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Review

Addressing Climate Change Resilience in Pavements: Major Vulnerability Issues and Adaptation Measures

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Abstract: Climate change is the one of the greatest challenges of our time, and it poses a threat to the surrounding built and natural environments. This review paper addresses climate change resilience in pavements by considering major vulnerability issues and adaptation measures. First, a review on foundational information of climate change related to transportation infrastructure is provided to bring all transportation professionals and practitioners to the same knowledge base on climate change terminology. Such information includes sources of climate information, climate scenarios, downscaling climate data, and uncertainty in climate projection information. Relevant climate stressors to pavements are discussed in some depth, including the most significant ones, which are increases in temperature and precipitation intensity. Thus, the proposed different engineering-informed adaptation measures relevant to the climate stressors of interest were evidence-based with reference to published peer-reviewed articles and case studies. Such adaptation solutions are related to monitoring pavement key performance parameters and pavement adaptations in structural design, robust materials and mix design, along with adaptation in maintenance, regulation, and construction. Efforts to adapt pavement systems to climate change are ongoing. In addition to such research works, this study concludes that impacts of adaptation measures on pavement and environment should be incorporated in the decision-making process in planning and design. This makes it important to integrate practical adaptation strategies in design and construction standards and guides, and implement awareness and education of climate change adaptation among engineers and practitioners.

Keywords: climate change resilience; adaptation strategies; mitigation measures; robust materials; mix design; uncertainty; pavement design

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1. Introduction

1.1. Background

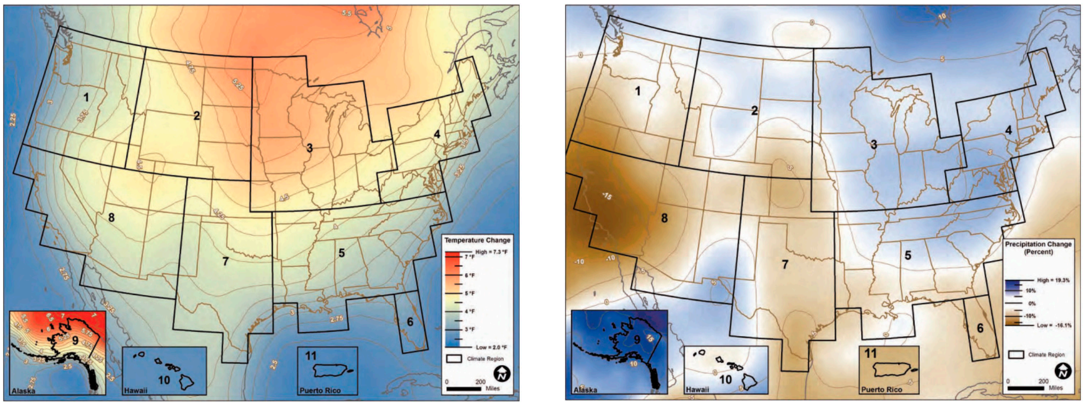
Recent weather events have shown that infrastructure assets are vulnerable to climate-related impacts; such vulnerabilities increase as the climate changes [1]. Existing models on global climate change, including optimistic scenarios, show projections of a continuous change at an increasing rate over the next century [2]. In fact, climate change has a wide range of impacts that affect infrastructure on a broad scale, though this is context-sensitive to different influences of the location and adaptive resilience capacity of governments and communities [3]. In this regard, the formal definitions of resilience and vulnerability adopted in this text are as per the Federal Highway Administration (FHWA) order 5520 [4], which are clear and comprehensive, and drive all FHWA-supported studies in relation to:

- **Resilience**: the ability to anticipate, prepare for, and adapt to changing conditions, and withstand, respond to, and recover rapidly from disruptions;
- **Adaptation**: adjustments in natural or human systems in anticipation of or response to a changing environment in a way that effectively uses beneficial opportunities or reduces adverse effects.

The impacts of climate change generally span different areas such as droughts, ecosystem alteration and disruption of transportation networks, and even health effects such as respiratory and cardiovascular diseases. In the transportation sector, however, the following key impacts were provided by Melillo et al. [5] in no particular order of significance:

- High temperatures and heatwaves, changes in precipitation, sea level rise, and storm surge, and their effect on capacity and reliability of the transportation system;
- Increase in probability of risk of coastal impacts on transportation infrastructure resulting from sea level rise in conjunction with storm surge;
- Extreme weather events effects on the disruption of transportation networks and projected rise in such disruption;
- General impact of climate change on the total cost of transportation systems and users.

As a rough idea of such future changes, Figure 1a,b below show examples of a general increase in average air temperature and percentage change in summer precipitation, respectively, in the United States by 2050, derived from specific climate scenarios and sensitivity models [6].



(**a**) (**b**)

Figure 1. (**a**) Estimated increase in temperature (°F) in 2050 relative to 2010; (**b**) estimated percentage change in summer precipitation in 2050 relative to 2010 [6].

State and federal guidelines for addressing the resilience of transportation infrastructure to climate change impacts have increased in recent years [7], and AASHTO's Center for Environmental Excellence [8] contains a catalogue of states' studies, efforts, and publications. However, the literature on specific effects on pavement systems and related engineering-informed adaptation studies is not widely covered, though it is now emerging [3]. Furthermore, the state of the practice lacks specific adaptation strategies and is only limited to general observations. Examples of such limited work include projected large-scale impacts, integrating climate change into project planning (discussed further in a later section), and assessing the vulnerability of transportation assets [3].

Most work on adaptation strategies specific to pavements focuses on integrating climate change into pavement design or predicting pavement performance in future climate. An example of such efforts is the study by Mills et al. [9], which investigated the effect of average temperature, total precipitation, and freeze–thaw cycles on pavement performance in southern Canada.

Consequently, the purpose of this review paper is to propose the integration of climate considerations into pavement engineering and design at the project level, whether at the rehabilitation of existing projects, performance of pavements in future time windows, or for new pavement or highway projects.

1.2. Objectives

This review paper investigates addressing climate change resilience in pavements by considering major vulnerability issues and engineering-informed adaptation measures on the basis of studies from peer-reviewed journal papers and technical reports. The objective of this review paper is to investigate whether climate change impacts affect the existing and new pavement assets, and if there is an urge to adapt pavement infrastructure to make them more resilient in the short, medium, and long term. This paper outlines a brief methodology, foundational information on climate change, climate-change-induced pavement stressors, and adaptation strategies and measures, and concludes with a discussion of review results and limitations.

