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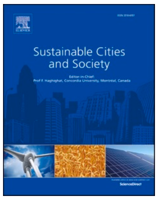

Impacts of future climate change on flexible road pavement economics: A life cycle costs analysis of 24 case studies across the United States

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ABSTRACT

Highway agencies are facing pressure for repairing and replacing underfunded and aged road pavement networks that were initially designed for historical climatic conditions. Road pavements must be updated while accounting for the impacts of climate change, which are likely to be exacerbated in the years to come, and with limited budgets. Methodologies and frameworks that help agencies incorporate the long-term effects of climate change on pavement performance and make informed decisions on how to spend their limited funds are therefore of utmost importance. This paper presents a methodological framework that combines downscaled climate projections, pavement performance predictions using the AASHTOWare Pavement ME Design$^{\text{TM}}$ tool, maintenance and rehabilitation strategies, and life cycle costs analysis (LCCA) in a comprehensive system. The proposed methodological framework was adopted in the LCCA of 24 case studies across the contiguous United States under four alternative periods corresponding to simulated climate projections for four 20-year periods (1981-2000, 2001-2020, 2041-2060, and 2081-2100) with a higher Representative Concentration Pathway (RCP8.5). The case study results show that climate change per degree Celsius will lead to approximately $650-700 million/year additional agency costs in the U.S. In addition, climate change will have greater impacts on the costs incurred during the maintenance and end-of-life phases.

1. Introduction

Climate change is already impacting transportation infrastructure in many parts of the world and future climate projections indicate that its impacts are likely to become more severe (e.g., Arent et al., 2014; Jacobs et al., 2018). The United Nations Framework Convention on Climate Change is attempting to limit global warming to 1.5°C compared to the pre-industrial global surface temperature level (IPCC, 2018). Notwithstanding the uncertainties related to the degree and severity of climate change in the future, the Climate Science Special Report, Volume I of the Fourth United States (U.S.) National Climate Assessment, states that the annual average temperature for the contiguous U.S. has increased by between 0.7°C and 1.0°C since the start of the 20th century (USCGRP, 2018). Projections indicate that this warming trend will continue with the annual average temperature increasing by another 1.4-1.6°C between 2021 and 2050, depending on whether a lower or higher future scenario is considered (Representative Concentration Pathway (RCP) 4.5 and 8.5, respectively).

The impacts of climate change vary across regions with temperature generally showing greater warming trends at higher latitudes (Vose et al., 2017). The U.S. West, Southwest, and Southeast have experienced decreases in annual precipitation, whereas the Northern and Southern Plains, the Midwest, and the Northeast have experienced the opposite effect. Heavy precipitation events have increased in intensity and frequency in nearly all regions. These trends are projected to continue in the years to come (Easterling et al., 2017).

Asphalt road pavements cover vast surface areas and therefore can be significantly affected by changes in the local climate. Climate factors such as temperature, precipitation wind, cloud cover, groundwater, and freeze-thaw cycles can all impact pavement performance in different ways (Qiao. et al., 2013; Yang et al., 2017; Piryonesi, 2019; Kwiatkowski, 2017). Specifically, asphalt concrete becomes much softer at higher temperatures and allows permanent deformation (i.e., rutting) to accumulate rapidly under traffic loading.

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In the past, various studies were conducted to evaluate costs associated with "active" climate adaptation measures, e.g., upgrading binder grades. It was found that the costs for the adaptation plans can be significant (Underwood et al. 2017). The study presented in this paper investigates pavement climate adaption from an opposite perspective: What if the asphalt pavements "passively" (instead of "actively") adapt to future climates? And if so, how much will the additional costs for highway agencies and road users be due to climate change? In this study, passive adaption refers to a situation where no active adaptation will be adopted and pavement design and maintenance methods remain unchanged.

To answer these questions, this paper presents development of a methodological framework to analyze the impacts of climate change on pavement life cycle costs (LCC). The framework integrates high-resolution climate projections, pavement performance predictions, maintenance and rehabilitation strategies, and life cycle costs analysis (LCCA) as a comprehensive system. Using the proposed framework, climate change induced costs are derived by subtracting the LCC associated with future periods from those related to historical periods. Furthermore, the economic impacts of climate change incurred during the different pavement life cycle phases (including materials production and transportation, construction, maintenance, operation, and end-of-life (EOL)) are quantified and expressed in terms of the net present value (NPV).

The structure of the paper is as follows. First, Section 2 describes the literature review. Section 3 introduces the proposed methodological framework, which is used to conduct LCCA using 24 case studies across the continuous U.S. The procedure to generate future localized climate projections for each location is also described. Section 4 describes the characteristics of the selected pavements for the case studies. The anticipated relation between future temperature increases and pavement LCC is discussed in Section 5. Section 6 presents a sensitivity analysis intended to identify key factors influencing the LCCA results. Finally, conclusions, limitations of the methodological framework and recommendation for future work are suggested in Section 7.

2. Literature review

Recently, the analysis of climate change impacts on pavement performance and economics have received particular attention. Several studies have modelled the impacts of projected regional and local future climates on pavement performance. It was found that pavement deterioration (e.g. rutting, roughness, and cracking) can be accelerated, to different extents, by climate change (Mills et al., 2009; Mndawe et al., 2015; Stoner et al., 2019; Tighe et al., 2008). Meagher et al. (2012) applied the Mechanistic–Empirical Pavement Design Guide (MEPDG) model to simulate flexible pavement performance and deterioration for four sites across New England from three North American Regional Climate Change Assessment Program scenarios. They concluded that pavement rutting can be greatly impacted by climate change. Furthermore, Gudipudi et al. (2017) found that rutting could increase 9–40% as temperature increases in the future by using the AASHTOWare Pavement ME software to simulate the pavement performance for five different locations with the average of 19 different CMIP5 climate models and three individual models (MIROC-ESM, CCSM4, and MRI-CGCM3) for both RCP8.5 and RCP4.5 scenarios. All these studies were based on deterministic methods such as mechanistic-empirical regression models. More recently, machine learning algorithms were applied to predict pavement life cycle performance considering uncertainties caused by climate change (Piryonesi & El-Diraby, 2021a; Qiao et al. 2020a). For a deeper review of past studies focused on the impacts of climate change on pavements, the reader is referred to Qiao et al. (2020b).

Some researchers have gone beyond the impacts of climate change on pavement performance by adopting methods to quantify economic metrics related to the impacts of climate change on pavements (Austroads, 2004; Gudipudi et al., 2017; Mallick et al., 2014; Qiao et al., 2019a; Mahpour and El-Diraby, 2021). Increasing temperature and more severe and frequent rainfall were found to have negative impacts on pavement performance, incurring unexpected costs in different phases of pavements' life cycle. For instance, Chinowsky et al. (2013) found that climate change will increase the annual costs of the U.S. road network by \$2.8 billion with a global mean temperature increase of 1.5°C compared to 2010. Underwood et al. (2017) completed a comprehensive study investigating additional budgets to "actively" adapt U.S. pavement infrastructure to projected future climate. It was estimated that climate change can incur \$21.8-35.8 billion in increased costs by 2070 if pavement binder performance grades will have to be adapted to the "correct" grades to adapt to climate change. Clearly, the additional budget can be a burden for highway agencies to afford, especially considering the aging pavement networks (NAPA, 2017) and the cronic insufficient budgets.

