Addressing climate change resilience in pavements: major vulnerability issues and adaptation measures

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1.0 INTRODUCTION

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 projection of a continues change at an increasing rate over the next century [2]. In fact, climate change has produced a wide range of impacts that affected infrastructure on a broad scale, though this is context sensitive to different influences of location and adaptive resilience capacity of governments and communities [3].

The impacts of climate change generally span different areas such as droughts, ecosystem alteration and disruption of transportation network and even health effects such as respiratory and cardiovascular diseases. In the transportation sector however, the following key impacts are provided by Melillo, et al. [4] in no particular order of significance:

- High temperatures and heat waves, 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 effect on disruption of transportation networks and projected rise in such disruption.
- General impact of climate change on total cost of transportation systems and to users

State and Federal guidelines for addressing resilience of transportation infrastructure to climate change impacts have increased in recent years [5], and AASHTO's Center for Environmental Excellence[1] contains a catalogue of States' studies, efforts and publications. However, literature on specific effects on pavements systems and related engineering-informed adaptation studies is not widely covered, though it is now emerging [3]. Furthermore, state of the practice is lacking 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, and assessing vulnerability of transportation assets [3].

[1] https://environment.transportation.org/

Most work on adaptation strategies specific to pavement focus on integrating climate change into pavement design or predicting performance of pavement in future climate. An example of such efforts is the study by Mills, et al. [6] that investigated the effect of average temperature and total precipitation as well as freeze-thaw cycles on pavement performance in southern Canada.

Consequently, the purpose of this 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/highway projects.

2.0 FOUNDATIONAL INFORMATION

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

2.1 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.

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 1 which 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, 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 identify local climate stressors that could influence the project design or feasibility [1].

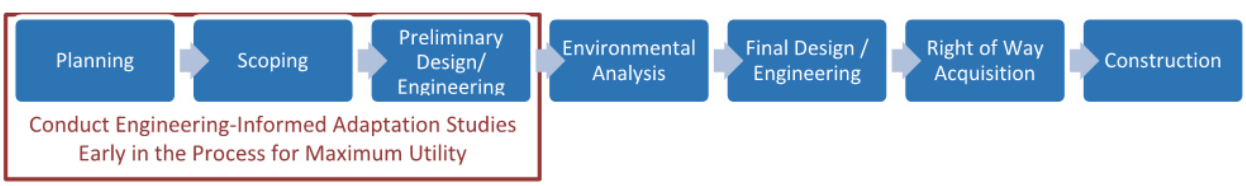

Figure 1: Stages of project development process and integration of adaptation studies[1]

2.2 Sources of Climate Information

There are many available sources of climate information for transportation engineers to utilise in their analysis and design. In this report, only sources for temperature and precipitation will be briefly highlighted since these are the most relevant to pavement system climate adaptation. The reader is referred to Choate, et al. [1] for 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 od downscaled formats. The former is most useful for vulnerability coarse screening and the latter are necessary for site-specific conditions, as in this project report. 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[1]
- USGS Geo Data Portal[2]
- Coordinated Regional Climate Downscaling Experiment (CORDEX)[3]
- North American Regional Climate Change Assessment Program (NARCCAP)[4]

2.3 Climate Scenarios

There are different scenarios for future climate change, which depend primarily upon the 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) adopted from [7]. The RCPs span a quite 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] as shown in Figure 2. They are predicted based on change in future factors such as economic growth, population, energy consumption, etc. [1].

