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Adaptive Maintenance Strategies to Mitigate Climate Change Impacts on Asphalt Pavements

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Abstract

This study aims to explore the potential of optimization-based maintenance strategies in adapting asphalt pavements to future climate change. Based on a highway network in Jiangsu, China, the impacts of climate change, characterized by global warming and intensified precipitation, on pavement life cycle cost (LCC) and performance were quantitively assessed, and the benefits of maintenance optimization in mitigating climate change impacts were examined. The findings indicate that climate change may increase pavement rutting depth and reduce pavement roughness and skid resistance, while its effect on transverse cracking varies over time. Adjusting the maintenance schedules, but still following the threshold-based approach, would increase the LCC by about 15.5%~19.1%. The optimization-based maintenance decision-making model significantly mitigates climate change impacts, ultimately even saving 0.6% of LCCs compared to the baseline. The outcomes will provide a quantitative understanding of the climate change impacts on asphalt pavements, as well as adaptive maintenance strategies to improve pavement resilience.

Keywords: asphalt pavement; climate change; maintenance optimization; life cycle cost; adaptation strategies

1 Introduction

There is a strong consensus that anthropogenic climate change has reached unprecedented scales in the past few hundred to several thousand years. According to the Intergovernmental Panel on Climate Change (IPCC), global surface temperatures caused by human activities may have increased by about 1.07°C in 2010-2019 compared to pre-industrial levels (1850-1900) (IPCC, 2021). What is even worse, global warming is expected to progress over this century. Under the intermediate greenhouses gas (GHG) emissions scenario, i.e., the Shared Socio-economic Pathway (SSP)2-4.5, global warming is projected to surpass the 1.5 °C and 2 °C targets relative to pre-industrial levels by the end of the 21st century (IPCC, 2021). With sustained global warming, heavy precipitation events are also very anticipated to increase and become more common in most places. (IPCC, 2021).

Transportation infrastructure systems are anticipated to experience significant impacts from climate change, stemming from both extreme and chronic changes in temperature, precipitation, humidity, wind, sea level rise, etc. One important component of this system that is prone to climatic stresses is the road pavement structures, as they are often directly exposed to the natural environment. Besides, most of the high-grade pavements worldwide are constructed from asphalt mixtures, which is a typical temperature and moisture sensitive material. The increasing attention has been drawn to the effects of climate change on asphalt pavements in the pavement community over the past decade. Possible adverse effects on pavements due to the changing climate include worse pavement performance (Gudipudi et al., 2017; Piryonesi and El-Diraby, 2021; Miao et al., 2022), shortened service life (Qiao et al., 2013; Stoner et al., 2019), more frequent maintenance needs (Qiao et al., 2019b; Haslett et al., 2021), increased life-cycle costs (Qiao et al., 2019b; Underwood et al., 2017), and/or more environmental impacts (Guest et al., 2020; Chen et al., 2021). These also constitute the metrics commonly used in the literature to measure the climate change impacts on asphalt pavements. Swarna and Hossain (2022) summarized the impacts of climate change on pavement performance from various studies and found that the direction of the impact is consistent on some performance indicators, but inconsistent on others. For example, there is widespread agreement that climate change will exacerbate pavement rutting and fatigue cracking, while the impacts on roughness and bottom-up cracking are controversial (Swarna and Hossain, 2022). The possible premature pavement distress in future climates will cause more frequent maintenance and rehabilitation (M&R), thereby increasing agency costs.

However, in practice, asphalt pavements are generally designed and maintained under the assumption of constant historical climate, without considering future climate changes. For example, the Chinese specification for highway asphalt pavement design requires that the mean air temperature of at least ten consecutive years in the past be utilized to verify the structure design of asphalt pavement (MOT, 2017). In the U.S., the default historical climate input in the Mechanistic-Empirical (ME) pavement design model used for future pavement design is from 1985 to 2004 (Chen et al., 2021). Pavement structures and maintenance plans designed based on the assumption of stationary climate may lead to premature damages and increased life cycle costs (LCCs). Underwood et al. (2017) found that incorrect selection of asphalt grades could incur an additional cost of up to $35.8 billion in the U.S. with warming temperatures. Therefore, adapting pavement design and maintenance schedules to the changing climate may help mitigate their negative effects. Typical adaptation strategies include increasing the thickness of asphalt/base layers, upgrading asphalt binder grade, using stabilized base layers, and optimizing M&R schedules (Knott et al., 2019; Swarna et al., 2022; Qiao et al., 2015). However, it is worth mentioning that in economically developed regions such as eastern China, the focus of road agencies has gradually shifted from the construction of new roads to the management and maintenance of existing roads. It can be expected that the adaptation costs of upgrading the materials and structures of all existing pavements would be very high. Thus, a more cost-effective adaptation strategy without the need to reconstruct existing pavements is required.

Overall, previous research has confirmed that climate change, characterized by global warming, will affect the life cycle performance and costs of asphalt pavements, while the magnitude and direction of impacts may vary across regions and studies. Meanwhile, it was also well demonstrated that developing adaptation strategies are important to make road infrastructure more resilient to climate change. However, the present literature still has certain limitations. Firstly, due to the ability of the ME pavement design model to examine the evolution of pavement performance under different climate conditions, most existing studies have focused on North America and flexible pavements, while very little research has been done on the semi-rigid base asphalt pavement in China. Secondly, some studies have assessed the impacts of climate change on pavements by comparing differences in pavement performance under varied climatic conditions in two widely separated time windows (Piryonesi and El-Diraby, 2021; Miao et al., 2022; Qiao et al., 2015), such as a comparison between the current year and the end of this century. In fact, climate changes gradually rather than suddenly changing to the level of decades later, and pavement performance also gradually deteriorates under the influence of climate, traffic load and other factors. Hence, such an approach fails to capture the long-term cumulative impacts of successive changes in climate and can overestimate the climate change impact in future years. Lastly, some adaptation strategies, such as increasing pavement thickness or upgrading asphalt grades, could be very costly if extended to the entire pavement network, as it requires resurfacing or overlaying of the existing pavements, which would consume a significant amount of raw material, fuel and labor costs. Therefore, more cost-effective strategies need to be developed, such as using an optimized M&R schedule to improve the pavement resilience (Qiao et al. 2015).

The overall goal of this research is to explore the potential of optimization-based maintenance strategies in adapting asphalt pavements to future climate change. To this end, the long-term impact of climate change on asphalt pavements in terms of life cycle performance and cost were quantitatively assessed. It is noteworthy that the focus of this study is on the impact of long-term climatological trends, including gradual global warming and increased frequency of extreme temperature and rainfall, on asphalt pavement performance and maintenance. Extreme weather events, such as floods, hurricanes, landslides, etc., which cause severe damage to road infrastructure and disruption of transportation systems in a short period of time, are outside the scope of this study because the damage they cause generally cannot be repaired by pavement M&R alone. Future climatic conditions are incorporated on a yearly basis to enable prediction of pavement performance and scheduling of M&R under changing climates. The potential of adaptation strategies, i.e., improving maintenance decision-making methods from reactive threshold-based to proactive optimization-based, on mitigating climate change impacts were examined. Thus, the present study is expected to provide a quantitative understanding of climate change impacts on pavement infrastructure in eastern China, as well as insights into feasible climate change adaptation strategies under the existing pavement management and maintenance framework.

2 Methodology

2.1 Overview

The methodological framework of this study is presented in Fig. 1. It starts with projections of future climate in the study region. The Statistical DownScaling Model (SDSM) (Wilby et al., 2002; 2007), calibrated using historical daily station observations, was employed to statistically downscale a subset of the Coupled Model Intercomparison Project Phase 6 (CMIP6) global climate models (GCMs). As a result, future daily temperature and precipitation can be projected on a regional scale. Climate variables were incorporated into the pavement performance model along with other factors to predict pavement conditions, based on which M&R decisions were determined through the maintenance decision-making model. Then, pavement conditions for the next year can be predicted based on this M&R decision and the following year's climate and other factors. This process was repeated until the end of the analysis period.

The hierarchical threshold-based approach (HT) and the multi-agent reinforcement learning (MARL)-based simultaneous network optimization (SNO) model were utilized for M&R scheduling under both historical and future climatic conditions, yielding four types of M&R schedules as a result. For example, SNO_f represents the M&R schedule obtained from the SNO model under future climate, which can be further subdivided into multiple schedules based on the future climate change scenarios considered, whereas HT_h corresponds to the M&R schedule derived from the HT model under historical climate. To explore the impact of climate change and the effect of adaptation strategies, the four M&R schedules were applied to both historical and future climates to construct eight types of cases, as shown in the lower right of Fig. 1. It should be noted that if more than one climate change scenario is considered, the exact number of cases will be more than eight, which will be introduced later. The suffix with the structure "_XY" indicates that the M&R schedule produced under the X climate scenario is used under the Y climate scenario (h= historical climate and f= future climate). Thus, "_hh" refers to current maintenance decision-making practices i.e., assuming that the climate remains constant during both the maintenance planning and implementation phases. "_hf" indicates the application of M&R schedules generated under historical climates to future climates without adaptation, which represents the worst case but is extremely unlikely to occur because of the increasingly annual availability of pavement condition data. By comparing the results of different cases, the impact of climate change can be quantitatively assessed, providing implications for highway agencies to better manage their pavement infrastructure under changing climate.

