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RESEARCH AND ANALYSIS

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Climate change impacts on asphalt road pavement construction and maintenance

An economic life cycle assessment of adaptation measures in the State of Virginia, United States

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Abstract

Pavement design and management practices must be adapted in response to future climate change. While many studies have attempted to identify different methods to adapt pavements to future climate conditions, the potential economic impacts of the adaptations still remain largely unquantified. This study presents the results of a comprehensive life-cycle cost analysis (LCCA) aimed at quantifying the potential economic impacts of a climate adaptation method, in which an upgraded asphalt binder (Performance Grade PG 76-22) is used in the construction and maintenance of flexible pavement sections in lieu of the original binder (PG 70-22) for improved resistance against high temperatures. For each of three major Virginia Department of Transportation (VDOT) districts with different climates, three case studies consisting of typical interstate, primary, and secondary pavement sections were considered. The LCCA accounted for the costs incurred during the mixture's production, maintenance, and use phases of the pavement life cycle by explicitly considering future climate projections, pavement life-cycle performance, maintenance effects, and work zone user delays. The study concludes that pavements using the upgraded binder not only perform better over time but are also economically advantageous compared to those with the original binder under the conditions of the anticipated future climate conditions (2020–2039).

KEYWORDS

adaptation, climate change, climate model downscaling, flexible pavement, life-cycle cost analysis, maintenance effects

1 | INTRODUCTION

There are over 2.7 million miles of roads in the United States, approximately 94% of which are paved with asphalt. All of these roads are directly exposed to the environment and are, as such, environmentally sensitive infrastructure. Flexible pavements are particularly vulnerable to extreme high temperatures that can cause a decrease in bitumen viscosity, potentially aggravating rutting (i.e., permanent deformation), roughness, and cracking. Increases in temperature are the main climatic concern for flexible pavements where climate projections point toward future changes (Chinowsky, Price, & Neumann, 2013; IPCC 2014; Tighe, Smith, Mills, & Andrey, 2008; Underwood, Guido, Gudipudi, & Feinberg, 2017). Historically, a stationary climate is assumed in the road pavement designing process, but this assumption may be challenged under a changing climate.

According to the Intergovernmental Panel on Climate Change (IPCC), an increase in global average surface temperature of 0.85°C was observed from 1880 to 2012 (IPCC 2014) and the projected increase in global mean surface temperature is between 0.3 and 0.7°C for the period 2016–2035 relative to 1986–2005 (IPCC 2014). Although such an increase in temperature may seem insignificant, regional projections differ, with higher temperature increases over land than ocean and generally higher increases toward higher latitudes (IPCC 2014; Wuebbles et al., 2017; Walsh et al., 2014). The annual average temperature in the United States increased 1°C between 1901 and 2016, with even higher increases observed in the Southwest, the Great Plains, the Midwest, the Northeast, and Alaska (Walsh et al., 2014). Over the next few decades (2021–2050), US annual average temperatures are expected to increase another 1.4 to 1.6°C relative to the years 1976–2005 (Vose et al., 2017) according to a lower and higher scenario, respectively. The regions that have observed the greatest warming are also the regions where future changes are projected to be the highest in the United States. (Vose et al., 2017). Although small changes are not likely to cause significant problems for flexible pavement over a short time period (e.g., 1 day/month), their effects can accumulate over time and gradually become significant from a life-cycle perspective. Furthermore, because of the projected increase in extreme events, such as prolonged, more frequent, and more severe heatwaves (Vose et al., 2017; Walsh et al., 2014), projected changes in the climate should prompt serious concerns among the pavement community and motivate design practices to be adapted accordingly (Qiao, Flintsch, Dawson, & Parry, 2013).

The adaptation of highway infrastructure design, construction, and management to climate change is urgent but may also be costly. Chinowsky et al. (2013) conducted a quantitative study on the costs of climate adaptation for the US road network and estimated an increase of $2.8 billion in adaptation costs in 2050 relative to 2010 expenses. This study considered various road degradation mechanisms that can be accelerated by climate change including rutting, cracking, and erosion for sealed or unsealed roads. Cost quantification was based on adaptation costs for paving with adaptive asphalt binder and changes in the frequency of maintenance due to the additional degradation caused by climate change. However, Chinowsky et al. (2013) did not consider the detailed pavement deterioration mechanisms and the indirect economic effects of the additional degradation due to climate change. Schweikert, Chinowsky, Kwiatkowski, and Espinet (2014) presented a tool to quantify climate adaptation costs of road infrastructure, considering the costs associated with long-term changes in climate or flooding, during the construction and maintenance phases of road infrastructure. The authors also considered other indirect adaptation costs incurred by road users, such as the costs caused by changes in travel time, repair of vehicles, fuel consumption, as well as vehicle CO_2 emissions. However, they did not consider the totality of local factors such as materials, construction practices, and climate. Mallick, Radzicki, Daniel, and Jacobs (2014) explored the interactions of the climate-pavement-maintenance and rehabilitation (M&R) system and concluded that it is important to obtain reliable climate data, improve the accuracy of the pavement performance prediction models (PPPM), and conduct site-specific modeling for accurate projection of climate change impacts on roadways and respective economic factors of adaptation.

In addition to presenting a comprehensive overview of the research work existing in the literature on this topic, Underwood et al. (2017) performed a comprehensive network analysis to investigate the costs of upgrading asphalt binders nationwide and estimated that an approximate budget of $19–26.3 billion would be needed to complete the binder upgrade by 2040, when current binders will not be suitable for the anticipated future climate conditions in most places. The AASHTOWare Pavement ME Design (henceforth, referred to as Pavement ME), a state-of-the-art pavement analysis tool that considers advanced pavement deterioration mechanisms and field calibration, was used to conduct performance analysis and consequent maintenance scheduling. The costs were quantified with a Life-Cycle Cost Analysis (LCCA) approach, in which only M&R costs were considered. However, the study did not discuss, from a life-cycle perspective, how the M&R improved performance and the subsequent M&R schedule. Moreover, the authors did not consider the effects of pavement quality degradation on the costs incurred by road users.

Despite the undeniable merits and achievements of the aforementioned studies, several aspects of these studies underpin the need for further studies to expand the knowledge in this domain:

1. They make climate projections without analyzing the impacts of those projections on pavement performance, thereby ignoring the nature of eventual adaptation strategies and the consequent cost implications.
2. They make general assumptions, thereby disregarding the technical specificities and factors related to the geographical context.
3. They do not consider the evolution of pavement quality over time, or if so, considerations are based on simplistic and general models, ignoring the practices and considerations taken into account by the relevant governing authorities and agencies existing in the geographical area to which the study refers. Therefore, they do not accurately consider the pavements' behavior.
4. They do not consider the road user costs related to the degradation of the pavement quality over time and the application of the M&R treatments.

To address this gap in the literature, this research study aims to conduct a detailed LCCA to investigate the potential life-cycle economic impacts on highway agency and road user costs of pavement design and M&R adaptation to climate change in the state of Virginia, taking into account projected local climate conditions and field-calibrated PPPM and maintenance effect models.

2 | METHODOLOGY

The methodology consists of three main steps: (a) analysis of climate data, (b) prediction of the pavement performance during its life-cycle, and (c) the pavement LCCA.

TABLE 1 Features of the pavement structures considered for each type of road

Item	Road type					
	Interstate		Primary		Secondary	
Total width in each direction including shoulders (ft)	36		32		32	
Layer	Thickness (in)	Material	Thickness (in)	Material	Thickness (in)	Material
Asphalt course	10	SM[a]-12.5D (PG[b] 70-22) or SM-12.5E (PG 76-22)	5	SM-12.5D (PG 70-22) or SM-12.5E (PG 76-22)	1.5	SM-12.5D (PG 70-22) or SM-12.5E (PG 76-22)
Base course	8	Granular material	4	Granular material	3	Granular material
Sub-base	10	Granular material	10	Granular material	6	Granular material
Subgrade	–[c]	Sand	–	Sand	–	Sand

[a]Surface mixture.
[b]Superpave performance grade.
[c]Subgrade depth is infinite.