[1] https://gdo-dcp.ucllnl.org/downscaled_cmip_projections/dcpInterface.html
[2] https://cida.usgs.gov/gdp/
[3] https://na-cordex.org/
[4] http://www.narccap.ucar.edu/

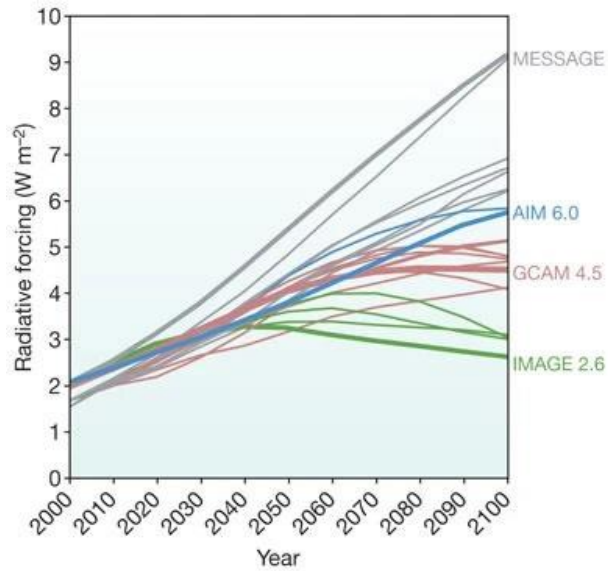

Figure 2: Changes in radiative forcing for different RCPs; bold lines indicate the four RCPs[7]

2.4 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 would 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. On the other hand, the *dynamic method* uses the coarse climate model output as an input to a model with finer resolution.

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

2.5 Uncertainty in Climate Projection Information

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

- ***Scientific (or model) uncertainty***: this has to do with scientists' understanding and ability to accurately capture climatic conditions in a numerical fashion.

- ***Scenario (or human) uncertainty***: this as to do with inability to predict the human behaviour as in the case of RCPs discussed earlier.
- ***Natural variability in the climate system***: this has to do with natural variations in climate and weather from one year to another.

The contributions of each of these uncertainties vary in magnitude and in time as well as effect on temperature and precipitation.

3.0 CLIMATE STRESSORS RELEVANT TO PAVEMENTS

Research is generally nascent on the resilience to reduce pavement vulnerability to climate change hazards. Having said that 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 an asset had been previously affected by extreme weather events. Rowan, et al. [8] document transportation asset sensitivities to a range of climate stressors, and this is referred to as the Sensitivity Matrix.

For pavements, extreme temperatures, precipitation, permafrost thaw, sea level rise, storm surge drought, and freeze-thaw cycles are stressors that could affect pavement systems, although the first three are the most impactful. Table 1 below is an excerpt of the sensitivity matrix for impacts of different stressors on paved roads where is there is a documented relationship.

Table 1: Sensitivity matrix showing sensitivity of Paved roads to different climate stressors[9]

Asset Categories	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. 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.

In general, pavement is very sensitive to extreme temperatures in 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).

A significant impact of climate stressors in cold regions is on the restriction policies for seasonal truckload. Authorities impose a policy that allows heavy truck loads during winter times with multiple successive cold days since more pavement strength and support can be attained with frozen ground [10]. This leads to the introduction of the winter weight premium (WWP) and spring load restriction (SLR) concepts where the former allows an increase in the capacities of truck loading and the latter help prevent distress buildup during period of thaw-weakening [11]. In the case study on temperature and precipitation impacts on cold region pavement in Maine [12], temperature impacts on restriction policies of future seasonal load were analysed under RCP 8.5 and found a decrease in WWPs, the extent to which such decrease was examined is shown in Figure 3.

