Addressing Highway Pavement Resilience amid Climate Change: A Review of the Major Vulnerabilities and Adaptation Strategies

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ABSTRACT

Anthropogenic climate change is among the greatest challenges we face, given the threat it poses to the natural and built environments. This paper addresses resilience of pavements in the context of climate change by reviewing the major vulnerabilities and adaptation measures. First, the basic concepts relevant to this topic, such as sources of climate information and downscaling climate data, climate scenarios, and uncertainty in climate projection, are introduced. The climate-induced pavement stressors of particular interest in this regard are increases in temperature and precipitation intensity. As such, the proposed engineering-informed adaptation measures relevant to these stressors are evidence-based, and they relate to monitoring pavement key performance parameters and pavement adaptations in structural design, materials, and mix design, along with adaptation in maintenance, regulations, and construction. The measures proposed in various research studies include increasing pavement layer thickness, using stiffer binders, use of geotextiles, performing more frequent maintenance, and enforcing more stringent acceptance tolerances for mixes and materials. This study concludes that climate adaptation measures in pavement should be incorporated in the decision-making process at the planning and design stages. In turn, this underscores the importance of integrating practical adaptation strategies in design and construction standards and supporting awareness of, and education on, climate change adaptation among engineers and practitioners.

Keywords: Adaptation Strategies; Climate Change Resilience; Mitigation Measures; Mix Design; Structural Design; Pavement Stressors; Robust Materials; Uncertainty.

1. INTRODUCTION

1.1 Background

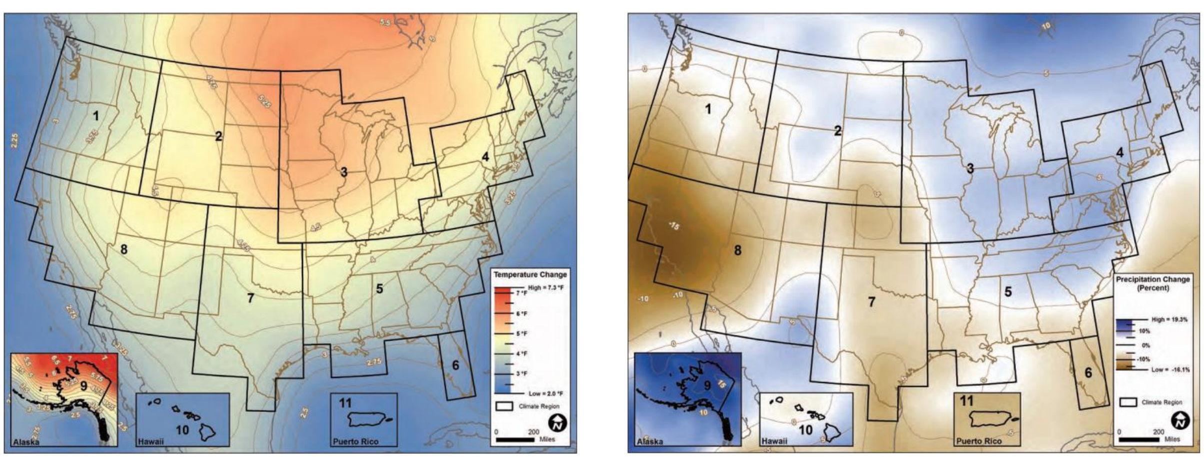
Infrastructure assets have been shown to be vulnerable to climate-related impacts based on recent weather events, and this vulnerability only increases as the climate undergoes further and more rapid changes [1]. Existing climate change models show projections of continuous change at an increasing rate over the next century [2], and climate change has a wide range of impacts that affect infrastructure on a broad scale, (though this is context-sensitive to location and adaptive resilience capacity of communities and governments) [3]. The formal definitions of resilience and vulnerability adopted for the purpose of the present study are drawn from the Federal Highway Administration (FHWA) order 5520 [4]:

- 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 span a number of different areas, but the key impacts within the transportation sector have been defined by Melillo et al. [5] as follows:

- high temperatures, changes in precipitation, sea level rise, and storm surge, and their effect on reliability and capacity 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;
- effects of extreme weather events on the disruption of transportation networks; and
- general impact of climate change on the total cost of a transportation system and its users.

