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Life Cycle Cost of Flexible Pavements and Climate Variability: Case Studies from Virginia

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Abstract

Climate factors have not become a typical metric to consider for pavement life cycle cost analysis (LCCA). Changes in climate may affect pavement rutting, roughness, and cracking and lead to consequent changes in maintenance decision-making and life cycle costs. This study develops a methodology to incorporate the effects of climate variability into flexible pavement LCCA and to derive the additional life cycle costs incurred due to changes in climate. Case studies were performed for three road sections in Virginia (US) to demonstrate the methodology, using approximate mean climate change trends predicted for the investigated regions. It is estimated that climate change will incur additional vehicle operating costs ranging between US$2.30 and $4.40 on average per vehicle/annum if roads are used under a 2050 high greenhouse gas emission scenario and without being maintained. Assuming responsive maintenance, the budget demand for maintenance will arrive much earlier in the pavements' life cycles (7–11 years earlier under the 2050 high-emission scenario). This is found to add up to 64% of agency costs (net present value) to repair each kilometer of the investigated roads in a 40-year design life. Agencies need to be aware of earlier or more frequent demands on their maintenance budgets.

Keywords: pavement, climate, resilience, life cycle costs, net present value, maintenance, performance, system

1. Introduction

Flexible pavements are environmentally sensitive infrastructure and their performance can be impacted by changes in climate. Though environmental conditions may change over a pavement's life cycle, current pavement design and management is mainly based on the assumption of static climatic conditions. Although there remains considerable uncertainty in the degree of future climate change that can be expected, the Intergovernmental Panel on Climate Change (IPCC) estimates that the global mean surface temperature will likely increase between 0.3 °C and 1.8 °C by around the year 2050 compared to the period between 1985 and 2005 (IPCC 2013). The future climate is likely to be warmer with fewer cold days. Heat waves may become more frequent, more intense, or have a longer duration. There will likely be more frequent and intense precipitation in many areas (IPCC 2013). Furthermore, low-lying and coastal roads are at risk due to rising water levels or may even suffer full/occasional inundation, with predicted sea levels increasing between 0.2 m and 0.38 m by around 2050 compared to the period between 1985 and 2005 (Knott et al. 2018). Rising groundwater levels adjacent to coasts or where higher rainfall occurs will likely reduce pavement support conditions. These climatic challenges will impact the longevity of pavements, lead to changes in the way we manage them over their life cycles, and, eventually, incur unexpected costs.

It is urgent to understand how pavement systems respond to these challenges. The term "pavement system" does not only refer to physical pavement structures, but also to how they are practically maintained and operated. This requires investigations into how pavements respond to future climates in terms of deterioration rates, maintenance decision-making, cash flows in the whole management cycle, and their net present value (NPV). The results of such investigations can help pavement engineers justify possible future budget requests for climate adaptation and build climate resilience into pavement management cycles.

Although climate variability can impact pavement performance, the consequent maintenance scheduling, and related costs, it has not been considered as an input in traditional pavement life cycle cost analysis (LCCA). Therefore, current pavement LCCA and LCCA-based decision-making may be inaccurate or invalid under future climates. This research aims to incorporate future climate conditions in flexible pavement LCCA, particularly focusing on developing a methodological framework that models the interactive system among climate, life-cycle performance, maintenance scheduling, and various related life cycle cost components. This framework will provide an approach to determine whether pavement life cycle costs will increase under anticipated future climatic conditions and to quantify the additional climate-induced costs/benefits for different LCCA components. The novelty of this research is that it investigates the pavement system as an integrated and interactive system, whereas the literature has generally only treated it as being independent or partly independent.

The structure of the paper is arranged as follows. Firstly, a methodological framework to assess the impact of climate variability on the interactive pavement system is described in the section 'Methodology'. Secondly, case studies are introduced for three pavement sections from Virginia (US), where a medium warming trend is expected (Meyer et al. 2011). The case studies are presented to demonstrate how to use the proposed methodological framework. Then, climate-related life cycle cost components are identified, focusing on the maintenance and use phases (see the section 'Life cycle cost analysis'). After that, LCCA is performed for the case studies under alternative climate scenarios (historical and 2050 predicted climates). By comparing the alternatives, changes in pavement LCCA due to changes in climate are derived. Finally, conclusions are drawn, and the limitations of the study are discussed. The calculated life cycle costs due to changes in climate may broadly represent the magnitude of costs as a national average for similar sections.

2. Methodology

2.1. Methodological framework

The methodological framework of this study is shown in Figure 1. The inputs to the system are the baseline (historical) and future climate scenarios, and the output is the LCCA results. The inputs and traffic loads, through interactions in the management processes, influence the eventual outputs. It is known that pavements are vulnerable to high temperature in the asphalt layers and excessive moisture in the granular layers and subgrade (Huang 2004; Dawson 2009). High pavement temperature can be caused by exposure to high air temperature and solar radiation, and it can affect the bituminous layers as asphaltic mixtures are viscoelastic. Asphalt stiffness, and the consequential ability to spread the load, decreases with increasing temperature, which can accelerate the deterioration in asphalt layers (Huang 2004).

Precipitation events, especially heavy ones, can cause excessive moisture to enter and be retained in pavement sublayers (Dawson 2009). Furthermore, high groundwater level can also increase the moisture in the pavements by capillary action. Excessive moisture can significantly reduce the stiffness and the ability of pavements to resist vertical plastic deformation (rutting), and shear will decrease (Dawson 2009; Lekarp et al. 2000).

Other climatic factors, including the amount of sunshine and wind speed, may affect the deterioration of flexible pavements (Dawson and Carrera 2010; AASHTO 2009). For example, the aging of pavement surfaces is associated with ultraviolet radiation, which can accelerate the development of cracking. The wind can increase the convection of heat between the air and the pavement's surface and thus helps to cool the pavement down. However, the impacts of sunshine hours and wind speed may not be as significant as temperature or moisture (Qiao et al. 2013; Yang et al. 2015).

Figure 1 here.

If unhelpful climate changes were to occur, pavements would deteriorate faster, and the additional deterioration would accumulate over the life cycle to become significant. To model the impact of climatic factors on pavement performance and service life, the MEPDG was adopted (Tighe et al. 2008; Underwood et al. 2017). The MEPDG is a state-of-the-art mechanistic-empirical pavement design and performance analysis tool that can account for pavement structure, material, traffic, and environmental factors. The MEPDG takes hourly records of air temperature, precipitation, sunshine percentage, wind speed, and groundwater level over an approximately 10-year period as the environmental inputs. As a part of the MEPDG, the Enhanced Integrated Climate Model (EICM) can translate the climatic factors into pavement temperature and moisture profiles (Zapata and Houston 2008). With the profiles, the stiffness of pavement asphalt and granular layers, which is as a metric of pavement elasticity and is related to durability, can be estimated (AASHTO 2009; Witczak et al. 2000). Then, pavement performance indicators, including the International Roughness Index (IRI), rutting, and fatigue cracking, can be predicted considering site-specific traffic volumes.

As a consequence of climate-induced additional deterioration, maintenance may need to be performed much earlier or more frequently (Qiao et al. 2015). To model the impacts of climate on maintenance scheduling and its subsequent maintenance effects on performance, a realistic performance-based maintenance decision-making system was modeled in this study in which maintenance is triggered whenever performance thresholds (IRI, rutting, or fatigue cracking) are reached. After maintenance, pavement performance levels will be improved. The immediate maintenance effect models of a typical maintenance treatment 'mill-and-fill' in Virginia are considered in this study (as described later in the section 'Life cycle cost analysis'). This feedback loop is performed when maintenance is needed in the life cycle of the investigated pavements (Figure 1).

Maintenance also incurs agency costs and work zone (WZ) user costs (differentiated from general 'user costs' in this study which, in general, will be reduced by maintenance), and therefore impact pavement life cycle costs (Mallick et al. 2014). User vehicle operating costs (VOC, the general 'user costs') due to pavement-vehicle interaction (PVI), megatexture (i.e., roughness), macrotexture, and dissipation, will also be impacted by pavement maintenance and, perhaps, by climate alone as well (Chatti & Zaabar 2012; Wang et al. 2014; Akbarian et al. 2014). In summary, an LCCA is conducted to estimate agency costs, user costs, and WZ user costs over a pavement's life cycle (as described later in the section 'life cycle cost analysis'). Eventually, pavement performance, maintenance decision-making, and life cycle costs will be compared between the baseline and future climate.

Other than climate inputs (Figure 1), other variables, such as traffic demand, fuel efficiency, pavement design, and maintenance type, were kept constant over a pavement's service life in both the baseline and future scenarios. For example, local traffic may increase or decrease in the future and can affect pavement performance, maintenance, and life cycle costs. However, if changes in these variables (e.g., traffic) were considered in the study, the LCCA results would perhaps be more sophisticated, but the differences in the LCCA results would not only reflect changes in climate but include impacts from the other variables as well. A constant traffic demand (i.e., 0% traffic growth rate) ensures that the comparisons for performance, maintenance, and costs are fair since the same number of vehicles will pass over the pavements during their design lives under both the baseline and future climate scenarios. Even if a 4% traffic growth rate is assumed, the average annual daily traffic (AADT) would be 7 times greater in 2050 than in 2000. In that case, traffic-related deterioration would dominate maintenance decisions and costs, while the impacts from climate would become insignificant. Moreover, to the authors' knowledge, no reliable traffic prediction is available for the period around 2050. Therefore, taking climate as the only inputs to the system allows the net effects of climate to be separated out. However, the framework (methodology) of this study (Figure 1) does account for the traffic input and its impact can be reassessed when the traffic demand around 2050 can be reliably predicted.

