerning month and day of specific intervention
 2 operations and measurements, it may be a problem that some interventions were made, prior to
 3 condition measurements of the first year instead of after it. In this case, the differences between the
 4 first and second year measurements exclude the effects of interventions and can only indicate the
 5 deterioration occurred during the period between the two measurements. Without maintenance,
 6 pavement performance becomes worse with time. For instance, IRI measured in year n (IRI_n) should
 7 be less than that in year n+1 (IRI_{n+1}), i.e. $\Delta IRI = IRI_n - IRI_{n+1} < 0$. Therefore, the selected data
 8 with negative ΔIRI and ΔRut were excluded from the analysis to address this problem.

9 Ideally, the pavement performance would be measured just before and after the interventions
 10 so that the immediate effect can be derived. In practice, this is not the case and the difference in
 11 measurements before and after interventions, may include the maintenance effect and about one year
 12 of subsequent deterioration. In this way, the maintenance effects may be underestimated because the
 13 deterioration is likely to reduce the differences in pavement performance. In the studied case, the
 14 mean and standard deviation of ΔIRI is (29.1 in/mi, 17 in/mi), based on the maintenance effects of
 15 overlays and mill and fill of 281 records. Compared to the predicted annual IRI development in the
 16 studied pavement (at maximum 3.7 in/mi/year), the underestimation, was not considered to be
 17 significant.



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19 **FIGURE 6a Regression analysis for maintenance effect of M&F on IRI.**



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1 **FIGURE 6b Regression analysis for maintenance effects of M&F on rutting.**

2 There were in total 281 sets of data selected that included intervention types and differences
 3 in performance indices before and after the intervention. In particular, a point with an original IRI
 4 ($IRI_0 = 319.5$ in/mi), $\Delta IRI = 272$ in/mi) was removed because it was an outlier and had a greater
 5 impact on the linear regression according to its Cook's distance ($D > 1$) as a common practice
 6 (William and Terry, 2011).

7 The linear approach showed a moderate to very strong correlation between modelled and
 8 measured IRI reduction and a moderate correlation between modelled and measured rutting reduction
 9 (see Figure 6a & 6b; Table 2).

10 **TABLE 2 Maintenance effects validation and maintenance costs**

Maintenance effects on	1) Thin overlay	2) Overlay + IM	3) M&F
IRI (in/mi) :	ΔIRI $= 0.81 \times IRI_0$ $- 39.7$	$\Delta IRI = 0.33 \times IRI_0$ $+ 6.03$	$\Delta IRI = 0.81 \times IRI_0$ $- 39.7$
R^2	0.59	0.28	0.84
Permanent Deformation (in):	ΔRut $= 0.60 \times IRI_0$ $- 0.04$	ΔRut $= 0.59 \times IRI_0 - 0.01$	ΔRut $= 0.48 \times IRI_0 - 0.02$
R^2	0.38	0.47	0.37
Costs (\$/square yard) (28)	5.0	6.0	8.0

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 12 Thus M&F showed a far more consistent effect on reducing roughness whereas overlaying
 13 with a 3 inch intermediate layer had a very unreliable effect. None of the treatments provided a very
 14 reliable decrease in rutting.

15 **2.4. LCC calculation**

16 The LCCA approach was used in this study to find economical intervention combinations over the
 17 pavement's life cycle. The LCCs were compared under different maintenance frequencies and climate
 18 scenarios, only considering the costs that differ among alternatives.

19 **2.4.1. Agency costs**

20 The maintenance costs were selected to represent the agency costs. Construction costs under different
 21 climate scenarios were considered to be the same. Estimated costs of the three treatments are listed in
 22 Table 2. The costs were dependent on features such as location, project size, surface preparation, the
 23 degree of traffic control, and material costs variations (Peshkin et al., 2011). Thus to account for
 24 uncertainties in the agency costs, the maintenance costs were weighted by a weighting factor (WF) in
 25 the LCCA optimization. Once again, because the objective is to compare costs, before and after
 26 climate change, the accuracy of the unit price of treatments is not expected to be important.