TABLE 2 Traffic properties values considered for each type of road

Traffic property	Road type		
	Interstate	Primary	Secondary
AADT[a]/direction	47,165	16,527	10,422
Truck percentage (%)	8.8	3.2	1.1

[a]Annual average daily traffic.

First, projections from a climate model (GCM) included in the newest archive of the Coupled Model Intercomparison Project (CMIP5) under the higher Representative Concentration Pathway (RCP8.5) were downscaled using a state-of-the-art statistical downscaling model (see the Section 4 below). Next, the road pavement life-cycle performance is predicted by using the Pavement ME, with locally calibrated traffic factors and a 20-year design life, under baseline (1980-1999) and future (2020-2039) climate conditions. Moreover, the dynamic modulus testing results of local asphalt mixtures are used as inputs to the PPPM for a more accurate modeling of the response of asphalt materials to climate variability (namely the temperature). Finally, the LCCA was conducted to compare the economic impacts of pavements with an upgraded binder with improved resistance against high temperatures compared to pavements with the original and commonly used binder. The LCCA explicitly accounts for the differences in material production costs, pavement life-cycle performance, maintenance triggers, maintenance effects, vehicle fuel consumption costs, and work zone (WZ) user delay costs. In addition, the Virginia Department of Transportation (VDOT) Pavement Management System (PMS) data on traffic, pavement structure, materials, and performance monitoring data were used in all the case studies.

3 | FEATURES OF THE CASE STUDIES

The methodology developed was applied to three case studies, which considered, respectively, three typical pavements in three major VDOT districts—Bristol, Richmond, and Roanoke—all of which have slightly different climates. The climatological observations were obtained from the nearest Global Historical Climatology Network (GHCN) weather station providing hourly data. The weather stations considered were located at the R.E. Bird International Airport (Weather-Bureau-Army-Navy ID [WBAN] 13740), Woodrum Airport (WBAN 13741), and the Tri-Cities Airport across the border in Tennessee (WBAN 13877) for Richmond, Roanoke, and Bristol, respectively. The PMS data for the three districts were extracted from the VDOT PMS database. Three different categories of road pavement structures were considered: an interstate, primary, and secondary road (see Table 1), all of which have two lanes in each direction. The Annual Average Daily Traffic (AADT) and truck percentage values considered were the average values corresponding to the three districts (Table 2). Also, the traffic growth rate was assumed to be equal to 0% for all locations. The information on pavement width, layer thickness, and materials was taken from the VDOT PMS database and represents the values commonly found in the Virginia road pavement network. The subgrade soils considered were adopted from the Virginia Agronomy Handbook, which lists all three locations as having sandy subgrade (Brann & Mullins, 2000). In total, nine cases were created by assuming that each of the three districts has the three pavement structures described in Table 1.

In Virginia, two types of asphalt surface mixtures are commonly used: SM-12.5D and SM-12.5E. Both are designed with the same “medium” to “coarse” aggregates, with a nominal maximum grain size of 12.5 mm. The Superpave Performance Grade (PG) of the binder used in the mixture

TABLE 3 Dynamic modulus testing results (Apeagyei & Diefenderfer, 2011)

Mixture $\|E^*\|$ (psi) for SM-12.5D (PG 70-22)						
Temperature (°F)	0.1 Hz	0.5 Hz	1 Hz	5 Hz	10 Hz	25 Hz
14	1990,691	2290,870	2420,244	2696,686	2816,149	2959,543
40	1245,825	1580,766	1730,928	2054,169	2195,049	2372,188
70	431,294	612,252	725,043	983,066	1112,439	1290,642
100	136,621	198,557	244,872	377,968	454,838	559,169
130	50,280	65,804	83,044	139,198	166,842	217,847
Mixture $\|E^*\|$ (psi) for SM-12.5E (PG 76-22)						
Temperature (°F)	0.1 Hz	0.5 Hz	1 Hz	5 Hz	10 Hz	25 Hz
14	2,621,992	2,998,558	3,143,257	3,435,991	3,549,894	3,675,642
40	1,309,159	1,678,280	1,846,958	2,217,095	2,376,733	2,580,511
70	5,47,517	762,125	891,692	1,198,156	1,347,980	1,547,697
100	147,489	210,256	268,852	415,581	498,011	615,008
130	100,434	123,664	140,749	206,244	239,796	295,829

SM-12.5D is PG 70-22. In turn, the mixture SM-12.5E is designed with a binder with additives (PG 76-22 binder) for better rutting resistance at high temperatures. The values of the responses of these mixtures to temperature and loading frequency were tested in a study aimed at calibrating the Mechanistic-Empirical Pavement Design Guide for Virginia (Apeagyei & Diefenderfer, 2011) and can be found in Table 3. Due to the use of the PG 76-22 binder, the SM-12.5E mixture is approximately 20% more expensive ($84/ton[1] in 2006) than the SM-12.5D mixture ($71/ton in 2006) (McGhee & Clark, 2007).

4 | CLIMATE INPUTS

The projected future values of daily minimum and maximum temperature, precipitation, and minimum and maximum relative humidity were generated for the three locations by statistically downscaling the output of those variables from the higher RCP8.5 pathway for the GFDL-ESM2G GCM (Dunne et al., 2012), using the Asynchronous Regional Regression Model (Stoner, Hayhoe, Yang, & Wuebbles, 2013) with values from the hourly GHCN climate data, aggregated to daily values, as the baseline.

A simplified diagram of a general statistical downscaling methodology is shown in Figure 1, which depicts how daily historical output from a coarsely gridded GCM (often on the order of 100 × 100 miles per grid cell or more) was used together with daily observations at each site to build a statistical model to resolve the relationship between the two datasets. The statistical model was then used with future GCM output to calculate locally relevant projections for the site in question. A more detailed description of the ARRM method can be found in Stoner et al. (2013).

The methodologies for disaggregating the daily climate variables to hourly values differ depending on the variable. Downscaled daily values of temperature and relative humidity were disaggregated to hourly values by (a) creating a two-dimensional 24-h by 365-day surface from the hourly observed data, (b) smoothing the surface using a low-pass filter to reduce noise that could otherwise cause overfitting of the statistical model, (c) interpolating the surface over the full range of daily minimum and maximum values, and finally (d), projecting the surface to the downscaled daily maximum and minimum values to determine appropriate hourly conditions for each day of the year and location.

The daily total precipitation values were disaggregated into hourly values by using a variation of the methodology described in Socolofsky, Adams, and Entekhabi (2001), which randomly separates the daily amount of precipitation into storms. The method was modified in such a way that the number of storms allowed to occur per day was limited by binning the historical daily total rainfall into eight quantiles by rainfall amount, while keeping track of how many storms occurred per day. Each daily precipitation amount was assigned to a maximum number of allowed individual rainfall events per day by randomly sampling from the number of events per day from the bin that encompassed the daily total rainfall amount. The start and end times were randomly selected while constraining each storm to begin and end within a 24-h period and adding rainfall from overlapping storm events.

The hourly values of wind direction and percent sunshine were generated by randomly sampling a day (24-h values) in the historical observations with similar daily total rainfall amounts that occurred in a 3-month season surrounding the day in question. For instance, if March 5, 2020, was projected to have a total rainfall amount of 15 mm, a day in the historical data between the months of February and April with a similar amount of total daily rainfall (within 6 mm), would be randomly selected, and that day's 24-h wind speed and percent sunshine would be

[1] Throughout this article the use of "tons" refers to short tons.