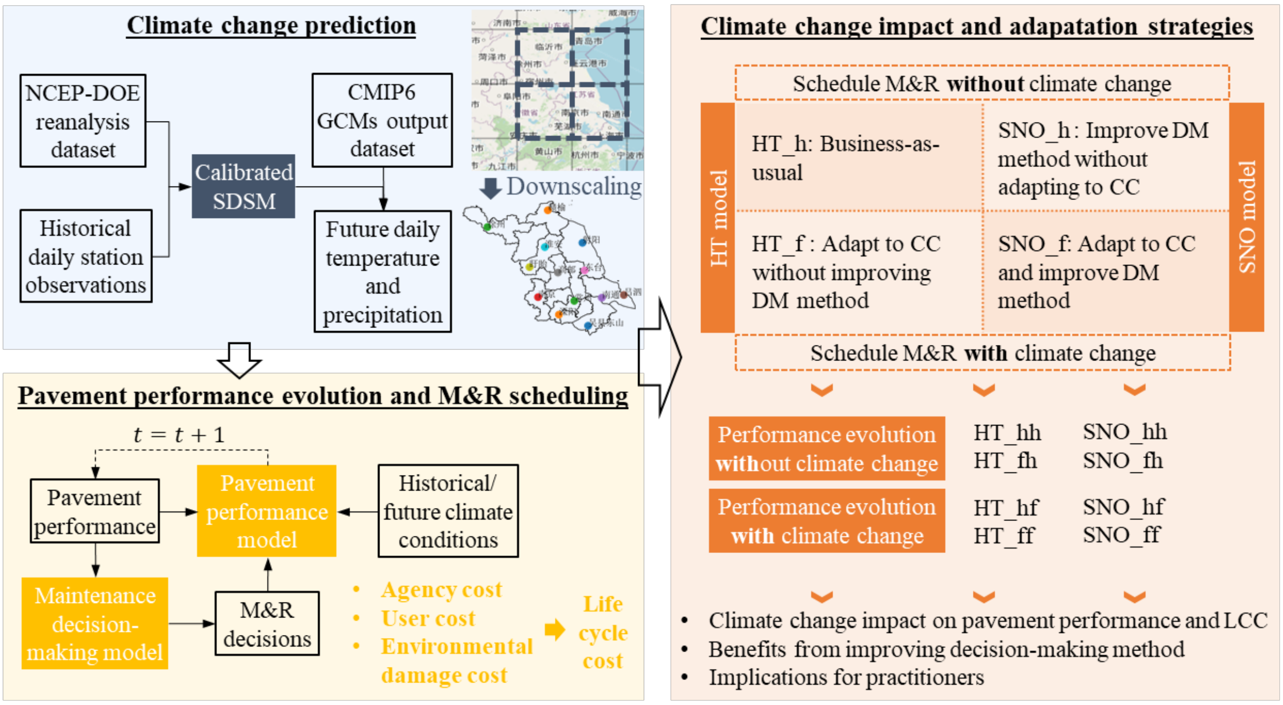


Fig. 1. An overview of the methodology

2.2 Climate change predictions

2.2.1 Global climate models and scenarios

Climate models play a crucial role in comprehending historical and potential future climate changes, as they simulate the intricate interactions of the atmosphere, land, and oceans, encompassing physics, chemistry, and biology. The CMIP6 of the World Climate Research Programme (WCRP), provides a large number of GCMs that were produced by many different modeling groups around the world and have served as important input to IPCC AR6. In CMIP6, a set of five illustrative emissions scenarios, referred to as SSP1-1.9, SSP1-2.6, SSP2-4.5, SSP3-7.0, and SSP5-8.5, were developed, which cover the range of possible changes in socioeconomic development up to 2100. This study only considers two climate change scenarios commonly used in the literature, namely SSP2-4.5 and SSP5-8.5 (denoted as SSP245 and SSP585 for simplicity) (Qin et al., 2022; Streletskiy et al., 2023; Gudipudi et al., 2017), where SSP585 represents the worst-case scenario for future GHG emissions, and SSP245 is the most likely pathway under current mitigation policies (Hausfather and Peters, 2020).

2.2.2 Downscaling of GCM output

Generally, GCMs provide estimates of global climate change with a spatial resolution of hundreds of kilometers. This coarse resolution is usually insufficient to describe the variations in climate at local scales. Thus, the output of GCMs needs to be downscaled to produce climate projections at scales that reflect site-specific conditions. There are two categories of downscaling techniques in the literature, i.e., statistical and dynamic downscaling. Dynamic downscaling employs a high-resolution climate model focused on a relatively small region, with its boundary conditions determined by the output fields of GCMs, whereas statistical downscaling develops a statistical relationship between GCM output and observed climate variables that are then used to bias-correct and downscale both historical and future GCM simulations (Kotamarthi et al., 2021).

In this research, the statistical downscaling approach was adopted due to its advantages of being less computationally intensive and easier to implement. More specifically, the SDSM (Wilby et al., 2002; 2007) was employed, which has been demonstrated in many studies for its ability to construct daily time-scale climate change scenarios for individual sites from GCM outputs (Chu et al., 2010; Huang et al., 2011; Peng et al., 2023). The SDSM can be considered as a hybrid of the stochastic method and regression-based method (Wilby et al., 2002; 2007). It calibrates a multiple linear regression model between selected gridded predictors and single-site predictands, such as temperature and precipitation, using large-scale predictors from the National Centers for Environmental Prediction (NCEP) reanalysis dataset and local-scale predictands from meteorological stations (Wilby et al., 2002; 2007). Stochastic methods are employed to artificially increase the variance of downscaled data series, aligning them with real-world observations. Predictor variables are screened through correlation analysis and scatterplots, and physical plausibility should also be examined (Wilby et al., 2002; 2007). The calibrated model needs to be validated with the remaining independent data. After the SDSM is calibrated, it is then utilized to generate synthetic daily weather series based on the predictor variables provided by climate models (NCEP or GCMs).

To apply this model, daily predictor variables from the NCEP reanalysis dataset and a subset of CMIP6 GCMs, as well as climate data preprocessing methods, provided by the Canadian Climate Data and Scenarios (CCDS, 2022), were utilized and followed. Site-scale predictands, including daily average, minimum, and maximum temperature, and daily total precipitation, were collected. Table 1 presents the detailed information of the GCMs, predictor variables, and predictand variables used for downscaling in this research.

Table 1

Details of the GCMs, Predictor Variables, and Predictand Variables.

CMIP6 GCMs			
Model Name	CanESM5	NorESM2-MM	MPI-ESM1.2-HR
Institute	Canadian Centre for Climate Modelling and Analysis, Canada	Norwegian Climate Centre, Norway	Max Planck Institute for Meteorology, Germany
Resolution ($lat \times lon, °$)	2.8 × 2.8	1.9 × 2.5	0.9 × 0.9
Equilibrium climate sensitivity (ECS) (°K)	5.6	2.5	3.0
Predictor variables			
Variable ID	Predictor variable	Variable ID	Predictor variable
mslp	Mean sea level pressure	p500	500 hPa Geopotential
p1_f, p5_f, p8_f	1000, 500, 850 hPa Wind speed	p850	850 hPa Geopotential
p1_u, p5_u, p8_u	1000, 500, 850 hPa Zonal wind component	prcp	Total precipitation
p1_v, p5_v, p8_v	1000, 500, 850 hPa Meridional wind component	s500	500 hPa Specific humidity

p1_z, p5_z, p8_z	1000, 500, 850 hPa Relative vorticity of true wind	s850	850 hPa Specific humidity
p1th, p5th, p8th	1000, 500, 850 hPa Wind direction	shum	1000 hPa Specific humidity
p1zh, p5zh, p8zh	1000, 500, 850 hPa Divergence of true wind	temp	Air temperature at 2 m

Predictand variables

Variable ID	tas	tasmin	tasmax	pr
Predictand variable	Daily average temperature	Daily minimum temperature	Daily maximum temperature	Daily total precipitation
Unit	°C	°C	°C	mm

2.3 Pavement performance modeling and maintenance planning

The relationship between climate factors and pavement performance is established through pavement performance modelling. In this study, four pavement performance indicators (PPIs) were considered, including rutting depth (RD), international roughness index (IRI), side-way force coefficient (SFC), and transverse cracks evaluation index (TCEI). A separate performance model was built for each indicator using the Bayesian neural network (BNN) approach, where the TCEI model was developed and demonstrated in the authors' previous research (Yao et al., 2022a). All four models were built on the multi-year observation data of a large-scale highway pavement network in Jiangsu, a province in eastern China. More than 20 years of meteorological data were collected from multiple weather stations, based of which multiple climate variables were synthesized, including averages and extremes. They were then incorporated into pavement performance models to predict the performance deterioration of asphalt pavements under various climatic conditions.

Two methods were employed to develop pavement M&R schedules in this research. The first is the traditional HT approach, which compares pavement performance indicators against a series of hierarchical thresholds and triggers corresponding M&R actions when the thresholds are met (Wang, 2019). It is a commonly used method in practice due to its ease of implementation and adjustment.

However, the HT method is a reactive rather than an optimization-based method, and previous studies have demonstrated that its performance is inferior to optimization model (Yao et al., 2022b).

The other is the SNO model built upon the MARL algorithm called QMIX (Rashid et al., 2018), which incorporates the heterogeneity and interdependency among pavement segments into the network-level long-term maintenance optimization, as described in another of the authors' paper under review. In the SNO model, behind each one-lane-kilometer pavement segment there is a virtual decision-maker responsible for formulating the M&R plan, who is also an agent in the multi-agent system. At each time step, each agent perceives its own observations, which are information related to individual pavement segments and is used to make M&R decisions (Yao et al., 2022a). The agent then selects an action, i.e., a certain M&R treatment (Yao et al., 2022b), according to its local action-observation history. This leads to the transition of the state of the pavement network, i.e., the joint observation of all segments. To account for the segment interdependencies arising from the dynamic traffic distribution, it is assumed that the state is first transferred to an intermediate state, i.e., the immediate state after M&R. Based on this, the network traffic flow is redistributed, and the next state is predicted using the pavement performance models (YAO et al., 2022a). A global reward is then obtained, which is the negative value of the sum of the agent cost (AC), user cost (UC) and environmental damage cost (EDC) for the current time interval. The ultimate goal of cooperative agents is to learn decentralized policies, i.e., their respective M&R strategies, to maximize the return of the global reward. Fig. 2 is a schematic diagram of the QMIX-based SNO model. More details about the QMIX algorithm can be found in Rashid et al. (2018).