27 **2.4.2. User costs**

28 User costs usually consist of VOC, delay costs, and accident costs (Huang, 2004). VOC is correlated
 29 to the pavement condition, thus may change on roads under different climate change scenarios. As
 30 VOC can account for a great portion of the user costs, it was considered in this study. Conventional
 31 VOC models relate VOC to road roughness by a linear regression model as follows (NCHRP, 1985):

32
$$\text{Passenger car VOC} = 120.7 + 18.65 \times IRI \quad (3)$$

$$1 \quad \textit{Articulated vehicle VOC} = 933.2 + 135.88 \times \textit{IRI} \quad (4)$$

2 \textit{VOC} = vehicle operating costs (USD/1000 km; 1000 km = 621 miles)

3 \textit{IRI} = international roughness (m/km; 1 m/km = 63.36 in/mi)

4 As \textit{VOC} is a combination of different cost components which are affected by traffic, vehicle
5 conditions and road conditions, the coefficients of the model will, therefore, vary from place to place.
6 However, in the LCC comparison, the difference between alternatives is more important than the
7 absolute value, thus the default value was adopted.

8 In this initial study neither delay nor accident costs are included. If the post-climate change
9 maintenance regime keeps pavement condition similar to the current value, then the omission of
10 accident costs, even though they are a function of a pavement condition, should be cost-neutral, when
11 comparing maintenance intervention “before” and “after” climate change. User delay costs are also
12 ignored in this study (because of the difficulty in modelling the effect) and this omission may be less
13 valid if more frequent intervention, that causes congestion, is needed.

14 **2.4.3. NPV calculation**

15 All future costs including agency costs and user costs were discounted to the current year to generate
16 a Net Present Value (NPV). The discount rate, typically between 3-5%, was chosen to be 4%. This
17 value has been used in the previous research as a typical discount rate for a road LCCA project in
18 Virginia (VDOT, 2002).

19 **3. OPTIMIZATION PROCESS**

20 With the LCCA models, the most cost-effective intervention combinations can be found using a
21 binary non-linear programming method. The optimization was made using the Evolutionary Solving
22 method by solver function in Microsoft Excel, which uses a generalized reduced gradient method for
23 non-smooth optimization. The result of the optimization, perhaps not the global optimal solution, is
24 improved based on an initial solution. Thus by defining the same initial solution for pavement
25 performance under different climate change scenarios, the local optimal maintenance interventions
26 can be derived and compared. The aim of the optimization is to minimize either:

27 1) Agency LCC (\times MF), or;

28 2) Total LCC (i.e. user costs + MF \times agency costs).

29 When the agency costs were at minimum, the pavement was maintained with minimum effort
30 and the treatment(s) would be applied as late as possible. By minimizing the total costs, the most
31 economic combination of treatments will be revealed. Thus the target of the optimization was to
32 minimize costs by optimizing parameters:

$$33 \quad X = X_1, X_2, X_3, \dots X_n; (X_n = 0 \textit{ or } 1) \quad (5)$$

$$34 \quad Y = Y_1, Y_2, Y_3, \dots Y_n; (Y_n = 0 \textit{ or } 1) \quad (6)$$

$$35 \quad Z = Z_1, Z_2, Z_3, \dots Z_n; (Z_n = 0 \textit{ or } 1) \quad (7)$$

36 ...

37 Where,

38 n = number of years of analysis

39 X, Y, Z, \dots = different intervention types

1 Pavement IRI and rutting, as originally predicted by MEPDG, can be affected by maintenance
 2 effects. If any of the three interventions is planned, immediate maintenance effects (see Table 2) are
 3 applied to the original predictions. The treated pavement performance IRI and rutting at year t can be
 4 expressed as $Rut(t, X, Y, Z, \dots)$ and $IRI(t, X, Y, Z, \dots)$. As a boundary for the rutting and IRI, the
 5 optimization shall be limited by:

$$6 \quad Rut_{min} \leq Rut(t, X, Y, Z, \dots) \leq Rut_{max} \quad (8)$$

$$7 \quad IRI_{min} \leq IRI(t, X, Y, Z, \dots) \leq IRI_{max} \quad (9)$$

8 The maximum is used to represent the maintenance thresholds and minimum is to constrain
 9 the indices within an overall performance standard in the investigated regions.

10 4. RESULTS AND DISCUSSIONS

11 The pavement performance for 40 years under high/medium/low greenhouse gas emission scenarios
 12 and the baseline (BL) was evaluated by the LCCA for three alternatives:

- 13 • Alternative 0: no maintenance performed on the pavement;
- 14 • Alternative 1: minimum (responsive) maintenance (minimized agency costs, treatment
 15 applied when IRI or rutting threshold is reached); and
- 16 • Alternative 2: frequent maintenance (minimized LCC).