Moreover, changes in climate may lead to changes in local traffic demand. For example, sea level rise and inundation may make coastal roads impassable, or extend spring load restrictions in cold regions. Hence, an additional dashed arrow exists between the 'future climate' box and the 'traffic' box in Figure 1, and this link needs to be better studied in the future.

In addition, analyses were performed on the climate sensitivity of pavement performance. The baseline climatic data, including temperature, precipitation, wind speed, sunshine percentage, and groundwater level, were increased 5% from their historical average values, each at a time, to observe changes in predicted performance indicators at the end of 40 years. The absolute value of the relative sensitivity was calculated using the following equation:

$$Sensitivity = \left| \frac{change\ in\ performance / performance}{change\ in\ input / input} \right| \quad (1)$$

where,

$Sensitivity$ = absolute value of the relative sensitivity

$change\ in\ performance$ = change in performance indicators

$performance$ = pavement performance indicators

$change\ in\ input$ = change in climatic factor

$input$ = climatic factor

2.2. Case study

The three pavement sections used in the case study included one primary road section (Sec01) and two interstate highway sections (Sec02 and Sec03). The AADTs for the three sections were 4,463, 20,180, and 43,230, respectively (see also Table 1), representing a low, medium, and high traffic level in Virginia (VDOT 2007). Table 1 provides the structure, materials, and other descriptive statistics about the three sections. The sections are far away from the coast and at relatively high altitude (at least 100 m above sea level), so these roads will not be impacted by sea level rise.

Table 1 here.

The MEPDG was used to predict the pavement performance indicators under the baseline and future climate for the investigated sections. Accurate evaluation of the response of pavement performance to climatic factors is dependent on reliable inputs for asphalt and unbound material (including subgrade). In the MEPDG, the responses of asphalt and unbound material usually can be modeled at different calibration levels (i.e., Level 1, 2, and 3). For example, the inputs regarding the resilient modulus of the asphalt materials can be chosen from three calibration levels. Level 1 (the more detailed level) requires laboratory measurements of the dynamic modulus. Level 2 and 3 use existing material models, for example the Witczak model (Witczak 2004), which relates dynamic modulus to various parameters such as viscosity, air void ratio, binder content, sieve size, etc. In this study, the results of dynamic modulus testing of similar local asphalt mixtures were used to apply Level 1 inputs for the elastic response of the asphalt mixture under different temperature and loading conditions (Apeagyei and Diefenderfer 2011).

2.3. Life cycle cost analysis

LCCA is an analysis technique that is used to assess the long-term economic efficiency of alternative investment options. In general, LCCA can be used to calculate the cash flow from cradle to grave of a project or a product. LCCA has been applied in various pavement studies and agency practices to select cost-effective construction or maintenance methods (Santos et al., 2018; Bryce et al. 2014; Santos et al. 2014; VDOT 2011; FHWA 1998). In this study, the LCCA was applied as a tool to evaluate the impact of climate change on maintenance and its subsequent life cycle costs. The absolute value of the life cycle costs is not of great importance, but the difference between alternatives is. Thus comparisons were performed to obtain these differences in the life cycle costs of flexible pavements under baseline and future climate.

Generally, the life cycle costs of pavements include three components: agency costs, road user costs, and environmental costs (VDOT 2011). Agency costs may include construction costs, maintenance costs, labor costs, and road design costs. In normal operation, typical road user costs include VOC, delay costs, and accident costs. In addition, when maintenance is in underway, there are also WZ costs. Environmental costs usually include outputs to the environment such as the emission of greenhouse gases, toxic gases, water pollution, and noise. Due to difficulties in quantifying the monetary values of these environmental impacts, environmental costs are usually excluded from pavement LCCA (Walls III and Smith 1998). It is worth mentioning that the environmental costs are incurred in broad proportion to user costs (as user costs are closely linked to fuel consumption, which, in turn, relates to emissions) and in proportion to agency costs (as agency costs are closely related to raw material usage and debris disposal costs). Therefore, the increases or decreases in user and agency costs, which are the emphasis in this paper, will likely be matched by a commensurate increase or decrease in environmental disbenefit. For this reason, while not explicitly computing environmental costs, the difference in such costs can reasonably be assumed to 'shadow' the difference in monetary costs as computed below, albeit in a different 'currency' (e.g., mg equivalent CO_2). In addition, environmental impacts are usually considered in a life cycle assessment, which sees the highway system as a product and estimates the environmental impacts from a cradle-to-grave perspective (Huang et al. 2013; Harvey et al. 2014). The life cycle assessment is a more suitable approach to quantify the environmental 'cost'.

As the study aimed to compare life cycle costs under the baseline and future climate, only the cost components that were related to changes in climate in the LCCA maintenance and use phases were considered, including:

- Agency costs due to changes in the maintenance time or frequency.
- 'General' user costs – Maintenance can impact pavement performance (by maintenance effects) and have a long-term impact on 'general' user costs, through PVI (e.g., repaired pavements with smoother surfaces can reduce the fuel consumption of road users). The PVI relationship is expressed by using a VOC model, which relates user costs to pavement roughness.
- WZ road user costs – Changes of WZ road user costs due to changes in maintenance time, in terms of WZ VOC and delay costs.

The considered costs are eventually converted to the NPV as follows:

$$LCC(NPV) = \sum_{n=1}^{N} \frac{AC_n + VOC_n + WZC_n}{(1+i)^{n-1}} \qquad (2)$$

where,

$LCC(NPV)$ = Life cycle costs in NPV ($)

N = analysis period (years)

AC_n = agency costs in year *n* (costs of maintenance in this study) ($)

VOC_n = user VOC in year *n* ($)

WZC_n = WZ costs in year *n* ($)

i = discount rate

The discount rate is 4% in this study, to account for the time value of money. The Federal Highway Administration (FHWA) has reviewed costs in national pavement design and recommended a discount rate between 2% and 5% for pavement LCCA practice in the US, and this has been widely adopted in various studies (FHWA 1998; Zhang et al. 2008). The 4% is used in this study to represent the value of money for the baseline and future scenarios.

If maintenance will be performed more frequently in the future, it is likely that more traffic accidents would occur due to the more frequent WZ activities. More accidents would mean increasing WZ user costs such as VOC and delay costs. However, in this paper, the accident costs are excluded, as no suitable model was found to relate accident costs to climatic factors in pavement LCCA.

2.3.1. Agency costs and maintenance effects

In Virginia, mill-and-fill is a typical major maintenance rehabilitation, and thus was considered appropriate to be applied to the sections in the case studies. Mill-and-fill is performed by milling 2 inches (50 mm) of the surface material and refilling this depth with an overlay of the surface mix with a nominal maximum aggregate size of ½ inch (12.5 mm). Mill-and-fill is estimated to cost

\$40/square yard (\$48/m^2), including the costs of the material, machinery costs, and labor (Peshkin et al. 2011).

The maintenance effectiveness of mill-and-fill was adopted from another study (Qiao et al. 2016). That study investigated the immediate maintenance effects of mill-and-fill on IRI and rutting from the same region (VA) using field data. For the present study, this was supplemented by considering fatigue cracking. The maintenance effect model can be expressed as follows:

$$\Delta IRI = 0.811 \times IRI_0 - 39.74 \quad (3)$$

$$\Delta RUT = 0.475 \times RUT_0 - 0.023 \quad (4)$$

where,

$\Delta IRI, \Delta RUT$ = improvement of IRI (in/mi) and rutting (in) after maintenance (1 in/mi = 0.0158 m/km, 1 in = 25.4 mm)

IRI_0, RUT_0 = IRI (in/mi) and rutting (in) before maintenance

Mill-and-fill requires pre-treatment of underlying cracking, and mill-and-fill also provides a crack-free pavement surface. Therefore, the maintenance effect of mill-and-fill on fatigue cracking is to reset it to zero.

2.3.2. Vehicle operating costs

The calibrated Highway Development and Management (HDM-4) fuel consumption model (FC model) is used to represent VOC in this study, as fuel consumption cost is usually the most significant VOC cost component (Chatti & Zaabar, 2012). The HDM-4 FC model can estimate the fuel consumption of certain types of vehicles (cars, light trucks, articulate trucks, etc.) based on the operating speed and road roughness (in IRI). All of the three investigated sections have a normal operating speed of 65 mph (104 km/h). The IRI for each section in each year can be predicted by the MEPDG under different climate change scenarios, with consideration of maintenance triggers and maintenance effects on IRI (Equation 3). For the truck volume in each section, it is considered that 60% are light trucks and 40% are articulated trucks. These numbers are estimated from a VDOT traffic report (VDOT, 2017).

With the above information, the fuel consumption rate (liters of fuel per kilometer per vehicle) can be estimated. Eventually, the fuel consumption costs are calculated by multiplying the fuel consumption rate with section length, vehicle volume (of car, light truck, or articulated truck), and fuel price ($2.50/US gallon for gas [$0.66/L] and $2.40/US gallon for diesel [$0.63/L]) (Chatti & Zaabar 2012).