2. Methods

The present study reviews current developments in the adaptation of pavement assets to make them more resilient against climate change and resulting stressors. A literature search was carried out by using suitable keywords, including climate change resilience, adaptation strategies, and mitigation measures in the context of pavement engineering. The literature was limited to reliable materials and was obtained from several well-established databases, including Elsevier, and agency websites such as the United States' Federal Highway Administration. Following multiple phases of checking for duplication and irrelevance, in excess of 40 relevant articles and reports were identified and explored in the making of this review paper. The focus of the literature was on research projects and studies with tested data and hypotheses from peer-reviewed journal papers and official technical reports from governmental and federal agencies, and departments of transportation where a physical measure is recommended. The focus was also on the most recent literature as appropriate, with a publication date from 2010 to present, with a few exceptions as necessary. The paper begins with a review of foundational information of climate change related to transportation infrastructure, including sources of climate information, climate scenarios, downscaling climate data, and uncertainty in climate projection. The next section discusses increases in temperature and precipitation intensity as climate stressors to pavements. The following section reviews proposed engineering-informed adaptation strategies of different categories and measures.

This paper sets the stage for any similar future work expanding on the same scope, or any other experimental and modelling research work focused on one issue and its adaptation solution. The overall flowchart of sequential steps for the process of methods and literature review is shown in Figure 2 below.

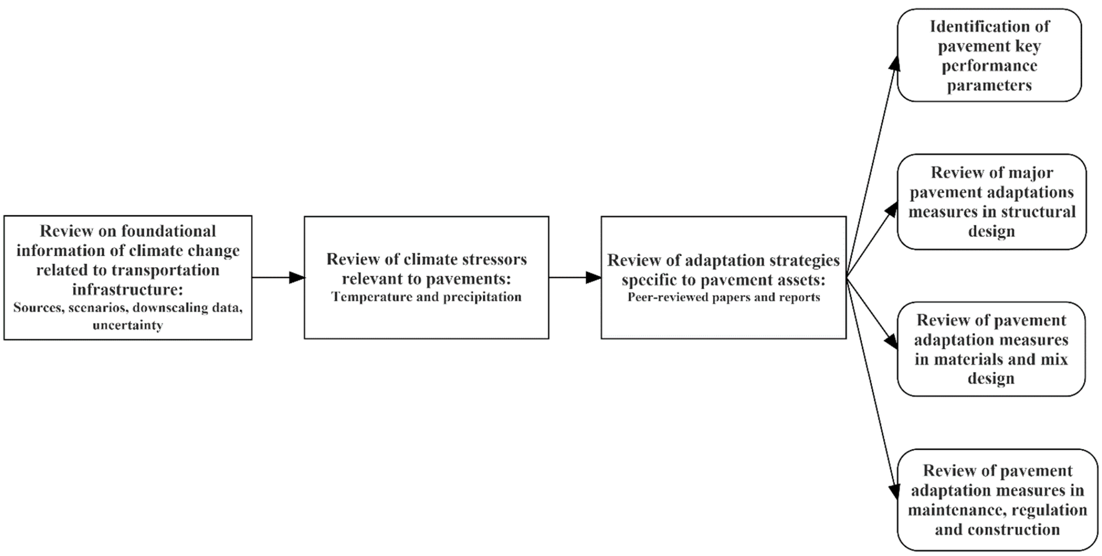


Figure 2. Flowchart of the process for methods and literature review.

3. Foundational Information

Before discussing relevant climate stressors to pavement engineering applications, it is essential to introduce some important concepts related to climate change that pave the way for a more meaningful discussion of climate impact on pavement systems.

The Federal Highway Administration (FHWA) has been at the forefront of developing useful information on future risk of climate impact and extreme weather events on transportation infrastructure; see FHWA's database on sustainable transportation [10] and its focus areas, including resilience. FHWA's effort included large-scale projects for the assessment of transportation assets vulnerability and evaluation of adaptation measures with an initial focus on large-scale geographic regions for assessing systemwide vulnerabilities. FHWA's methods, developed to support risk assessments and vulnerabilities and adaptation measures at the project level, are relevant to this review paper. The most notable examples of such studies include Gulf Coast Study, Phase 2, Task 3.2 in 2014, and Transportation Engineering Approaches to Climate Resiliency (TEACR) in 2016 [11].

3.1. Integrating Climate Change into the Transportation Project Development Process

In any transportation project endeavour, and prior to any design work, certain activities are conducted to fully understand the project concept; this is known as the project development process. This process is important so that any issues are uncovered and understood for consideration in the project design before any initiation of environmental assessment analysis e.g., under the federal National Environmental Policy Act (NEPA).

Common stages of a transportation project development process are: planning, scoping, preliminary design/engineering, environmental analysis, final design/engineering, right-of-way acquisition, and construction, see Figure 3. This figure also shows that adaptation studies should be integrated early on for optimum benefits in order to ensure that asset resilience is incorporated into the project design. This is also where the greatest impact and available flexibility for the design features of the project can be achieved. As such, the incorporation of climate change can effectively inform decision making for meeting the objective of each stage of the process. For example, such incorporation may help in identifying local climate stressors that could influence the project design or feasibility [1].

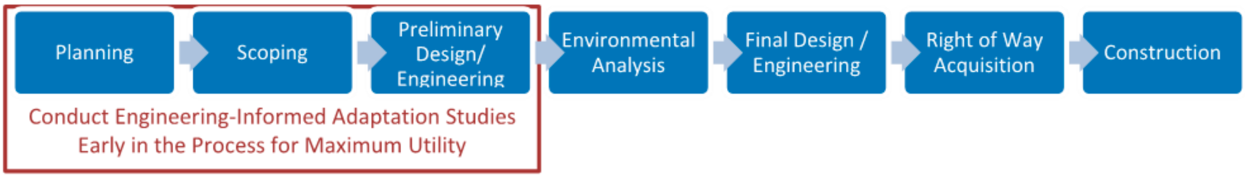


Figure 3. Stages of project development process and integration of adaptation studies [1].

Framework to integrate Climate Considerations into Project Development

Best practice to integrate novel climate stressors such as rising temperature, which reflect risks associated with nonstationary climate change, has not been established in design guides and practices. However, engineers consider stressors on the basis of historical records in the design of infrastructure systems such as pavement drainage systems, and these weather- and climate-related stressors also influence the frequencies of asset maintenance [12]. The adaptation decision-making assessment process (ADAP) is a framework suggested by FHWA [13] and a refined 11-step process applied in general transportation project adaptation assessment. However, in this review paper, a simplified version proposed by Choate et al. [1] was adopted. The key elements of this process for carrying out an adaptation study are shown in Figure 4, which were found to be crucial through the testing of the various engineering guidance manuals.