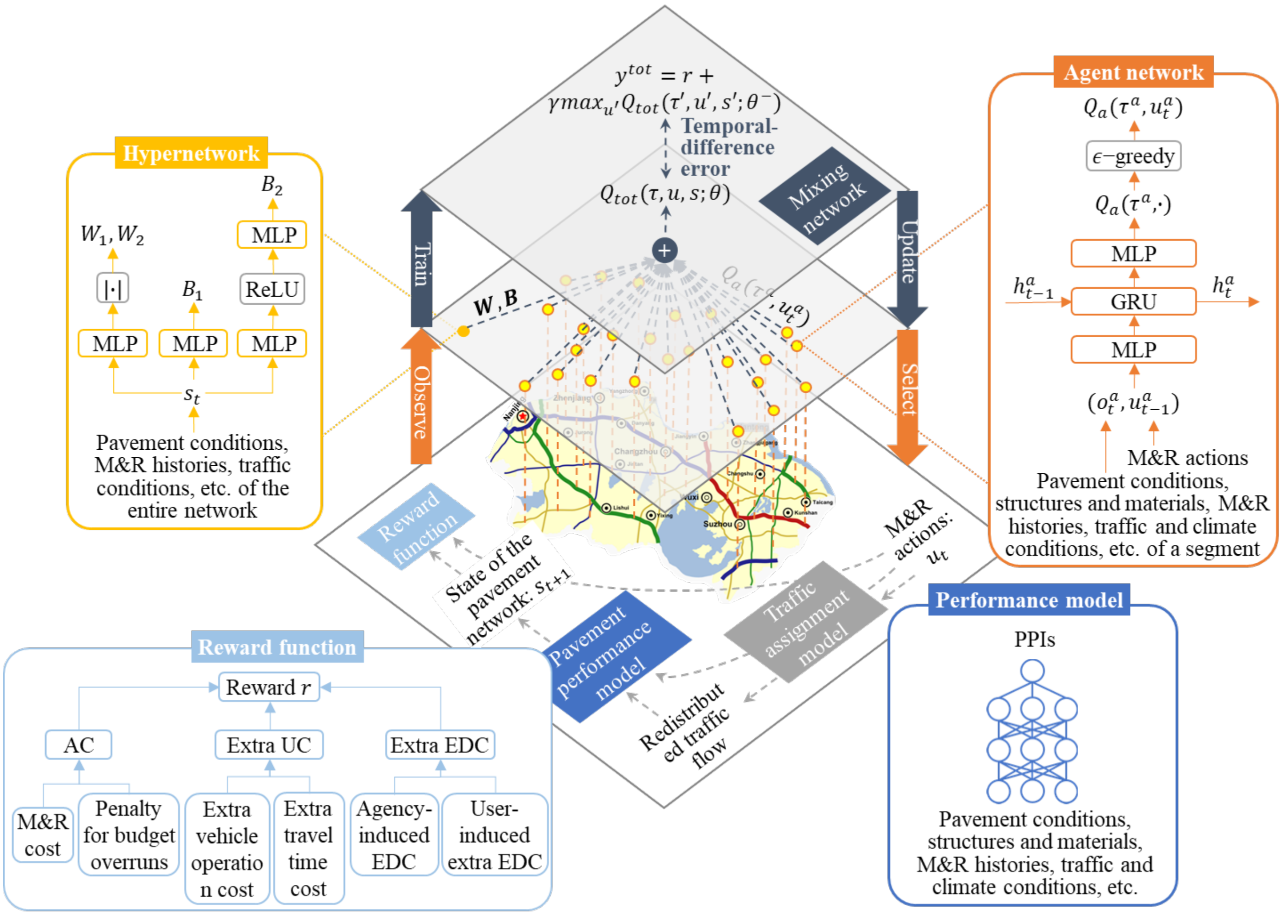


Fig. 2. A schematic diagram of the QMIX-based SNO model

Moreover, highway asphalt pavements in China are typically designed for a 15-year lifespan before reconstruction (MOT, 2017), while climate change is generally not very noticeable until at least several decades later. To explore the impact of climate change on pavement infrastructure over the forecast period of climate models (usually until 2100), it is assumed that road pavements will be reconstructed after 40 years of service, and M&R actions are scheduled between the two reconstruction time points using either the HT approach or the SNO model. The three climate scenarios (i.e., SSP245, SSP585, and no climate change) and two maintenance decision-making methods (i.e., HT and SNO) correspond to six M&R schedules, and their application under changing and constant climate yielded a total of 14 cases. By comparing HT_hh with SNO/HT_ff_SSP245/585 and

SNO/HT_hf_SSP245/585, the impact of climate change with or without adaptive M&R schedules and improved M&R decision-making can be obtained. Moreover, a comparison with SNO/HT_fh_SSP245/585 may also reveal whether the proposed adaptation strategies are no-regrets strategies (Kirshen et al., 2015).

2.4 Integrated pavement life cycle assessment (LCA) and LCCA

Climate change can affect pavement performance and maintenance schedules, thereby further exerting influence on pavement LCCs and GHG emissions. In this study, these impacts were quantified by integrating the LCA and LCCA methods (Harvey et al., 2016; Walls and Smith, 1998), which involved converting GHG emissions into monetary values to form a unified economic indicator. Therefore, the cost items in LCC mainly include agency costs, additional users and environmental damage costs. Agency cost is the cost of maintaining and rehabilitating the pavement, including material, machinery, and labor costs, which was calculated from local reference prices. Additional user costs mainly consist primarily of increased vehicle operating costs (VOC) and travel time costs due to pavement deterioration, maintenance work, and the dynamic distribution of network traffic flows. The calibrated HDM-4 fuel consumption model (Chatti and Zaabar, 2012) was used to calculated the additional fuel consumption of vehicles traveling on the uneven pavements. The Bureau of Public Roads (BPR) function (BPR, 1964) was adopted to estimate the extra travel time due to reduced capacity in work zones. Moreover, additional EDCs were calculated by translating the GHG emissions related to material production, transportation, construction, and pavement-vehicle interaction (PVI) into monetary values. The data sources for calculating these costs were the same as (Yao et al., 2022b). In addition, the extra crash cost due to poor pavement skid resistance was also included so as to quantify the economic loss caused by the deterioration of other PPIs besides roughness. To this end, the regression model of SFC and rainy-day crash rate (CRR) (Xu et al., 2013) built on data from a highway (i.e., Huning expressway in China) included in this study was adopted to estimate the number of extra rainy-day crashes due to skid resistance deterioration, as shown below:

$$CRR = (\frac{88.6}{SFC})^{4.134} \tag{1}$$

$$\Delta CNR = \frac{CRR - CRR_0}{10^8} \times L \times AADT \times 365 \tag{2}$$

where CRR= rainy-day crash rate at certain SFC level (unit: number of rainy-day crashes per 10^8 vehicle kilometers travelled), CRR_0= rainy-day crash rate at baseline SFC, ΔCNR= number of extra rainy-day crashes per year due to skid resistance deterioration, L= length of road section, and $AADT$= annual average daily traffic. The number of traffic accidents and their direct property damage costs (PDCs) on expressways in Jiangsu in the past few years were obtained from the Transportation Knowledge Service System of China Knowledge Centre for Engineering Sciences and Technology (CKCEST) (CKCEST, 2017), which were then used to calculate the unit PDC per traffic accident. Before averaging the unit PDCs of previous years, the consumer price indexes (CPIs) of Jiangsu acquired from Jiangsu Statistical Yearbook 2022 (Jiangsu Provincial People's Government, 2022) were used to discount the unit PDCs to the monetary values of the current year. Furthermore, according to the National Highway Traffic Safety Administration (NHTSA) of U.S. Department of Transportation (USDOT), PDC only accounts for about 9% of the comprehensive cost incurred by vehicle crashes (Blincoe et al., 2022). Based on these considerations, the extra annual crash cost (EACC) of a pavement segment can be calculated following equation (3).

$$\mathrm{EACC} = \Delta CNR \times \frac{1}{t_2 - t_1} \sum_{t=t_1}^{t_2} \left[\left(\prod_{t'=t+1}^{t_2} \frac{CPI_{t'}}{100} \right) \times \frac{PDC_t}{CN_t} \right] \times \frac{1}{P_{PDC}} \tag{3}$$

where t_1, t_2= the starting and ending year for calculating the average unit PDC, $CPI_{t'}$= CPI in year t', PDC_t= total PDC in year t, CN_t= number of crashes in year t, and P_{PDC}= the percentage of PDC in the comprehensive cost.

3 Case Study

The developed methods were applied and demonstrated on a real-world expressway network south of the Yangtze River in Jiangsu, an eastern province of China, as illustrated in Fig. 3. The climate in the research region is subtropical, with four distinct seasons, moist air, abundant rainfall, and a long frost-free period. The network consists of 20 expressways divided into 6,364 one-way segments, each approximately one lane-km long with service ages ranging from 6 to 26 years. These pavement segments vary in terms of material, structure, traffic conditions, weather conditions, maintenance history, etc. For example, the equivalent single-axle load (ESAL) on some segments can be as low as 200 thousand, while on others, it can go up to 120 million. The analysis period is from 2022 to 2100, during which time it is assumed that the pavement will be reconstructed every 40 years of service. The baseline IRI and SFC were set to 1.0 m/km and 70, respectively, representing the initial performance values for a new pavement without performance degradation. After these pavement segments have been in service for 6-26 years and some segments have undergone M&R, the mean values (and standard deviations (SD)) of RD, IRI, SFC, and TCEI of these segments in 2022 are 6.5 mm (SD=1.5 mm), 1.2 m/km (SD=0.3 m/km), 45 (SD=5), and 80 (SD=17), respectively. The average unit PDC was calculated to be about 53,898 CNY per traffic accident. The pavement structure and material data, pavement performance data, traffic load data, M&R records, and weather station data were extracted from the pavement management system (PMS) in Jiangsu.