To help us visualized what these future changes might look like, Fig. 1a and Fig. 1b below show the projected increase in average air temperature and the percentage change in summer precipitation, respectively, in the United States by 2050, derived from specific climate scenarios and sensitivity models proposed in the literature [6].



(a) (b)

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

In the United States, state and federal guidelines for addressing the resilience of transportation infrastructure amid climate change have expanded and become more robust in recent years [7]. For example, the AASHTO Center for Environmental Excellence maintains an expansive catalogue of states' publications, studies, and efforts in this area [8]. However, literature concerning the impacts of climate change on specific pavement systems and related engineering-informed adaptation studies are not common, although this is an emerging domain of research [3]. Furthermore, the state of practice lacks detailed adaptation strategies and is limited to general observations. 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 for rehabilitation of existing projects, prediction of future pavements' performance, or for the design new highway projects.

1.2 Basic Climate Change Concepts

1.2.1 Sources of climate information and downscaling climate data

In this section, studies on temperature and precipitation changes are briefly highlighted since these are the most relevant to the adaptation of pavements to a changing climate. The reader is referred to [1] for a thorough catalogue and discussion of sources for different climate stressors. For both temperature and precipitation, information on projections can be obtained from the same climate resources and is available in regional or downscaled formats; major studies on downscaled projections include the Coupled Model Intercomparison Project [9], a study by Blodgett that used US Geological Survey data [10], and work by the North American CORDEX Program [11] and the North American Regional Climate Change Assessment Program [12]. The regional format is most useful for coarse vulnerability screening, while the downscaled format is used for site-specific conditions. In this regard, it should be noted that downscaling is a technique for refining the temporal and spatial resolution of climate projections for use in local environments, and this can be carried out using either of two methods. The statistical method considers the statistical relationship between weather variables and climate variables as the basis for adjusting the model outputs. It 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 employs the coarse climate model output as an input to a model with finer resolution output. This method produces a richer set of outputs, but has a higher computational burden.

1.2.2 Climate scenarios

There are different scenarios, in terms of projecting future climate change, that largely depend upon future greenhouse gas (GHG) emissions concentrations and trends. The Intergovernmental Panel on Climate Change (IPCC) uses a recently devised set of four scenarios, known as representative concentration pathways (RCPs), adapted from Moss et al. [13], with each scenario having associated with it a set of conditional probabilities [14]. RCPs vary from a scenario in which emissions are substantially reduced from the current pathway (RCP 2.6) to one in which emissions continue to be high and to increase through the end of the current century (RCP 8.5). When determining which scenario(s) should be applied for which project, Kilgore et al. [15] recommend that practitioners use a range of different scenarios to ensure a sound decision. In addition, they advise against averaging out projections across scenarios, since each future scenario is distinct in its underlying assumptions and calculations.

1.2.3 Uncertainty in climate projection information

For temperature and precipitation projections, there are various sources of uncertainty that need to be considered and managed [1]. Scientific (or model) uncertainty, as one potential source of uncertainty, has to do with the ability of scientists to capture climatic conditions in a numerical fashion. To address this uncertainty, analysis should be based on an assortment of models as opposed to a single model. Scenario (or human) uncertainty, meanwhile, has to do with the inability to predict human behaviour [16]. To address this uncertainty, analysis should be based on multiple scenarios with respect to human behaviour. Natural uncertainty in the climate system, finally, refers to the natural variations in weather and climate from one year to another. To address this uncertainty, climate projections should be based on averages over multiple years rather than a single year.

2. OBJECTIVE

The present paper reviews current developments in the adaptation measures implemented to make pavement assets more resilient in response to climate change and its associated stressors. The objective of this study is to investigate whether, and the extent to which, climate change impacts affect existing and new pavement assets, and whether there is an impetus to adapt pavement infrastructure to make them more resilient in the short and long term.