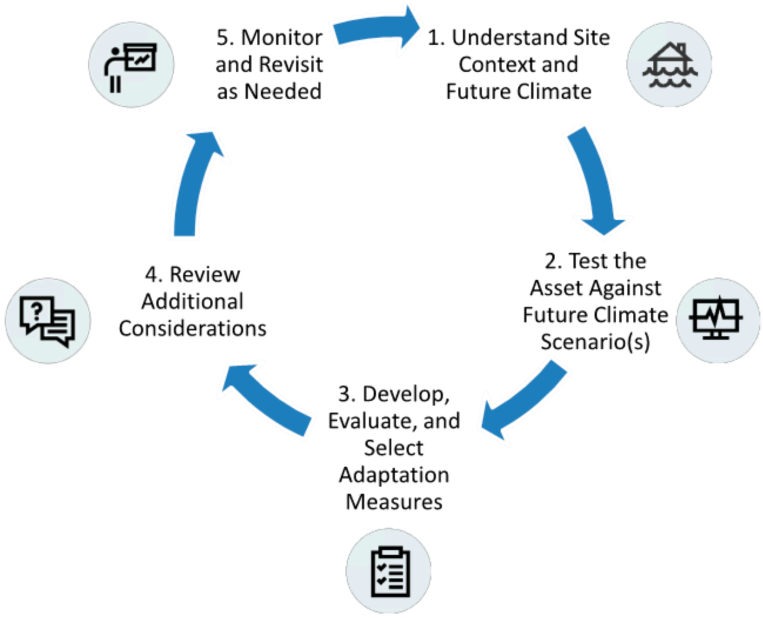


Figure 4. Key elements of an adaptation study process [1].

The process starts with understanding both asset or site context (e.g., design life, function, location) and future climate expectations (e.g., changes in precipitation and temperature). Next, the (proposed) asset is evaluated for impact under projected climate change scenarios. Then, practical adaptation strategies are identified if climate change is found to negatively impact the assets. Since multiple options can be proposed, a comprehensive and detailed economic assessment over the lifetime of the asset may be warranted to further refine the available measures. After that, it is necessary to take into account additional considerations in addition to economic analysis. Such considerations include the surrounding environment, socioeconomic factors, governance, and agencies' priority and accessible budget. Lastly, since transportation system and communities keep changing (e.g., land use, demographics), and as climate projections improve, adaptation studies should be revisited when such major changes are observed. The World Road Association [12] proposed a very similar process for developing a climate change adaptation plan.

In this review paper, a major part is dedicated to element 3 of this process, where case studies are explored for adaptation measures or solutions that were adopted to address resilience in pavement systems.

3.2. Sources of Climate Information

There are many available sources of climate information for transportation engineers to utilise in their analysis and design. In this review paper, only sources for temperature and precipitation are briefly highlighted, since these are the most relevant to pavement system climate adaptation. The reader is referred to [1] for a comprehensive catalogue and discussion of different sources for different climate stressors.

For both temperature and precipitation, information on projections can be obtained from the same climate resources. Such projections are available in regional or downscaled formats. The former is most useful for coarse vulnerability screening, and the latter is necessary for site-specific conditions, as in this review paper. Downscaling is a technique for refining the spatial and temporal resolution of climate projections for use in local conditions. Thus, major sources for downscaled projections include:

- Downscaled CMIP3 and CMIP5 Climate and Hydrology Predictions (DCHP) database, see [14].
- USGS Geo Data Portal, see [15].
- Coordinated Regional Climate Downscaling Experiment (CORDEX), see [16].

- North American Regional Climate Change Assessment Program (NARCCAP), see [17].

On a different note, technical guidance available for information on temperature and precipitation includes Hydraulic Engineering Circular No. 17 (Highways in the River Environment-Floodplains, Extreme Events, Risk, and Resilience) and Hydraulic Engineering Circular No. 25 (Highways in the Coastal Environment: Assessing Extreme Events).

Various assumptions, such as concentrations of greenhouse-gas (GHG) emissions in the future are made to develop climate projection models. The following sections briefly discuss how to assess climate change at the project level by considering local projections. This involves the selection of appropriate climate scenarios, models, downscaling, and the awareness of underlying uncertainty.

3.3. Climate Scenarios

There are different scenarios for future climate change that primarily depend upon future concentrations and trends in GHG emissions. The Intergovernmental Panel on Climate Change (IPCC) uses a new set of four scenarios, known as representative concentration pathways (RCPs) adapted from Moss et al. [18], with conditional probabilities attached to each scenario [12]; see Figure 5.

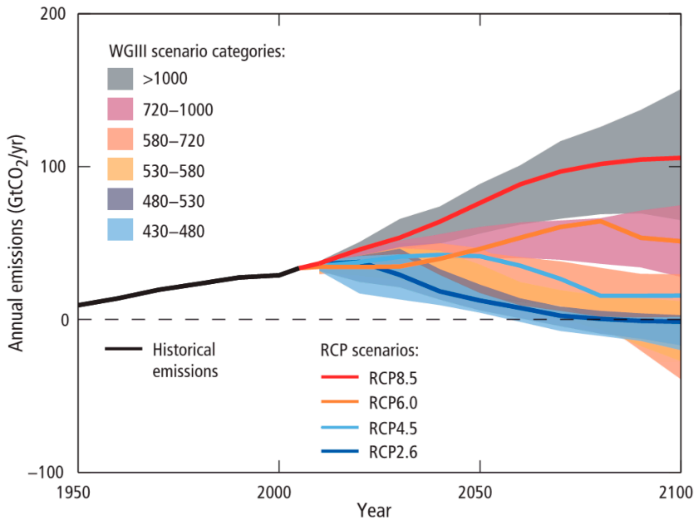


Figure 5. Changes in annual anthropogenic CO2 emissions for different representative concentration pathways (RCPs); bold lines indicate the four RCPs and WGIII is Working Group III [19].

RCPs span quite a wide range of possibilities and assume different targets for radiative forcing. Radiative forcing is the capacity of the concentrations of greenhouse gases to contribute to climate change [1] and they are predicted on the basis of changes in future factors such as economic growth, population, and energy consumption. Such factors are translated into emissions and concentrations of greenhouse gases over time, which are then used as inputs through designated climate models to project the future values of climate stressors such as temperature and precipitation. Evaluating the impact of different factors on the RCPs scenarios is a sophisticated process that involves many factors (including the ones mentioned earlier) that are intertwined and dependent on one another. For example, shifts in population, land use, or loss of service on other major roadways cause traffic volumes to evolve over time, which causes more energy consumption. Such factors also contribute to the uncertainty in climate projection information, as is discussed in Section 3.5.

Table 1 below summarizes GHG concentrations and global surface temperature change for the RCP scenarios by 2100 relative to 2010. RCPs vary from a scenario where emissions are substantially reduced from the current pathway (RCP 2.6) to one where high emissions continue to increase through 2100 (RCP 8.5); the latter was taken to be the most representative of all RCPs.

Table 1. Greenhouse-gas concentrations and temperature change in 2100 relative to 2010 for different representative concentration pathways (RCPs) [19].