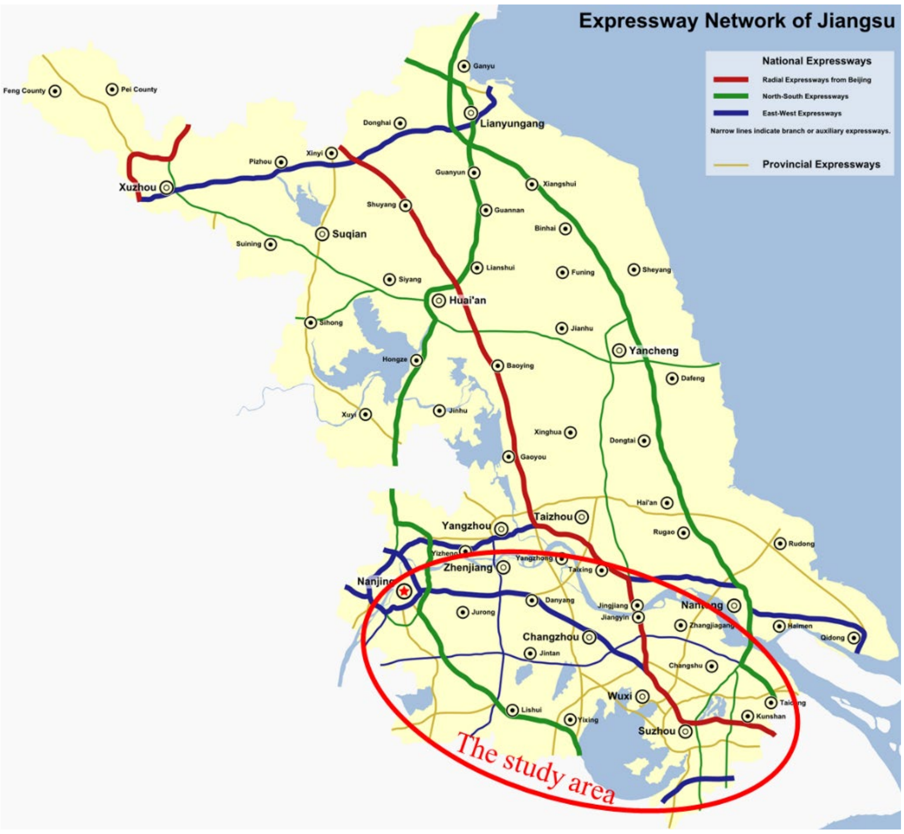


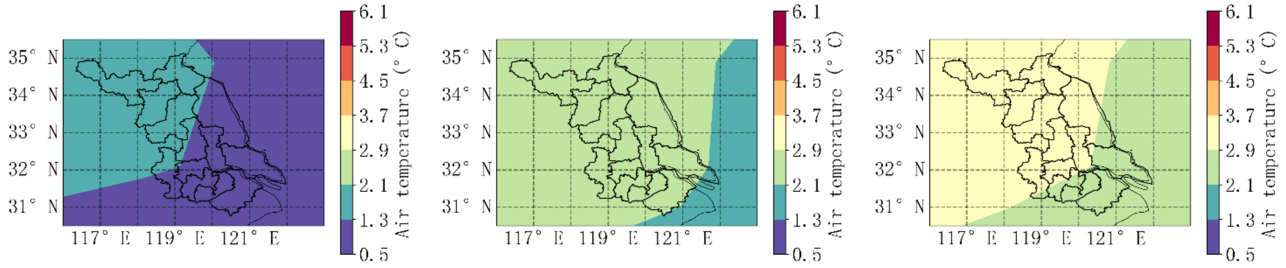
Fig. 3. A map of the expressway network in this study

4 Results and Discussion

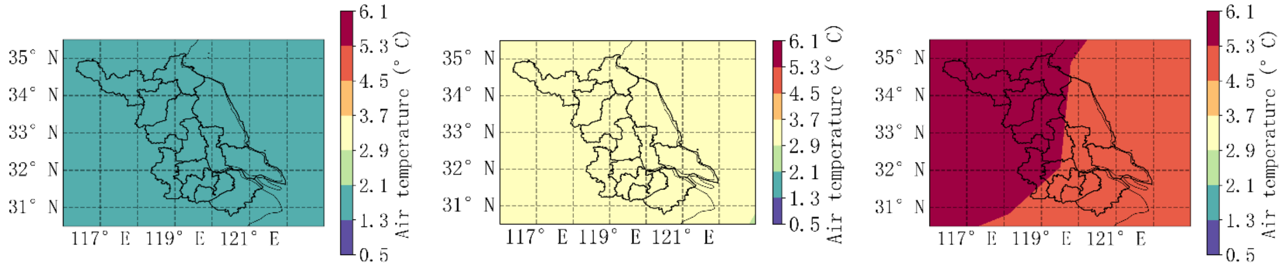
4.1 Future climate

4.1.1 Projected changes from GCMs

Fig. 4 and Fig. 5 map the changes in daily average temperature and daily total precipitation relative to 1990-2014 for various future periods under the two climate change scenarios based on the multi-model ensemble means (MMEMs) of the three GCMs. MMEM is calculated by averaging the output of an ensemble of GCMs, which is equivalent to assigning equal weights to each GCM, a concept that has been widely adopted in the literature (Yue et al., 2021; Zhu et al., 2021; Gudipudi et al., 2017; Zhang et al., 2022; Qiao et al., 2019a). It can be observed from Fig. 4 that the future daily average temperature shows an increase across Jiangsu. Meanwhile, inland regions in the northwest appear to experience greater warming than coastal regions in the southeast. Under the SSP585 scenario, the temperature rises in the northwestern inland areas such as Xuzhou, Lianyungang, Suqian, and Huai'an will reach a maximum of 5.71°C in the last two decades of this century. Regarding changes in precipitation, Fig. 5 shows that there will be more precipitation in Jiangsu in the future, although the magnitude of changes varies across cities and scenarios. In addition, it is obvious that climate projections from GCMs have a relatively coarse resolution, which necessitates the use of downscaling techniques to produce climate data with finer resolution at the local scale.

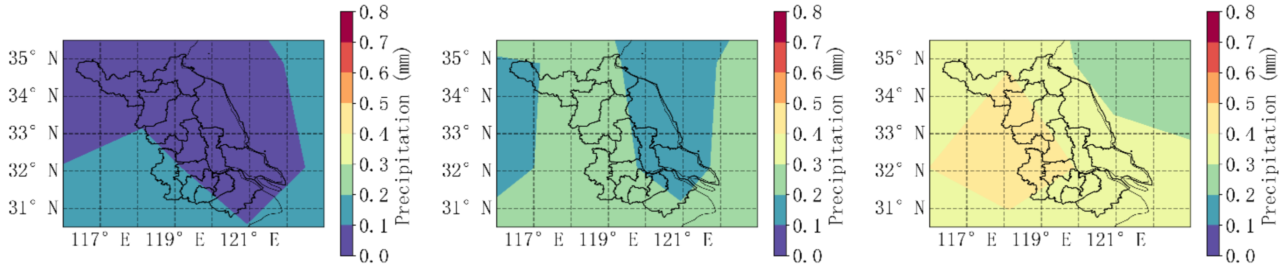


(a) SSP245, 2025-2049 (b) SSP245, 2050-2074 (c) SSP245, 2075-2100

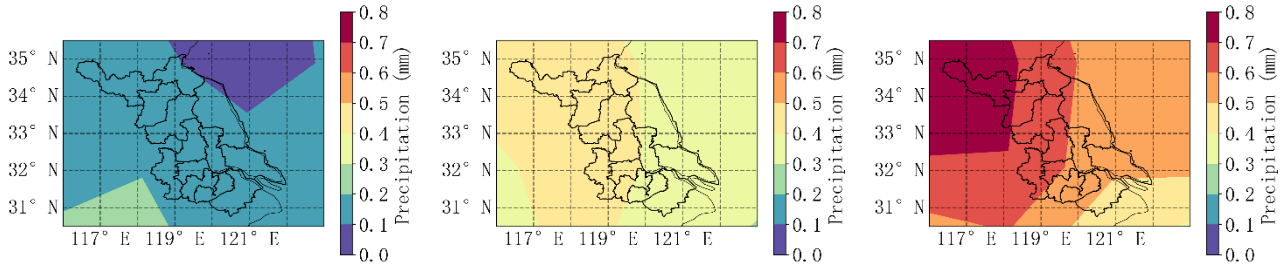


(d) SSP585, 2025-2049 (e) SSP585, 2050-2074 (f) SSP585, 2075-2100

Fig. 4. Projected changes of daily average temperature from MMEMs relative to 1990-2014 under the two SSP scenarios