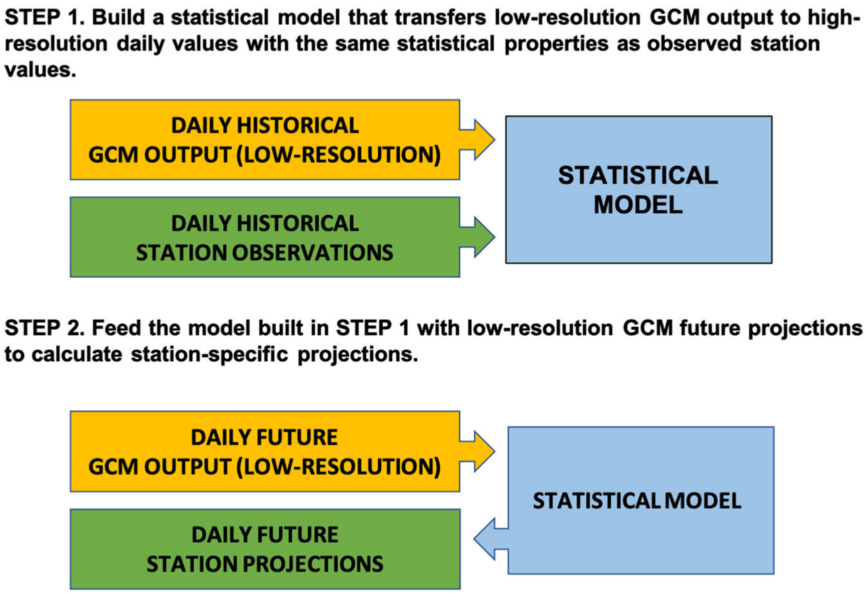

FIGURE 1 Simplified diagram of the concept of statistical downscaling

used for March 5, 2020. If no historical day exists with rainfall within 6 mm of the future daily rainfall, then the day with the closest daily rainfall amount would be selected. The same procedure was used for days with no rainfall. The hourly climate data are included in the Supporting information S2.

5 | PAVEMENT LIFE-CYCLE PERFORMANCE AND MAINTENANCE EFFECTS

The type of asphalt binder selected can impact the performance and service life of road pavements. In this context, maintenance is likely to have different frequencies in pavements with different asphalt binders. Pavement performance levels after maintenance are also likely to be distinct.

In this study, pavement performance indicators, including rutting, roughness (as measured by the International Roughness Index [IRI]), longitudinal cracking, transverse cracking, and alligator cracking, were predicted using the Pavement ME for a 1980–1999 baseline period and for a projected future climate during the period 2020–2039. The Pavement ME is a comprehensive tool for pavement performance predictions widely used to assess the impacts of climate on pavement performance (Mills, Tighe, Andrey, Smith, & Huen, 2009; Tighe et al., 2008; Underwood et al., 2017). The prediction of the pavement performance is a function of cumulative traffic, truck percentage, pavement structure, material, and climate conditions and can be expressed by Equation (1):

$$P_{j,\ t} = f_j\left(\sum_{n=1}^{t} C_{traffic},\ truck\%,\ pavement,\ \sum_{n=1}^{t} climate\right), \tag{1}$$

where $P_{j,t}$ is the pavement performance in year t for indicator j; f_j is the damage transfer function of deterioration for indicator j; $\sum_{n=1}^{t} C_{traffic}$ is the cumulative traffic load in year t, typically expressed in Equivalent Single Axle Load (ESAL); *truck%* is the percentage of heavy vehicles; *pavement* represents the pavement structure and material properties; and $\sum_{n=1}^{t} climate$ is the accumulated climate load in year t.

The Enhanced Integrated Climate Model incorporated into the Pavement ME is efficient in "translating" climatic (environmental) factors, including air temperature, precipitation, wind speed, sunshine percentage, and humidity, into pavement temperature and moisture profiles (Zapata & Houston, 2008). This allows the model to effectively predict the pavement performance under various climatic conditions as discussed in the previous section.

Various field calibration factors were used in the pavement modeling, including dynamic modulus inputs (see Table 3), local vehicle class distribution, lane distribution factors, and axles per truck. These factors were all obtained from VDOT studies (Apeagyei & Diefenderfer, 2011; VDOT 2017). Locally calibrated input values are recommended for the sake of greater accuracy in predicting pavement performance. However, there is no quantification of the degree of accuracy that can actually be achieved.

The predicted pavement performance was then used for scheduling maintenance activities, which were considered to occur whenever the maintenance triggers were reached. The trigger values adopted for roughness, rutting, asphalt course bottom-up cracking, and asphalt course thermal cracking were those considered by default in the Pavement ME, which are as follows (AASHTO 2016): 172 inch/mi (1.14 m/km), 0.75 in (19 mm), 25 % lane area and 1000 ft/mi (189 m/km), respectively. Crack sealing and filling were assumed to be performed when the asphalt course thermal cracking exceeded its trigger value. In turn, an overlay operation was considered to be performed whenever one of the remaining trigger values was reached. The rationality behind the consideration of the maintenance effects centers on the fact that it can improve the level of pavement serviceability. After the application of maintenance treatments, roughness, rutting, and cracking are reduced or reset to the condition of a new pavement. As a result, vehicles run on smoother pavements and, thus, vehicle operating costs are expected to be reduced. Although the application of maintenance treatments means that costs will be incurred by the highway agency, the improvement of the pavement performance is expected to save road user costs. The maintenance effects were modeled by using the overlay roughness and rutting parameters given in Equation (2). As far as the asphalt cracking is concerned, the overlay operation was considered to reset surface cracking.

$$\Delta P_{j,\ t} = \begin{cases} \Delta IRI_t = 0.631 \times IRI_t - 22.49 \\ \Delta Rut_t = 0.596 \times Rut_t - 0.04 \end{cases} \tag{2}$$

where, $\Delta P_{j,t}$ is the improvement in the performance of the indicator j due to maintenance in year t; ΔIRI_t and ΔRut_t are respectively the reduction in IRI (inch/mi) and rutting (inch) due to maintenance in year t; and IRI_t, Rut_t are respectively the IRI (inch/mi) and rutting (inch) values in year t. In addition, crack sealing and filling was considered as the other maintenance option to reset surface cracking when the overlay option is not necessary (i.e., rutting or roughness does not reach maintenance triggers).

The overlay maintenance effect models were calibrated by using the VDOT overlay and performance data with SM-12.5D (1.5–2 inch) and SM-12.5E (2 inch). The detailed approach is described in Qiao, Dawson, Parry, and Flintsch (2016). The pavement performance immediately after the application of a given maintenance activity is then a function of the predicted pavement performance and the calibrated maintenance effect models when maintenance is triggered (Equation (3)).

$$P'_{j,\ t} = P_{j,\ t} + \Delta P_{j,\ t}, \tag{3}$$

where, $P'_{j,t}$ is the performance of the indicator j in year t considering the maintenance effects, and $\Delta P_{j,\ t}$ is the improvement in the performance of the indicator j due to maintenance in year t.

6 | PAVEMENT LIFE-CYCLE COST MODEL

An LCCA is a structured methodology used to quantify the potential economic impacts of a product from cradle to grave (Santos, Bryce, Flintsch, & Ferreira, 2017). In this study, the LCCA was conducted to compare the life-cycle costs (LCC) of pavements with the original asphalt binder (i.e., PG 70-22 used in the asphalt mixture SM-12.5D) and the upgraded binder (i.e., PG 76-22 used in the asphalt mixture SM-12.5E), under the baseline and future climate conditions.

In general, all the phases of the pavement life cycle should be considered when performing an LCCA. These phases include the raw material acquisition, the mixture's production, construction, transportation, maintenance, use, and end-of-life (Santos et al., 2017). As this study is a comparative LCCA, only the phases that were different between the pavement alternatives (i.e., pavements with SM-12.5D or SM-12.5E) were considered. That means that only the mixtures production, maintenance, and use phases were taken into account.

The reasons why the LCCA was constrained to these phases are as follows:

1. The prices of the two types of binders and consequently mixtures are different. The production of mixture SM-12.5E is 20% more expensive than mixture SM-12.5D (McGhee & Clark, 2007).
2. Pavements with different types of binders/mixtures can perform differently and will require maintenance with different frequencies, leading to different costs in both maintenance and use phases.
3. More frequent maintenance activities will also increase user delays during WZs, as road users may need to queue. This situation will increase travel time, which in turn, can be expressed as a monetary cost, based on the value of time as a function of the travel purpose.