Scenario Name	Concentrations (ppm CO_2)	Global Surface Temperature Change
RCP 2.6	430–480	0.3–1.7 °C
RCP 4.5	580–720	1.1–2.6 °C
RCP 6.0	720–1000	1.4–3.1 °C
RCP 8.5	>1000	2.6–4.8 °C

When deciding which scenario should be used for which project situations, Kilgore et al. [20] recommended that practitioners use a range of scenarios (with a focus on RCPs 4.5, 6.0, and 8.5) for a robust decision across those scenarios. In addition, they advised against averaging out projections across scenarios because they are distinct future scenarios.

3.4. Downscaling Climate Data

As mentioned previously, climate models output projections in regional coarse format with a raster cell size at approximately 100 miles. The size of such projections tends to mask important information when working at the level of a project or an asset. Hence, climate data need to be downscaled to a finer cell resolution. Briefly, there are two methods for downscaling, and each has its advantages and disadvantages. The *statistical method* looks at the statistical relationship between weather variables and climate variables to adjust model outputs. This method requires less computational power and hence it is more common, but it is most appropriate for analyses that aim to determine inherent uncertainty in climate projections. On the other hand, the *dynamic method* uses the coarse climate model output as an input to a model with finer resolution. This method requires more computational effort, but produces a richer set of outputs. For a list of some resources for downscaling climate projections, refer to Section 3.2. In addition to downscaling, outputs from downscaled climate models require postprocessing to convert raw data into the appropriate temperature and precipitation variables relevant to the analysis and design of the transportation engineering and planning project.

Downscaling is essential for project-level analysis, but additional significant uncertainty can be introduced. The next section discusses uncertainty and its types.

3.5. Uncertainty in Climate Projection Information

In the case of temperature and precipitation projections, there are several types or sources of uncertainty that can be managed. Below are the different types [1]:

1. Scientific (or model) uncertainty: Scientists' understanding and ability to accurately capture climatic conditions in a numerical fashion. Therefore, different climate models are expected to project different climate changes. To address this uncertainty, analysis should be based on an array of models as opposed to a single model.
2. Scenario (or human) uncertainty: The inability to predict the human behaviour as in the case of RCPs discussed earlier. This is why no one scenario is more likely to occur [19]. To address this uncertainty, analysis should be based on multiple scenarios.
3. Natural variability in the climate system: Natural variations in climate and weather from one year to another. To address this uncertainty, climate projections should be averaged over multiple years (up to 30 years for example) rather than a single year.

The contributions of each of these uncertainties vary in magnitude, time and effect on temperature and precipitation. Figure 6 qualitatively shows the varying impact of the three types of uncertainty on temperature and precipitation in the near term and the end of the century.

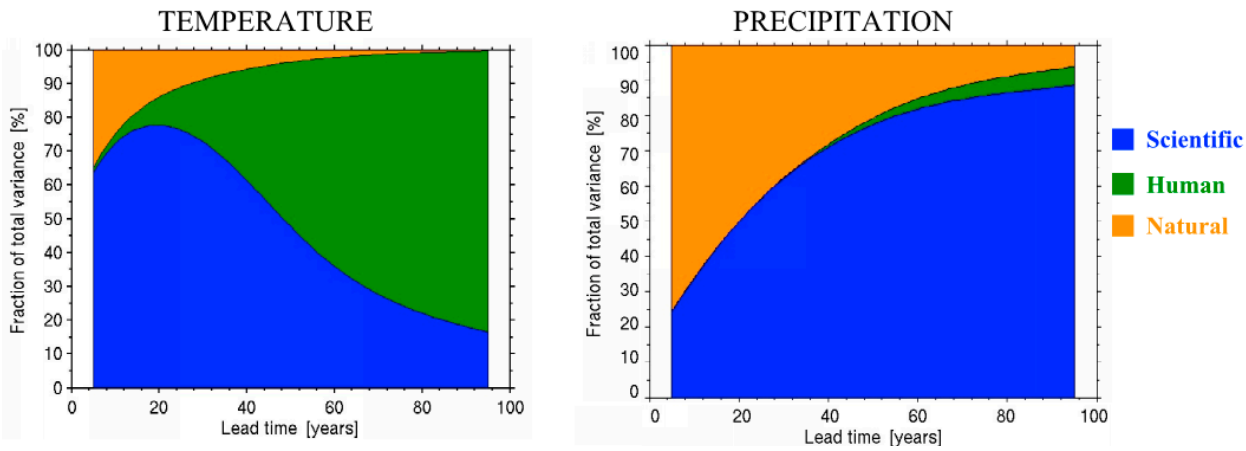


Figure 6. Relative importance of different types of uncertainty in climate for future years [21].

In a different report [12], other uncertainties associated with climate change were also determined that arise from such factors as statistical variation, measurement error, variability, approximation, linguistic imprecision, and subjective judgement.

4. Climate Stressors Relevant to Pavements

Research is generally nascent on the resilience to reduce pavement vulnerability to climate change hazards. However, one way to identify relevant climate stressors to pavements is to tap into existing agency knowledge (e.g., departments of transportation) since engineers and practitioners are familiar with how an asset had been affected by extreme weather events. Rowan et al. [22] documented transportation asset sensitivities to a range of climate stressors. This is what they refer to as the sensitivity matrix that was a part of the Gulf Coast Phase 2 project, which is a pilot project assessing the vulnerability of the transportation system in Alabama, United States. The World Road Association [12] states that the latest available probability-based regional climate change scenarios are to be consulted for identifying climate change effects and appraising their potential impacts on road pavements.

For pavements, extreme temperatures, precipitation, permafrost thaw, sea level rise, storm surge, drought, freeze–thaw cycles, wind speed, cloud cover (or percent sunshine), and humidity are stressors that could affect pavement systems, although the first three are primarily the most impactful. However, this study focuses on the most critical pavement stressors, namely, increases in temperature and precipitation intensity. Table 2 below is an excerpt of the sensitivity matrix for impacts of different stressors on paved roads where there is a documented relationship. The reader is referred to [23] for full list of documented effects of different climate stressors on different asset categories.

In general, pavements are very sensitive to extreme temperatures, so that pavement distresses are expected to increase; these include fatigue cracking and rutting in flexible asphalt pavements, and punchout failure potential in continuously reinforced concrete pavement (CRCP).

Table 2. Sensitivity matrix showing sensitivity of paved roads to different climate stressors [23].