The methodological framework presented in this paper builds on the knowledge gained from the above literature and goes a step further by analyzing the asphalt pavement performance and economic impacts during its life cycle when it is passively adapted to future climates. Thus, the research work presented in this paper contributes to the scarce literature on costs estimates of climate change effects on pavement deterioration and maintenance.

3. Methodological framework

The framework presented in this paper builds on the original framework described in Qiao et al. (2019). This study further establishes a comprehensive methodological framework, which is used to model the dynamic interactions between climate, long-term pavement performance, maintenance and rehabilitation interventions, and costs from a life cycle perspective. Climatic factors can impact pavement performance, thereby leading to changes in maintenance decision-making. Consequently, various LCC components can decrease/increase and accumulate over the pavement life cycle. The primary variable in the system is the climate since its change can lead to modifications in the dynamics of the entire system. The methodological framework includes four steps, each described in individual subsections below (Figure 1):

- Step 1: Climate data collection and projections (Section 2.1)
- Step 2: Pavement performance prediction (Section 2.2)
- Step 3: Pavement maintenance decision-making (Section 2.3)
- Step 4: Life-cycle cost analysis (Section 2.4)

In this study, the framework was adopted to conduct a "what-if" analysis, i.e., what will the LCC be if the current climate changes according to projected climates for the 2041-2060 and 2081-2100 periods for a global climate model following the RCP8.5 future scenario.

3.1. Climate data and projections

This research considers case studies for 24 locations across the contiguous U.S. and uses the same climate projections described in detail in Stoner et al. (2019). Seven of the locations are in a dry-freeze climate zone, as classified by the Federal Highway Administration's Long-Term Pavement Performance (LTPP) program (Schwartz et al., 2015), six locations are in a wet-freeze zone, three locations are in a dry-nonfreeze zone, and eight locations are in a wet-nonfreeze zone. Figure 2 shows the 24 locations as well as the 1981-2000 average surface temperature according to the Livneh high-resolution gridded dataset (Livneh et al., 2013).

Hourly values of temperature, wind speed, percent sunshine, precipitation amount, and relative humidity for each location were obtained from the AASHTO website (AASHTO, 2018) for the period 1979-2015 (Gudipudi et al., 2017). Projected daily values of minimum and maximum temperature, precipitation, and minimum and maximum

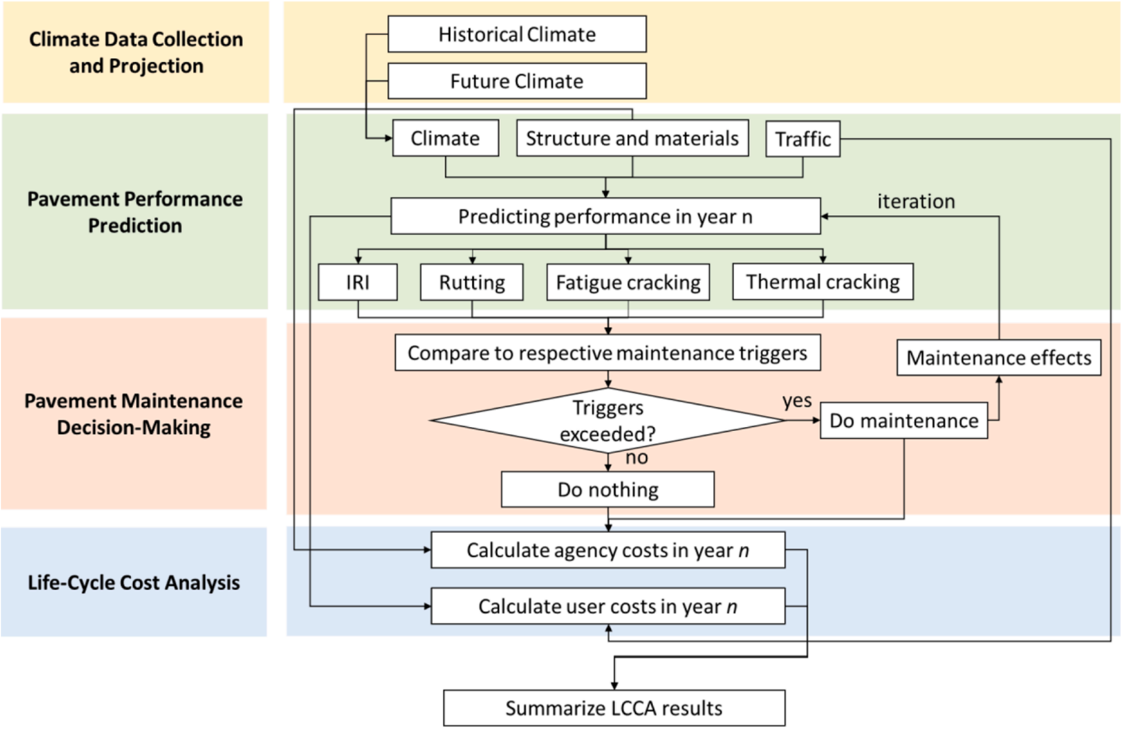


Figure 1. Methodological framework.

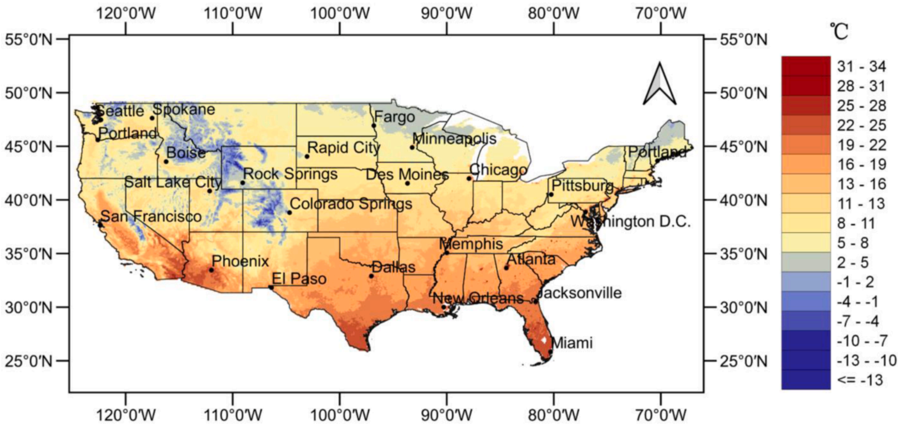


Figure 2. 1981–2000 average temperature across the contiguous U.S.

relative humidity for 2006-2100 were obtained for the GFDL-ESM2G Global Climate Model (GCM) (Dunne et al., 2012) from the Fifth Climate Model Intercomparison Project (CMIP5) archive for the higher Representative Concentration Pathway (RCP8.5). Only one GCM was used in this study, as an example, to demonstrate how future climate projections can impact the pavement life cycle performance and cost and to quantify how their variations may differ in varying climatic regions.

GCM output was statistically downscaled to individual weather stations for each of the 24 locations using the Asynchronous Regional Regression Model (Stoner et al., 2012), with daily aggregated values from the AASHTO climate files as the baseline. Simulated daily values of each variable were then disaggregated to hourly values using the method described in Stoner et al. (2019). Finally, hourly values of wind speed and percent sunshine were generated by randomly sampling a day (24 hourly values) in the historical data with similar daily total rainfall amount and that occurred in a three-month season surrounding the day in question.