3. PAVEMENT STRESSORS RESULTING FROM CLIMATE CHANGE

3.1 Pavement-specific Climate Stressors

Rowan et al. [17] documented transportation asset sensitivities to a range of climate stressors. The World Road Association [14], meanwhile, has suggested that the latest available probability-based regional scenarios for climate change should be consulted in any effort to identify climate change effects or appraise their potential impacts on road pavements. For pavements, extreme temperatures, precipitation, sea level rise, storm surge, permafrost thaw, freeze–thaw cycles, drought, wind speed, cloud cover (or percent sunshine), and humidity are all stressors that could affect pavement systems. The present study, however, focuses on the most critical pavement stressors, namely, increases in temperature and precipitation intensity. In general, pavements are very sensitive to extreme temperatures and, hence, pavement distresses (such as fatigue cracking and rutting, in the case of flexible asphalt pavements) are expected to increase in response to extreme temperatures. Moreover, if this consideration is extended to include subgrade soils, then changes in frost penetration depth, cycles of freeze–thaw/wet–dry, and permafrost thaw will all have a bearing on the long-term durability and smoothness of pavement, and on the strength and deformation characteristics of soil.

A notable impact of climate stressors in cold regions has to do with restriction policies for seasonal truckloads. Authorities typically impose policy that allows for trucks to haul heavy loads during winter (a season that, in cold climates, is often characterized by multiple successive days of temperature well below freezing) [18]. This provides the context for understanding the concepts of winter weight premium (WWP) and spring load restriction (SLR), where the former allows for a higher maximum truck loads, while the latter mitigates the risk of distress during the spring thaw (when the pavement is weakening) by decreasing the maximum loads trucks are permitted to haul during this season [19]. A recent study of temperature and precipitation impacts on restriction policies in cold region pavement in Maine under the RCP 8.5 scenario [20] resulted in a projection of a drastic reduction in WWPs from 8+ weeks (in 1950) to as little as 2–3 weeks by the year 2050, along with the posting of WWPs occurring later in the season (Fig. 2).

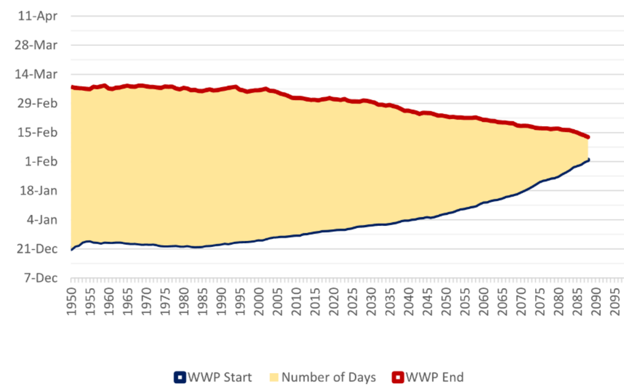


Fig. 2. Projected future start- and end-dates of winter weight premium under RCP 8.5 scenario [20].

3.2 Pavement Key Performance Parameters

A study by Mills et al. [21] on climate change implications for flexible pavement design and performance in southern Canada indicated that changes are required in order to adapt pavement designs to future climate scenario. They noted that the key issue with respect to adaptation has to do with "*when to modify current design and maintenance practices*". As such, monitoring of the key performance parameters of pavements is critical when it comes to detecting trends, and to determining whether climate change may influence the rate or type of such trends. Indeed, monitoring facilitates identification of the pavement distresses that may trigger maintenance, with these distresses often differing from one location or class of roadway to another [3]. With regard to flexible asphalt pavements, Bentsen [22] identified the main asphalt pavement distresses to be rutting, fatigue (or alligator cracking), and low-temperature cracking. Table 1 shows the key indicators for monitoring the impacts of climate change on flexible asphalt pavements.

Table 1. Key pavement indicators to monitor for climate change impacts [3].

Asphalt Pavement Indicators
Rutting of an asphalt surface
Fatigue cracking and potholes
Low temperature (transverse) cracking
Block cracking
Ravelling
Rutting of subgrade and unbound base
Stripping

4. CLIMATE CHANGE-INDUCED PAVEMENT STRESSORS AND PROPOSED MEASURES

Climate change will influence the manner in which roadways are planned, designed, constructed, operated, and maintained [14]. This section discusses several adaptation strategies and measures spanning different themes to increase pavement resilience and specifically address the projected impacts of increases in temperature and precipitation intensity.

4.1 Increase in Temperature

4.1.1 Adaptation measures in materials and mix design

A recent study by the FHWA on pavements on expansive soils [23] proposed adjusting the asphalt binder grade based on future temperature projections as a way of offsetting the effects of asphalt concrete softening and decreasing fatigue damage and rutting. Moreover, the study authors recommended that, in order to control asphalt concrete rutting, the binder content should be decreased for the pavement's surface layers, but increased for the layers closer to the bottom. They also recommended using higher proportions of crushed aggregates and manufactured fines to improve aggregate interlock, as well as the addition of lime to stiffen the mix.