Asset Category	Relative Sea Level Rise (Gradual)	Storm Surge (Inc. Wave Action and SLR * Impacts)	Increase in Frequency or Duration of Heavy Rain Events	Increase in Frequency or Duration of Heat Events
Paved roads (surface and subsurface)	Sea level rise increases the risk of erosion and flooding damage to coastal roads. The threshold depends on elevation of road, coastal protection, and other factors.	Direct damage to road begins occurring once storm surge overtops road, particularly if waves are in direct contact with road structure.	While lower functional class roadways are typically designed for the 10–25 year storm, roads are generally designed for larger storms.	Pavement may exhibit sensitivity at sustained air temperatures over 40°, particularly on routes with a high level of truck traffic.

* Spring load restriction.

If this consideration of climate stressors is extended to include subgrade soils, then changes in frost penetration depth, cycles of freeze–thaw and wet–dry affect the long-term durability and smoothness of pavement, and strength and deformation characteristics of soil. Of a similar significance is permafrost thaw, which affects the structural properties of supporting soil in cold regions such as Alaska, leading to performance issues such as travel-way and shoulder deformation. Permafrost is any ground that remains completely frozen for at least two years straight and is most common in Earth's higher latitudes.

In particular, temperature and precipitation changes can result in high adaptation costs, especially for enhancements at the agency level rather than the project level, where the cost premium of the latter might be low. This distinction is highlighted in TEACR's case study on the impact to pavements on expansive soils [24] because of their systematic and long-term adverse consequences. However, it is accepted that, considering the current design life of pavement, immediate adaptation is not warranted, but in the long run, adaptation solutions must be planned for implementation [1,3].

A significant impact of climate stressors in cold regions is on the restriction policies for a seasonal truckload. Authorities impose a policy that allows for heavy truckloads during winter times with multiple successive cold days, since more pavement strength and support can be attained with frozen ground [25]. This leads to the introduction of the winter weight premium (WWP) and spring load restriction (SLR) concepts, where the former allows for an increase in the capacities of truck loading, and the latter helps prevent distress build-up during the period of thaw weakening [26]. In the case study on temperature and precipitation impacts on cold region pavement in Maine [27], temperature impacts on restriction policies of future seasonal load were analysed under RCP 8.5. A decrease in WWPs was found; the extent to which such decrease was examined is shown in Figure 7. This figure shows that, relative to the present time with an 8-week WWP time, there will be a drastic reduction by the end of the century to only 2–3 weeks with a delayed posting of WWPs by more than four weeks.

This section gives a glimpse of major climate stressors on pavement systems. For a comprehensive and detailed description of all known documented impacts on pavement by temperature, precipitation, sea level rise, etc., the reader is referred to [1,12]. Furthermore, Table C2 of World Road Association [12] (not included here) discusses potential climate change impacts on pavements specific to Canada, the Canadian climates, and many other countries.

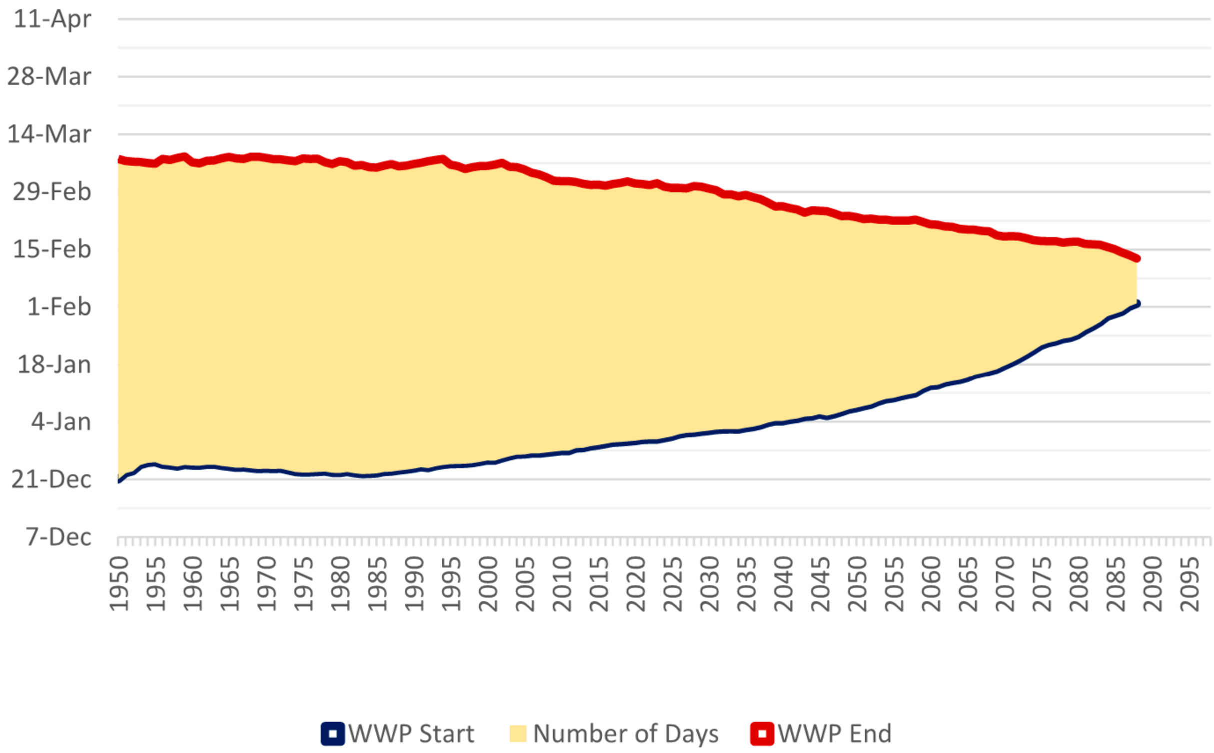


Figure 7. Projected future winter weight premium (WWP) start and end dates under RCP 8.5 scenario [27].

5. Adaptation Measures in Existing Projects

This section discusses several adaptation strategies spanning different themes to increase pavement resilience and address the projected impacts of climate change. Climate change clearly impacts the way in which roadways are planned, designed, constructed, operated, and maintained [12]. These adaptation measures are needed to avert any negative consequences on the serviceability of road networks, and they indicate the types of actions that engineers and practitioners could consider in their project.

5.1. Pavement Key Performance Parameters

A study by Mills et al. [9] in southern Canada on climate change implications for flexible pavement design and performance indicates that changes are required to adapt pavement to future climate, but indicates that the key issues with adaptation in essence pertain to "when to modify current design and maintenance practices". As such, monitoring pavements' key performance parameters becomes critical over short and long periods of time to detect any shifts in trends. Climate change may influence the rate or type of such trends. Such monitoring aids with identifying pavement distress that would trigger rehabilitation, which can be different from one location to another or one class of roadway to another [3].