3.2. *Pavement performance prediction*

This study adopts the AASHTOWare Pavement ME Design^{TM} tool (from here on referred to as Pavement ME tool) that builds on a mechanistic-empirical method for predicting pavement performance. Pavement ME is one of the most comprehensive pavement analysis tools and its Enhanced Integrated Climate Model (EICM) allows “translation” of climatic conditions into pavement temperature and moisture profiles. For this reason, Pavement ME has been widely applied in assessing the impacts of a changing climate on pavements (e.g. Mills et al., 2009; Qiao et al., 2019b; Stoner et al., 2019; Underwood et al., 2017).

Pavement life cycle performance indicators, including rutting, roughness (measured by the International Roughness Index (IRI)), fatigue and thermal cracking were modelled using the Pavement ME tool for standard primary and interstate roads at the 24 locations listed above, for a 1981-2000 baseline period and three 20-year analysis periods representing different historical or future climates (i.e., 2001-2020, 2041-2060 and 2081-2100). The primary inputs of the

Pavement ME tool include Annual Average Daily Traffic (AADT), truck percentage, pavement structure, pavement materials, and 20-year climate conditions.

Pavement performance is likely more affected by traffic (AADT and truck percentage), structure, and materials than by the climate alone. However, these factors are not the primary concern of the climate-pavement system. Therefore, they were taken as secondary inputs in the system and kept constant in the performance prediction module to capture the isolated effects of climate change on pavement systems (e.g., Qiao et al., 2019b).

The above pavement life cycle performance indicators were chosen because they are the most concerned distresses and direct outputs of the Pavement ME tool. It should be noted that some distresses (e.g., bleeding) cannot be captured by any of these indicators (Piryonesi & El-Diraby, 2021b). Although they usually do not trigger immediate rehabilitation/reconstruction activities, neglecting such distresses may result in underestimating related repair costs.

3.3. Pavement maintenance decision-making

A Responsive Maintenance Decision-Making Model (RMDMM) was used in this study to automatically make maintenance decisions based on the performance indicators predicted with the Pavement ME tool, and considering the effects of applied maintenance. It relies on a decision-tree to determine the type and year of application of maintenance interventions needed over each pavement life cycle according to a pre-set maintenance logic and maintenance triggers (see Figure 3). Each pavement section was considered to be in need of maintenance when the predicted pavement performance indicators reach the respective trigger value. Three types of common maintenance activities were considered: i) overlay, ii) crack sealing and filling, and iii) “do nothing”. The above-mentioned activities were selected to demonstrate the methodology but they can be replaced or complemented with other types of maintenance activities when needed.

An overlay can be triggered by IRI, rutting, and fatigue cracking at 2.71m/km, 20 mm, and 25% lane area fatigue cracking, respectively (AASHTO, 2016). The overlay intervention is expected to reduce IRI and rutting and to reset fatigue and thermal cracking. The immediate maintenance effects of the overlay were modelled according to the Highway Development and Management (HDM-4) maintenance effect models as follows (Equation 1) (Morosiuk and Riley, 2004):

$$\mathrm{ME}_t = \left\{ \begin{array}{c} \Delta Rut_t = 0.85 \ \times Rut_t \\ \Delta IRI_t = max\{0,\ 0.9 \ \times [\min(4,\ IRI_t) - 2.71]\} \end{array} \right. \quad (1)$$

where ME_t = maintenance effect in year *t*; ΔRut_t = reduction in rutting due to the maintenance treatment applied in year *t*; ΔIRI_t = reduction in IRI due to the maintenance treatment applied in year *t*; Rut_t = rutting in year *t*; and IRI_t= IRI in year *t*.

Crack sealing and filling is triggered when the predicted thermal cracking exceeds 189 m/km (AASHTO, 2016) and has the effect of resetting thermal cracking, without improving IRI, rutting, or fatigue cracking. In this study, thermal cracking refers to a top-down type of cracking and can be sealed from the surface. Fatigue cracking exceeding 25% surface area is considered severe and will trigger overlay intervention (see also in Figure 3).

Finally, a Visual Basic for Applications (VBA) based spreadsheet was created to implement the RMDMM and to perform the LCCA based on all Pavement ME results.

3.4. Pavement life cycle costs analysis

LCCA is an analytical technique used to quantify the long-term economic performance of assets or projects (Santos et al., 2017a). In this study, the net present value (NPV) was adopted as a metric to quantify and compare the climatic impacts on pavement historical/future LCC incurred during different life cycle phases. In general, the pavement LCC can be categorized into the agency costs and user costs listed below:

- Agency costs:
  - ■ Materials production costs: quantity and unit prices of the asphalt binder, aggregates, and subgrade gravel materials used in the construction of the initial pavement structures at their prices in different states in 2020 (State Indexes, 2020).
  - ■ Construction costs: placement and compaction utilization costs (i.e., paver and roller, respectively) used in the initial pavement construction. Caterpillar 120H (placement) and Dynapac CA 262D (compaction) were used for gravel and sand, whereas Dynapac F25C (placement) and Pneumatic-Dynapac CP134 (compaction) were used for HMA (Valle et al., 2017).
  - ■ Transportation costs: truck hauling costs to transport materials from mixing/quarry plants to the construction site of the initial

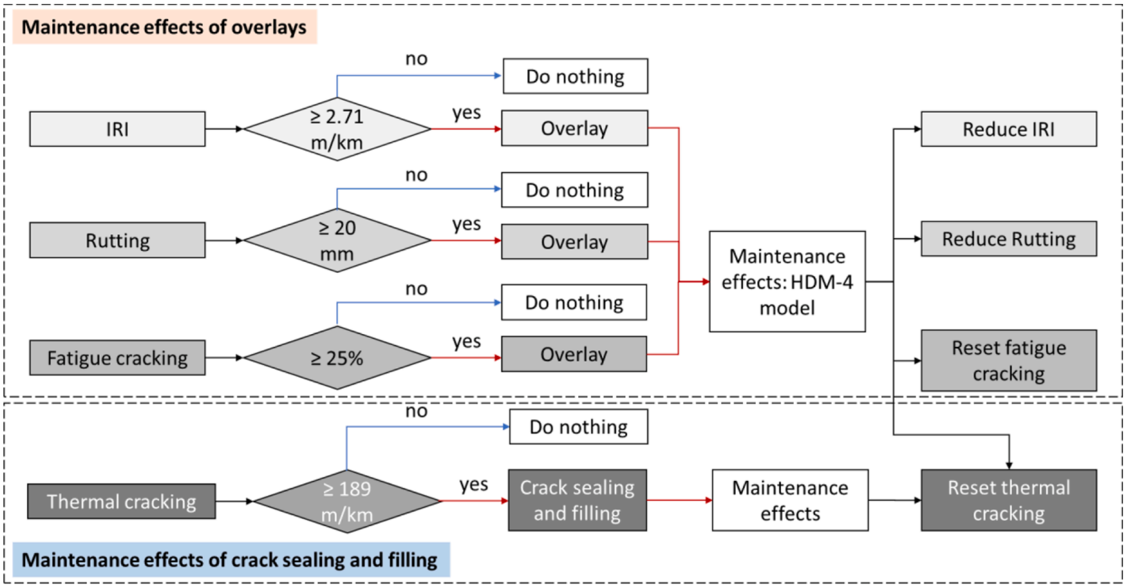


Figure 3. Maintenance triggers and effects considered in the RMDMM.

pavement structures. The distances to asphalt plants and quarries were all assumed to be equal to 32 km and 24 km, respectively. The volume per truck was 7.65 m^3 and the diesel consumption rate of transportation trucks was 0.588 l/km.