2.3.3. Work zone costs

In a WZ, the speed limit will be reduced compared to normal operating conditions. Vehicles need to reduce speed and may even have to stop for queueing, after which they will accelerate to the normal speed limit when exiting the WZ. Additional VOC (referred to as WZ VOC) will be caused due to the changes in vehicle speed, as vehicles have different rates of fuel consumption at different speeds. Furthermore, the WZ will also cause user delays when vehicles accelerate/decelerate, moving slowly to pass the WZ (i.e., moving delay), and queueing delays if there are any.

In this study, the WZ VOC is considered to be the additional fuel consumption due to WZ speed limits. This impact was calculated using a VOC model by Bennett and Greenwood (2003) that is associated with operating speed (Equation 5):

$$FC = a_0 + \frac{a_1}{S} + a_2 S^2 + a_3 RISE + a_4 FALL + a_5 IRI \qquad (5)$$

where,

FC = fuel consumption in US gal/mi (1 US gal/mi = 2.35215 L/km)

S = vehicle speed (mph) (1 mph = 1.6 km/h)

$RISE, FALL$ = rise or fall of the road (in/mi), assumed to be zero in this study (1 in/mi = 0.0158 m/km).

WZ delay costs are calculated as the cost sum of the moving delay and the queueing delay (if any). The moving delay is calculated from the difference of time to pass the WZ at the WZ speed limit and the transit time at the normal speed limit. In a normal traffic flow, the normal operating speed 65 mph (104 km/h) will be reduced to 35 mph (56 km/h) during WZ operation (VDOT 2007). The length of the WZ is considered to equal the length of the section and WZ. The mill-and-fill is assumed to last 7 days/lane-mi (4.3 days/lane-km) for each section with one lane closed during operations.

During maintenance operations, a queue is considered to occur if the traffic demand exceeds the capacity of the lane. The highway capacity under normal operation was calculated according to the Highway Capacity Manual (TRB 2010), and the WZ capacity was calculated with the model described by Memmott and Dudek (1982). An example of the queueing delay for Sec03 is shown in Figure 2. The mill-and-fill started at midnight and finished at 8:00 a.m. The demand at 6:00 a.m. exceeded the WZ capacity, and thus a queue was considered to start and continue until 7:00 a.m. The number of vehicles in the queue in a specific hour can be calculated by subtracting the accumulated number of outgoing vehicles from the incoming vehicles, using a deterministic queueing theory (Chien et al. 2002). The calculated vehicle-hours for the delay were then multiplied by the time value for the drivers ($15 for truck drivers and $8 per car driver; FHWA 2015).

Figure 2 here.

2.4. Future climate

Approximately 10 years of hourly measurements of temperature, precipitation, wind speed, sunshine percentage, and groundwater level from the MEPDG-adopted ground stations in Virginia (Roanoke, Richmond, Wakefield, Lynchburg, Richmond/Ashland, and Danville) were used to represent baseline climatic data (2000–2009) for the selected sections (AASHTO 2009). The 10-year climatic record was repeated four times to represent the design life of the pavements (40 years). Future climate in terms of changes in temperature and precipitation was investigated by the MAGICC/SCENGEN program at local scale (Wigley 2008). Climate models, including CCSM_30, GFDLCM2.1, NCARPCM1, MIROC, IPSL_CM4, MRI-2.3.2A, MPIECH-5, HadCM3, and HadGEM,1 were selected in MAGICC/SCENGEN because these models are believed to lead to more representative local conditions (Meyer et al. 2011).

MAGICC/SCENGEN is a tool to provide global/local climate change predictions based on a variety of chosen candidate climate models. The baseline temperature and precipitation can be used to create a likely future climate. The future climate is dependent on the future greenhouse gas emission pathway due to human activities (IPCC 2013). However, the pathway is uncertain and thus three emission scenarios (high, medium, and low) were used to account for this uncertainty. MAGICC/SCENGEN predicted the changes in average annual temperature and precipitation in 2050 compared to the baseline (Table 2).

Table 2 here.

The changes in temperature or precipitation in 2050 (under each emission scenario) were added to the 10-year baseline hourly temperature and precipitation to create possible future temperature and precipitation, using the equations:

$$T_{i,future} = T_{i,baseline} + \Delta T \quad (6)$$

$$P_{i,future} = P_{i,baseline} \times \Delta P/100 \quad (7)$$

where,

$T_{i,future}$ = future temperature in hour *i*

$T_{i,baseline}$ = historical temperature in hour *i*

ΔT = changes in future temperature compared to the baseline (Table 2)

$P_{i,future}$ = future precipitation in hour *i*

$P_{i,baseline}$ = historical precipitation in hour *i*

ΔP (%) = percentage changes of precipitation compared to the baseline (Table 2)

This allowed 'likely' 10-year climate records to be determined for around the year 2050 for low-, medium-, and high-emission scenarios. The created 10-year 2050 climate was then repeated four times while performing the MEPDG analysis to predict performance indicators in the 40-year design-life of the pavements under a likely 2050 climate. To examine the validity of the generated future climate, the future maximum and minimum temperatures were compared to the predicted temperature data from three random individual climate models (CCSM, GFDL, and MIROC). The data included maximum and minimum temperatures for the three sections in each day from 2030 to 2070 (see Downscaled CMIP5 Climate Projections in Reclamation, 2013). The comparison results for Sec01 are presented in Figure 3 as an example:

Figure 3 here.

It can be seen from Figure 3 that variabilities exist in the predicted average daily maximum/minimum temperature using different climate models. Figure 3 also shows that the generated temperature (labelled 'Future: Low', 'Medium' and 'High' in Figure 3) seems to have a reasonable match with the predicted temperature, considering the variabilities in predictions of different climate models. For example, the average of the generated maximum temperature is almost equivalent to that predicted by the GFDL model. The average of the generated minimum temperature is generally greater than that predicted by the three models, indicating overestimations on low temperatures. However, the maximum temperature is more important because extreme high temperature does significantly more damage to pavements (e.g., rutting). Particularly as (thermal) cracking is not considered in this study, the overestimation on the daily minimum temperature will not likely impact the results. Therefore, the generated future climate can be used further in the study for pavement performance analysis.

3. Results and discussions

3.1. Sensitivity analyses

Performance indicators at the end of 40 years were first calculated using the MEPDG under the baseline climate, assuming no maintenance. The hourly climatic factor was then increased by 5% (Table 3) and the performance indicators were calculated again with the MEPDG. The change of performance indicators due to these changes in climatic factors for the three sections is shown in Table 4 to observe their relative influence on the performance indicators (calculated using Equation 1).

Table 3 here.

Table 4 here.

It can be seen from Table 4 that temperature is the most influential climatic stressor for almost all performance indicators (all sections), with the sunshine percentage (Sec 03 – high traffic road) and groundwater level (Sec 01 – low traffic road) being secondary factors. However, the sunshine percentage and groundwater level are not always secondary factors (the magnitudes of the sensitivity results are less compared to temperature; see the sensitivity for other sections). The significant sensitivity to groundwater level in Sec01 is partly because the groundwater level is only 5 ft (1.5 m) below the pavement surface (see Table 3), and the pavement is much thinner than the others, making it more vulnerable to changes in moisture content which may occur due to rising groundwater level. In general, IRI is much less sensitive to climatic factors compared to rutting (Table 4). Similar to rutting, the influential climatic factors for IRI are temperature and groundwater level for Sec01 and temperature for Sec02 and Sec03. Fatigue cracking is also found to be sensitive to temperature (Sec01 to Sec03), and groundwater level is found to be influential (on fatigue cracking) only when the original groundwater level is high (Sec01). From the sensitivity analysis, it can be seen that:

- Changes in temperature are always influential for rutting, IRI, and fatigue cracking;
- Changes in groundwater level can be influential for pavements with high groundwater but become insignificant when it is low;
- For Sec03, 5% more sunshine had a small but noticeable impact on both rutting and fatigue cracking, but this was small compared to the influence of temperature, which does not increase independently of increased sunshine. Therefore, due to its small impact and because part of its impact will, in practice, be accounted for in temperature change impacts, changes in sunshine percentage are neglected;
- Changes to wind speed are never influential. Although future predictions of wind speed are not available, the likely changes can be neglected when predicting performance indicators under future climate.

From Table 4, it also seems that temperature increases are more critical (as regards rutting, IRI, and fatigue cracking) for thick pavements (Sec02 and Sec03, both interstate roads), compared to thin pavement (Sec01, primary road). Firstly, thick pavements have greater layer thickness for the accumulation of rutting. Secondly, the greater volume of traffic can lead to greater rutting, especially when asphalt temperature is greater or subject to more extreme high-temperature events. Therefore, thicker pavements with a greater volume of traffic (e.g., interstate roads) may be more vulnerable to changes in temperature.

Because existing climate models usually do not predict the other climatic factors, including wind speed, sunshine percentage, and groundwater level, their impacts can only be assessed by the sensitivity analysis. In this case, they were not found to be critical. However, the method described in this study may not be suitable for cases when the influences of wind speed, sunshine percentage, or groundwater level on pavement performance are significant and where these factors will change significantly in the future.