The densities of the two mixtures were almost identical. Consequently, the volumes and, thus, the costs of the mixtures' transportation and pavement construction were approximately the same. In addition, it was assumed that the pavements will be repaired at the end-of-life with nearly identical postmaintenance performance levels. This assumption leads to an equal salvage value in both scenarios, which justified its exclusion from the analysis. For all the phases considered and described above, the LCC were converted to the Net Present Value (NPV) according to Equation (4):

$$NPV = \sum_{t=1}^{T} \frac{\sum_{n=1}^{N} Pr_0 + M_t + Op_t + WZ_t}{(1+i)^t}, \tag{4}$$

TABLE 4 Parameter values considered in the LCCA

Pavement life-cycle phase	Parameter	Value	Unit
Mixtures production	SM-12.5D production cost	71	\$/ton material
	SM-12.5E production cost	84	\$/ton material
	Gravel production cost	12.5	\$/ton material
	Sand production cost	13.5	\$/ton material
	Density of the asphalt mixtures (SM-12.5D and SM-12.5E)	1.93	ton/yd^3
	Density of gravel	1.35	ton/yd^3
	Density of sand	1.25	ton/yd^3
Maintenance	Cost of 2-inch asphalt overlay with the mixture SM-12.5D	71	\$/ton material
	Cost of 2-inch asphalt overlay with the mixture SM-12.5E	84	\$/ton material
Use	Percentage of passenger cars (gasoline)	90	%
	Percentage of light trucks (diesel)	6	%
	Percentage of articulated trucks (diesel)	4	%
	Gasoline cost	2.5	\$/gallon
	Diesel cost	2.4	\$/gallon
WZ	Vehicle speed for normal operation conditions	65	mph
	Vehicle speed at WZs	35	mph
	Value of time for passenger cars	20	\$/vehicle
	Value of time for trucks	30	\$/vehicle

where *NPV* is net present value; Pr_0 is the mixture production cost in year 0; M_t is the maintenance cost in year *t*; Op_t are the vehicle operation costs in year *t*; WZ_t are the WZ costs, incurred by the road users, in year *t*; *n* is the nth LCC component; *N* is the total number of LCC components; and *i* is the discount rate, which in this case study was considered to be equal to 4.6% (EM 2017).

The cost components considered in each pavement life-cycle phase are as follows:

a. Mixtures production phase: the costs for pavement materials, including asphalt mixtures, base course (100% gravel), and subgrade (100% sand) course.

b. Maintenance phase: the costs for the 2-inch overlay due to the use of different mixtures.

c. Use phase: the fuel consumption costs for passenger cars (medium car), light trucks, and articulated trucks. The light trucks and articulated trucks accounted for 60.5 and 39.5% of all trucks, respectively. The fuel consumption costs were calculated by using the World Bank Highway Development and Management (HDM-4) model calibrated for US conditions by Chatti and Zabaar (2012), which estimates the fuel consumption for different types of vehicles at different operating speeds, when operating on pavements with different roughness levels (IRI).

d. WZ phase: the costs incurred by road users during this phase were estimated by multiplying the queueing delay time by the economic value of time for passenger cars and trucks. The queueing delay time was determined according to the Highway Capacity Manual (HCM 2010) and Memmott and Dudek's model (Memmott & Dudek, 1982).

During the WZ operations, which were set to occur between midnight and 8:00 a.m., one lane was considered closed while the other lane remained open. The traffic demand considered was the default daily traffic distribution of the Pavement ME. Whenever the traffic demand exceeded the capacity (either the free flow capacity or the WZ capacity), a traffic queue was considered to occur. The traffic delay of the queue was then calculated by using the deterministic queueing theory, in which a graphic solution was employed. That graphic solution is based on the cumulative incoming and outgoing traffic flow curves versus time, and the delay equals the area between the curves (Mannering, Washburn, & Kilareski, 2009). An inventory of the parameters used in the calculation of LCC is shown in Table 4 (Goedkoop, Oele, Leijting, Ponsioen, & Meijer, 2016; McGhee & Clark, 2007; Nathman, 2008, VDOT 2011).

In the LCCA, the project analysis period considered was the 20-year period (2020–2039) corresponding to the period of the downscaled future climate data. The costs incurred in all phases were converted into the NPV corresponding to the year 2011 according to Equation (4). The costs of the mixtures SM-12.5D and SM-12.5E, initially in 2006 US dollars, were adjusted to 2011 US dollars by using yearly adjustment rates from the Federal Reserve Bank (EM 2017). All other values were assumed to be in 2011 US dollars. For the baseline cases, the analysis periods were also from 2020 to 2039 for comparison purposes, but the climate conditions adopted the baseline climates (1981–1999). Moreover, the costs were normalized into US dollars per mile of pavement per year (\$/mile/year).

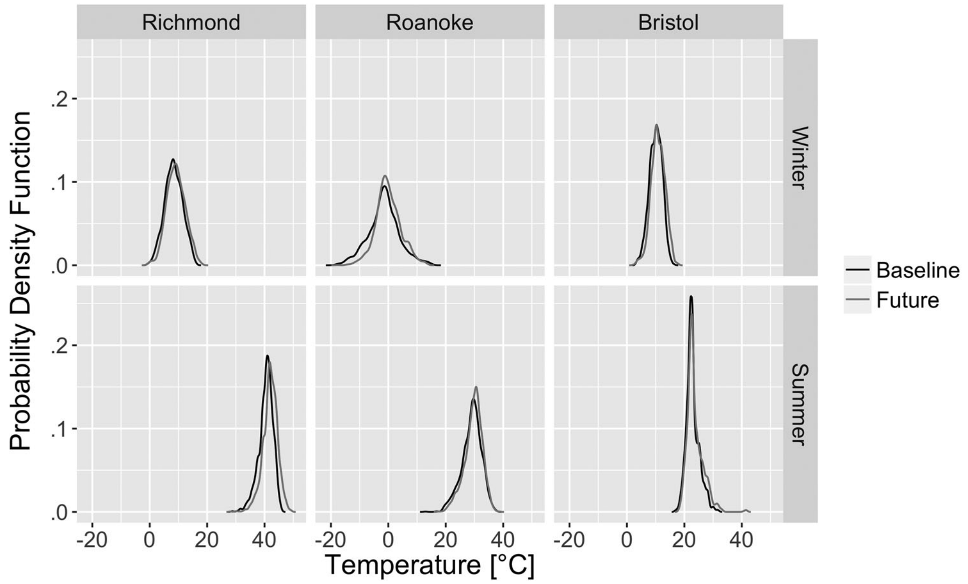

FIGURE 2 Probability density functions (PDFs) of the winter (December, January, and February) minimum and summer (June, 4 July, and August) maximum surface air temperature for Richmond, Roanoke, and Bristol. Baseline (1980–1999) and future (2020–2039) temperatures are shown in black and grey, respectively

7 | RESULTS AND DISCUSSION

7.1 | Climate change

Although the three sites in the three VDOT districts are within the same state, there is still significant variation in their climates. Richmond, with an elevation of only 50 m, has the warmest climate of the three locations. For the baseline period (1981–1999), the annual average temperature in Richmond was 24.1°C, with an annual average standard deviation of 9.7°C, whereas the average precipitation was 1,054 mm per year. At an elevation of 350 m, Roanoke sits in the valley between the Blue Ridge Mountains and the Allegheny Mountains, both part of the larger Appalachian Mountain Range. Roanoke was found to have an annual average temperature for the baseline period of 13.5°C, with an annual average standard deviation of 10.0°C, and an average precipitation of 1,013 mm per year. Finally, Bristol is located in the southwestern Appalachian Mountain Range, and with an elevation of 465 m is the site with the highest elevation among the three locations. Bristol was found to have an average annual temperature of 16.8°C during the baseline period, with a standard deviation of only 4°C, and an average precipitation amount of 975 mm per year.

The statistically downscaled output for the GFDL-ESM2G GCM and the higher RCP8.5 scenario indicate that for the future period (2020–2039) the annual average temperature is expected to increase by 1.1, 1.2, and 0.7°C for Richmond, Roanoke, and Bristol, respectively, compared to the baseline climate values. The increases in the temperature of the hottest day of the year for Richmond and Bristol are expected to be higher (2.4 and 2.7°C, respectively) than for Roanoke (0.4°C). Figure 2 shows the probability density functions (PDFs) at the three locations for the baseline and future scenarios for the minimum surface temperature during winter (December, January, and February) and the maximum surface temperature during summer (June, July, and August).