  - Maintenance costs: production, transportation, and machinery utilization costs (i.e., Dynapac F25C and Pneumatic-Dynapac CP134) for the HMA overlay. The costs of cracking sealing and filling ($120/km) consisted of material costs (bitumen), and labor costs (Manik et al., 2019).
  - EOL costs: correspond to the remaining service life value at the end of the 20-year life span calculated according to Equation 2 and named salvage value (see Santos et al., 2017a).
- User costs: vehicles' fuel consumption costs calculated according to the HDM-4 model calibrated for U.S. conditions by Chatti and Zaabar (2012). It estimates the fuel consumption for different types of vehicles at different operating speeds when operating on pavements with different roughness levels (IRI).

$$\mathrm{Cost}_{\mathrm{Salv}} = -\mathrm{Cost}_{\mathrm{AC}} \times \min\left(\frac{\mathrm{IRI}_{\mathrm{trigger}} - \mathrm{IRI}_{\mathrm{EOL}}}{\mathrm{IRI}_{\mathrm{trigger}} - \mathrm{IRI}_{\mathrm{initial}}}; \frac{\mathrm{Rut}_{\mathrm{trigger}} - \mathrm{Rut}_{\mathrm{EOL}}}{\mathrm{Rut}_{\mathrm{trigger}} - \mathrm{Rut}_{\mathrm{initial}}}; \frac{\mathrm{FC}_{\mathrm{trigger}} - \mathrm{FC}_{\mathrm{EOL}}}{\mathrm{FC}_{\mathrm{trigger}} - \mathrm{FC}_{\mathrm{initial}}}\right) \tag{2}$$

where $Cost_{Salv}$ = remaining service life value; $Cost_{AC}$ = cost of the asphalt concrete layer; $IRI_{trigger}$, $Rut_{trigger}$, $FC_{trigger}$ = maintenance trigger values for IRI (2.71m/km), rutting (19mm), and fatigue cracking (189 m/km) (AASHTO, 2009), respectively; IRI_{EOL}, Rut_{EOL}, FC_{EOL} = IRI, rutting, and fatigue cracking values at the end of life, respectively; $IRI_{initial}$, $Rut_{initial}$, $FC_{initial}$ = IRI, rutting, and fatigue cracking values at the beginning of pavement life cycle, respectively.

The total cash flow for both baseline and future periods was calculated as the NPV assuming that the climate equals the baseline or anticipated future climates under the RCP8.5 scenario. The discount rate value was set at 2%, which is used to convert future costs to its current value (EM, 2020). The NPV of LCC can be calculated according to Equation 3. The detailed pavement LCCA modelling methods, inventory data, and models are described in Qiao et al. (2019a).

$$NPV_{LCC} = NPV_P + NPV_C + NPV_T + NPV_M + NPV_O + NPV_{EOL} \tag{3}$$

Where NPV_{LCC} = NPV of life cycle costs for pavement; NPV_P = NPV of production costs; NPV_C = NPV of construction costs; NPV_T = NPV of transportation costs; NPV_M = NPV of maintenance costs; NPV_O = NPV of operation costs; NPV_{EOL} = NPV of end-of-life costs.

Finally, only LCC components that can be affected by changes in the climate were considered. For agency costs, the selected costs can be affected by climate change due to the following: a) different asphalt materials were used in different climate zones, which can further impact pavement production, construction, and transportation costs, and; b) climate change can impact pavement performance and thus influence subsequent maintenance decision-making (e.g. earlier or delayed maintenance). For road users, climate change can impact user costs because the deterioration of pavement performance leads to additional fuel consumption costs due to the pavement-vehicle interaction (i.e., vehicles usually consume more fuels when driving over rougher roads) (Qiao et al., 2020b).

4. Features of the road pavement sections

The methodological framework (Figure 1) was applied to two types of standard road pavement structures at each of the 24 locations to evaluate the impacts of climate change on pavement performance, maintenance, and LCC. More detailed information about the climates, pavements, and traffic conditions can be found in Stoner et al. (2019).

The road pavement structures considered include interstate and primary roads, both having two lanes per direction (with an individual width equal to 3.66 m) and a length of 1 mile (1.31 km). For the two pavement structures the AADT was considered to be equal to 11,875 (interstate) and 4,750 (primary roads), both with 10% trucks. Additional information about the features of the pavement structures is shown in Table 1. Detailed information, such as binder content, air voids, and nominal maximum aggregate size can be found in Stoner et al. (2019). The same pavement structures and traffic conditions were applied to all 24 cities and the only difference was the climate in each city. This was intentionally controlled to ensure climate was the only differentiator in the system (see Figure 1).

5. Results and discussion

The Pavement ME tool was run multiple times for each standard pavement structure in the 24 cities under the 20-year baseline climates corresponding to the nearest weather stations and 20-year projected future climates. Figure 4 shows a summary of the 20-year average temperature increases compared to the baseline climate. The annual average temperatures are projected to increase at all 24 locations, with an average increase of 0.8 °C, 2.0 °C and 4.1 °C for the three periods (2001-2020, 2041-2060, and 2081-2100) compared to the baseline (1981-2000) for the RCP8.5 scenario and GFDL-ESM2G climate model. Higher temperature increases are generally expected in the northern states with locations such as Des Moines (Iowa) and Spokane (Washington) projected to increase by 4.5 °C and 4.1 °C, respectively, in the 2081-2100 period, while the average 20-year temperature in a more southern location such as Atlanta (Georgia) is projected to increase by 3.6 °C in the same period for this climate model and higher scenario, compared to the average baseline temperature for these locations.

Previous studies have shown that temperature is the most influential climatic factor for pavement performance (Qiao. et al., 2013; Yang et al., 2017). To determine the relationship between temperature and pavement performance a regression analysis was performed and shown in Figure 5. It illustrates the 20-year terminal rutting values versus corresponding temperature increases, compared to the baseline for all pavement sections under all future periods. The terminal performance

Table 1
Characteristics of the pavement structures.