3.2. Maintenance

For maintenance, two types of schemes were considered, including ‘do nothing’ and responsive maintenance. Similar to most current maintenance practices, the responsive maintenance was triggered whenever pavement performance level reached practical maintenance thresholds (VDOT 2012; AASHTO 2009):

- IRI: 190 in/mi (3 m/km)
- Rutting: 0.75 in (20 mm)
- Fatigue cracking: 25% (lane area)

In Virginia, a poor interstate or primary road typically has an IRI between 140 and 190 in/mi (2.2–3 m/km) and is considered deficient in ride quality (VDOT, 2016). According to the upper boundary of the Virginia criteria, the IRI threshold for maintenance is set to 190 in/mi (3 m/km). The rutting and fatigue cracking thresholds are adopted from the MEPDG. It is important to note that different agencies have implemented different thresholds. For example, the FHWA uses 150–250 in/mi (2.4–3.9 m/km) as the IRI threshold for rehabilitation (mill-and-fill) (FHWA, 2013). To account for variabilities in the thresholds, a sensitivity test was added to this study. In the test, the above thresholds are increased or decreased by 10% respectively to demonstrate how different maintenance thresholds can affect the results.

In addition, locally calibrated maintenance effects are incorporated (see also Equation 3 and 4). Eventually, the life cycle costs (including agency costs, user costs, and WZ costs) were calculated for the three sections under baseline and future climate scenarios. The results are described below for the "do nothing" and responsive maintenance rehabilitation schemes.

Do nothing

The terminal values (in year 40) of the performance indicators were compared to their respective thresholds. For all three sections, all indicators were found to increase under various high-emission scenarios compared to the baseline. In general, the increases for the indicators are the greatest in the high-emission scenario and the least in the low-emission scenario. It was estimated that the increases in terminal IRI (in year 40) can range between 0.18% and 0.9%, 4.1% and 4.2%, and 0.38% and 0.58% (depending on the emission scenario) for Sec01, Sec02, and Sec03 in the future climate, compared to the baseline. For rutting, the increases can range between 5.9% and 10.8%, 16.3% and 19.4%, and 11.2% and 15.2%. The increases are 13.3%–25.2%, 8.3%–8.9%, and 16%–21.7% for fatigue cracking. Figure 4 shows the ratios between the terminal values of the indicators (under the 2050 high-emission scenario and the baseline climates as an example) and their thresholds respectively.

Figure 4 here.

Figure 4 indicates that both Sec01 and Sec02 need to be maintained because one or more indicators exceeded their thresholds within 40 years (rutting for Sec01 and all indicators for Sec02). Hence, the 'do nothing' scheme does not apply to Sec01 and Sec02. All performance indicators in Sec03 are predicted to be below their thresholds. The fatigue cracking in Sec03 is predicted to be much less than the threshold and is almost negligible. Hence, the 'do nothing' scheme is applicable to Sec03.

The life cycle costs in NPV were calculated for the three sections under the 'do nothing' scheme. Although they require maintenance treatments, Sec01 and Sec02 are also included in the calculation for comparison purposes. In general, life cycle costs were found to be greater in the future climate. The life cycle costs equal road user VOC, as no maintenance is assumed (agency and WZ costs excluded). The road user costs are a function of IRI (see Chatti & Zaabar 2012). The additional cumulative NPV due to changes in climate can then be derived by subtracting the cumulative NPV under the baseline from that under the future climate scenarios (Figure 5). For comparison purposes, the functional unit (vertical axis) is chosen as US dollars per km.

Figure 5 here.

In general, changes in climate can cause increases of life cycle costs (road user costs). The increases are more for the high-emission scenario and less for the low-emission scenario. It can be summarized from Figure 5 that changes in climate will increase life cycle costs between approximately up to \$12,000/km and \$28,000/km for the investigated sections over the 40-year design lives of the pavements under the high-emission scenario. Considering the total amount of average travel mileage per vehicle in Virginia (approximately 15,000 mi/year), this is equivalent to an additional \$2.30 to \$4.40 fuel consumption per year per vehicle on average caused by climate change. Such costs can be significant at state or national levels. Even though the proportion of the climate induced cost is not significant for the total life cycle costs (approximately 0.03%–0.16%), the cost can nevertheless be significant due to the magnitude of the total costs over 40 years.

Responsive maintenance

Sec01 and Sec02 reach maintenance thresholds within 40 years that would trigger the mill-and-fill (Figure 6). The maintenance is triggered due to rutting for Sec01 and fatigue cracking for Sec02. Immediately after maintenance, IRI, rutting, and fatigue cracking will be reduced. The immediate maintenance effects are calculated by Equations 3 and 4. The fatigue cracking will reset. Maintenance will be triggered significantly earlier in the future climate for Sec01 (up to 11 years, see Figure 6(a)). Maintenance frequency will increase in the future climate for Sec02 from one time to two times (see Figure 6(b)). Maintenance is not triggered for Sec03, and thus Sec03 will be excluded from the following analysis.

Figure 6 here.

The life cycle costs (in NPV) were then calculated, now including agency maintenance costs, user costs (based on PVI), and WZ costs. Figure 7 shows the additional cumulative NPV caused by climate change, which is derived by subtracting the cumulative NPV under the baseline climate from that under the future climate scenarios (see the dark coloured broken lines). In the beginning, the climate-induced cost increases with time (before maintenance is triggered under all climate scenarios; this is represented by the early phases of the curves in Figure 5 for Sec01 and Sec02). The increases are due to the additional deterioration caused by climate change. The total costs incurred at the end of this period are greater under the high-emission scenario compared to the costs under the medium- and low-emission scenarios.

Figure 7 here.

The cost trend has sudden increases when maintenance is triggered under the future climate and premature maintenance and WZ cash flows occur (around year 20 for Sec01 and year 15 and 35 for Sec02). The premature maintenance cash flow will mean that (a) maintenance will be triggered much earlier due to changes of climate (Figure 6) and road agencies will need to prepare for an accelerated budget and traffic management; and (b) the NPV of the agency costs will be greater when maintenance needs to be performed earlier or more frequently (up to 64% additional NPV in the future climate for the investigated sections, see Table 5).

Table 5 here.

After the premature maintenance, the cumulative life cycle costs slowly decrease (Figure 7) because of the maintenance effect. The earlier-triggered maintenance resulted in less cumulative life cycle costs under the future climate scenarios compared to the baseline. This is followed by a sudden decrease in the cumulative costs when maintenance is triggered under the baseline, where negative cumulative costs are added to the curves. For Sec02, there are secondary rapid increases in the cumulative costs around year 35 because maintenance is triggered for a second time under the 2050 climate scenarios (Figure 6(b)). The total additional cumulative costs incurred by changes in climate are shown at the end of the 40-year period. For Sec01, there will be 1.1%, 1.7%, and 1.9% additional life cycle costs caused by changes in climate. For Sec02, the same figures are 1.06%, 1.05%, and 1.04%. However, user VOC due to PVI is found to decrease in the 2050 climate scenarios (Table 5). This is because earlier or more frequent maintenance can reduce the overall pavement roughness and thus reduces PVI related to VOC.

Compared to Sec01, the cost differences among different climate scenarios for Sec02 are less significant (Figure 7). This is because the performance indicators that triggered the maintenance are different (rutting for Sec01 and fatigue cracking for Sec02), and fatigue cracking in Sec02 (sensitivity = 0.4) is not as sensitive to climate as rutting in Sec01 (sensitivity = 1.02, see Table 4). This observation is also shown in Figure 8. It can be seen in Figure 8(a) that rutting and the subsequent maintenance scheduling are significantly affected by different climate scenarios. Figure 8(b) shows that the fatigue cracking in Sec02 will develop faster under various 2050 climate scenarios compared to the baseline, when the temperature is 4.9 °F, 3.8 °F, and 2.9 °F higher than the baseline on average (see also Table 2). However, the cracking differences among different 2050 climate scenarios become much less. This seems to indicate that the influence of temperature on fatigue cracking starts to reduce further as it becomes hotter. For another example, the sensitivity of fatigue cracking to most of the climatic factors is less in a hotter location (Sec02 compared to Sec01 or Sec03, see Table 3 and Table 4). When the temperature is higher, some non-climatic factors (e.g., loading) probably significantly dominate the development of fatigue cracking and the influence from temperature ceases to increase with increases in temperature.

In general, the sensitivity test shows that different maintenance thresholds can significantly impact the LCCA cash flows (mainly for maintenance) and the cumulative costs. When the thresholds decrease by 10% (thresholds −10% in Figure 7), maintenance cash flows will occur much earlier in the pavement's life cycle. For Sec01, changes in the thresholds (thresholds −10%) do not seem to be influential on the terminal values of additional cumulative costs; however, the influence on the terminal values of additional cumulative costs is significant for Sec02. This is because the decreases in the thresholds for Sec02 can increase the maintenance frequency under the baseline so that the maintenance frequency under the baseline and future climates becomes the same (two times in 40 years instead of one time in 40 years under the baseline climate, see also Figure 6). When the thresholds increase by 10% (thresholds +10% in Figure 7), the cash flows and the cumulative costs are also affected. For Sec01, maintenance is no longer needed under the baseline so that the terminal values of additional cumulative costs become greater. For Sec02, the terminal values of additional cumulative costs reduce significantly when the thresholds increase by 10%. This is because maintenance is only needed once in 40 years under the future climate (instead of twice, see Figure 6).

Figure 8 here.