17 With the dashed lines indicating maintenance thresholds (IRI: 175 in/mi; Rutting: 0.75 in), the
 18 IRI and rutting curves for all alternatives are presented as follows:

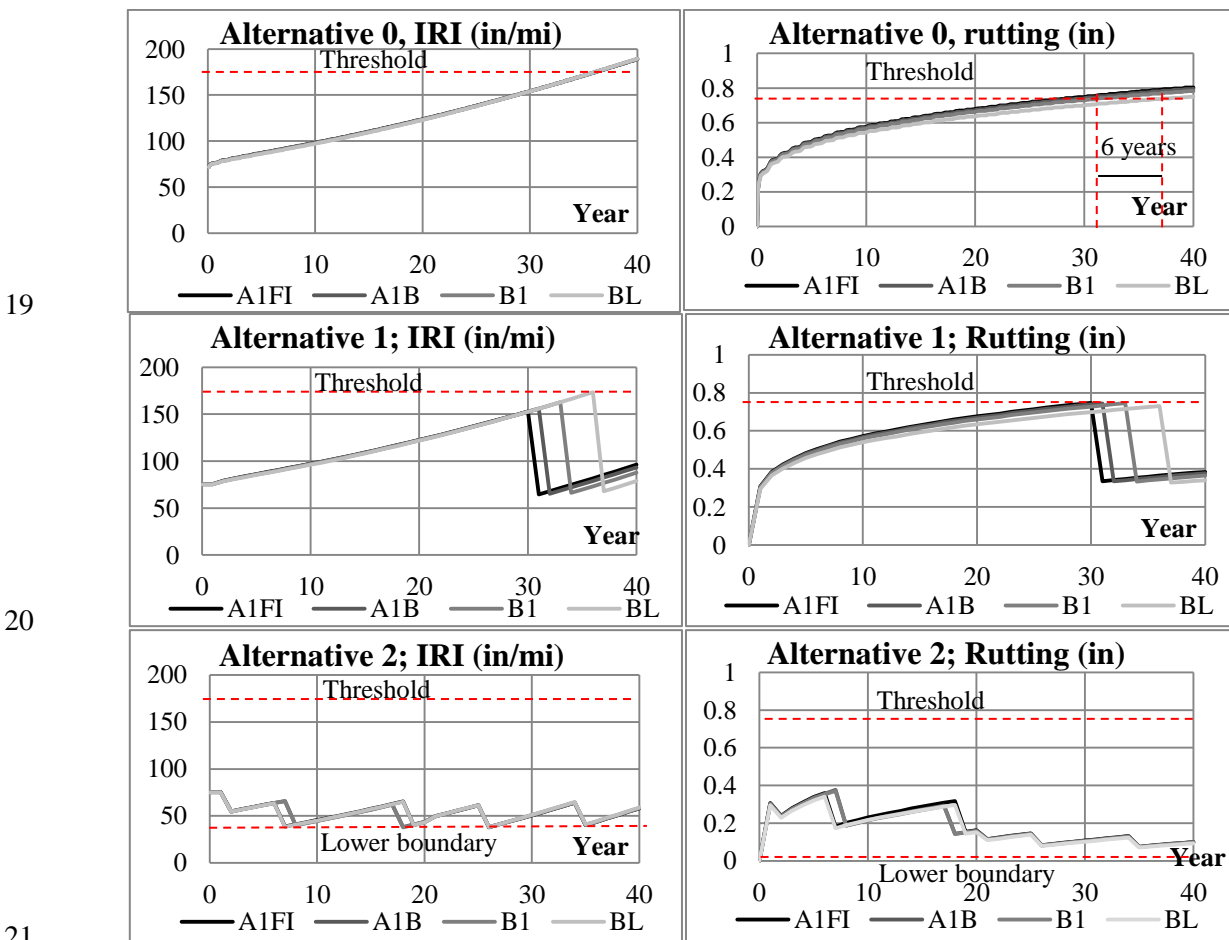


FIGURE 7 (a, b, c, d, e, and f) IRI and rutting under all alternatives. (BL = baseline)

The type of interventions and their application time under Alternative 1 and 2 can be found in TABLE 3.