All three locations were found to have increases in the days per year with temperatures above their baseline 90th percentile of maximum temperature. For Richmond, the baseline 90th percentile of maximum temperature was 41.4°C and for the 2020–2039 period, the number of days per year exceeding that value was expected to be 64, which represents an increase of 27 days per year compared to the baseline period. For Roanoke, the baseline 90th percentile maximum temperature was 30.6°C and for the 2020–2039 period that value was projected to exceed an average of 50 days per year, which represents an average increase of 13 days per year. The baseline 90th percentile maximum temperature in Bristol was 24.9°C with 55 days per year with temperatures hotter than that during the future period, which means an average increase of 18 days per year.

A Mann–Whitney–Wilcoxon test was performed to test whether the baseline and future extreme temperatures were in fact significantly different. The 10th percentile coldest temperatures during winter and the 90th percentile hottest temperatures during summer were compared. Table 5 shows that the *p-values* from the significance tests were all less than the $\alpha = .05$ level, except for the summer 90th percentile maximum temperatures for Roanoke. Apart from the exception previously mentioned, these results indicate the extreme temperatures are expected to be different for the 2020–2039 period compared to those of the 1980–1999 period.

TABLE 5 *p-values* resulting from the Mann–Whitney–Wilcoxon test comparing the 10th percentile coldest minimum temperatures during winter (December, January, and February) and 90th percentile hottest maximum temperatures during summer (June, July, and August) between the baseline (1980–1999) and future (2020–2039) time periods in each of the three sites

Period of the year	Richmond	Roanoke	Bristol
Winter 10th percentile	.0032	.0000	.0074
Summer 90th percentile	.0000	.8181	.0090

Values below .05 signify that the baseline and future distributions are significantly different at the $\alpha = .05$ level.

Although increases in temperature have the largest impact on the behavior of flexible pavements, precipitation can also affect their durability. Precipitation was also projected to increase for all three locations, with an annual average increase of 109, 152, and 119 mm for Richmond, Roanoke, and Bristol, respectively, between the baseline and future periods.

7.2 | Pavement life-cycle performance

The results of the pavement performance prediction at the end of the 20-year design life (i.e., terminal values of the performance indicators) are presented in Figure 3. In general, the trigger values for rutting were exceeded for most of the cases and, thus, rutting was found to be the main distress causing maintenance interventions. The asphalt concrete (AC) bottom-up cracking trigger was also reached several times, whereas the IRI trigger was only reached for the interstate pavement in Richmond. These distresses all require the application of overlay interventions. For the AC thermal cracking, the severity of the predicted distress levels was inferior to that corresponding to the maintenance trigger. As such, the crack sealing and filling were not scheduled to take place at any time during the design life period, and thus, sealing and filling cost information is not presented. For the investigated pavement sections, AC bottom-up cracking was found to be more problematic than thermal cracking. In practice, for addressing this type of distress, highway agencies may start to intervene at an early stage using crack sealing and filling. However, this practice was not considered in this study. Even when sealing and filling is performed to address cracking, the cost and operation time is much less than that incurred for overlay operations.

Figure 3 shows that in most of the cases, rutting, IRI, and AC bottom-up cracking are expected to increase under future climate conditions, either with the original binder or the upgraded binder. The maximum increase is greater for terminal AC bottom-up cracking, which can be up to 35%. The increases for rutting and IRI were 4.9 and 1.9%, respectively. AC thermal cracking was found to mostly decrease under future climate conditions. However, as the magnitude of the AC thermal cracking was much less than the trigger value, it was not considered in the remainder of this study.

Pavements with the upgraded binder showed better resistance to almost all the distresses under both the baseline and future climates, indicating that the binder upgrade successfully addresses the additional deterioration caused by climate changes. Accordingly, a pertinent question to consider is whether or not it is worth using the upgraded binder under the future climate conditions due to the higher cost of SM-12.5E.

Firstly, the maintenance was scheduled for pavements with the original or upgraded binder under the future climates in order to assess the differences in maintenance frequency and service life. The maintenance scheduling was done according to the predicted performance of the indicators under the future climate conditions and according to their trigger values (see Figure 4). The life-cycle performance was evaluated by accounting for the local maintenance effects (Equation (2)). Most of the maintenance interventions were triggered by rutting, whose evolution can also be seen in Figure 4. In general, rutting starts at year zero and increases over time. When it exceeds 0.75 inch, an overlay treatment is implemented, which allows its reduction to approximately 0.34 inch, as determined according to Equation (2). By applying this intervention, the IRI is also reduced, whereas the surface cracking is completely eliminated.

The service life of the pavements are shown in Figure 4 for the different case studies. According to the results shown in this figure, the pavements with the upgraded binder usually required less frequent maintenance and exhibited longer service lives. For example, the interstate highway in Richmond with the original binder required three maintenance interventions over 19 years, whereas only two interventions were needed with the upgraded binder over 13 years. The average service life values were 6.3 and 6.5 years.

For some pavement sections (e.g., the secondary pavement in Bristol), no distresses were found to be severe enough to trigger any maintenance. Therefore, the service lives were found to be the same as the design lives (20 years). Regarding the period of time considered for the pavement design life, it is important to note that the 20-year design life is typical for flexible pavements. Different highway agencies may consider either a longer or shorter design life. However, this will not affect the finding that the service life of pavements using the upgraded binder is not inferior to original binder.

In addition, an additional statistical analysis was performed to calculate the pavement conditions after the overlay for each case. The results obtained showed that the conditions after maintenance are nearly the same. From a practical point of view, this supports the consideration that the restored pavements have similar performance levels at the end of their life cycles (or at the beginning of the next life cycle). Hence, the salvage values are nearly equivalent for all pavement sections and, thus, can be excluded from the LCCA.