With reference to flexible asphalt pavements, Bentsen [28] identified the main asphalt pavement distresses to be rutting, fatigue or alligator cracking, and low-temperature cracking. Table 3 shows the key pavement indicators to monitor climate change impacts for both flexible asphalt and rigid concrete pavements. As indicated by World Road Association [12], this may require in situ installed technology to monitor road conditions and facilitate remote transfer of condition data to road owners and operators. This technology enables the real-time analysis of pavement strength as an early warning system about the state of infrastructure and risks imposed by the natural environment and traffic volumes.

Table 3. Key pavement indicators to monitor for climate change impacts [3].

Asphalt Pavement Indicators	Concrete Pavement Indicators
Rutting of an asphalt surface	Blow-ups (JPCP [1])
Low temperature (transverse) cracking	Slab cracking
Block cracking	Punch-outs (CRCP [2])
Ravelling	Joint spalling
Fatigue cracking and potholes	Freeze–thaw durability
Rutting of subgrade and unbound base	Faulting, pumping, and corner breaks
Stripping	Slab warping

[1] jointed plain concrete pavement. [2] continuously reinforced concrete pavement.

5.2. Pavement Adaptation in Structural Design

In a study by Knott et al. [29] that considered pavement adaptation planning, short-term and seasonal pavement response trends were addressed. The study used a hybrid bottom–up/top–down approach to quantify the impact of incremental temperature rise from 0 to 5 °C on a two-lane regional connector in coastal New Hampshire. Then, a simple adaptation strategy represented in the increase in pavement layers' thicknesses was investigated. In this study, the primary distress mechanisms were assumed to be fatigue cracking and rutting, whereas thermal cracking was ignored.

The study concluded that, in order for the pavement to achieve its design life with minimal 85% reliability, a 7% to 32% increase in hot mix asphalt (HMA) layer thickness is recommended in the pavement design to guard the base and subgrade layers. This recommendation is based on the rise in temperature with a 95% confidence interval projected into 2080, and the assumption that the base layer is held constant without increase as 406 mm gravel base. The study also showed the required gravel-base layer thickness assuming that the HMA layer is held constant at 140 mm. The authors of that study define in their paper that the early century is 2000 to 2020, early mid-century is 2020 to 2040, mid-century is 2040 to 2060, and late mid-century is 2060 to 2080.

Wistuba and Walther [30] conducted a parameter study in six European cities for considerations of climate change in the pavement mechanistic design using the linear-elastic multilayer theory. In their work, they considered every hour of the design period for the purpose of calculating temperature-induced stresses and strains in the pavement. They conclude that knowledge of local temperature is of paramount importance as it influences the results of design, and that for some climates in the central Europe territory, there is a need to adapt pavement structural design to future requirements. Details on the recommendations of what aspects of design to be adapted are not included.

Similarly, in a research project funded by partner highway administrations across different European countries titled Pavement Performance and Remediation Requirements following Climate Change [31], the impact of climate change on highways was studied. A variety of pavement types and representative climatic zones were included, and the study examined differences in moisture contents resulting from climate change. The study concluded that, for pavements with long design life, road design methods need to be updated, especially for lower pavement layers that cannot be accessed for modification during future rehabilitation and reconstruction. The author attributed the reason to overcoming the possibility of climate change-related lower performance of current road designs.

In FHWA's case study on the impact of pavements on expansive soils [24], potential impacts of projected changes were evaluated on pavement performance of a proposed state highway near Dallas, Texas. This was estimated utilizing mechanistic–empirical pavement performance prediction models. The study found that there is a steady increase in aridity and ambient temperature throughout the current century, with a corresponding mild increase in pavement distresses. Adaptation solutions with high potential, but also with high costs, were proposed for this project for both flexible (adaptation option 1 in the study report) and CRCP rigid (adaptation options 2 and 3 in the study report) pavements in the design stage for mitigating climate impacts. In adaptation option 1, it was suggested to use stiffer binder in the asphalt overlay during rehabilitation, and in adaptation options 2 and 3, it was suggested to use an increased content of reinforcing steel in the new construction of the project highway in order to control distresses and decrease the width of cracks.

Another similar large-scale study by FHWA on temperature and precipitation impacts on cold region pavement in State Route 6, 15, and 16 in Piscataquis County, Maine [27], and according to climate impact findings similar to the former study, found that winters will be shorter and will require adjustments to seasonal load allowances and/or restrictions. In fact, the study expects that there will be no opportunities for winter weight premiums by the early 2080s, and that early posting of load restrictions will be imposed by at least four weeks. Since the involved routes exist, the proposed adaptation solutions can be implemented as part of routine pavement rehabilitation. As mentioned in Section 5.1, it would be important to monitor climate trends and re-evaluate future decisions related to pavement design using newly available climate information. Thus, the suggested adaptation measures include strengthening by increasing pavement and base thickness to control fatigue cracking and subgrade rutting, and allowing for opportunities for winter weight premium. Moreover, to reduce asphalt concrete (AC) rutting, it is recommended to use polymer modified asphalt binders starting in the early 2060s.

As a measure to reduce moisture infiltration into pavement subgrade and prevent base erosion, in both latter studies, FHWA recommends the installation of geotextiles or mulch (type not specified) in the shoulders to improve subsurface drainage. An interesting outcome of the recommendations of the first study is that the costs of such adaptation solutions are deemed high enough that they warrant an economic analysis to determine their cost-effectiveness, though it was not conducted for these studies. This, however, should also apply to the latter study for cost-effectiveness.

5.3. Pavement Adaptation in More Robust Materials and Mix Design

As a medium-term solution to combat the impact of increased frequency of intense precipitation events, the World Road Association [12] recommended adjustments to asphalt mix design to improve resistance to water damage by the use of special additives and fillers. It was also suggested to mitigate precipitation effects to develop hydrophobic coatings suitable for use at the micromechanical and/or pavement surfacing level. They expanded the discussion on implementing strict restrictions on the use of secondary material with possible leaching environmental problems such as incineration bottom ash because of the rise in groundwater table unless special isolating measures are in place. This material is prohibited from contact with water to avoid environmental threats.

In addition, a potential solution to address the adverse effect of the increase in precipitation intensity resulting from climate change is the use of porous pavements as a resilient solution against extreme weather events. In this respect, Zhu et al. [32] conducted a study to simulate the effect of permeable pavement using a storm water management model (SWMM) on controlling stormwater and reducing surface runoff. This type of pavement could reduce delay peak time, and some surface runoff by more than 50%. In this study, a permeable material is defined as porous surface layer on top of an open-graded aggregate base layer. Although there is no specific mention of adaptation to climate change, this type of pavement structures proves to be a potential engineering-informed adaptation measure that can be tailored towards induced climate change stressors. In carrying out such a task, it is very important to be aware of specific issues relevant to this type of pavement, including durability and functionality. For example, a study by Hu et al. [33] experimentally investigated the moisture sensitivity and damage evolution of porous asphalt mixtures, and their main finding was that, under long-term moisture damage, the moisture sensitivity of porous asphalt mixtures is a concern. They also found that tensile strength and resilience modulus decreased with the increasing loading cycles, and in order to extend the service life of porous asphalt mixtures, maintenance is needed when the decrement of these properties exceeds 60%. Furthermore, moisture damage had significant influence and an acceleration function on the damage evolution of porous asphalt mixtures. For better understanding similar issues, the reader is referred to Wu et al. [34] for a full review of durability and functionality, and the common distress of open-graded friction course mixtures, which is the broad term for porous asphalt concrete.