Interstate pavement *Layer*	*Material*	*Thickness (cm)*
Surface AC	Asphalt concrete comprising a binder with a performance grade that depends on climates in the states of the cities (Stoner et al., 2019)	7.62
Base AC	Asphalt concrete comprising a binder with a performance grade that depends on climates in the states of the cities (Stoner et al., 2019)	15.24
Base	Nonstabilized permeable aggregate	45.72
Subgrade	A-1-b	Sem-infinite
Primary pavement		
Layer	***Material***	***Thickness (cm)***
AC	Asphalt concrete comprising a binder with a performance grade that depend on climates in different states (Stoner et al., 2019)	10.16
Base	Nonstabilized permeable aggregate	25.40
Subgrade	A-1-b	Sem-infinite

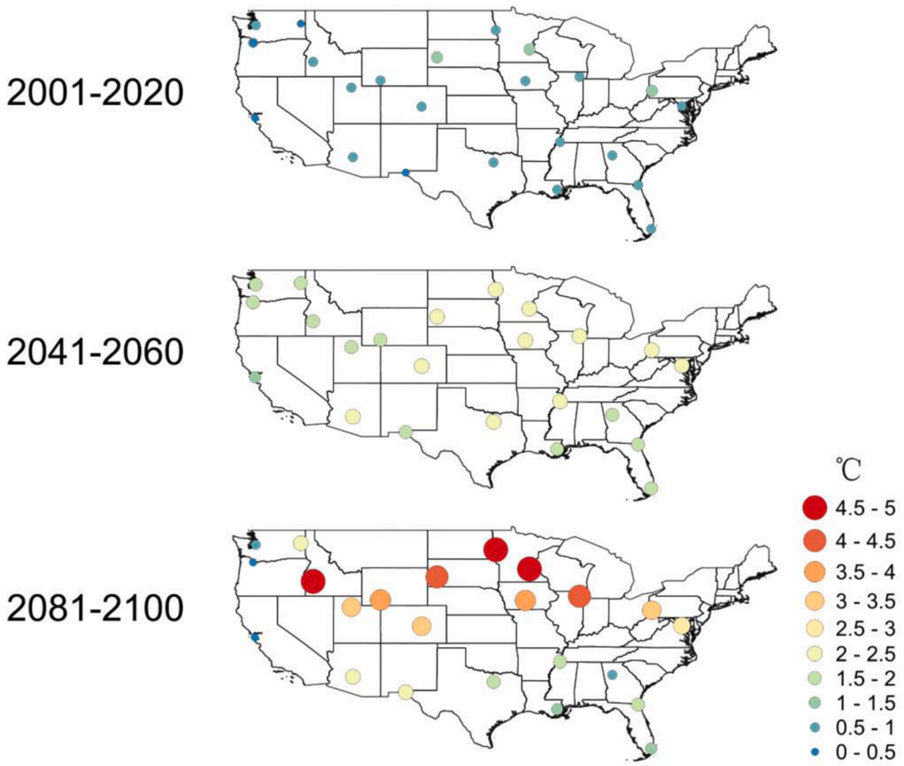


Figure 4. Increases of the 20-year average temperatures in 24 cities compared to the baseline period (1981-2000).

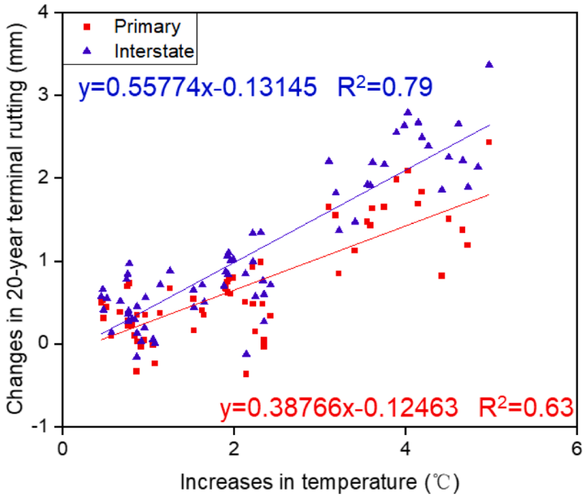


Figure 5. Regression analysis for changes in 20-year terminal rutting and temperature increases for interstate roads (blue) and primary roads (red).

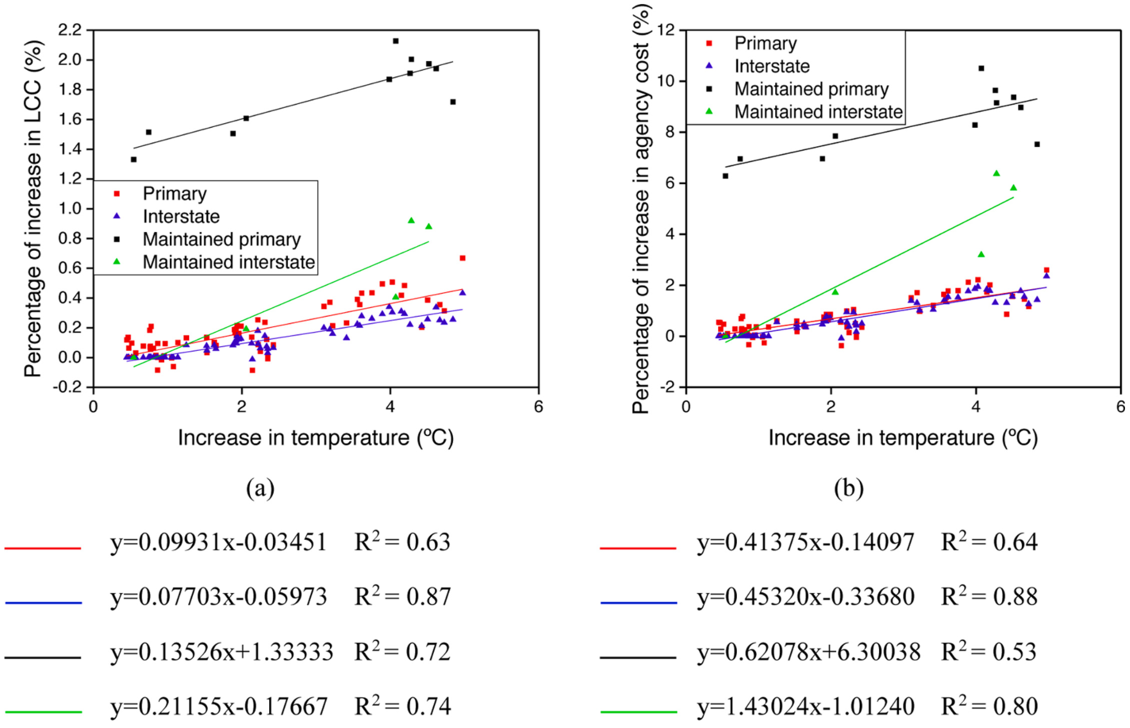
indicators including rutting, IRI, fatigue cracking, and thermal cracking are obtained directly from the Pavement ME results without consideration of maintenance treatments first (and their effects).

Linear, exponential, and logarithmic regressions were performed to investigate the correlation between increases in temperature and terminal performance. It was found that the linear regressions had the greatest R^2 values and thus were adopted. Figure 5 shows that increases in temperature have a positive correlation with rutting in interstate ($R^2 = 0.79$) and primary road ($R^2 = 0.63$) pavements. Increases in temperature are known to lead to a reduction of asphalt layer stiffness, thus accelerating rutting development under traffic loading, particularly when the temperature is relatively high. Figure 5 also shows that increases in temperature have greater impacts on rutting of interstate pavements than on rutting of primary pavements. Specifically, an increase of 1 °C can lead to approximately 0.6 mm additional rutting at the end of the 20-year service life for the interstate pavements and 0.4 mm for the primary pavements.