The World Road Association [14] has recommended the use of a sulphur-extended asphalt modifier (a patented Shell additive) as a way of reducing pavement rutting and cracking and thereby improving road strength. In their approach, it is added to asphalt mixtures as a mix modifier and binder extender and used in applications involving heavy and concentrated loads, such as those common in truck terminal yards and container ports.

4.1.2 Adaptation measures in structural design

A study by Knott et al. [24] considered pavement adaptation planning and also addressed short-term and seasonal pavement response trends. They conducted a case study of a two-lane regional connector in coastal New Hampshire, and used a hybrid bottom–up/top–down approach to quantify the impact of incremental rises in temperature from 0 °C to 5 °C. They then explored the adaptation strategy of increasing the thickness of a pavement layer, with the primary distress mechanisms considered being rutting and fatigue cracking. The study concluded that, in order for a pavement to achieve its design life with 85% reliability and to guard the base and subgrade layers, a projected increase of 46% in the thickness of the hot mix asphalt (HMA) layer will be required by 2080, compared to the existing thickness of 140 mm. This recommendation assumes that the gravel base layer is held constant at 406 mm. Correspondingly, their study projected that the required increase in gravel base layer thickness by 2080 would be 53%, compared to the existing thickness (406 mm) assuming that the HMA layer is held constant at 140 mm.

Meanwhile, the FHWA conducted a case study on the impact of pavements on expansive soils in which potential impacts of projected changes were evaluated using mechanistic–empirical pavement performance prediction models [23]. The study projected that, throughout the current century, there will be a steady increase in aridity and ambient temperature with a corresponding mild increase in pavement distresses. The adaptation solution proposed accordingly for flexible pavement was to use a stiffer binder in the asphalt overlay during rehabilitation in the design stage in order to mitigate these climate impacts.

Another large-scale study by the FHWA on temperature and precipitation impacts on cold region pavement suggested that, in future years, winters will be shorter and that this will necessitate adjustments to seasonal load allowances and restrictions [20]. The study forecasted that, by the early 2080s, there will be no opportunities for WWPs, and that posting of load restrictions will be imposed four weeks earlier. Since the routes used in this study already exist, the proposed adaptation measures can be implemented as part of routine pavement rehabilitation and, hence, it is essential to monitor climate trends. Thus, the suggested adaptation solutions noted in their study include strengthening the pavement by increasing both the surface and base thickness to control fatigue cracking and subgrade rutting, and thereby allow for opportunities for WWPs. Moreover, they recommended introducing the use of polymer-modified asphalt binders by the early 2060s as a means of reducing asphalt concrete rutting.

Wistuba and Walther [25] conducted a parameter study in six European cities using the linear-elastic multilayer theory as a way of giving consideration to climate change effects in the pavement mechanistic design. For the purpose of calculating temperature-induced stresses and strains in the pavement, they considered every hour of the design period. They concluded that knowledge of local temperature is crucial because it influences the outcomes of the design, and that there is a need to adapt pavement structural design to future requirements for some climates in the Central Europe region. However, the study did not provide details as to what aspects of design should be adapted.

4.2 Increase in Precipitation Intensity

4.2.1 Adaptation measures in materials and mix design

As a medium-term solution to mitigate the impacts of increased frequency and intensity of precipitation events, the World Road Association [14] recommended the use of special additives and fillers to modify the asphalt mix design. They also recommended the development of hydrophobic coatings suitable for use at the micromechanical and pavement surfacing level to mitigate precipitation effects. Moreover, they expanded the discussion on implementing strict restrictions on the use of such secondary materials as incineration bottom ash, which poses leaching environmental problems because of the rise in groundwater table (given that interactions between this material and water pose serious environmental threats).