Furthermore, to improve road strength and reduce pavement rutting and cracking resulting in longer road life, sulphur extended asphalt modifier, which is a patented Shell additive, can be used. It is added to asphalt paving mixtures as a binder extender and a mix modifier, and in applications with heavy and concentrated loads (such as container ports and truck terminal yards).

TEACR's study on pavements on expansive soils [24], in order to compensate for the softening of asphalt concrete and decrease fatigue damage and rutting, proposed to adjust the grade of the asphalt binder on the basis of future temperature projections. Similarly, to control asphalt concrete rutting for pavement layers closer to the surface, binder content should be decreased, but it should be increased for layers closer to the bottom. Moreover, to improve aggregate interlock, higher percentages of crushed aggregates and manufactured fines are recommended. To stiffen the mix, the addition of lime is also recommended.

In a different approach for adapting material and mix design, MacLeod [35] provides data and information to help establish practical parameters for using supplementary cementing materials (e.g., fly ash, and slag) in concrete pavement applications exposed to freeze/thaw. The idea is to help reduce Canada's greenhouse-gas emissions by enriching recycling processes and practices for minerals and metal in a way that meets the performance and durability requirements of concrete pavements in the Canadian environment.

In a study by Emery et al. [36] on two taxiways at Toronto Pearson International Airport, a light hydrated lime coating was applied on the finished HMA upper surface course to increase albedo and surface colour effect on thermal behaviour. Albedo or solar reflectance is the percentage of solar energy reflected by a surface and the main determinant of a material's maximal surface temperature. The result is less black-body absorption and lower temperature. Hence, this can also be an adaptation that would tend to reduce the environmental impact of warm surface drainage runoff and reduce heat island effects in urban areas. In turn, there is positive impact on both costs and reduced use of energy resources.

5.4. Pavement Adaptation in Maintenance, Regulation and Construction

This subsection aims to highlight some of the recommended adaptation studies in other broad areas such as construction, maintenance, and regulatory standards. For example, Enríquez-de-Salamanca et al. [37], and Regmi and Hanaoka [38] discussed the importance of more frequent maintenance represented in shortening revisit periods, and the latter reference also emphasized that roads along important routes would require more frequent inspection and monitoring of conditions. The World Road Association [12] also discussed more frequent maintenance and rehabilitation or reconstruction, and specifically more frequent surfacing.

With regards to regulatory standards and from the foregoing discussions on climate impacts on pavements, Enríquez-de-Salamanca et al. [37] highlighted the ultimate need for the relaxation of design and construction standards without much discussion, especially in cold regions where the impact is more pronounced. As an example, to reduce material variabilities and air voids in pavements, FHWA recommended a modification to specifications to tighten pavement quality characteristics and the enforcement of more stringent acceptance tolerances for mix and materials.

Likewise, White et al. [39] studied how pavement production and construction contribute to climate change. In the study, they developed a methodology to examine direct CO_2 emissions from pavement production and constriction; by adjusting the design model parameters, adaptation measures can be optimised for a specific highway project based on climate conditions, traffic volumes, etc. The World Road Association [12] also called for the use of more energy-efficient construction techniques, taking into consideration the project whole life cycle. Furthermore, Muench and Van Dam [3] talked about how climate change impacts may influence the time periods when paving is allowed, especially that current specifications often ban paving during the winter, and recommend short- and long-term solutions. Short-term solutions include, if possible, expanding the construction season by using existing technologies (such as warm mix asphalt and precast slabs) and extending existing temperature limitations for paving. On the other hand, long-term solutions include, in addition to expanding allowable paving seasons, the review of worker safety and comfort requirements, particularly in areas with extreme (hot and cold) temperatures.

The authors of the World Road Association [12] introduced a very interesting concepts related to adaptation measures, namely, the climate analogue, which is simply defined as the current climate in location A that is similar to the projected future climate of a given location B. The idea, therefore, would be to adopt solutions from location A, which had already experienced the projected climate scenarios, into location B. What this implies is that most likely it would not be necessary to develop new design rules, standards, or specifications. This, in turn, emphasises the importance of transferring learning of local conditions for adoption and that sharing of best practices for solving local problems is promoted through different platforms such as technology-sharing forums.

As a special case scenario, the choice of adaptation solution for long-life pavements might be a little challenging for current design philosophies in that the practitioner is presented with two potential options to adopt: should they implement a robust but more costly design, or opt for more economically efficient design with the potential for upgrade in the longer term? This is something to be considered in pavement system by stakeholders of a new highway project. To shed some light on this issue, a study by Schweikert et al. [40] used a software tool, Infrastructure Planning Support System (IPSS), to run a vulnerability assessment across the state of Colorado, United States. The objective was to analyse the vulnerability of road infrastructure to climate change impacts through the year 2100 at the county level using 54 numerical models known as general circulation models (GCMs). In principle, the study considered the annual average costs associated with climate change impacts from two scenarios, Adapt and No Adapt, relative to the baseline, with no historic climate change approach. The former aims to increase road infrastructure resilience to climate change, whereas the latter aims to react to climate change impacts on road infrastructure. In the medium (year 2050) and long (year 2090) terms, the cost of the resilient approach was lower than that of the reactive approach, depending on the quartile climate model. For example, the maximal cost (100th%) for the 2050 and 2090 decades revealed that, for the paved road inventory, the potential annual cost savings of using an Adapt approach exceeds USD 20 million. However, in the short term (year 2030), the cost of the reactive approach can be less. Nevertheless, the study authors emphasized that social benefits such as access and mobility, and several other factors may prove otherwise when memorised and taken into consideration.

Mallick et al. [41] used system dynamics to create a framework to understand the long-term impact of climate change on pavement performance, its life, and its maintenance activity. They applied their proposed methodology on a two-lane highway along the coast of New Hampshire. Because of predicted changes in the climate, they calculated that (in addition to increases in maximal pavement temperature, number of 100% saturation months, and the number of inundations), the cost of maintenance is expected to nonlinearly increase by more than 160% over a period of 100 years. The authors of [41] concluded that work is needed in pavement design and construction adaptation to make pavements more resilient to future climate change effects.