(a) SSP245, 2025-2049 (b) SSP245, 2050-2074 (c) SSP245, 2075-2100



(d) SSP585, 2025-2049 (e) SSP585, 2050-2074 (f) SSP585, 2075-2100

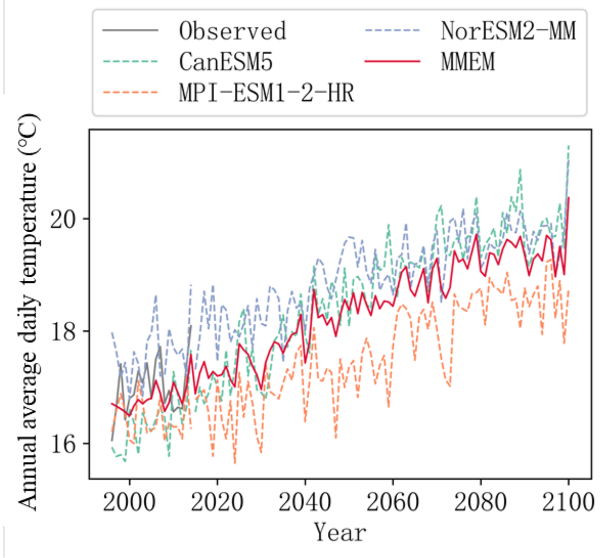
Fig. 5. Projected changes of daily total precipitation from MMEMs relative to 1990-2014 under the two SSP scenarios

4.1.2 Validation of SDSM

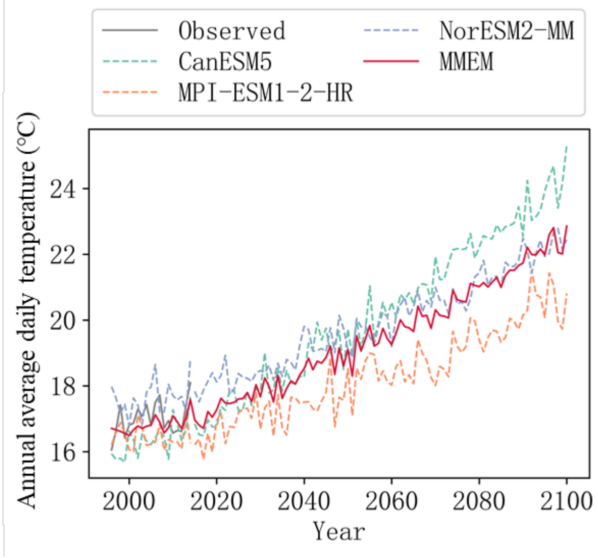
The SDSM was first calibrated and validated with the NCEP reanalysis dataset and daily station observations, and then the calibrated model was utilized to downscale the GCM outputs (Wilby et al., 2002; 2007; Huang et al., 2011). The downscaled climatic data has a geographical and temporal resolution of site-specific and daily, respectively. The coefficients of determination (R2) for the calibration and validation phases of all temperature-related predictands were above 0.95 for all weather stations. As for daily total precipitation, the R2 ranged from 0.2 to 0.3, which is in accordance with many studies (Huang et al., 2011; Tatsumi et al., 2013; Hessami et al., 2008; Sigdel and Ma, 2016), as the proportion of explained variance for heterogeneous random variables such as daily precipitation could be less than 40%, according to the literature (Wilby et al., 2002; Huang et al., 2011). However, downscaling precipitation in monthly or seasonal time steps can greatly improve the applicability of SDSM (Huang et al., 2011; Sigdel and Ma, 2016). In this study, the R2 values for seasonal precipitation were improved to 0.7 to 0.8. Since pavement inspection and maintenance planning are usually conducted on a yearly basis, such a precision was considered adequate for this study.

4.1.3 Climate projection after downscaling

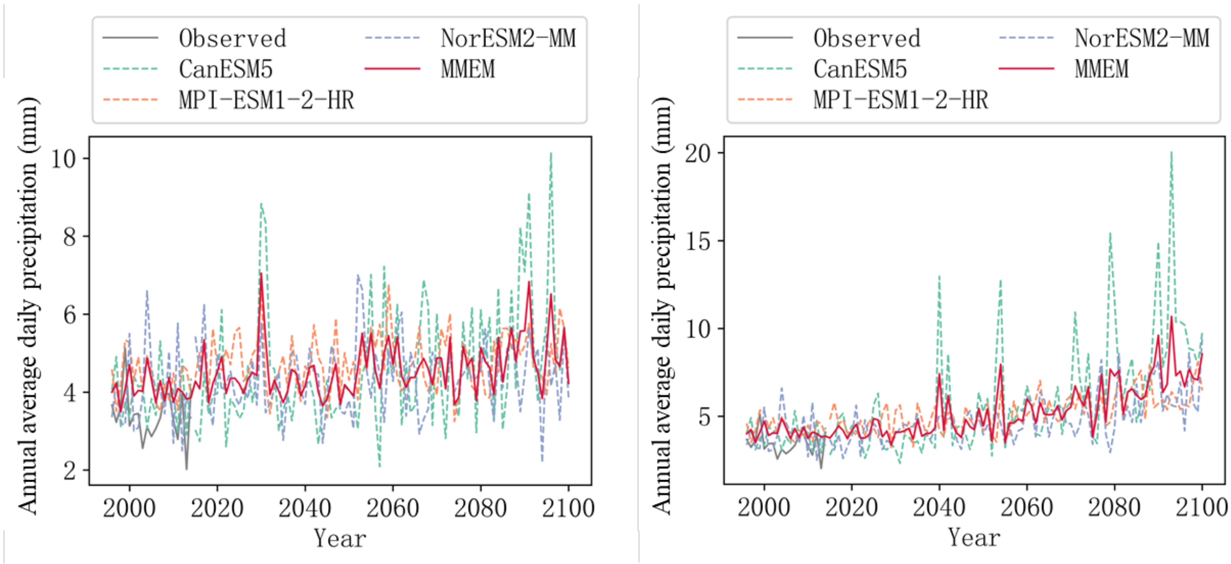
The calibrated SDSM model was then adopted to downscale the outputs of the three GCMs to obtain station-scale daily temperature and precipitation for the future decades up to 2100. Accordingly, the MMEM after downscaling can be calculated. Fig. 6 presents the climate prediction results of annual average daily temperature and precipitation for a weather station numbered 58358 in Suzhou, Jiangsu Province. An upward trend in annual average daily temperature and precipitation can be clearly seen. Meanwhile, while the climate predicted by various climate models is highly uncertain, MMEM is able to provide projections that are much closer to historical observations than individual models, which is in general agreement with previous studies (Yue et al., 2021; Zhu et al., 2021). Thus, MMEM was employed in this research to explore the future changes in temperature and precipitation and the resulting impact.



(a) Annual average daily temperature under SSP245



(b) Annual average daily temperature under SSP585

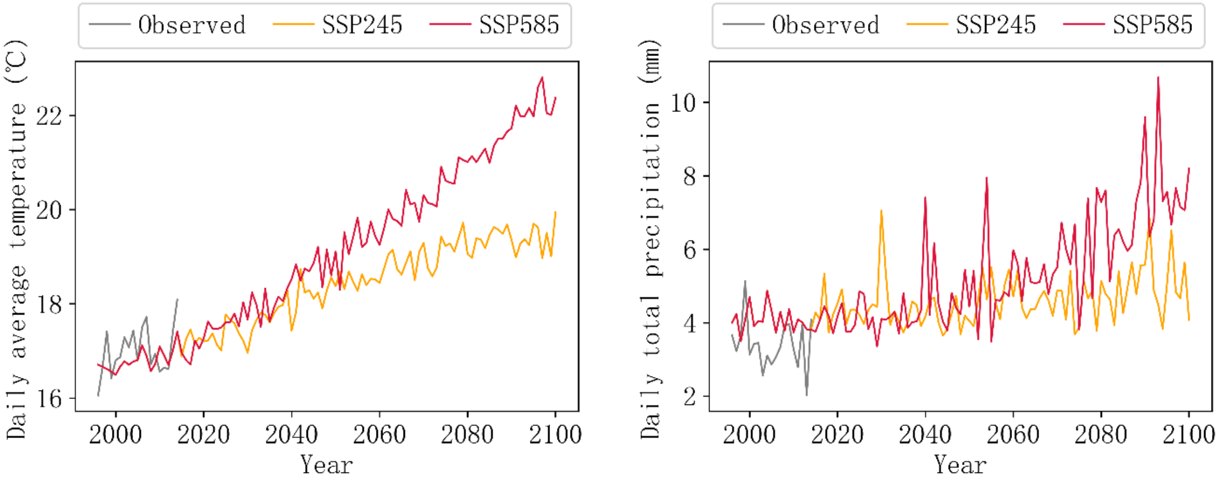


(c) Annual average daily precipitation under SSP245

(d) Annual average daily precipitation under SSP585

Fig. 6. Projections of annual average daily temperature and precipitation at weather station 58358

Fig. 7 compares the MMEMs of daily temperature and precipitation predictions for the same weather station under the two climate change scenarios. It can be noticed that the increase in temperature and precipitation is more significant in the SSP585 scenario than in the SSP245 scenario.



(a) Average daily air temperature

(b) Average daily precipitation

Fig. 7. MMEMs of predicted daily temperature and precipitation at weather station 58358 under two climate scenarios

4.2 Climate change impacts under current maintenance practices

This study first analyzes the results from the HT approach to evaluate the impact of climate change, characterized by global warming and intensified precipitation, on pavement life-cycle performance and costs under the current maintenance practice. The benefits from the application of the pavement maintenance optimization model were then explored.