For IRI, fatigue cracking, and thermal cracking, their correlation with temperature increases is generally positive but only a small component of the variance is explained ($R^2 < 0.3$). This is likely because these factors are not overly sensitive to changes in the temperature (e.g., IRI) or that they are more affected by temperature variation (e.g., for thermal cracking), which is not well represented by the increase of average temperatures (Qiao et al., 2013). Nevertheless, they are important factors that can trigger maintenance decisions over the life cycle of pavements and affect the LCC. Therefore, they are still considered in the analysis.

To determine the relationship between increases in temperatures and increases in the total LCC and agency costs, another regression analysis was performed (Figure 6). In some pavements, the life cycle performance did not deteriorate to the level that required the implementation of a maintenance treatment. Figure 6 presents the results according to two classifiers: a) interstate or primary pavement sections; b) maintained or not maintained pavement sections. From the analysis of Figure 6, the following observations can be made:

- Regardless of whether maintenance is required or not, there are strong positive correlations between temperature increases and LCC/agency costs increases. That is likely to be explained by the higher costs of asphalt binders used in warmer locations.
- For pavements where overlay treatment is triggered, this can be attributed to the negative impact of increased temperatures on pavement performance, primarily on rutting, which triggers the maintenance, thereby requiring agencies to invest in pavement overlay(s).
- The increases in LCC and agency costs due to increases in temperature (absolute values of the percentages in Figure 6) are greater in



(a)

(b)

$y=0.09931x-0.03451$ $R^2=0.63$

$y=0.07703x-0.05973$ $R^2=0.87$

$y=0.13526x+1.33333$ $R^2=0.72$

$y=0.21155x-0.17667$ $R^2=0.74$

$y=0.41375x-0.14097$ $R^2=0.64$

$y=0.45320x-0.33680$ $R^2=0.88$

$y=0.62078x+6.30038$ $R^2=0.53$

$y=1.43024x-1.01240$ $R^2=0.80$

Figure 6. Regression analysis for the percentages of increases in agency cost and LCC due to temperature increases. Legend: “Primary” and “Interstate” represent primary and interstate pavements, respectively, that did not require maintenance. In turn, “Maintained primary” and “Maintained interstate” represent primary and interstate pavements, respectively, that required maintenance according to the procedure illustrated by Figure 3.

primary roads than in interstate roads, particularly for maintained pavements.

- The slopes of the curves for pavements that do not require maintenance are relatively similar, indicating that increases of LCC and agency costs due to increases in temperature follow a nearly constant positive relationship. For each degree Celsius of increase in temperature, LCC increases by 0.08% and 0.10% whereas agency costs increase 0.45% and 0.41% for interstate and primary roads respectively. Considering national highway agency investment being $150,000 million (for example in 2014, see Bidnet, 2020), the climate change induced annual cost is approximately $650-700 million nationwide. This cost is within the range of that estimated by Underwood et al. (2019) (approximately $440-720 million per year).

Figure 7 shows the relative proportions of different LCC cost components, based on the average of LCC components of all pavements under all periods. The operation costs are the major LCC component, accounting for 76-85% of the total LCC. The second largest LCC component is the construction costs for the primary roads and production costs for the interstate roads. The share of maintenance costs can be up to 5% of the LCC when maintenance is needed. Salvage values are negative, since they represent the remaining value of a pavement at its EOL phase. They contrast with positive spending values related to

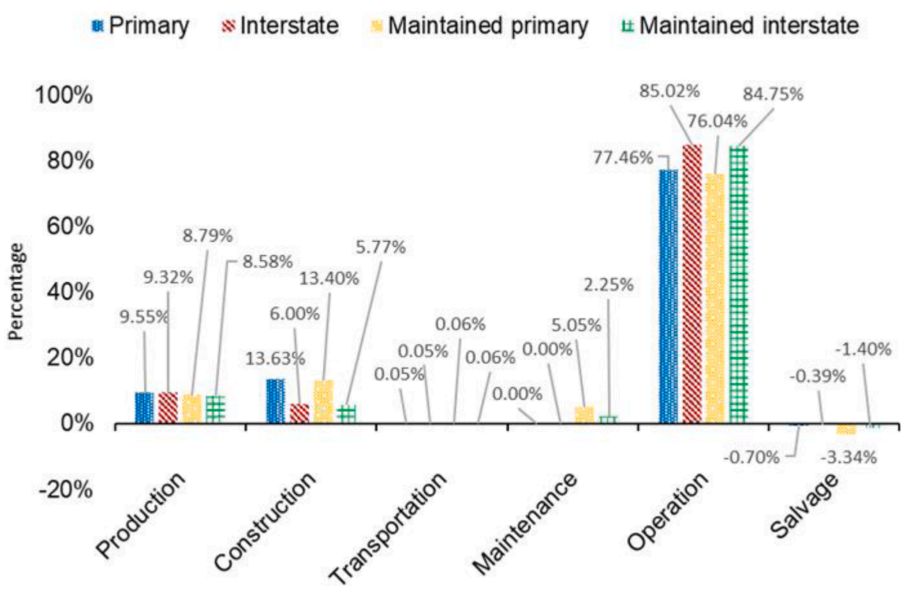


Figure 7. The averaged proportions of life cycle costs components. Note: production, construction and transportation costs are referring to the initial pavement structures. Legend: “Primary” and “Interstate” represent primary and interstate pavements, respectively, that did not require maintenance. In turn, “Maintained primary” and “Maintained interstate” represent primary and interstate pavements, respectively, that required maintenance according to the procedure illustrated by Figure 3.

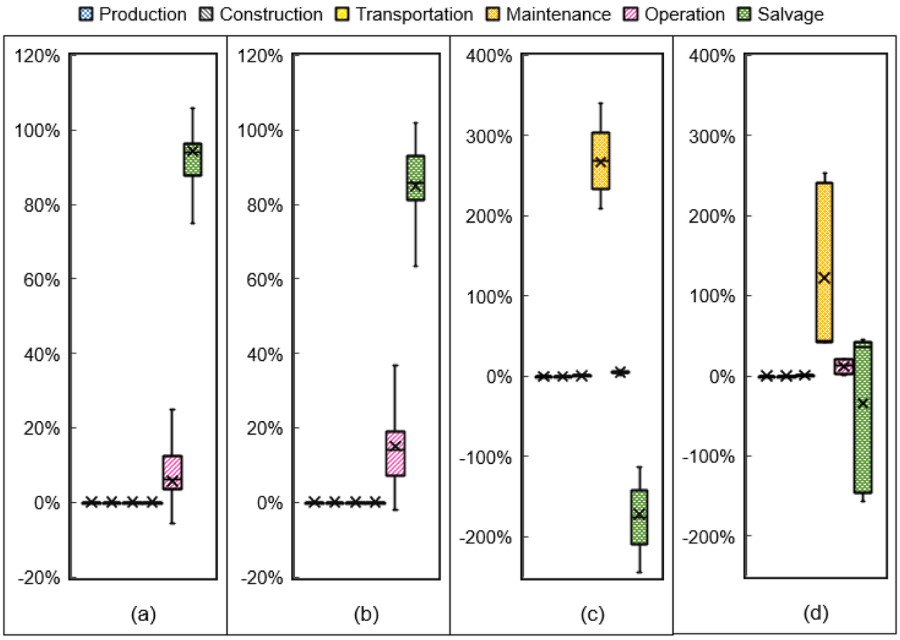


Figure 8. Box and Whisker plots for percentage changes of LCC components in 2000-2100 climates compared to the baseline climate: (a) primary roads without maintenance, (b) interstate roads without maintenance, (c) maintained primary roads, (d) maintained interstate roads.

pavement construction and maintenance. The salvage value represents approximately 1-3% of the total LCC and the absolute values are greater when maintenance is performed.