A potential solution is the use of porous pavements as a resilient technology capable of withstanding increases in precipitation intensity. In this respect, Zhu et al. [26] conducted a study to simulate the effect of permeable pavement on reducing surface runoff and controlling stormwater. Although they made no specific mention of adaptation to climate change, they found that the use of this type of pavement resulted in a delay of the peak time, and a reduction in some surface runoff by more than 50%. This type of pavement structure can be tailored towards mitigating the effect of climate change-induced stressors; however, in carrying out such a task, it is important to be aware of issues particular to the case at hand, including durability and functionality. For example, a study by Hu et al. [27] investigated experimentally the moisture sensitivity and damage evolution of porous asphalt mixtures. They found that moisture sensitivity of porous asphalt mixtures is a concern under long-term moisture damage which also had an acceleration function on the damage evolution of porous mixtures. They also observed that, with increasing loading cycles, the tensile strength and resilience modulus of porous pavement decreased. Hence, it was concluded that, in order to extend the service life, maintenance would be needed when the decrement of these properties exceeds 60%.

4.2.2 Adaptation measures in structural design

As a measure to improve subsurface drainage and reduce moisture infiltration into the pavement subgrade, and hence prevent base erosion, the FHWA recommended in two different studies [20, 23] the installation of geotextiles or mulch (type not specified) in the shoulders of the roadway. However, a notable observation from the first of these studies was that the cost of proposed adaptation solutions is sufficiently high to warrant an economic analysis to determine their cost-effectiveness.

In a research project funded by partner highway administrations of different European countries [28], the impact of climate change on highways was studied. A selection of representative climatic zones and pavement types was considered to assess variations in moisture content resulting from climate change. The study concluded that, in order to achieve pavements with a long design life, road design methods need to be updated, especially for the bottom pavement layers that cannot be easily accessed during future maintenance, rehabilitation, or reconstruction.

4.3 Adaptation in Construction, Maintenance and Regulations

Studies by Enríquez-de-Salamanca et al. [29] and Regmi and Hanaoka [30] discussed the importance of more frequent maintenance, emphasizing more regular inspection and monitoring of conditions for important routes. The World Road Association [14] also discussed more frequent pavement surfacing as an adaptive maintenance measure. With regards to regulatory standards and reducing material variability and air voids in pavements, the FHWA recommended modifying the specifications to tighten pavement quality characteristics and enforcing more stringent acceptance tolerances for mixes and materials.

White et al. [31] developed an approach for evaluating the direct CO_2 emissions incurred from pavement production and construction. They showed that, by adjusting the design model parameters, adaptation measures can be optimized for a specific highway project based on climate conditions, traffic volume, and other factors. The World Road Association [14] also called for the use of more energy-efficient construction techniques, taking into consideration the project's whole life cycle. Muench and Van Dam [3], meanwhile, discussed how climate change impacts may influence the pavement construction season, and recommend short- and long-term solutions for paving during winter. The short-term solutions they proposed included expanding the construction season using existing technologies (such as warm mix asphalt) and extending existing temperature limitations for paving. The long-term solutions included reviewing worker safety and comfort requirements, particularly in areas with extreme (hot and cold) temperatures.

The World Road Association [14] introduced an interesting concept related to climate change adaptation, namely, the climate analogue. It seeks to draw an analogy between the current climate in location A that is similar to the projected future climate of a given location B. The idea, therefore, is to adopt solutions from location A—which is already experiencing the projected climate scenarios—into location B. Such an approach eliminates the need to develop new design standards, specifications, or rules, since existing applicable standards and specifications can be leveraged. Their discussion serves to underscore the importance of sharing knowledge on best practices to solve local problems, which can be promoted through various platforms such as technology-sharing forums.

Given that climate change is a direct result of higher concentrations of greenhouse gases, it is worth considering that adaptation strategies and measures implemented to result in a more resilient pavement may inadvertently contribute to exacerbating climate change. In other words, the environmental impacts of the adaptation solutions themselves must also be evaluated. In this regard, Enríquez-de-Salamanca et al. [29] discussed the positive and negative environmental impacts of various adaptation strategies, examining the direct and indirect primary environmental impacts of climate change on pavements, as well as the secondary environmental impacts resulting from the implementation of various adaptation strategies. They also recommended using mitigation measures for selected adaptations, such as the use of recycled aggregates and lower-carbon-footprint materials. These mitigation strategies were categorized as preventive (to avoid the occurrence of an impact), corrective (to minimize unavoidable impacts), or compensatory (to achieve better environmental conditions). They emphasized that the environmental impacts of adaptation measures should not be ignored in the decision-making process.