4.2.1 Pavement performance

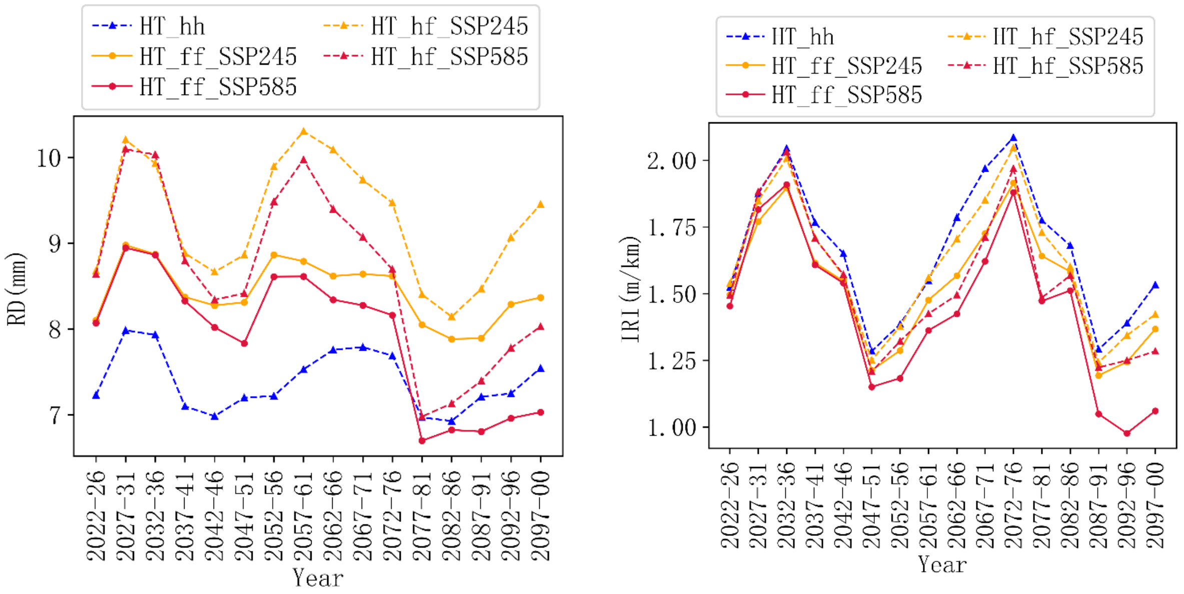
Fig. 8 illustrates the pavement network performance over time for the HT strategy-related cases, as measured by the traffic-length weighed indicator (TWI) (Guo et al., 2020), which was obtained by alternating pavement performance prediction and maintenance decision-making. HT_hh refers to the baseline case in which the HT approach is used for M&R scheduling and the climate is assumed to remain constant during both the maintenance planning and implementation phases. The SNO/HT_fh_SSP245/585 cases are not included in the performance comparison as they are mainly used to identify no-regrets adaptation strategies, and their inclusion would make Fig. 8 very busy and difficult to interpret.

From Fig. 8 (a), it is observed that the RD of the pavement network will increase under climate warming and intensified precipitation relative to the baseline, independent of whether the M&R schedules are adjusted, but adaptive M&R schedules (HT_ff_SSP245/585) can mitigate such effects. However, one thing that is surprising is that the RD in the SSP585 scenario is even smaller than its counterpart in the SSP245 scenario. While the cause of this has to be further researched, one possible explanation is that more precipitation in the SSP585 scenario may help lower pavement temperature, thus mitigating rutting.

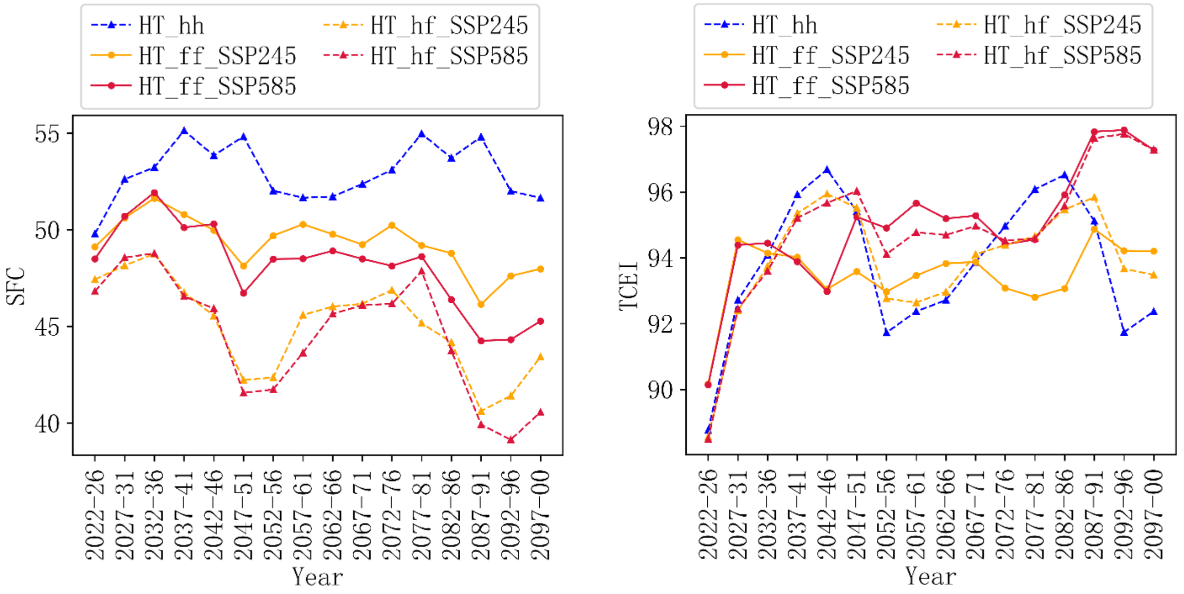
As for IRI, it can be seen from Fig. 8 (b) that climate change appears to be beneficial for decreasing pavement roughness, which is consistent with some of the previous studies (Tighe et al., 2008; Fifer Bizjak et al., 2014; Swarna et al., 2021). Hence, when analyzing the impact of climate change on pavement infrastructure, considering only IRI, as many existing studies in the field of pavement management have done, might lead to biased conclusions, which also demonstrates the necessity of integrating multiple pavement performance indicators for M&R decision-making.

Fig. 8 (c) indicates that climate warming may reduce the skid resistance of asphalt pavements, which is in agreement with some studies showing a negative correlation between average annual temperature and long-term pavement skid resistance (Rezapour et al., 2022; Wang and Wang, 2013). Furthermore, it is noteworthy that the reported SFC has been corrected for air temperature and vehicle speed at the time of measurement (MOT, 2019), while actual pavement skid resistance could be much worse under certain conditions (e.g., hot or rainy days, high-speed driving). Therefore, even if the reported SFC remains constant, the actual SFC may decrease with warming temperatures, which indicates that the crash rate under future climate could be even higher than those estimated by equation (1). Fig. 8 (c) also reveals that adapting M&R schedules to climate change can significantly reduce its negative impact on pavement skid resistance.

The causes of transverse cracks in semi-rigid base asphalt pavements are diverse and complex, such as thermal cracking in asphalt concrete layer, reflective cracking due to the shrinkage of semi-rigid base, and/or fatigue cracking due to the repetitive temperature variation and traffic loading (Zhou et al., 2014; Fu et al., 2022). Previous studies have revealed that climate change may exacerbate fatigue cracking but mitigate thermal cracking (Swarna and Hossain, 2022). Comparing the three cases (three dashed lines) with the same M&R schedule in Fig. 8 (d), it can be found that the order of the TCEI in the three cases reverses at around 2047 and 2087, and the pavement transverse cracking condition corresponding to the historical climate turns from the best one to the worst one. Given that other factors are the same in the three cases, this change should be caused by different climate conditions. Therefore, at least around these two time points, climate change should have a positive impact on pavement transverse cracks. Similarly, at around 2072, climate change is considered to have a negative effect on the TCEI. It is interesting to note that in 2047 and 2087 most of the pavement segments had just been reconstructed (about 78.6%), while in 2072 most of the segments had been in service for a long time (the minimum is about 16 years). Hence, it can be inferred that in the early years after new pavement construction, transverse cracks in semi-rigid base asphalt pavements may be mainly thermal and reflective cracks, so the warming climate would alleviate transverse cracks. After a long period of service, fatigue cracking may begin to play a dominant role due to the severe aging of pavement, so climate warming leads to an increase in transverse cracks.



(a) RD (b) IRI



(c) SFC (d) TCEI

Fig. 8. Pavement performance evolution in differnent cases

4.2.2 Life cycle cost

The total LCCs and their breakdowns for the entire pavement network were calculated and compared for different cases, as shown in Fig. 9. It can be seen that under the SSP245 and SSP585 climate change scenarios, the worst case, i.e., HT_hf_SSP245/585, would lead to a significant increase in total LCCs across the entire pavement network of around 264.72 (62.0%) and 278.66 (65.3%) billion CNY over the baseline (HT_hh) for the period 2022 to 2100, respectively. This growth is mostly attributed to increased crash costs caused by poor pavement skid resistance as a result of climate warming. Adjustments to the M&R schedule (HT_ff_SSP245/585) could relatively mitigate the impacts of climate change. In these cases, the LCC would increase by about 66.24 (15.5%) and 81.36 (19.1%) billion CNY under the SSP245 and SSP585 scenarios, respectively, compared to the baseline. The HT_ff_SSP245/585 cases are more likely to occur under current pavement management practices, i.e., the hierarchical threshold-based approach is still the most common pavement maintenance decision-making method, but yearly inspection data for pavement conditions are becoming increasingly available. However, adapting the M&R schedule to a changing climate would greatly increase agency costs. This is because, as discussed in the previous section, climate change may exacerbate pavement deterioration, such as deepening rutting, reducing skid resistance, and, in some cases, increasing transverse cracks. Therefore, more frequent M&R schedules and higher maintenance expenditures will be required under climate change scenarios to avoid pavement performance deteriorating to unacceptable levels. Moreover, the comparison between the HT_fh_SSP245/585 cases and the baseline (HT_hh) indicates that adapting the M&R schedule to climate changes that do not occur can result in slightly lower total costs. Adjusting M&R schedules can therefore be considered a no-regrets adaptation strategy, as it generates net benefits under all future climate scenarios.