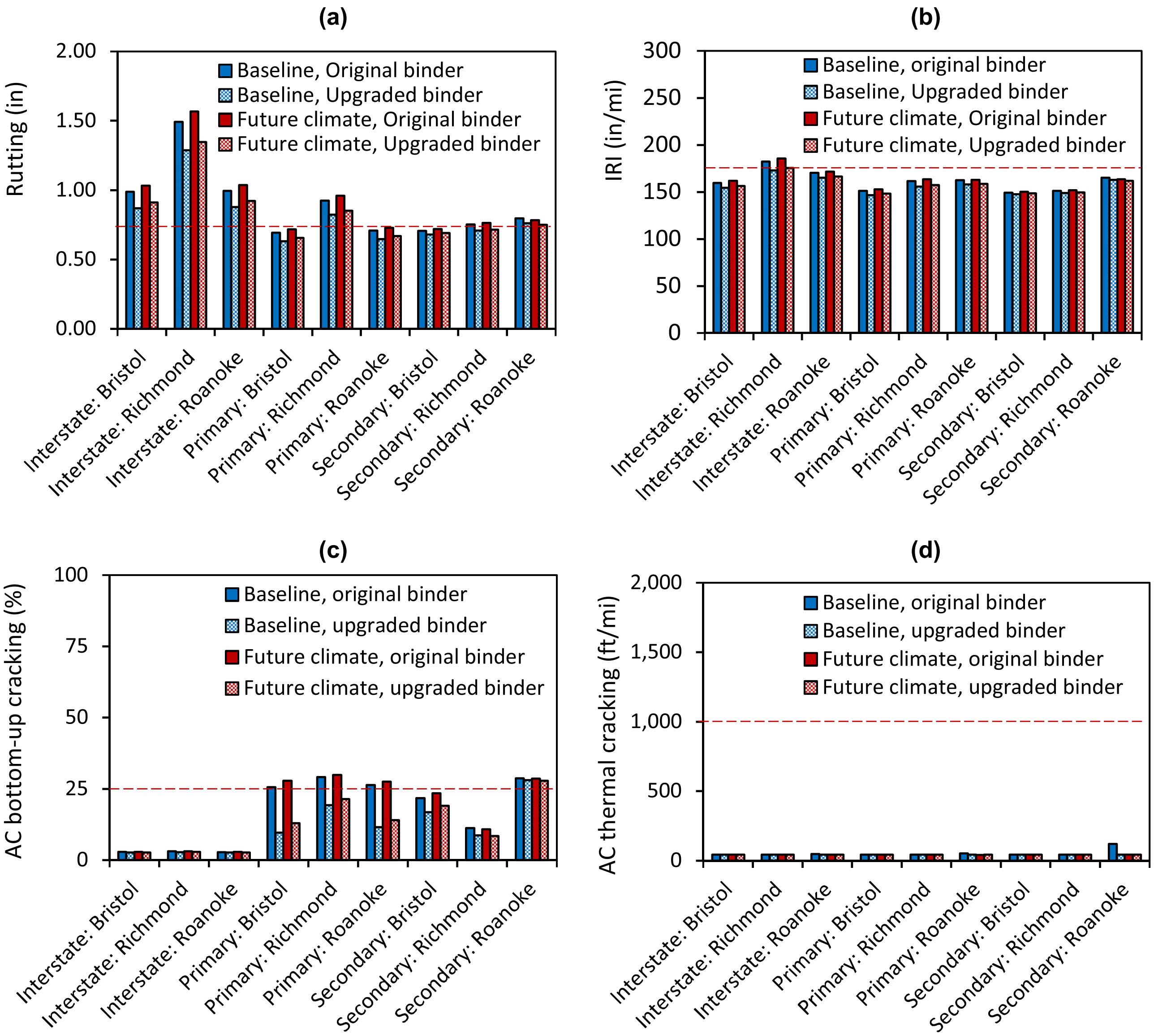

FIGURE 3 Terminal values of the pavement performance indicators predicted by Pavement ME for the year 20 (the dash lines represent maintenance triggers): (a) terminal rutting; (b) terminal roughness in IRI; (c) terminal asphalt concrete bottom-up cracking; and (d) terminal asphalt concrete thermal cracking. Underlying data used to create this figure can be found in the Supporting information S1

7.3 | Life-cycle costs analysis

Figure 5 shows the LCC corresponding to the phases considered as well as the LCC components of the pavements with the original and upgraded binder under future climate conditions. From the analysis of this figure, the following observations can be made:

1. Although the mixture with the upgraded binder (i.e., SM-12.5E) is more expensive than that using the original binder, in most cases the yearly costs were found to be less during the pavements' lifetime. This result is observed because pavements with the upgraded binder last long enough so that a part of the extended service life can compensate the additional material costs. Figure 5 shows that the yearly costs of the upgraded binder were less for all pavement sections, except for the primary pavement in Bristol and the secondary pavements in Bristol and Richmond. These exceptions can be explained by the fact that the extended service life for these pavements was not significant enough, as it was found to increase by only 1 year or remain the same as a result of the binder upgrade (Figure 4).
2. Maintenance costs of pavements with the upgraded binder were less for almost all cases, except for the secondary pavement in Bristol. The reduction was either due to reduced maintenance frequency (the interstate pavement in Richmond) or delayed maintenance, notwithstanding the greater material costs for the overlay with SM-12.5E. Another reason for the cost reductions has to do with the fact that the service lives of the pavements with the upgraded binder were longer and the yearly costs were lower (Figure 5).

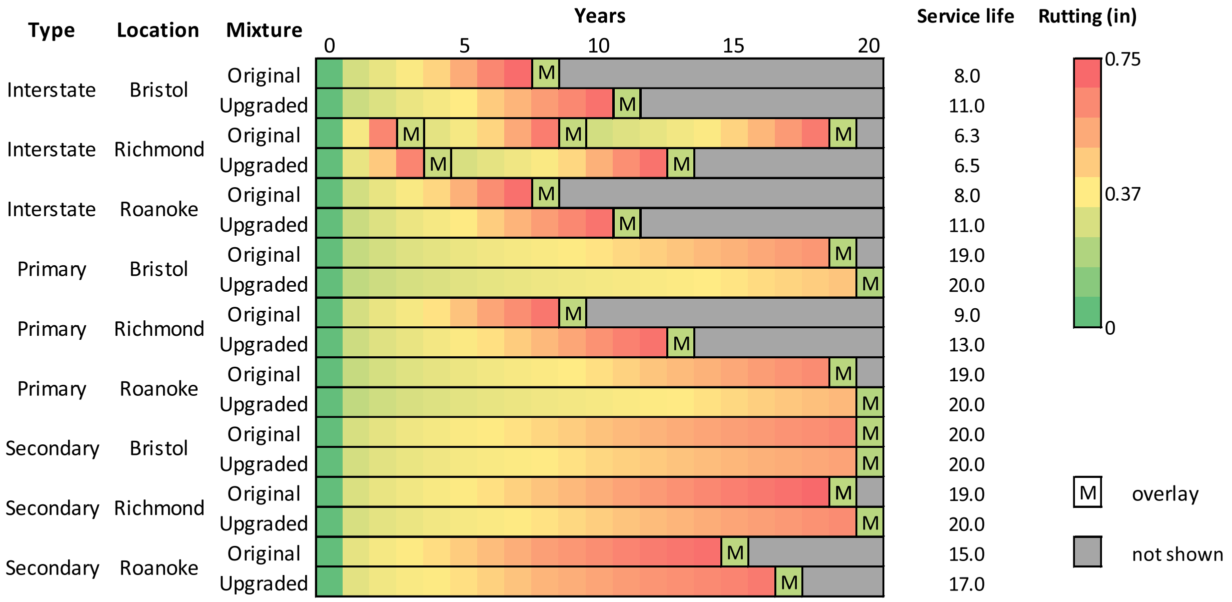

FIGURE 4 Maintenance interventions and rut depth under future climate conditions. Underlying data used to create this figure can be found in the Supporting Information S1

3. Pavements with the upgraded binder lead to reduced fuel consumption. This result is observed because the average IRI over pavement service lives is less for pavements with the upgraded binder. The fuel consumption costs were also found to be substantially different in pavements of different categories. This is because the total fuel consumption is strongly dependent on the traffic volume and distribution. Although the fuel consumption is also affected by pavement roughness (Chatti & Zabaar, 2012), and the roughness for pavements with different binders can be different (see the terminal values of the IRI in Figure 3), the impacts were only minimal (differences in the use phase costs ranged between 0.01 and 0.12% between pavements with different binders).
4. WZ user costs decreased for pavements with the upgraded binder compared to those with the original binder. The reasons for the reductions were similar to the cost reductions observed in the maintenance phase, that is, a combination of less frequent maintenance, delayed maintenance, and longer service life for pavements with the upgraded binder. Queues of vehicles during WZs were only expected to occur in interstate pavements. Thus, the queueing delay costs for the primary and secondary roads were found to be null. In general, the WZ user costs were an insignificant component of the total LCC (0.04–0.11%). Although other WZ user cost components, such as, the moving delay and WZ fuel consumption costs, were not included in the analysis, the total LCC does not seem to be driven by the WZ costs.

The total LCC of the pavements with the original and upgraded binders under the baseline and future climates is shown in Figure 6. This figure shows that pavements with the upgraded binder were found to be less costly in all cases. These results indicate that the binder upgrade can be an economical alternative to the original binder under warmer future climate conditions, with LCC reductions ranging between 0.3 and 34%. In addition, the binder upgrade was also found to decrease the total LCC under the baseline climate (0.2–33% reduction). The reduction can be much greater under future climate conditions than under the baseline climate conditions (e.g., Interstate: Richmond in Figure 6).

Although this study adopts representative cases, the conclusion can be generalized for pavements in other regions that expect to become warmer in the future. This is primarily because the upgraded binder shows advantages in performance and its cost-effectiveness overcomes the fact that its material costs are higher. In regions where changes in the precipitation levels are going to be significant, the conclusions reported in this article may or may not be applicable. Therefore, further investigation is needed. The investigated road sections in the case studies are typical interstate/primary/secondary roads in Virginia, which also represent three different climate subregions (warmer/mild/cooler) in Virginia. Therefore, the conclusions can be extended both to other cases in Virginia and regions with similar climates.

Some limitations and challenges were encountered in this study, all of which are appropriate topics to be addressed in future research. The majority of those limitations and challenges are related to uncertainties in the LCC calculations, although they have been acknowledged and partly considered in this study. Specifically, the uncertainties stem mainly from the following:

1. Climate projections: these are associated with a range of uncertainties, from scientific and model uncertainties to uncertainties in human behavior. No current projection allows objective quantification of the errors related to future climate projections, as the future development pathway of society and, thus, the quantity of future greenhouse gas emission is uncertain (IPCC 2014). In this study, the RCP8.5 scenario is used to represent a future high emission scenario of climate uncertainty in the investigated region.