5. CONCLUSION

Anthropogenic climate change is among the great challenges of our time. Extreme weather events such as hurricanes, as well as steady changes such as global warming, increases in precipitation, and rising sea levels, pose a serious threat to the environment. The impacts of climate change also extend to transportation infrastructure and pavement systems, making pavements vulnerable to climate change effects. As a result, processes and procedures should be initiated to adapt pavement design standards and construction, maintenance, and rehabilitation efforts.

This review paper considered current sources of climate change, different climate stressors, and future greenhouse gas scenarios, as well as the importance of downscaling and uncertainty awareness. Among the climate stressors relevant to pavements that were discussed, the most significant in driving the discussion on adaptation solutions were identified as increases in temperature and precipitation intensity. Accordingly, various engineering-informed adaptation strategies relevant to the climate stressors of interest were discussed: monitoring the pavement's key performance parameters, adaptations in the pavement's structural design, use of robust materials and mix designs, and revisions to maintenance, regulatory, and construction practices. The specific measures proposed by different researchers and practitioners in pavement engineering include increasing the thickness of different pavement layers (surface, base, sub-base, etc.), the use of stiffer binders, changes to load allowances and restrictions, the use of geotextiles, performing more frequent maintenance, and enforcing more stringent acceptance tolerances for mixes and materials.

One of the primary motivations underlying adaptation is the importance of safety for all users of highway pavements, which must be always upheld. In fact, the World Road Association regards a climate change adaptation scheme that lacks adequate safety provisions as a failure. They recommend making road users' (and workers') safety the prominent feature of any climate change risk assessment, where climate change-related risks may include hydroplaning (due to water accumulating on the pavement), skidding (due to lack of friction), and losing control of or reduced visibility (due to intense precipitation events and sandstorms).

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REFERENCES

[1] A. Choate *et al.*, "Synthesis of Approaches for Addressing Resilience in Project Development," Federal Highway Administration (US), 2017.

[2] T. Stocker, *Climate change 2013: the physical science basis: Working Group I contribution to the Fifth assessment report of the Intergovernmental Panel on Climate Change*. Cambridge University Press, 2013.

[3] S. Muench and T. Van Dam, "Climate change adaptation for pavements," 2015.

[4] FHWA. "FHWA Order 5520: Transportation System Preparedness and Resilience to Climate Change and Extreme Weather Events." https://www.fhwa.dot.gov/legsregs/directives/orders/5520.cfm (accessed 17 February 2021.

[5] J. M. Melillo, T. C. Richmond, and G. W. Yohe, *Climate change impacts in the United States: The Third National Climate Assessment.* US Global Change Research Program, Washington, DC., 2014.

[6] M. Meyer *et al.*, "NCHRP report 750. Strategic Issues Facing Transportation, volume 2: climate change, extreme weather events, and the highway system: practitioner's guide and research report," *Transportation Research Board of the National Academies, Washington, DC,* 2014.

[7] FHWA, "Climate change & extreme weather vulnerability assessment framework," US Department of Transportation Federal Highway Administration Washington DC, 2012.

[8] AASHTO. "Center for Environmental Excellence by AASHTO." https://environment.transportation.org/ (accessed 19 February 2021.

[9] Reclamation. "Downscaled CMIP3 and CMIP5 Climate and Hydrology Projections: Release of Downscaled CMIP5 Climate Projections, Comparison with preceding Information, and Summary of User Needs." https://gdo-dcp.ucllnl.org/downscaled_cmip_projections/dcpInterface.html#Welcome (accessed 13 February 2021.

[10] D. L. Blodgett, "The US Geological Survey Climate Geo Data Portal: an integrated broker for climate and geospatial data," 2013.

[11] NA-CORDEX. "The North American CORDEX Program: Regional climate change scenario data and guidance for North America, for use in impacts, decision-making, and climate science." https://na-cordex.org/ (accessed 13 February 2021).

[12] NARCCAP. "North American Regional Climate Change Assessment Program." http://www.narccap.ucar.edu/ (accessed 13 February 2021.

[13] R. H. Moss *et al.*, "The next generation of scenarios for climate change research and assessment," *Nature,* vol. 463, no. 7282, pp. 747-756, 2010.

[14] World Road Association, "Dealing with the Effects of Climate Change on Road Pavements," *A Report of Working Group,* vol. 5, 2013.