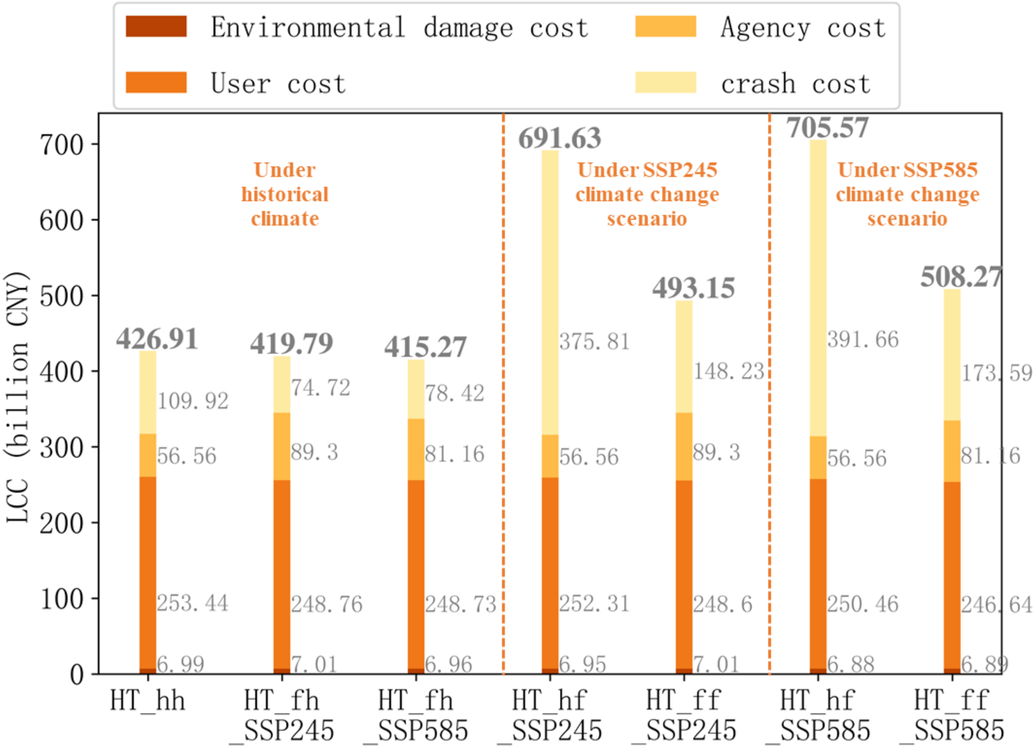


Fig. 9. Total LCCs of the pavement network for different cases

In addition, although severe rutting can also have an impact on driving safety, it has not been converted into monetary values in this study as there are no readily available models capable of estimating the joint effects of pavement rutting and skid resistance on crash rates. Meanwhile, although this study assumes that pavements are reconstructed every 40 years, poor pavement conditions may also advance the timing of pavement reconstruction. However, this was not taken into account in the present study as there are no sound models for predicting pavement structural performance in the study area and pavement reconstruction is typically determined by many factors besides the technical ones. Thus, if these factors are considered and HT strategies are followed, the impact of climate change could be greater.

4.3 Benefits from optimization-based M&R decision-making

An increasing number of pavement maintenance optimization models have been developed in the literature to optimize M&R schedules so as to reduce pavement LCCs and improve maintenance budget allocation. However, the potential of these models to reduce climate change impacts and thus enhance the resilience of pavement infrastructure has rarely been explored. Therefore, this section investigates the benefits of maintenance optimization in mitigating climate change impacts by comparing pavement LCCs under various climate scenarios and maintenance decision-making methods.

Fig. 10 shows a comparison of the LCCs generated by the HT and SNO models in different cases. It can be found that the LCC of the SNO model is lower than its counterpart under the HT approach in any type of case, regardless of whether the climate changes and the M&R schedule is adjusted. It suggests that improving maintenance decision-making by adopting advanced optimization models can reduce LCC in both changing and constant climates. In practice, decision makers are generally either unaware of climate change or unwilling to invest extra funds on mitigating climate change impact that may not become very significant until decades later. Therefore, the ability of adaptation strategy in reducing LCC under both changing and constant climates becomes very important. This makes adaptation strategies using maintenance optimization models potentially easier to implement and more acceptable than those that require upgrading asphalt binder grades or increasing pavement thickness, which do not necessarily provide benefits in a constant climate.

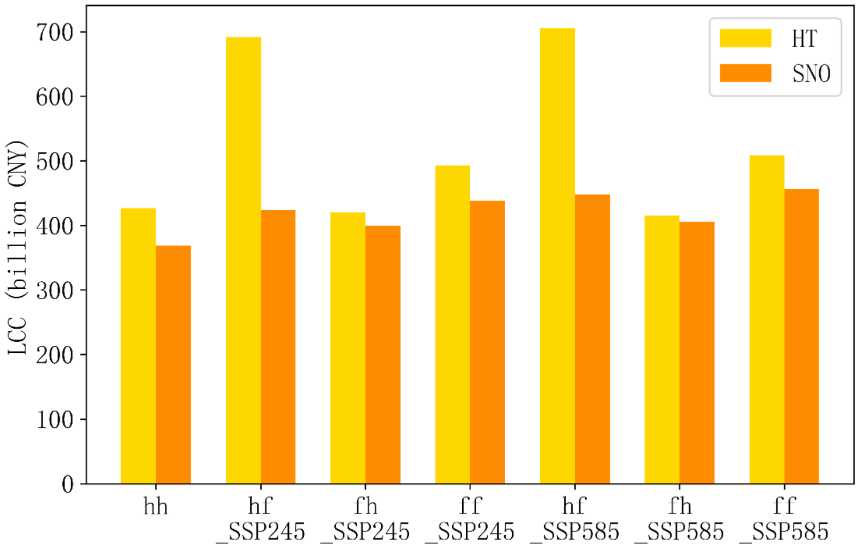
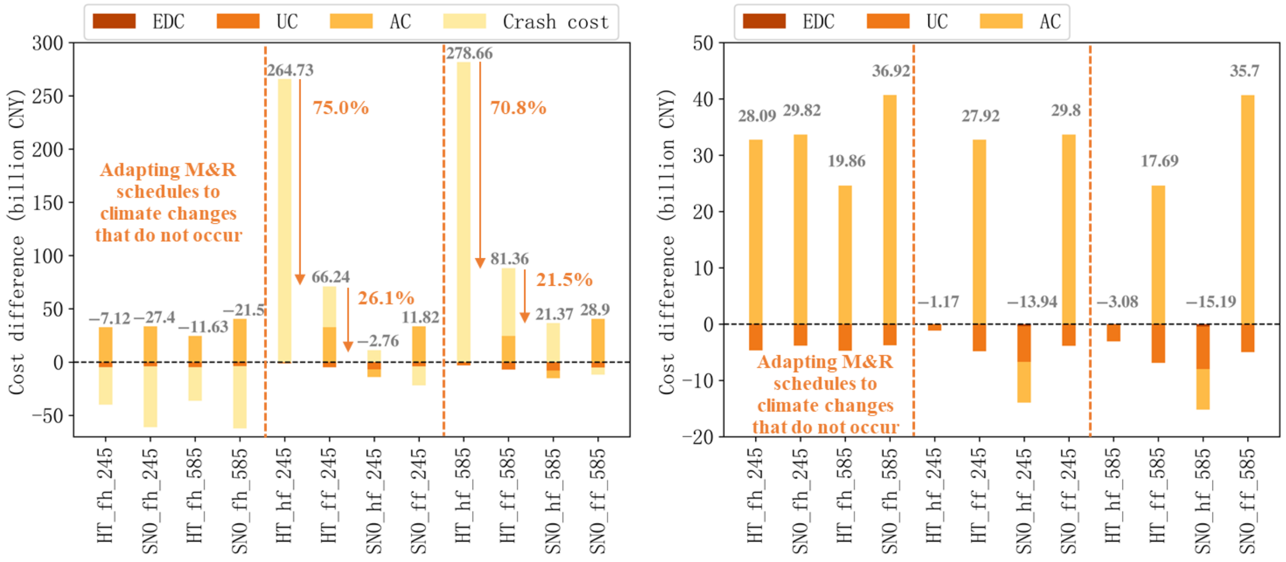


Fig. 10. LCCs produced by the HT and SNO models in different cases

Fig. 11 presents the differences in LCCs and their breakdowns for various cases compared to the baseline. Since the scale of crash costs is much larger than others, the cost differences excluding crash costs are also plotted in Fig. 11(b) for greater clarity. As can be seen in Fig. 11, applying the HT and historical climate-based M&R schedule without adapting to future climate conditions (HT_hf_SSP245/585) produces the greatest climate change impacts in terms of LCC increases under both climate change scenarios. While a climate change-adapted M&R schedule (HT_ff_SSP245/585) can mitigate most of such impacts, applying the SNO model for M&R scheduling can make further reductions. More specifically, using HT-based adaptive M&R schedules reduces the LCC increase by about 75.0% and 70.8% under the two climate change scenarios, respectively, and applying the SNO model would further reduce such increases by about 26.1% and 21.5%, respectively. Interestingly, when applied to the same climate change scenario, the unadjusted M&R schedule generated by the SNO model (SNO_fh_SSP245/585) might produce a lower LCC than the adjusted one (SNO_ff_SSP245/585), due to the high adaptation cost of the latter. Consequently, the LCC under climate change may even be smaller than that under the constant climate. Compared to the baseline without climate change, improving the maintenance decision-making method by adopting the SNO model can even generate 2.76 (0.6%) billion LCC savings under the SSP245 scenario, and only 21.37 (5.0%) billion increase in LCC under the SSP585 scenario. However, scheduling M&R to adapt to climate change will inevitably lead to increased agency costs, posing significant challenges for highway agencies in securing additional maintenance funds. In addition, the negative cost differences for the four cases on the left side of Fig. 11 (a) indicate that adapting M&R schedules to climate changes that do not occur, as compared to the baseline case, will reduce the LCC but require an increase in agency costs in exchange for a greater reduction in user and crash costs. It is therefore concluded that both adapting M&R schedules and improving M&R decision-making method can be considered as no-regrets strategies.