To find the pavement life cycle phases that are most affected by changes in climate, the relative variations of the different LCC components for the period 2001-2100 in relation to the baseline period (1981-2000) were determined (Figure 8). The percentages are calculated as climate change-induced variations in the relative proportion of different LCC components to the total LCC. Figure 8 shows that:

- Impacts of climate change on pavement LCC components depend largely on whether pavements are maintained.
- For pavements without maintenance, the LCC components most affected by climate change are salvage costs followed by operation costs. Climate change can increase the salvage costs (i.e., reductions in the absolute value of pavement residual value) because the road performance will decrease under future climates (e.g., Figure 5) and thus the absolute value of the salvage costs will decrease.
- When maintenance is required, the most impacted LCC component are maintenance costs, which are projected to increase 210-350% for primary roads and 40-250% for interstate roads. This is because the pavements' maintenance thresholds are triggered prematurely in future climates. Salvage costs may decrease (i.e., absolute values increase) due to maintenance effects. The percentage changes are greater for agency costs (including salvage costs and maintenance costs) than for user costs (i.e., operation costs).
- Climate change can also increase operation costs due to the same reason (i.e., pavement performance is projected to further deteriorate under future climates) leading to an increase in fuel consumption. However, in rare cases, operation costs decrease in future climates (Figure 8a and Figure 8b), which may be attributed to the decrease of IRI in some exceptional cases.
- Operation costs remain a dominating share of the total LCC (see Figure 7). However, they are the LCC component less affected by climate change.

6. Sensitivity analysis

A sensitivity analysis was performed to identify factors that can most influence the calculated LCC. However, due to the extent of the study, it is virtually impossible to include all factors in the sensitivity analysis. Hence, some cost-related factors of each pavement life phase were selected and included in the analysis. Most importantly, their sensitivity to LCC was compared with the sensitivity of climate.

In this study, the sensitivity ratio (SR) was used to determine the effect of a change in the value of an input alone on the LCCA results (Clavreul et al., 2012). This ratio can be defined as the ratio between the relative change of the LCCA results and the relative change of the input (Equation 4). 14 different inputs to the system were selected for the sensitivity analysis as presented in Table 2. In the analysis, each input was increased by 10% at a time and the LCCA was performed with the baseline climate for Seattle and Phoenix. The two locations were chosen as examples for discussing sensitivity, as their maintenance decision-making is different. Interstate and primary roads in Phoenix require overlay treatment, while no maintenance was triggered for the

Table 2
Inputs considered in the sensitivity analysis.

Input ID	Input Name	Initial value
1	Temperature (°C)	13.6
2	Discount rate (%)	2
3	Distance to asphalt plant (mi)	20
4	Distance to quarry (mi)	15
5	Gasoline cost for cars in the operation phase ($/gallon)	3.11
6	Diesel cost for trucks in the operation phase ($/gallon)	3.42
7	Virgin HMA cost ($/ton)	415.11/ 395.66*
8	Gravel cost ($/ton)	12.5
9	Sand cost ($/ton)	13.5
10	Diesel consumption rate of trucks in the transportation phase (gal/mi)	0.25
11	Paver utilization cost for gravel and sand placement ($/ft^2)	2
12	Roller utilization cost for gravel and sand compaction ($/ft^2)	2
13	Paver utilization cost for HMA placement ($/ft^2)	3.5
14	Roller utilization cost for HMA compaction ($/ft^2)	3.5

* Note: the virgin HMA costs in Seattle and Phoenix were 415.11 and 395.66 $/ton respectively.

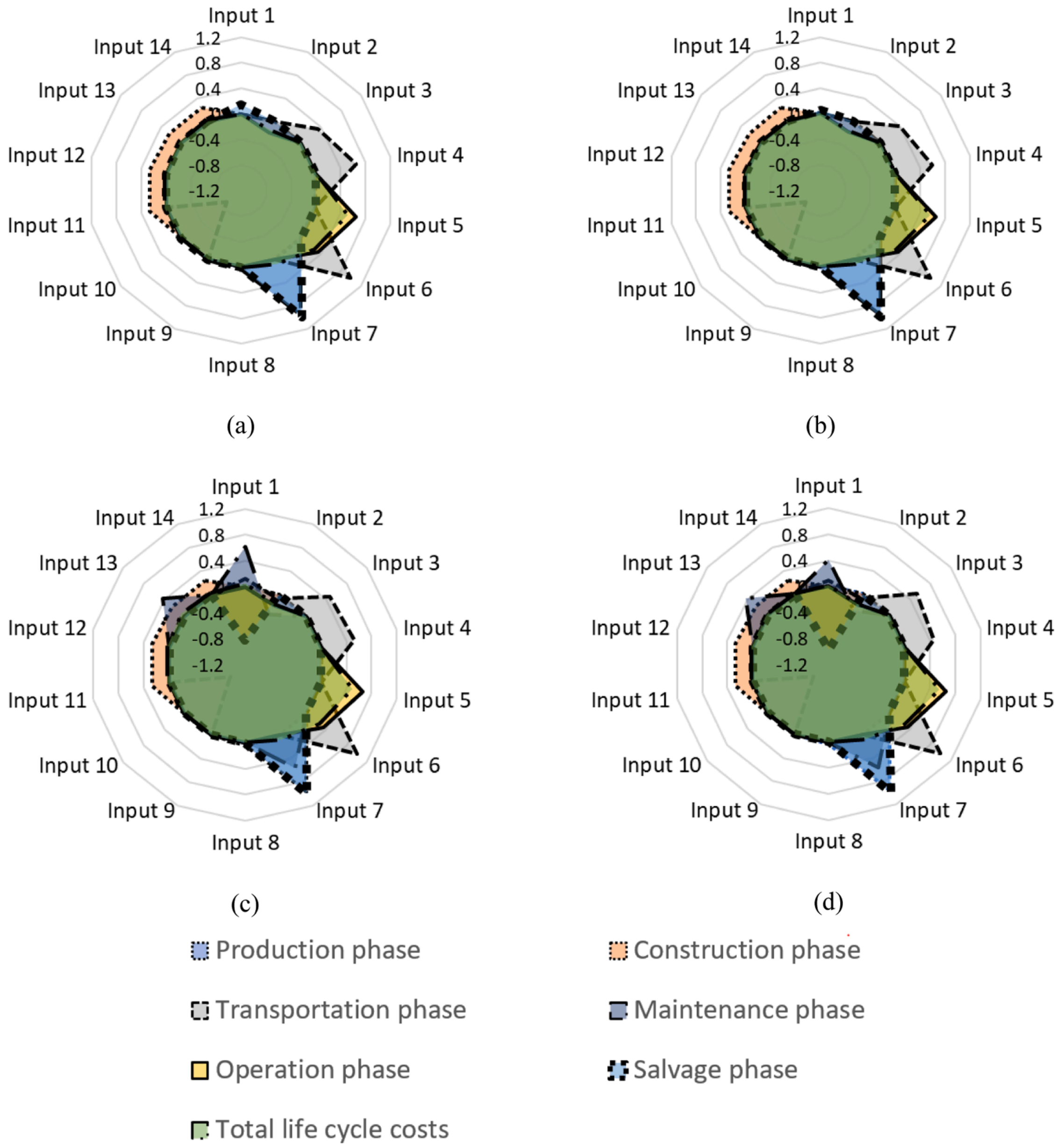
roads in Seattle. The percentage of input increment of 10% was chosen because this corresponded to the increase in average temperature in each 20-year period.

$$\mathrm{SR}_i = \frac{\frac{\Delta LCC_i}{LCC}}{\frac{\Delta Input_i}{Input_i}} \times 100\% \tag{4}$$

where, SR_i = sensitivity ratio for input i; ΔLCC_i= variation of the total LCC due to changes in the value of input i; LCC = total LCC in the baseline period; $\Delta Input_i$ = variation of the value of input i; $Input_i$ = value of the input i in the baseline period.