The NPV of the agency costs is relatively insignificant compared to the VOC (Table 5), which agrees with other studies (e.g., Santos et al. 2013). However, the timing of maintenance can be significantly changed due to climate change and thus can impact the total life cycle cost curves and user costs through PVI (Figure 7). Changes in climate may also impact WZ user costs in terms of NPV and occurring timing (the same as the maintenance cash flows). However, the proportion of the WZ user costs is insignificant in total life cycle costs (less than 0.26%, see Table 5) and thus can be neglected when assessing climate-induced costs.

3.3. Validating the MEPDG performance prediction

This section investigates whether the MEPDG-predicted deterioration matches with field measurements. It is important to do so as the performance prediction is a key step in the interactive system and can impact the LCCA (according to the methodological framework, see Figure 1). Pavement condition survey data were collected from the Pavement Management System (PMS) of VDOT, including rutting and fatigue cracking measured in different years (IRI data are not available). For example, rutting and fatigue cracking data were extracted for Sec02 (Figure 9). The horizontal axis represents the number of years since the latest rehabilitation (i.e., when the pavement performance was reset). The performance curves for rutting and fatigue cracking are predicted by the MEPDG based on the historical climate.

Figure 9 here.

Compared to the field measurements, it seems that both rutting and fatigue cracking are overestimated by the MEPDG. However, as there is no information on how trucks were distributed between the two lanes, a default of 90% of trucks in the design lane was used in the MEPDG modelling (the remaining 10% of trucks ran on the other lane). When the percentage of trucks in the design lane was overestimated, rutting or fatigue cracking (in the design lane) would be overestimated as well. If the predicted rut depth or fatigue cracking are averaged into two lanes, it seems the prediction matches better with the measurements (see the 50% MEPDG prediction curve in Figure 9). This could happen in a case when trucks were evenly distributed between the two lanes of Sec02 in reality, or purely be caused by inaccuracy of the MEPDG prediction. In addition, the trend of the rutting data could slowly increase with time and could match well with the trend of the 50% MEPDG prediction curve. The rutting measurements show fluctuations, probably due to the randomness of rutting development and/or deviations among survey locations. The measured fatigue cracking had a significant decrease after year 9, and this is probably because local patches were performed to restore pavement surfaces in that year and the maintenance effect is captured by the data. Overall, the MEPDG seems to have a reasonable prediction for the magnitudes and trends of rutting and fatigue cracking development, considering uncertainties in truck distribution between lanes and inherent uncertainties in the measured data.

4. Limitations of the study

Although comprehensive, this study adopts various assumptions. To better incorporate climate variabilities into pavement LCCA, these assumptions will need to be replaced by updated modelling approaches or, at least, improved with better quantification of uncertainties in the future. Some major assumptions, their limitations, and recommendations for future studies are listed in Table 6.

Table 6 here.

In addition, this study adopts a deterministic approach, rather than a probabilistic approach. This is because various models in the methodological framework are not stochastic, including the climate models, pavement performance model (the MEPDG results), maintenance effectiveness models, and various life cycle cost models. To conduct a 'real' probabilistic approach, additional information is needed (e.g., reliability of climate change prediction, a probabilistic pavement performance prediction tool, quantifiable variabilities in the economic inputs such as unit costs of materials, probabilistic fuel consumption models, discount rates, and so on). Substantial additional work will be required to collect information and data to develop a probabilistic approach and thus it is recommended as another avenue of future research.

5. Conclusions

This study attempts to account for climate variabilities in pavement LCCA. Case studies were performed on typical Virginia roads with different structures and levels of traffic. The following conclusions can be drawn for similar pavements under similar climatic conditions constructed around 2050:

- Pavement performance is most sensitive to temperature, and temperature is likely to impact pavement life cycle costs the most among other climatic factors. Rising groundwater was found to be influential only when the existing groundwater level is high (e.g., Sec01). Other factors such as precipitation, sunshine percentage, and wind speed were not found to have a significant impact on pavement performance and thus their impact on life cycle costs may be negligible.
- Major maintenance will be triggered much earlier (e.g., 7–11 years earlier under the 2050 climate compared to the baseline 2000–2009 climate for Sec01) or more frequently (two times in 40 years under the 2050 climate instead of one time under the baseline climate). Road agencies need to prepare for the premature/additional budget for maintenance. The budget could be significant on a state or national level.
- By accounting for change variabilities, pavement LCCA needs to consider not only the total costs of pavements, but also the timing of cash flow in the LCCA in order to plan maintenance budgets and practice pavement climate adaptation.
- If a road is not maintained (i.e., the ‘do nothing’ maintenance scheme) or is under-maintained (due to budget or other limitations), PVI related VOC and thus pavement life cycle costs will be increased by the anticipated changes in climate. On average, users will need to pay an additional $2.30 to $4.40 on fuel per year per vehicle.
- Pavement maintenance thresholds can have significant impacts on the occurrence time of maintenance cash flows and climate-induced costs. Therefore, it is important to incorporate accurate maintenance thresholds to assess the differences in life cycle costs caused by climate variabilities.

- Although changes of climate can cause earlier maintenance or more-frequent maintenance, the impacts of climate on the WZ costs can be negligible, considering the insignificant proportion of the WZ costs in a pavement's life cycle costs.

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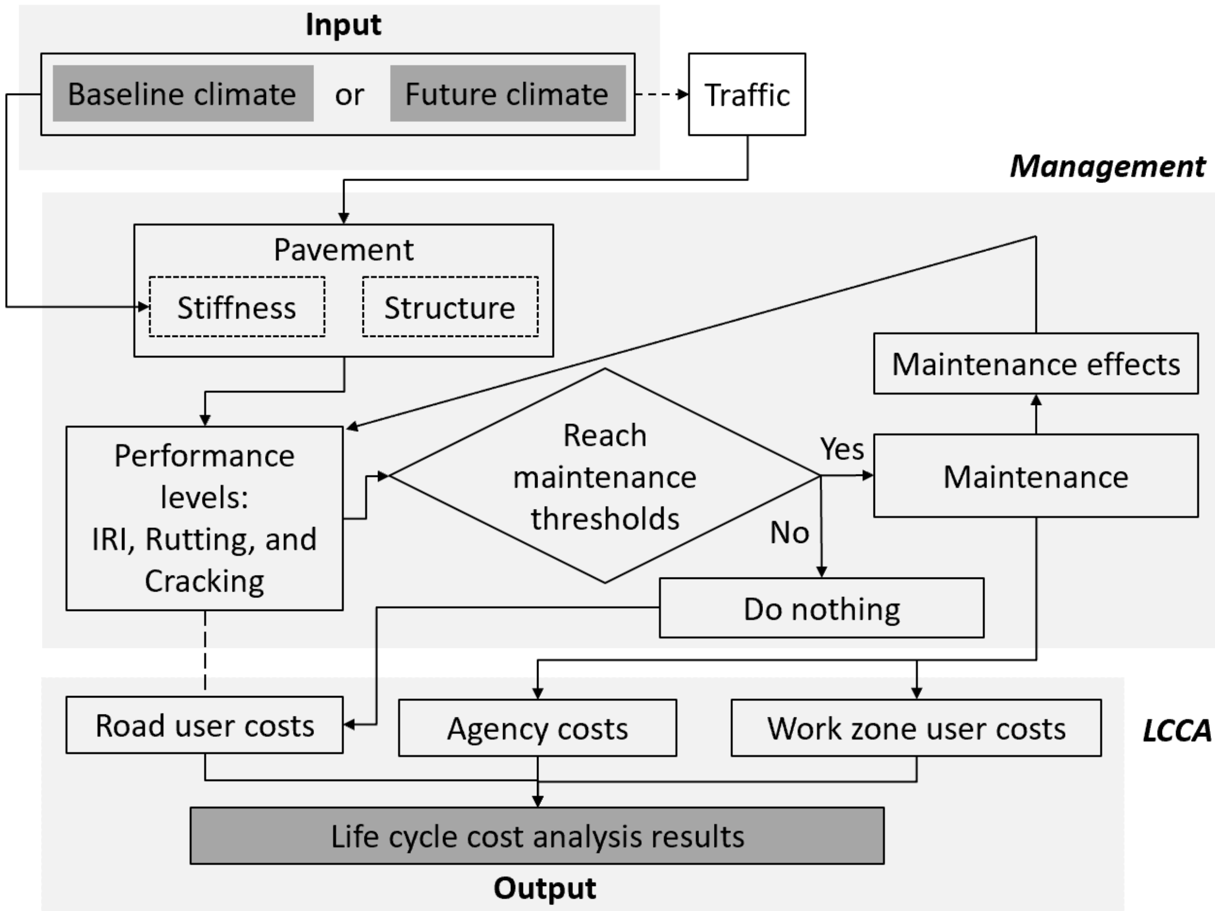

Figure 1. Methodological framework.