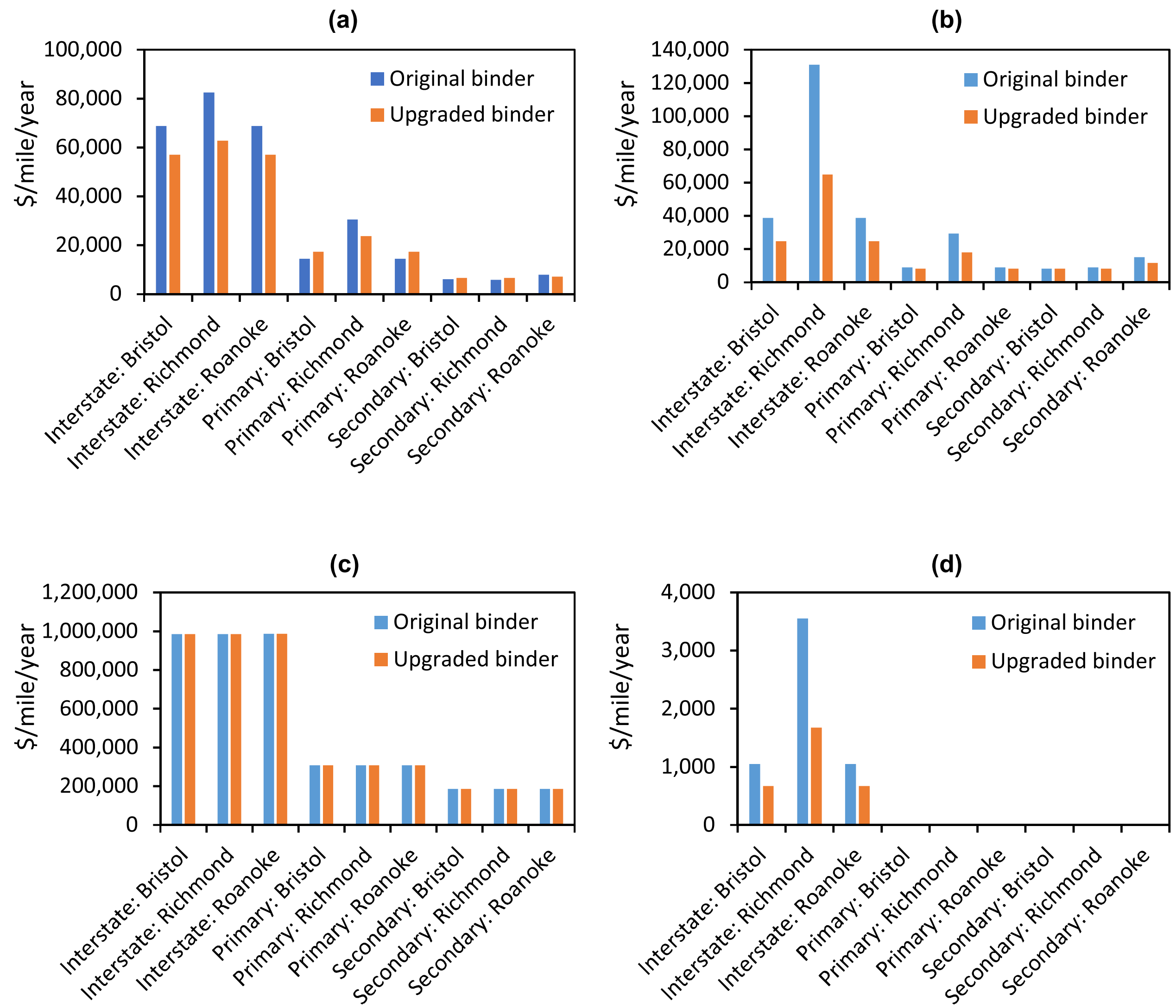

FIGURE 5 Life-cycle costs incurred during the different phases of the pavement life cycle under future climate: (a) material production phase; (b) maintenance phase; (c) use phase; and (d) work zone phase. Underlying data used to create this figure can be found in the Supporting Information S1

2. Pavement performance prediction over time: pavement does not necessary perform exactly as predicted by the Pavement ME software. When using this software, a design reliability of 90% was considered. This value means that there is a 90% chance that the designed pavements (using the Pavement ME) can satisfy performance criteria over their service life.
3. LCCA-related assumptions: there are various models/parameters in the LCCA for which values and assumptions taken from other studies referring to Virginia conditions/practices were considered. Different choices of LCCA components/models/parameters may influence the results found in this study.

Although out of the scope of this study, the uncertainties and their influences in the results can be quantified by using a probabilistic approach instead of the deterministic one. Climate projections and locally calibrated PPPM are key models in this study and are currently only available in a deterministic format. For climate projections, there is no probabilistic quantification on the likelihood of occurrence of a specific kind of emission scenario (i.e., high, medium and low). As far as the PPPM are concerned, the results (i.e., rutting, IRI, and cracking progression) are generated as deterministic values. Once probabilistic climate and PPPM are available, it would be worthwhile to update the research methodology adopted in this study by considering a probabilistic LCCA.

Lastly, the decision to use only one GCM and RCP was made based on the intention of this study to be presented as an initial overview of how the economic impact may differ under a changing climate. While this decision may limit the absolute validity of the conclusions, they still provide insights on the magnitude and direction of the trend of anticipated expenditures caused by a warmer climate. For decision making purposes, it would be beneficial to use as many GCMs and future scenarios as possible in order to capture the broad range of uncertainty caused by both

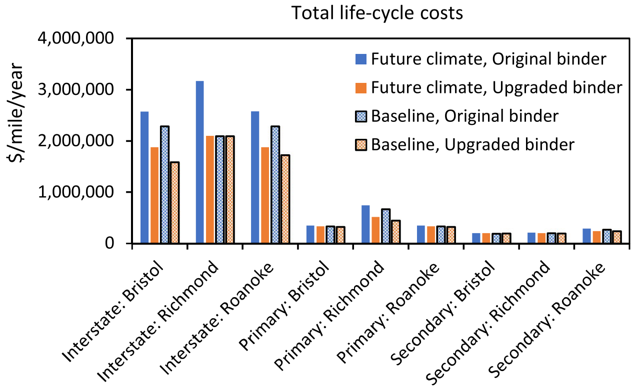

FIGURE 6 Net present value of the total life-cycle costs of the original binder and upgraded binder under baseline and future climate conditions. Underlying data used to create this figure can be found in the Supporting Information S1

scientific and model uncertainty, as well as the uncertainty in how our emissions will evolve over time due to human choices (Hayhoe et al., 2017). As such, it would be desirable to perform similar analyses using a broader range of GCMs and scenarios to evaluate to what extent the use of the upgraded binder in the asphalt mixtures can be adopted as an economic measure to be implemented in response to climate change.

8 | CONCLUSIONS

This study presents a comprehensive LCCA intended to investigate the potential economic benefits resulting from upgrading the asphalt binder from PG 70-22 (used in the asphalt mixture SM-12.5D) to PG 76-22 (used in the asphalt mixture SM-12.5E) for climate adaptation in the state of Virginia. Three case studies were considered involving typical interstate, primary, and secondary pavements in three major VDOT districts (i.e., Bristol, Richmond, and Roanoke) where climates vary, both under baseline and future conditions. In this study, the downscaled projected future climate, pavement life-cycle performance and service life were considered. Locally calibrated traffic, material parameters, and maintenance effect models were also adopted.

From the application of the methodology developed to the case studies it was found that, under the 2020–2039 projected climate, pavements with the upgraded binder have better performance compared to those with the original binder. This includes a 1–5% reduction in IRI, a 4–14% reduction in rutting, and a 3–53% reduction in AC bottom-up cracking. As far as the AC thermal cracking is concerned, it may increase or decrease depending on the specific cases. However, generally this type of distress is not an issue, as it was predicted to be insignificant and will not trigger maintenance interventions. Pavements with the upgraded binder were found (1) to require less frequent or delayed maintenance and (2) to have longer service life. In most of the cases, pavements with the upgraded binder also showed reductions in the costs incurred during the production, maintenance, WZ, and use phases. Furthermore, the use of the upgraded binder in the production of the asphalt mixtures was found to result in a 0.3–34% reduction in the total LCC.