TABLE 3 Intervention application years

		A1FI	A1B	B1	BL
Alternative 1	Thin overlay	31	32	34	37
	Overlay + IM	no	no	no	no
	M&F	no	no	no	no
Alternative 2	Thin overlay	2, 21	2, 21	2, 21	2, 21
	Overlay + IM	7, 19, 26, 35	8, 18, 26, 35	8, 18, 26, 35	7, 19, 26, 35
	M&F	no	no	no	no

It can be observed that M&F was not selected in both alternatives. This indicated that M&F is a less cost-efficient intervention compared to a thin overlay or an overlay with an intermediate layer, under the described constraints.

The result of the LCCA can be found in Figure 8.

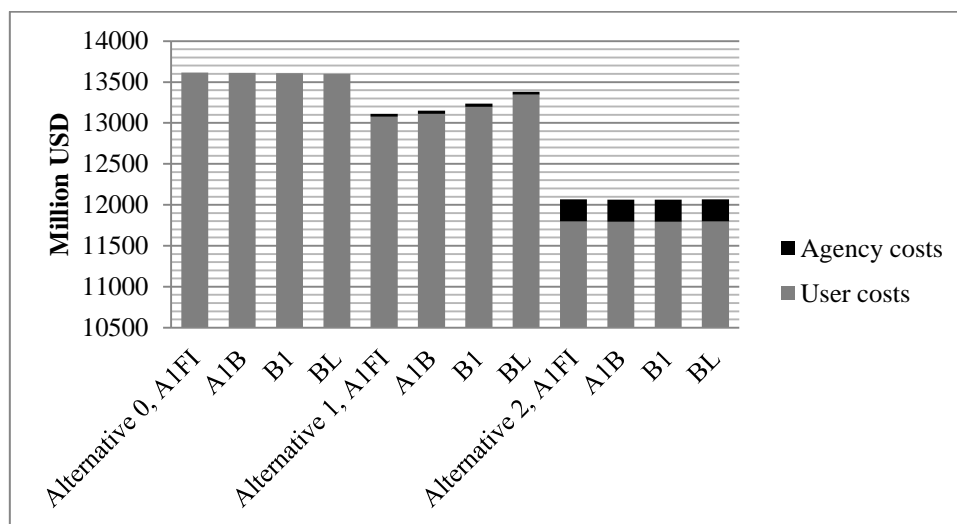


FIGURE 8 LCC comparisons.

4.1 Alternative 0

Without maintenance, a small increase in LCC was estimated for the 2050 climate. The greater the increase in temperature, the more the LCC will be. However, the difference in LCC is not significant, compared to the baseline (maximum increase of 0.1% under A1FI scenario). When no maintenance is performed, the agency costs equal 0 and all LCC are user costs, which are correlated to IRI. IRI increases as the temperature is higher, although the increase is not significant (see Figure 7a).

4.2 Alternative 1

Minimum agency costs to maintain the road in an acceptable condition were found to require a thin overlay applied as late as possible, because then the NPV for the treatment would be minimized. It was found that compared to baseline, maintenance was triggered 8 – 16% earlier depending on emission scenarios (see Figure 7c & d).

However, a reduction in the LCC (1 – 2%) was observed when the temperature was higher (see Figure 8), despite maintenance being triggered by rutting earlier. This is because, for the studied

1 pavement, early maintenance reduced IRI and thus user costs (over 99% of the LCC) which
 2 dominated the LCC. Although not included in the LCCA, the residual costs (salvage value) at the end
 3 of 40 years may be decreased by climate change because the rutting and IRI in the 40th year will be
 4 higher (see Figure 7c & d).