6. Discussion

It is clear from previous sections that anthropogenic climate change is happening, as it impacts both transportation infrastructure in general and pavement assets. Therefore, adaptations of engineering-informed measures are a necessity, as discussed in the previous section. The fundamental reasoning behind such a necessity is the inherent importance of safety provisions for all users of a highway (pavement) asset, which should be upheld at all times. In fact, the World Road Association [12] considers a project that lacks adequate safety provision a failure of the project climate change adaption scheme. They recommend making road users' (and workers') safety the prominent feature of climate change risk assessment. Such climate-change-related risks are envisaged to include hydroplaning and skidding caused by water accumulated pavement and the lack of friction, respectively. They also included lost control over a vehicle and reduction in visibility due to intense precipitation events and/or sandstorms.

A major concern for transportation agencies is the fact that climate- and weather-related design inputs in pavement standards and guidelines are both outdated and not updated to reflect a steadily changing climate. For example, in bridge design, used climate data are from the 1960s, which implies that generally new transportation infrastructures are not benefiting from recent climate information and the intrinsic changing climate conditions [42].

Hence, it is important to consider adaptation in new and existing pavement projects. In addition to what was discussed in Section 5, some other theoretical and plausible measures and guidelines adopted primarily from [1,3,6,12] include:

- Updating climate-related design values using the best climate data projections available if climate projections exceed default values for temperature and moisture.
- Consideration of, in addition to extreme weather events, smaller nuisance events with higher frequency.
- Updating historical data as frequently as possible if the data are still used in the design of new projects.
- Incorporating climate change impact on rates of deterioration in the calculations of lifecycle planning.
- Developing better analytical models and their calibration to understand thermal properties of asphalt mixtures exposed to warming temperatures.
- Evaluating benefits and costs of modifying existing pavement design guides and materials in anticipation of climate change.
- Lowering roadway profiles and using vegetated or compacted soil embankments in costal pavements.

The essence of this review paper is to evaluate the impact of climate change that is a direct result of higher concentrations of greenhouse gases. This implies that adaptation measures adopted to result in more resilient pavements may inadvertently contribute to exacerbating climate change. This means that environmental impacts of different adaptation solutions should be properly evaluated. In a study by Enríquez-de-Salamanca et al. [37], negative and positive environmental impacts were discussed. The paper covered the direct and indirect environmental primary impacts of climate change on pavements, and the resulting environmental secondary impacts from adopting a certain measure. It also suggested mitigation measures for selected adaptations, such as the use of lower-carbon-footprint materials and recycled aggregates. These mitigation strategies were categorised as *preventive* (to avoid the occurrence of an impact), *corrective* (to minimise unavoidable impacts), or *compensatory* (to achieve better environmental conditions). The authors concluded that the impacts of adaptation measures on the environment should not be ignored in the decision-making process.

Practitioners generally lack a detailed understanding of other related disciplines and how these disciplines are intertwined to make our communities more sustainable. This makes it important to implement awareness and education of climate change adaptation in infrastructure projects, including highways and pavement systems. The World Road Association [12] recognises such an essential element of the climate adaptation process. The two most notable such examples are:

1. Grants provided by the Climate Change Adaptation Skills for Professionals Program to tertiary education and training institutions, and professional associations, so as to revise or develop professional development and accreditation programs for engineers and planners.

2. Studies by the Australian Research Institute in Education for Sustainability (ARIES) to investigate opportunities to improve the capacity of graduate and existing practitioners through professional development and accredited university courses to respond to climate change adaptation challenges effectively.

7. Conclusions

Climate change is the greatest challenge of our time. Extreme events such as hurricanes and steady changes such as global warming, and an increase in precipitation and sea level rise pose a threat to the surrounding environments. Specifically, climate change is impacting transportation infrastructure and pavement systems—the emphasis of this review paper. This renders pavements vulnerable to climate change effects. As a result, processes and procedures should be commenced to adapt pavement design standards, and construction, maintenance, and rehabilitation efforts.

This review paper considered in detail foundational information to better understand the pavement climate change adaptation. This includes current sources of climate change, different climate stressors and future greenhouse gas scenarios and the importance of downscaling and uncertainty awareness. Then, climate stressors relevant to pavements were discussed in some depth, the most significant of which that drove the discussion in adaption solutions being increases in temperature and precipitation intensity. Lastly, different engineering-informed adaptation strategies relevant to the climate stressors of interest were discussed on the basis of evidence from peer-reviewed publications. These are related to monitoring pavement key performance parameters and pavement adaptations in structural design, robust materials and mix design, and maintenance, regulation, and construction. The measures proposed by different researchers and practitioners in the area of transportation and pavement engineering include increasing the thickness of a pavement layer (surface, base, subbase, etc), the use of stiffer binders, the use of more steel reinforcement for concrete pavements, load allowances and/or restrictions, the use of geotextiles, and updates of worker safety and comfort requirements.

Efforts to adapt pavement systems (including surface, subsurface, and subgrade layers) to climate change are large in volume and ongoing in nature. Such a noteworthy effort includes the work on Adaptation Climate Change by the Working Group of PIARC Committee D2 tasked to identify pavement vulnerability to climate change and adaptation strategies to alleviate resulting impacts. The most prominent outcome of this endeavour is a best-practice document globally sourced from many countries that aids engineers and practitioners with a better practical understating of the impacts of climate change on pavement systems and informed selection of mitigation solutions. It also equips them with systematic approaches for carrying out the vulnerability risk assessment, managing climate impacts and understanding policy implications.

As a concluding remark, considering the required amount of future infrastructure and monetary investment, Kancheepuram N. Gunalan, the past president of the American Society of Civil Engineers (ASCE) stated that “we have the foresight and talent to build better now before disaster strikes rather than spend more to retrofit to a higher standard after the event occurs”.

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Abbreviations

AASHTO	American Association of State Highway and Transportation Officials
AC	Asphalt Concrete
ADAP	Adaptation Decision-making Assessment Process
ARIES	Australian Research Institute in Education for Sustainability
ASCE	American Society of Civil Engineers
CMIP	Climate Model Intercomparison Project
CORDEX	Coordinated Regional Climate Downscaling Experiment
CRCP	Continuously Reinforced Concrete Pavement
DCHP	Downscaled Climate and Hydrology Predictions
FHWA	Federal Highway Administration
GCM	General Circulation Model
GHG	Greenhouse Gases
HMA	Hot Mix Asphalt
IPCC	Intergovernmental Panel on Climate Change
IPSS	Infrastructure Planning Support System
JPCP	Jointed Plain Concrete Pavement
NARCCAP	North American Regional Climate Change Assessment Program
NEPA	National Environmental Policy Act
RCP	Representative Concentration Pathways
SLR	Spring Load Restriction
SWMM	Storm Water Management Model
TEACR	Transportation Engineering Approaches to Climate Resiliency
USGS	United States Geological Survey
WWP	Winter Weight Premium

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