In the near future, this research work will proceed in four main directions. First, the potential environmental impacts associated with the use of the upgraded binder in asphalt mixtures will be assessed by using a Life Cycle Assessment (LCA) approach. Second, a probabilistic LCCA will be performed to ascertain the effect of uncertain input parameters on the LCC results. Third, a network level analysis will be performed to quantify the potential benefits resulting from the use of the upgraded binder in asphalt mixtures at state and national levels. Finally, a multiobjective optimization-based decision support system integrating the LCCA-LCA models will be applied to determine optimal economically-friendly and environmentally-friendly pavement maintenance strategies for adaptations to climate change.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

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REFERENCES

AASHTOWare. (2016). *AASHTOWare pavement ME design*. Washington, D.C.: AASHTOWare. Retrieved from https://me-design.com/MEDesign/?AspxAutoDetectCookieSupport=1

Apeagyei, A. K., & Diefenderfer, S. D. (2011). *Asphalt material design inputs for use with the mechanistic-empirical pavement design guide in Virginia Charlottesville*. Charlottesville, VA: Virginia Center for Transportation In novation and Research.

Brann, D. E., & Mullins, G. L. (2000). *Agronomy handbook*. Blacksburg, VA: Virginia Polytechnic Institute and State University.

Chatti, K., & Zabaar, I. (2012). *Estimating the effects of pavement condition on vehicle operating costs*. Washington, D.C.: NCHRP. Retrieved from http://www.trb.org/Publications/Blurbs/166904.aspx

Chinowsky, P. S., Price, J. C., & Neumann, J. E. (2013). Assessment of climate change adaptation costs for the U.S. road network. *Global Environmental Change*, *23*(4), 764–773. https://doi.org/10.1016/j.gloenvcha.2013.03.004.

Dunne, J. P., John, J. G., Adcroft, A. J., Griffies, S. M., Hallberg, R. W., Shevliakova, E., … Zadeh, N. (2012). GFDL's ESM2 Global coupled climate-carbon earth system models. Part I: Physical formulation and baseline simulation characteristics. *Journal of Climate*, *25*, 6646–6665.

EM. (2017). *Interest rates, discount rate for United States*. St. Louis, MO: Federal Reserve Bank. Retrieved from https://fred.stlouisfed.org

Goedkoop, M., Oele, M., Leijting, J., Ponsioen, T., & Meijer, E. (2016). *Introduction to LCA with SimaPro*. San Francisco, CA: PRe. Retrieved from https://www.pre-sustainability.com/download/SimaPro8IntroductionToLCA.pdf

Hayhoe, K., Edmonds, J., Kopp, R. E., LeGrande, A. N., Sanderson, B. M., Wehner, M. F., & Wuebbles, D. J. (2017). Climate models, scenarios, and projections. In D. J. Wuebbles et al. (Eds.), *Climate science special report: Fourth national climate assessment, Volume I*. Washington, DC: U.S. Global Change Research Program.

HCM. (2010). *Highway capacity manual*. Washington, D.C.: Transportation Research Record.

IPCC. (2014). *Climate change 2014*. Geneva, Switzerland: Synthesis Report.

Mallick, R., Radzicki, M., Daniel, J., & Jacobs, J. (2014). Use of system dynamics to understand long-term impact of climate change on pavement performance and maintenance cost. *Transportation Research Record: Journal of the Transportation Research Board*, *2455*, 1–9. https://doi.org/10.3141/2455-01.

Mannering, F. L., Washburn, S. S., & Kilareski, W. P. (2009). *Principles of highway engineering and traffic analysis* (4th ed). Hoboken, NJ: John Wiley & Sons, Inc.

McGhee, K. K., & Clark, T. M. (2007). *A Cost-comparison methodology for selecting appropriate hot-mix asphalt materials Charlottesville*. Richmond, VA: Virginia Transportation Research Council.

Memmott, J. L., & Dudek, C. L. (1982). A model to calculate the road user costs at work zones. In *Report No. FHWA/TX-87/20+292-1*. San Antonio, TX: Texas Transportation Institute.

Mills, B. N., Tighe, S. L., Andrey, J., Smith, J. T., & Huen, K. (2009). Climate change implications for flexible pavement design and performance in Southern Canada. *Journal of Transportation Engineering*, *135*, 773–782.

Nathman, R. K. (2008). *Palate user guide, example excercise, and contextual discussion*. Newark, DE: University of Delaware.

Qiao, Y., Dawson, A., Parry, T., & Flintsch, G. W. (2016). Immediate effects of some corrective maintenance interventions on flexible pavements. *International Journal of Pavement Engineering*, *19*, 502–508. https://doi.org/10.1080/10298436.2016.1176164.

Qiao, Y., Flintsch, G., Dawson, A., & Parry, T. (2013). Examining effects of climatic factors on flexible pavement performance and service life. *Transportation Research Record: Journal of the Transportation Research Board*, *2349*, 100–107.

Santos, J., Bryce, J., Flintsch, G., & Ferreira, A. (2017). A comprehensive life cycle costs analysis of in-place recycling and conventional pavement construction and maintenance practices. *International Journal of Pavement Engineering*, *18*(8), 727–743.

Schweikert, A., Chinowsky, P., Kwiatkowski, K., & Espinet, X. (2014). The infrastructure planning support system: Analyzing the impact of climate change on road infrastructure and development. *Transport Policy*, *35*, 146–153. http://doi.org/10.1016/j.tranpol.2014.05.019

Socolofsky, S., Adams, E. E., & Entekhabi, D. (2001). Disaggregation of daily rainfall for continuous watershed modeling. *Journal of Hydrologic Engineering*, *6*, 300–309.

Stoner, A. M. K., Hayhoe, K., Yang, X., & Wuebbles, D. J. (2013). An asynchronous regional regression model for downscaling of daily climate variables. *International Journal of Climatology*, *33*, 2473–2494.

Tighe, S. L., Smith, J., Mills, B., & Andrey, J. (2008). *Using the MEPDG to assess climate change impacts on southern Canadian roads. Seventh International conference on managing pavement assets*. Alberta, Canada: US Department of Transportation Federal Highway Administration.

Underwood, B. S., Guido, Z., Gudipudi, P., & Feinberg, Y. (2017). Increased costs to US pavement infrastructure from future temperature rise. *Nature Climate Change*, *7*, 704–707. Retrieved from https://www.nature.com/articles/nclimate3390#supplementary-information

VDOT. (2011). *Life cycle cost analysis*. Richmond, VA: Material division, Virginia Transportation Research Council.

VDOT. (2017). *AASHTOWare pavement ME user manual*. Richmond, PA: Pavement Design and Evaluation Section Central Office, Materials DivisionVirginia Department of Transportation.

Vose, R. S., Easterling, D. R., Kunkel, K. E., LeGrande, A. N., & Wehner, M. F. (2017). Temperature changes in the United States. In D. J. Wuebbles et al. (Eds.), *Climate science special report: Fourth national climate assessment, Volume I*. Washington, DC: U.S. Global Change Research Program.

Walsh, J., Wuebbles, D., Hayhoe, K., Kossin, J., Kunkel, K., Stephens, G., … Somerville, R. (2014). Our changing climate. In J. M. Melillo, T. C. Richmond, & G. W. Yohe (Eds.), *Climate change impacts in the United States: The third national climate assessment*. Washington, D.C.: U.S. Global Change Research Program.

Wuebbles, D. J., Easterling, D. R., Hayhoe, K., Knutson, T., Kopp, R. E., Kossin, J. P., … Wehner, M. F. (2017). Our globally changing climate. In D. J. Wuebbles et al. (Eds.), *Climate science special report: Fourth national climate assessment, Volume I*. Washington, DC: U.S. Global Change Research Program.

Zapata, C. E., & Houston, W. N. (2008). *Calibration and validation of the enhanced integrated climatic model for pavement design* (Vol. *602*). Washington, D.C.: Transportation Research Board.

SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section at the end of the article.

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