The results from the sensitivity analysis are shown and compared in Figure 9, which highlights the following points:

- LCC are not highly sensitive to climate alone. The inputs can be categorized into three classes of sensitivity according to the absolute values of the sensitivity ratios (either with maintenance or without maintenance, whichever is greater):
  - ■ High sensitivity (10-100%): gasoline and diesel unit costs.
  - ■ Medium sensitivity (1-10%): discount rate, HMA costs, climate and paver & roller utilization costs (listed from greater to smaller sensitivity ratios).
  - ■ Low sensitivity (<1%): gravel costs, sand costs, distance to quarry, and distance to the asphalt plant (listed from greater to smaller sensitivity ratios).
- The shape of the radar graphs looks similar regardless of whether it is an interstate of primary road, which indicates that the sensitivity of inputs does not depend significantly on the type of the roads.
- The total LCC are more sensitive to gasoline and diesel costs regardless of whether maintenance is performed. Therefore, innovative and more energy efficient vehicle power systems (e.g., electrical engine) have the potential to significantly reduce LCC in the future provided that the vehicle's electricity consumption and electricity cost are lower than the current counterpart. The shape of the radar graphs for the total LCC and operation costs is nearly the same.



(a) (b) (c) (d)

Figure 9. Sensitivity analysis results: (a) primary roads without maintenance in Seattle, (b) interstate roads without maintenance in Seattle, (c) maintained primary roads in Phoenix, (d) maintained interstate roads in Phoenix. (The names of the inputs are shown in Table 2).

This is due to the fact that operation costs are a major component of the total LCC (76-85%, see Figure 8).

7. Conclusions, limitations and recommendations for future work

7.1. Conclusions

This paper presents a methodological framework to assess the impact of climate change on road pavement LCC based on the LCCA of two standard road pavement sections located in 24 locations in the contiguous U.S. It contributes to the scarce literature on estimating the life cycle economic impacts of climate change on asphalt pavements. The methodological framework is helpful for agencies to incorporate the long-term effects of climate change on pavement performance and make informed decisions on how to spend their limited funds for effective climate adaptation. From the results of the case studies the following main conclusions can be drawn:

- Climate change induced costs will be inevitable. Road agencies need to plan for additional budgets for climate adaptation regardless of the approach they take i.e., “passive” or “active” (Underwood et al., 2017).
- Climate change will have greater impacts on the costs incurred during the maintenance and EOL phases, compared to other phases. When maintenance is required, the most impacted LCC component is maintenance costs, which are projected to increase up to 210-350% for primary roads and up to 40-250% for interstate roads.
- User costs are typically a dominating part of LCC, accounting for 76-85% of the total LCC, even though they are the LCC component least affected by climate change.
- Climate was found to be a medium sensitive input of pavement LCC. To achieve a more accurate quantification of the climate-induced economic losses/gains, higher sensitive inputs (e.g., gasoline/diesel fuel consumption models) must be predicted with greater accuracy.
- With passive climate adaptation, pavement LCC are estimated to increase by 0.08-0.21% per °C increase in temperature, whereas agency costs are projected to increase 0.41-1.43% for the same temperature increase. Climate change (per °C) alone will cause approximately $650-700 million/year of additional agency costs nationwide.

7.2. Limitations

Although the objective of the study presented in this paper were achieved, some limitations can be pointed out. Above all, it is difficult to assess the “real” impacts of future climates on pavement systems not only due to the uncertainty of how fast the climate is likely to change, but also due to the potential introduction of innovative pavement materials, pavement structures, construction and maintenance techniques, vehicle energy sources, recycling techniques, etc., which are likely to come to the market and therefore affect future pavement LCC. However, it is difficult or even impossible to predict these factors accurately, which is out of the scope of this study. Furthermore, here we analyzed results using climate projections from only one global climate model for just one future scenario. Introducing more climate models, as recommended by the scientific community, as well as including other future scenarios, will capture scientific and human uncertainties that are not discussed here. Hence, instead of accurately assessing the “real” impacts of climate change on pavement LCC in future periods, this study is designed to demonstrate the applicability of the proposed methodological framework and to provide insights on how current pavement design and management practices are exposed to the projected climates in the future period, thereby offering suggestions for future research directions.

7.3. Recommendations for future work

As a wide range of data with different climate conditions were evaluated, the results of the study are widely applicable elsewhere in the world provided that climatic, technical and economic contexts are similar. The methodological framework presented in this paper can be applied to quantify the economic impacts of climate change of a specific pavement at the state/national levels where input data are available. Such data include high-resolution climate projections, AADT, truck percentage, pavement structure, pavement materials, costs, etc. In addition, analysis tools such as Pavement ME or similar EICM based performance prediction tools are needed to apply this methodological framework to other countries. When such specific data and tools are (partly) not available, the methodological framework is still applicable with alternative data and “best” engineering assumptions. However, uncertainty may rise and reduce the accuracy of the analysis. To address this, some general data-driven methods (e.g., using falling weight deflectometer measurements or pavement condition monitoring data) are recommended as alternatives to assess the impacts of climate change on pavement performance (see an example in Qiao et al. 2020a).

Although the methodological framework is generally applicable, the conclusions are drawn based on a “worse” scenario i.e., RCP8.5. This is a limitation and different scenarios can be added in the future work. Furthermore, to improve the methodology framework, fuel (or energy) consumption models should be upgraded to include additional impacts of climate change, such as, for instance, more frequent utilization of air conditioning. Also, additional climate models can be included in the framework to quantify the range in scientific uncertainty of climate projections. Moreover, optimal performance triggers for pavement maintenance, rehabilitation and replacement activities can be determined for the different climate projections. Finally, it is also important to seek sustainable solutions for pavement climate adaptation, such as, for instance, the adoption of full depth reclamation technology in pavement reconstruction (Riekstins et al., 2020), and the development various decision support systems for selecting sustainable asphalt pavement types and road rehabilitation techniques (Santos et al., 2017b; Jato-Espino, 2018, Santos et al., 2019).

Declaration of Competing Interest

The contents of this paper reflect the views of the authors, who are responsible for the facts and the accuracy of the data presented. Any inclusion of manufacturer names, trade names, or trademarks is for identification purposes only and is not to be considered an endorsement. Moreover, this paper does not constitute a standard, specification, or regulation.

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