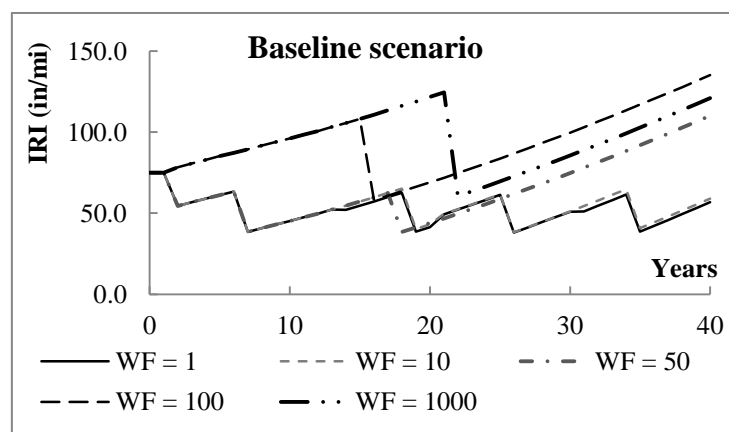
5 Alternative 1 gives an example for the roads which are maintained with minimum effort and
 6 have strict triggers for maintenance. The agency costs increase (approximately 1 – 2%) because
 7 maintenance is triggered earlier and the NPV of the treatment also increases. The road user costs may
 8 reduce due to the increase in the overall serviceability as a consequence of earlier maintenance.
 9 However, this conclusion may not be extrapolatable to other cases because, if the maintenance were to
 10 be performed earlier when IRI or rutting is lower, the effects of maintenance would be less (Equation
 11 1, 2), and, thus, may not help to improve the overall serviceability, which, in the above, led to lower
 12 user costs.

13 Given the shallow slope of rutting development (see Figure 7b), it is evident that agency costs
 14 could easily be kept constant under climate change if just a small relaxation in trigger value were to
 15 be adopted – e.g. change 0.75 to 0.8 inches as the trigger value for intervention to address rutting.

16 4.3 Weighting factor

17 The WF can influence the optimization process and uncertainties can be induced by this factor. A
 18 greater WF can emphasize the importance of agency costs, thus interventions will be applied as fewer
 19 as possible and reduce LCC (and vice versa). Therefore, uncertainties can be introduced by the WF. A
 20 sensitivity study was performed to investigate how the choice of WF impacted the maintenance
 21 optimization process and its subsequent LCC. It is also required in LCCA that a sensitivity study
 22 needs to be performed. Obviously, a lot of parameter is involved in the LCCA and it is impossible to
 23 perform a sensitivity study for each of them.

24 In the senility study, many different values of WF were applied, including 1, 10, 50, 100 and
 25 1000. These values gave emphasis on agency costs with different magnitude. For each WF, the
 26 optimization process in methodology under baseline climate scenario was repeated. As WF is
 27 independent of climate change, the influence of WF under baseline is considered to be representative
 28 of other scenarios. Results of optimised intervention strategies and LCC with different WF were
 29 compared as follows:



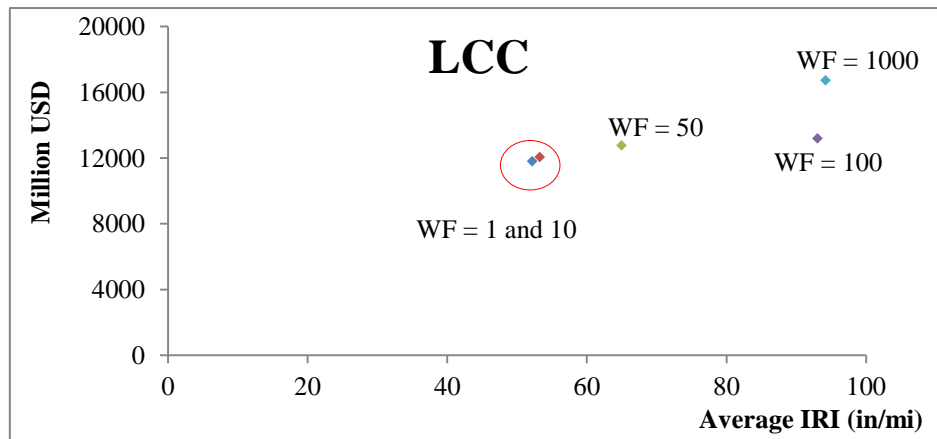
30
 31

FIGURE 9 Impact of weighting factors on optimised intervention strategies.

32 It can be observed from Figure 9 that optimised intervention strategies were significantly
 33 affected by WF. When WF is greater, maintenance was performed less frequently or was delayed. For
 34 instance, interventions were performed 8, 6 and 3 times in 40 years with WF of 1, 10 and 50

1 respectively (see Figure 9). This is because that a greater WF weighted agency costs more so that they
 2 seemed more “expensive”. Therefore, their application frequency reduced.