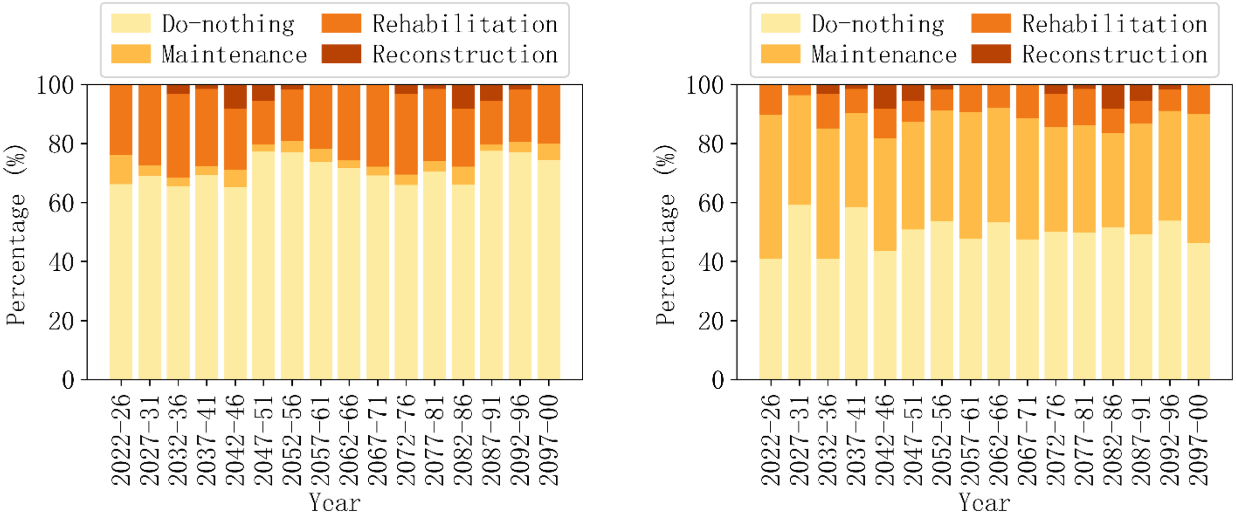
(a) Including the crash cost

(b) Excluding the crash cost

Fig. 11. Cost differences compared to the baseline case

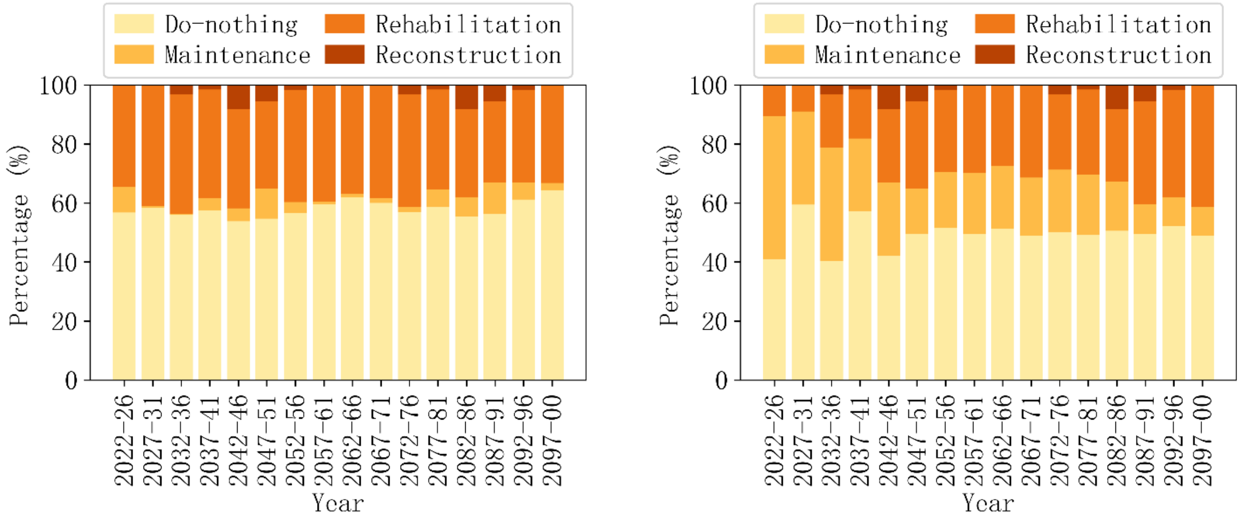
4.4 Differences in M&R schedules generated by the two models

Fig. 12 illustrates the percentage of different types of M&R under the two maintenance decision-making methods, i.e., HT and SNO, and two climate scenarios, i.e., historical and future (SSP245) climate. It can be seen that the HT method has a relatively higher percentage of rehabilitation over most of the time period, while the SNO method has a higher percentage of preventive maintenance. The more frequent preventive maintenance to reduce costly rehabilitation treatments may be one of the reasons why the optimization-based SNO model can mitigate the impact of climate change on asphalt pavements.



(a) HT model and historical climate

(b) SNO model and historical climate



(c) HT model and SSP245 scenario

(d) SNO model and SSP245 scenario

Fig. 12. Percentage of M&R under different maintenance decision-making methods and climate scenarios

5 Conclusions

This study developed a methodological framework to quantitatively assessed the long-term impact of climate change, characterized by global warming and intensified precipitation, on pavement life cycle performance and cost, as well as the effectiveness of adaptation strategies represented by improved maintenance decision-making methods, which is then applied to the expressway pavement network in Jiangsu. The outcome of the study facilitates the following conclusions:

(1) There is an upward trend in both future daily temperature and precipitation across Jiangsu. Under the SSP585 scenario, the temperature rise at the end of this century could reach nearly 6 °C. MMEM is able to provide projections that are much closer to historical observations than individual climate models.

(2) Compared to the baseline case, future climate warming can increase pavement rutting depth

regardless of whether to adjust M&R schedules, but adaptive M&R schedules would reduce such effects. The possible reduction of pavement temperature due to more precipitation in the SSP585 scenario may be one of the reasons for the smaller RD under SSP585 than under SSP245. As for IRI, climate change appears to be beneficial for decreasing pavement roughness. The long-term skid resistance of asphalt pavements will be reduced in a warming climate, thus posing a threat to driving safety. The impact of climate change on transverse cracks in semi-rigid base asphalt pavements varies in different periods. The warming climate has a mitigating effect on transverse cracks in the early years, as these may be mainly thermal and reflective cracks. It could have a negative effect on transverse cracks after the pavement has been in service for a long time, as fatigue cracks may then become dominant.

(3) Under the SSP245 and SSP585 scenarios, adjusting the M&R schedule to the changing climate would increase LCC by about 15.5% and 19.1%, respectively, compared to the baseline. This increase is mainly attributed to the increased crash costs due to poor pavement skid resistance. Besides, adapting M&R schedules to climate change will inevitably add to agency costs, posing significant challenges for highway agencies in securing additional maintenance funds.

(4) By using the optimization-based SNO model to improve maintenance decision-making, LCC can be reduced compared to its counterpart under the HT approach, making this adaptation strategy potentially easier to implement, even if decision makers are unaware of climate change or unwilling to invest extra funds on mitigating climate change impact that may not become very significant until decades later. Applying the SNO model to the SSP245 and SSP585 scenarios resulted in a 0.6% LCC savings and only a 5.0% increase in LCC compared to the baseline case

without climate change, respectively.

This study contributes to a better understanding of the impact of climate change on highway asphalt pavements, particularly for highways in eastern China. The effects of climate change on each of the four pavement performance indicators were investigated, as well as the distinct impacts on pavements with different service ages. This provides decision makers with a more holistic view of how individual segments in the road network will evolve in future climates, allowing them to develop targeted and differentiated adaptation strategies. The continuous evolution of pavement performance and climatic conditions, as well as their interactions, were captured, enabling more accurate forecasting of future conditions, as well as timely and flexible adjustment of adaptation pathways. Furthermore, the potential of maintenance optimization models to not only reduce the LCCs of pavements in the current climate, but also to mitigate the impacts of future climate change, is explored, thus providing increased motivation for agencies to upgrade their maintenance decision-making tools and suggesting pathways for adapting pavement infrastructures to future climates from a management perspective.

While this study has made significant contributions, there are still several opportunities for further expanding and enhancing this research. Firstly, M&R alternatives that are more cost-effective or more specific to future climates need to be developed to reduce the agency cost increase of adaptation strategies. Also, future research could incorporate agency cost increase as a constraint in maintenance decision-making models to develop adaptation strategies that are relatively less costly and therefore more acceptable and implementable by highway agencies. Secondly, this study did not consider uncertainties from various sources, such as those in climate change projections, pavement performance evolution, traffic conditions, and development in pavement materials and maintenance techniques.

Future research should incorporate these uncertainties to estimate the range of climate change impacts on road pavements so as to build more robust adaptation strategies, or to develop multiple strategies to accommodate these uncertainties. There is also a need to come up with ways to reduce these uncertainties, especially in predicting future climate and pavement performance.

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Author contributions

The authors confirm contribution to the paper as follows: Conceptualization: Linyi Yao, Zhen Leng; Data curation, formal analysis: Linyi Yao; Validation, visualization: Linyi Yao, Jiwang Jiang; draft manuscript preparation: Linyi Yao; resources, funding acquisition, writing - review & editing: Zhen Leng, Fujian Ni, Guoyang Lu. All authors reviewed the results and approved the final version of the manuscript.

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