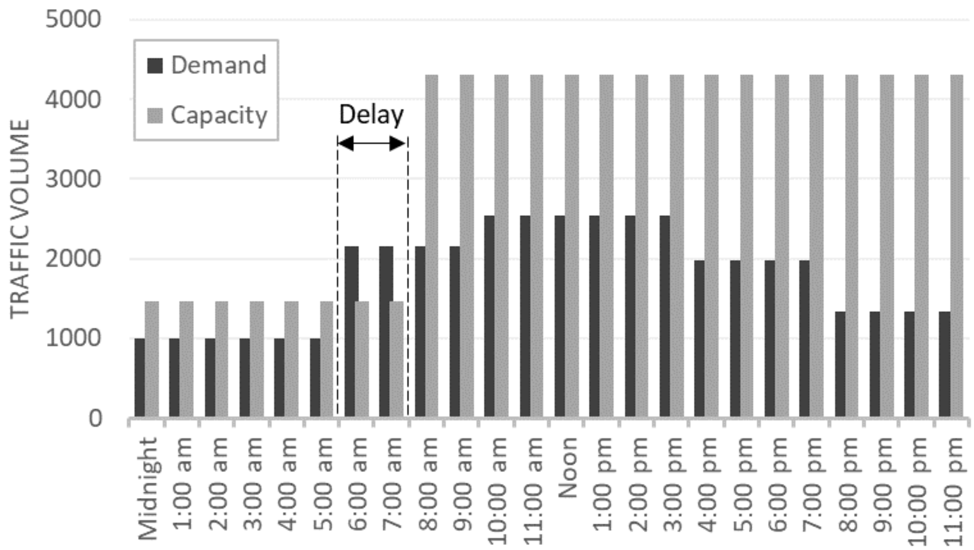

Figure 2. WZ capacity and traffic demand for Sec03.

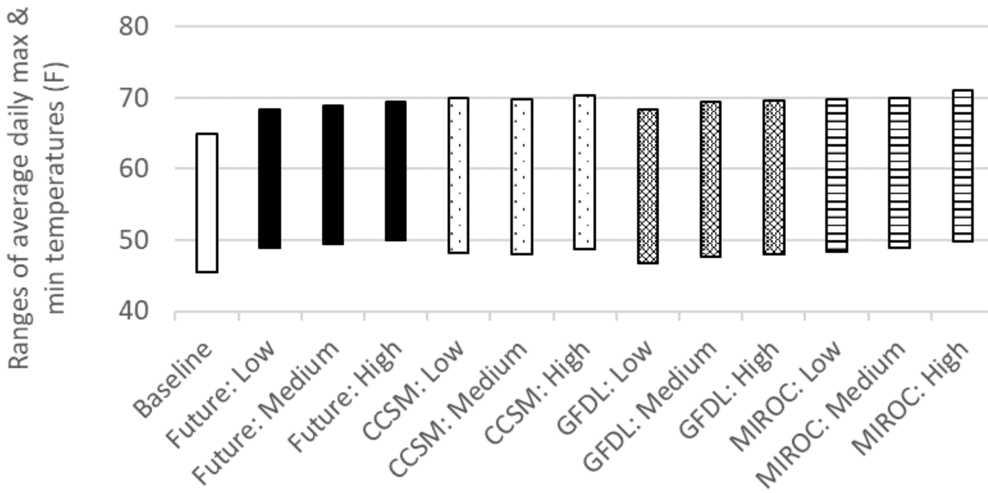

Figure 3. Comparisons of future climate data for Sec01 (50 ºF = 10 ºC, 70 ºF = 21 ºC, +1 ºF = + 0.56 ºC).

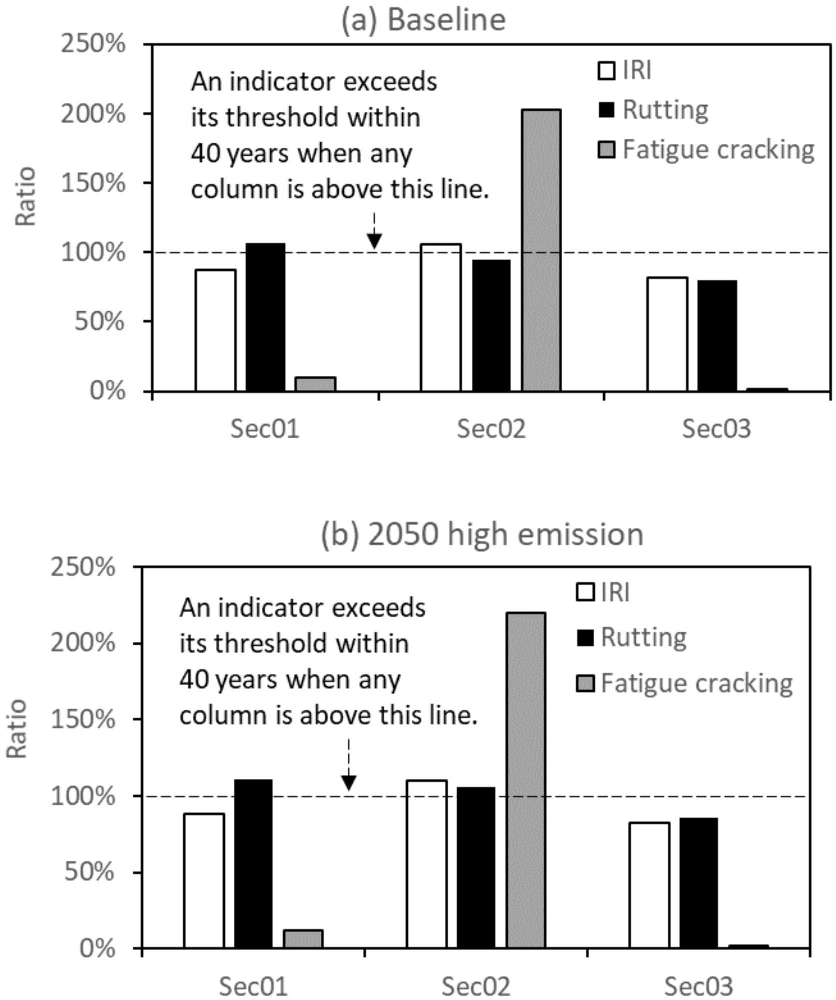

Figure 4. Ratios between the terminal values of performance indicators (under 2050 high emission scenario and baseline climates) and their respective thresholds.

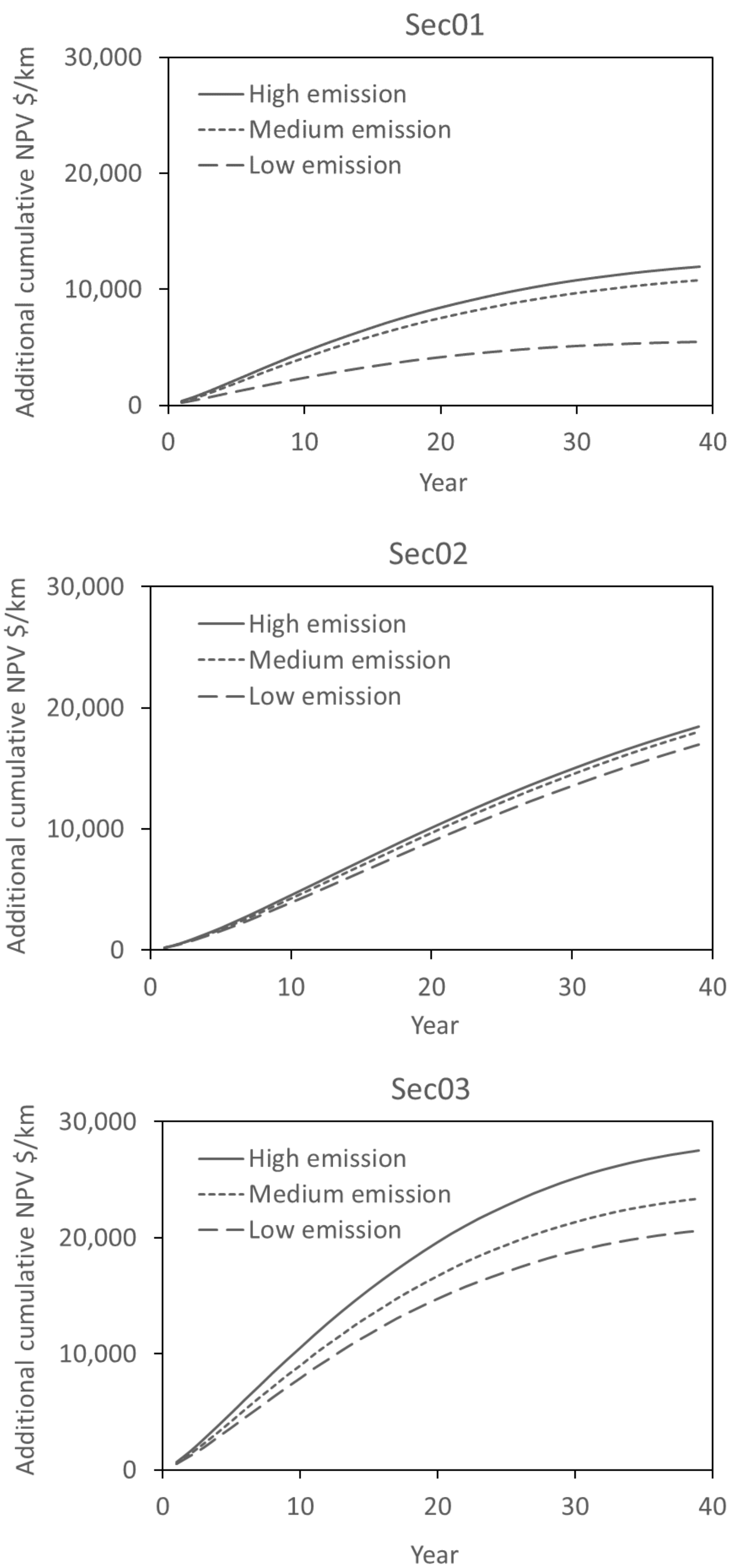

Figure 5. Do nothing: Additional cumulative costs (relative to cumulative baseline costs) due to changes in climate for all the sections.