3 With $WF = 100$, intervention was only performed once, the same as frequency with $WF =$
 4 1000 . Noticeably, intervention Option 1 was selected for both cases, however, it is performed later
 5 with $WF = 1000$ than that with $WF = 100$ (see Figure 9). The reason can be expressed as follows.
 6 When equaled 1000 , the WF made agency costs “dominating”. When user costs dominate, a delay in
 7 an intervention can result in an increase in the average IRI, resulting in an increased LCC. However,
 8 in this case ($WF = 1000$), a delay in maintenance can reduce LCC by reducing NPV of agency
 9 (maintenance) costs.



10
 11 FIGURE 10 Impact of weighting factors on LCC

12 Although WF had a significant influence on intervention strategies, the influence on LCC was
 13 not significant when $WF = 10$. $WF = 1$ weighted agency and user costs as equally important. This
 14 represents true monetary costs of an agency and users. However, maintenance frequency with $WF = 1$
 15 is too much and impractical. $WF = 50, 100$ and 1000 also reduced maintenance frequency, however
 16 LCC could be significantly changed (+ 8%, 11% and 37% respectively). $WF = 10$ reduced the
 17 frequency of maintenance, while keeping the change of LCC reasonable (+2%). For these reasons,
 18 $WF = 10$ was chosen for this study.

19 4.4 Alternative 2

20 When maintenance is planned to minimize the LCC, more frequent interventions will be expected so
 21 as to maintain the serviceability of the road at a better level. Thus more agency costs will be incurred.
 22 To illustrate this, a lower boundary for IRI (38 in/mi) was added to limit the maintenance applied.
 23 This value represents the lower 95th percentile IRI level in the three investigated districts in Virginia.
 24 It seemed that the lower limits determined the shape of the deterioration curves more than the upper
 25 limits (maintenance triggers) because greater agency costs will reduce the user costs, which
 26 significantly dominated the LCC. For Alternative 2, maintenance was affected by climate change
 27 under some scenarios but not as much as for Alternative 1. The maintenance was more influenced by
 28 the lower limit for Alternative 2 instead of the upper limit for Alternative 1.

29 Generally, the LCC reduced by approximately 11% under Alternative 2, compared to Alternative 0
 30 under all climate change and baseline scenarios (see Figure 8), while the agency costs under A1FI,
 31 A1B, and B1 scenarios were the same under the baseline climate. The user costs decreased only a
 32 very little (0.01% for A1FI and 0.03% for A1B and B1). Thus the LCC was not sensitive to the
 33 climate change scenario within Alternative 2. Furthermore, the salvage values of the pavement under
 34 different climate scenarios were similar because the final IRI and rutting was almost the same.

1 The Alternative 2 reflects a situation where maintenance is frequent and planned in advance.
2 Under this circumstance, the impact of climate change on the LCC can be eliminated if interventions
3 can be planned to adapt for climate change.

4 **5 CONCLUSIONS**

5 The following conclusions can be drawn:

- 6 • A method to estimate the impact of climate change on maintenance using MEPDG
7 predictions of pavement performance, and corresponding LCC, has been demonstrated.
- 8 • Pavement service life of a flexible pavement that is under responsive maintenance may have
9 significant reduction due to climate change.
- 10 • A pavement maintained with optimized interventions to achieve better cost-benefit may be
11 less affected by climate change in terms of intervention strategy and LCC, compared to a
12 responsively maintained pavement. Therefore, the utilization of maintenance optimization can
13 be a method to improve pavement system's resilience to climate change in terms of
14 intervention strategies and LCC.
- 15 • For the example pavement studied here, and likely for many others, minor adjustments
16 (diminution) to maintenance trigger values could obviate the need for any change in
17 maintenance strategy.

18 For the case study, which is thought to be representative of a large number of sites in the USA,
19 the following conclusions can be drawn with regard to pavement maintenance response to climate
20 change expected in about 40 years from the present:

- 21 • Without maintenance, climate change will likely increase the user costs, although the increase
22 is not significant.
- 23 • With minimum maintenance, climate change may have significant impact on road
24 maintenance planning. In the studied case, the treatment was triggered 8 – 16% earlier due to
25 climate change, corresponding to an increase of approximately 1 – 2% NPV for agency costs.
26 However, total LCC might then be reduced if the earlier maintenance increased the average
27 serviceability in the long term and thus reduced the user costs significantly, which will likely
28 dominate the total LCC.
- 29 • With optimized frequent maintenance strategies, the impact of climate change on pavement
30 maintenance and agency or total LCC can be mitigated. This could mean some treatment(s)
31 being performed in advance or delayed, compared to current optimized practice.

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