[15] R. T. Kilgore, D. B. Thompson, G. Herrmann, and W. O. Thomas, "Highways in the River Environment: Floodplains, Extreme Events, Risk, and Resilience," United States. Federal Highway Administration, 2016.

[16] R. K. Pachauri *et al.*, *Climate change 2014: synthesis report. Contribution of Working Groups I, II and III to the fifth assessment report of the Intergovernmental Panel on Climate Change*. IPCC, 2014.

[17] E. Rowan *et al.*, "Assessing the Sensitivity of Transportation Assets to Extreme Weather Events and Climate Change," *Transportation Research Record,* vol. 2326, no. 1, pp. 16-23, 2013, doi: 10.3141/2326-03.

[18] H. Miller, C. Cabral, M. Kestler, and R. Berg, "Aurora SPR-3(042), Phase 1: Review of Seasonal Weight Restriction Models for Comparison and Demonstration Project," 2015.

[19] A. Asefzadeh, L. Hashemian, N. T. Haghi, and A. Bayat, "Evaluation of spring load restrictions and winter weight premium duration prediction methods in cold regions according to field data," *Canadian Journal of Civil Engineering,* vol. 43, no. 7, pp. 667-674, 2016/07/01 2016, doi: 10.1139/cjce-2015-0554.

[20] FHWA, "Temperature and Precipitation Impacts on Cold Region Pavement: State Route 6/State Route 15/State Route 16 in Maine FHWA-HEP-17-019," US Department of Transportation Federal Highway Administration Washington DC, 2017.

[21] B. N. Mills, S. L. Tighe, J. Andrey, J. T. Smith, and K. Huen, "Climate change implications for flexible pavement design and performance in southern Canada," *Journal of Transportation Engineering,* vol. 135, no. 10, pp. 773-782, 2009.

[22] R. A. Bentsen, *Superpave fundamentals course no. 13153: reference manual*. Washington, D.C.: Federal Highway Administration: National Highway Institute (in English), 2000.

[23] FHWA, "Temperature and Precipitation Impacts to Pavements on Expansive Soils: Proposed State Highway 170 in North Texas FHWA-HEP-17-018," US Department of Transportation Federal Highway Administration Washington DC, 2017.

[24] J. F. Knott, J. E. Sias, E. V. Dave, and J. M. Jacobs, "Seasonal and long-term changes to pavement life caused by rising temperatures from climate change," *Transportation Research Record,* vol. 2673, no. 6, pp. 267-278, 2019.

[25] M. P. Wistuba and A. Walther, "Consideration of climate change in the mechanistic pavement design," *Road Materials and Pavement Design,* vol. 14, no. sup1, pp. 227-241, 2013.

[26] H. Zhu, M. Yu, J. Zhu, H. Lu, and R. Cao, "Simulation study on effect of permeable pavement on reducing flood risk of urban runoff," *International Journal of Transportation Science and Technology,* vol. 8, no. 4, pp. 373-382, 2019/12/01/ 2019, doi: https://doi.org/10.1016/j.ijtst.2018.12.001.

[27] X. Hu, X. Wang, N. Zheng, Q. Li, and J. Shi, "Experimental Investigation of Moisture Sensitivity and Damage Evolution of Porous Asphalt Mixtures," *Materials,* vol. 14, no. 23, p. 7151, 2021. [Online]. Available: https://www.mdpi.com/1996-1944/14/23/7151.

[28] A. Dawson, "Pavement Performance & Remediation Requirements following Climate Change (P2R2C2)," *Summary Final Report, ERA-NET ROAD, University of Nottingham,* 2010.

[29] Á. Enríquez-de-Salamanca, R. Díaz-Sierra, R. M. Martín-Aranda, and M. J. Santos, "Environmental impacts of climate change adaptation," *Environmental Impact Assessment Review,* vol. 64, pp. 87-96, 2017.

[30] M. B. Regmi and S. Hanaoka, "A survey on impacts of climate change on road transport infrastructure and adaptation strategies in Asia," *Environmental Economics and Policy Studies,* vol. 13, no. 1, pp. 21-41, 2011.

[31] P. White, J. S. Golden, K. P. Biligiri, and K. Kaloush, "Modeling climate change impacts of pavement production and construction," *Resources, Conservation and Recycling,* vol. 54, no. 11, pp. 776-782, 2010.