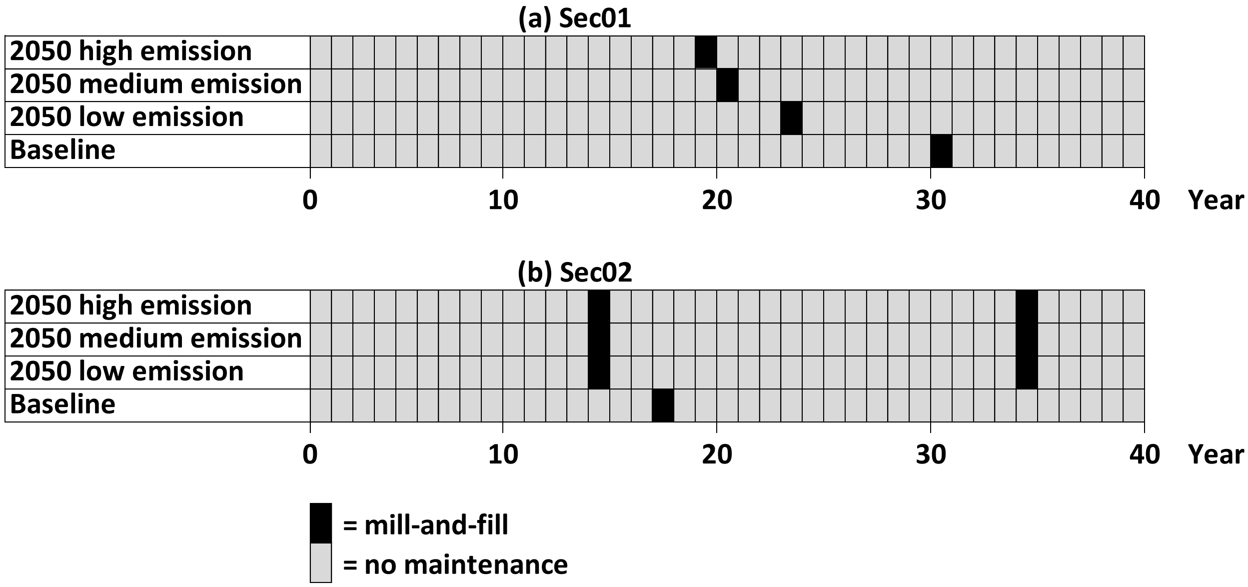

Figure 6. Responsive maintenance (mill-and-fill) scheduling for Sec01 and Sec02.

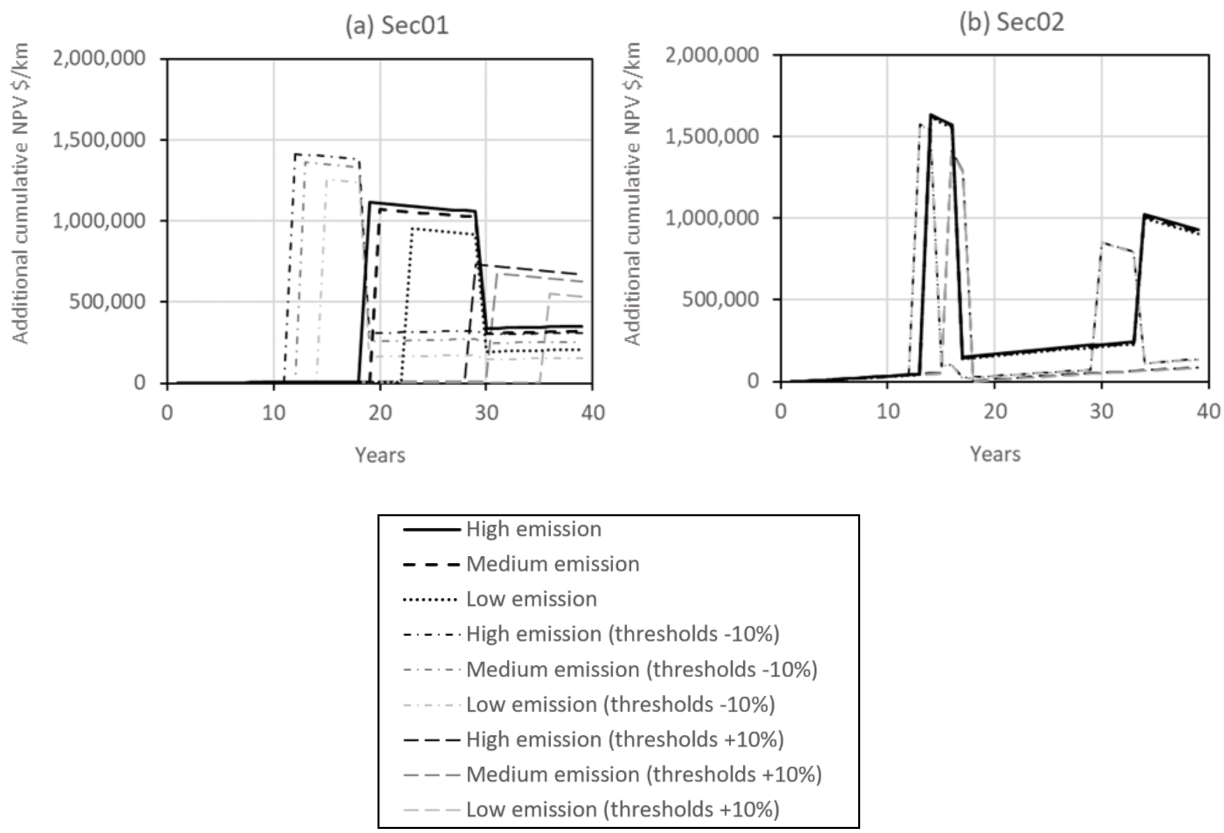

Figure 7. Responsive maintenance: Additional cumulative costs (relative to cumulative baseline costs) due to changes in climate for Sec01 and Sec02 (with sensitivity test).

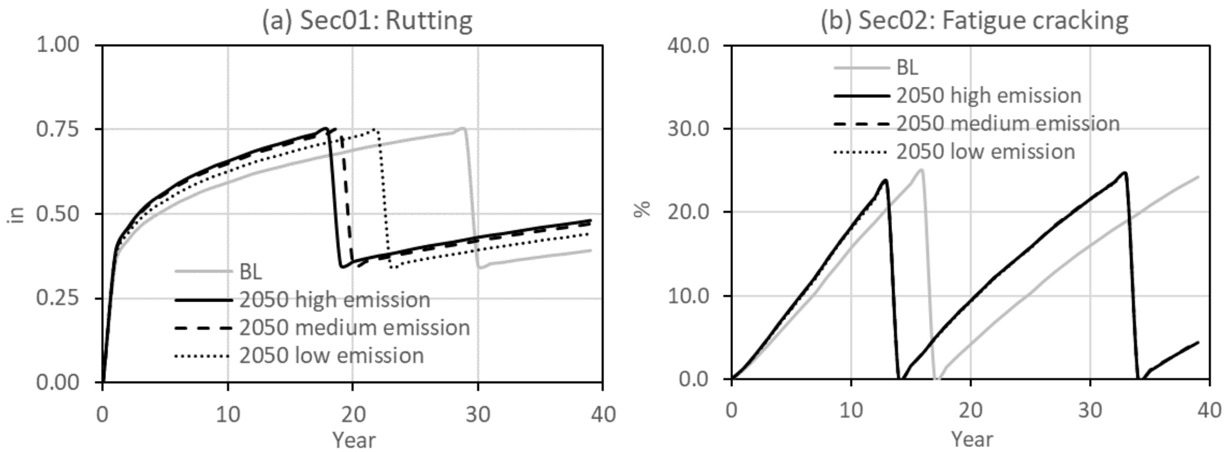

Figure 8. Dominating performance indicator for maintenance in Sec01 (rutting) and Sec02 (fatigue cracking) (1 in = 25.4 mm).

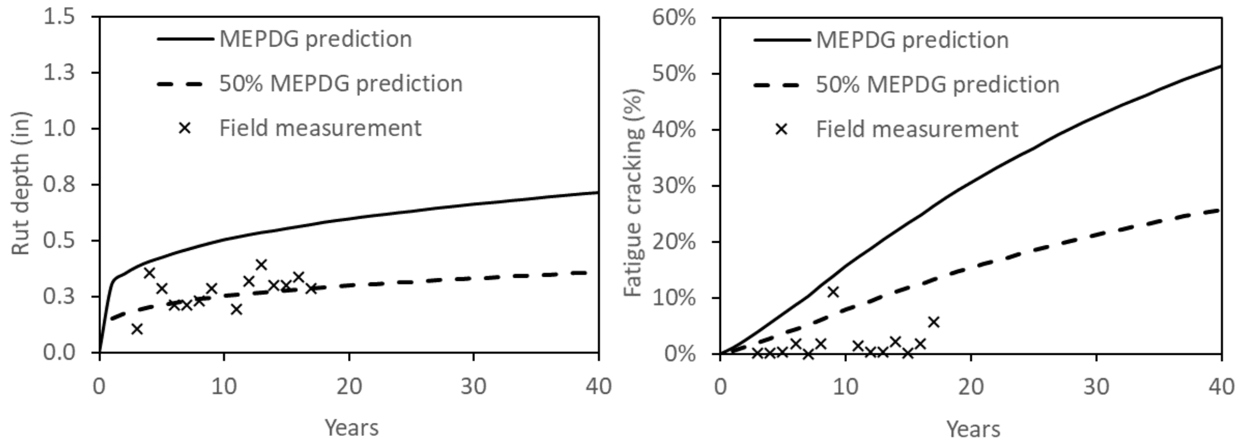

Figure 9. MEPDG rutting and fatigue cracking predictions and field measurements for Sec02.

Table 1. Layers and materials of Sec01, Sec02, and Sec03.

Layer	Type	Thickness (mm)	Specifications
Sec01: Primary (SR00100NB, Begin-End mile: 41.04 - 41.49); AADT: 4,463, Truck percent: 5.4%, Section length/width: 0.16 km/3 m × 2 lanes			
Layer	Type	Thickness (mm)	Specifications
1	Asphalt layer	40	SM-2A (PG grade: 64-22)
2	Base layer	100	B-3 (PG grade: 64-22)
3	Subbase	250	No. 21A (A-1-a), Resilient modulus: 29,000 psi
4	Subgrade	-	A-3, Resilient modulus: 24,500 psi
Sec02: Interstate (IS00085NB, Begin-End mile: 15.68 - 19.52); AADT: 20,180, Truck percent: 10.5%, Section length/width: 1.23 km/3.5 m × 2 lanes			
Layer	Type	Thickness (mm)	Specifications
1	Asphalt layer	40	SM-12.5D
2	Asphalt base	50	BM-25.0
3	Subbase	300	A-3, Resilient modulus: 24,500 psi
4	Subgrade	-	A-3, Resilient modulus: 24,500 psi
Sec03: Interstate (IS00081NB, Begin-End mile: 92.37 - 94.04); AADT: 43,230, Truck percent: 16.5%, section length/width: 0.55 km/3.4 m × 2 lanes			
Layer	Type	Thickness (mm)	Specifications
1	Asphalt layer	40	SMA-12.5E
2	Asphalt layer	36	SM-12.5D
3	Asphalt layer	30	CB-1 or H-2 (PG grade: 70-22)
4	Base layer	190	H-3 (3) (PG grade: 70-22)
5	Subbase	150	No. 21, Resilient modulus: 19,215 psi
6	Subgrade	-	Select unstabilized material, Resilient modulus: 39,000 psi

Note: 1,000 psi = 6.89 MPa; For material codes, see VDOT Road and Bridge Specifications (VDOT 2007). The resilient moduli of sub-surface layers adopt default design values from the MEPDG and VDOT Road and Bridge Specifications (VDOT 2007; MEPDG 2009).

Table 2. Climate change projections (T = temperature, P = precipitation) compared to the baseline (2000-2010, +1 ºF = + 0.5556 ºC).

Sections		**Sec01**		**Sec02**		**Sec03**	
Climatic factors		ΔT (ºF)	ΔP (%)	ΔT (ºF)	ΔP (%)	ΔT (ºF)	ΔP (%)
2050 emission scenario	High	+ 4.5	+ 7.0	+ 4.9	+ 6.7	+ 4.5	+ 7.0
	Medium	+ 3.9	+ 5.9	+ 3.8	+ 5.7	+ 3.9	+ 5.9
	Low	+ 3.4	+ 5.2	+ 2.9	+ 5.0	+ 3.4	+ 5.2

Table 3. A summary of average historical climate for the investigated sections.

Section	Average annual temperature (ºF)	Average annual precipitation (in)	Average annual wind speed (mph)	Average annual sunshine percentage (%)	Average annual groundwater level to pavement surface (ft)
Sec01	55.10	41.2	5.22	57.54	5.00
Factors +5%	+2.76	+2.1	+0.26	+2.88	+0.25
Sec02	57.81	52.5	4.48	62.31	21.00
Factors +5%	+2.89	+2.6	+0.22	+3.12	+1.05
Sec03	56.73	38.6	5.64	58.96	19.70
Factors +5%	+2.84	+1.9	+0.28	+2.95	+0.99

Note: +1 ºF = + 0.5556 ºC, T(°C) = (T(°F) - 32) / 1.8, 1 in = 25.4 mm, 1 mph = 1.6 km/h, 1 ft = 0.3 m.

Table 4. Results: sensitivity of performance indicators to climatic factors.

Climatic factors	Performance indicators	IRI	Rutting	Fatigue Cracking
Sec01	Temperature	0.13	1.02	1.69
	Precipitation	0.05	0.00	0.40
	Wind speed	0.02	0.12	0.24
	Sunshine percentage	0.04	0.18	0.58
	Groundwater level	0.12	0.55	1.85
Sec02	Temperature	0.27	1.47	0.40
	Precipitation	0.07	0.05	0.15
	Wind speed	0.07	0.18	0.11
	Sunshine percentage	0.03	0.18	0.07
	Groundwater level	0.00	0.00	0.00
Sec03	Temperature	0.29	2.60	3.33
	Precipitation	0.04	0.00	0.11
	Wind speed	0.04	0.23	0.33
	Sunshine percentage	0.08	0.63	0.53
	Groundwater level	0.00	0.03	0.06

Note: units used in the sensitivity analysis: IRI (in/mi), rutting (in), fatigue cracking (%), temperature (°F), precipitation (in), wind speed (mph), sunshine percentage (%), groundwater level (ft).

Table 5. Increasing percentage of life cycle cost components compared to the baseline and proportions of life cycle cost components.

Section	**Emission scenario**								
	High			Medium			Low		
	Agency cost	WZ cost	VOC	Agency cost	WZ cost	VOC	Agency cost	WZ cost	VOC
Sec01	+54%	+54%	-0.23%	+48%	+48%	-0.15%	+32%	+32%	-0.13%
% of life cycle cost components	5.93%	0.21%	93.85%	5.72%	0.20%	94.08%	5.11%	0.18%	94.70%
Sec02	+64%	+64%	-0.08%	+64%	+64%	-0.08%	+64%	+64%	-0.09%
% of life cycle cost components	2.48%	0.26%	97.25%	2.48%	0.25%	97.26%	2.49%	0.24%	97.27%

Table 6. Major assumptions, limitations, and recommendations.

Assumption 1 **The MEPDG can reliably predict pavement performance based on traffic, pavement structure, material, and climate.**	
Limitations	Pavement deterioration (e.g., cracking) can have more sophisticated mechanisms and may develop with a certain degree of randomness in practice. Hence, the MEPDG predictions may not always match with field measurements. Inaccurate performance modelling can impact subsequent maintenance scheduling and life cycle cost analysis in the modelling process (see Figure 1). Moreover, there are also other modes of deterioration that can be impacted by climatic variabilities but are not considered in the MEPDG. For example, excessive moisture in the asphalt mixtures (e.g., due to more frequent rainfalls or flooding) can weaken the bond between bitumen and aggregates, leading to more stripping (or raveling) and potholes as a consequence (Zhang et al. 2015; Yusoff et al. 2014). The MEPDG is adopted in this study, not only because it can predict pavement performance with high levels of accuracy but also because it is by far the most comprehensive and advanced pavement analysis tool with consideration of climatic inputs. In addition, the material and performance models in the MEPDG are calibrated by various testing and field data, which tend to maximize the accuracy of the predictions (AASHTO 2009).
Recommendations	The methodology of this study should be updated with newer versions of the MEPDG in order to improve the accuracy of pavement performance prediction. Furthermore, moisture damage models should be incorporated into the MEPDG so that it can account for other types of climate-related deterioration (e.g., stripping and potholes). It is also recommended to calibrate the MEPDG program with climate-related testing data (e.g., dynamic modulus testing) for local pavement materials to achieve better prediction accuracy. Such work will require substantial efforts and is beyond the scope of this study (Ceylan et al. 2009).
Assumption 2 **PVI in this study only considers pavement megatexture (i.e., roughness measured by IRI).**	
Limitations	Climate may also impact pavement macrotexture, which can increase/decrease the friction between pavement surfaces and tyres. It will also have influences on fuel consumption, tyre wearing, and vehicle repair costs.

Recommendations	Incorporate macrotexture-based PVI models to quantify the impacts of climate variabilities on pavement macrotexture and the consequent costs to road users (e.g., using the MIT or UCPRC models; Akbarian et al. 2014; Wang et al. 2014).
Assumption 3 **Fuel consumption costs are used to represent VOC. Other VOC (e.g., tyre wear and vehicle repairs), accident costs, and environmental costs are not considered in this study.**	
Limitations	It is known that fuel consumption costs are a major part of VOC (VTPI 2017). Adding tyre wear, vehicle repair costs, and accident costs will likely increase the proportion of user costs in the life cycle costs. However, adding these costs will not change the fact that user costs are dominating (Table 5). The accident costs may increase in the future in the investigated locations, as it is going to be wetter (i.e., more precipitation, see Table 2) and thus more accidents due to reduced skid resistance or visibility may occur (Parry and Viner 2005). In addition, LCCA is disadvantageous in quantifying the environmental impacts, as these impacts cannot be translated directly into monetary values. However, such 'costs' may be significant and need investigation.
Recommendations	Accident costs due to climate variabilities need to be further investigated. Environmental life cycle assessment should be applied to quantify the environmental costs.