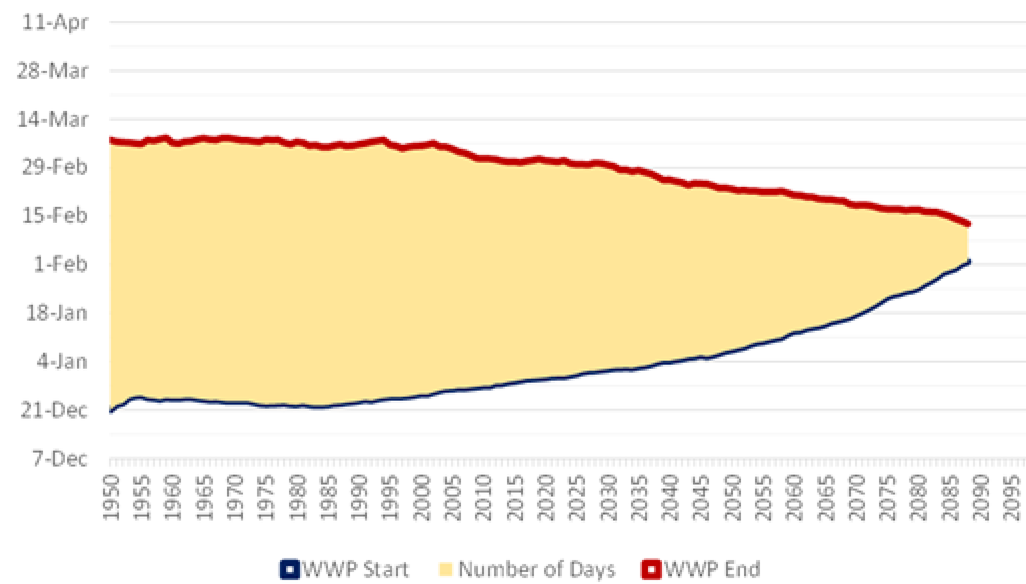

Figure 3: Projected future WWP start and end dates under RCP 8.5 scenario[12]

This figure shows that relative to the present time with an 8-week WWP time, there will a drastic reduction by the end of the century to only two weeks with a delayed posting of WWPs by more than two

4.0 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. 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.

4.1 Pavement Key Performance Parameters

A study by Mills, et al. [6] 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 will in essence pertain to "*when to modify current design and maintenance practices.*" As such, monitoring of pavement's key performance parameters becomes critical over short and long periods of time to detect any shifts in trends. Such monitoring will aid with identifying the pavement distress that would trigger rehabilitation, which can different from one location to another or one class of roadway to another [3].

With reference to flexible asphalt pavements, Bentsen [13] identify the main asphalt pavement distresses to be rutting; fatigue/alligator cracking and low temperature cracking. Table 2 shows the key pavement indicators to monitor for climate change impacts for both flexible asphalt and rigid concrete pavements.

Table 2: Key pavement indicators to monitor for climate change impacts[3]

Asphalt Pavement Indicators	Concrete Pavement Indicators
Rutting of asphalt surface	Blow-ups (JPCP)
Low temperature (transverse) cracking	Slab cracking
Block cracking	Punch-outs (CRCP)
Raveling	Joint spalling
Fatigue cracking and potholes	Freeze-thaw durability
Rutting of subgrade and unbound base	Faulting, pumping, and corner breaks
Stripping	Slab warping
Note: JPCP is Jointed Plain Concrete Pavement, and CRCP is Continuously Reinforced Concrete Pavement	

4.2 Pavement Adaptations in Structural Design

In a study by Knott, et al. [14] that considered pavement adaptation planning addressed short-term and seasonal pavement response trends. The study used hybrid bottom-up/top-down approach to quantify impact of incremental temperature rise from 0°C to 5°C on two-lane regional connector in coastal New Hampshire. The study concluded that in order to achieve its design life with a minimum 85% reliability, a 7% to 32% increase in hot mix asphalt layer is recommended in the pavement 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.

Wistuba and Walther [15] conducted a parameter study in 6 European cities for considerations of climate change in the pavement's mechanistic design using the linear-elastic multi-layer theory. In their work, they considered every hour of the design period for the purpose of calculating temperature-induced stresses and strains in 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.

Similarly, in a research project funded by partner highway administrations across different European countries [16], the impact of climate change on highways was studied. A variety of pavement types and representative climatic zones were included and examined the 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 will not be modified during future rehabilitation and reconstruction. The author attribute the reason to overcoming the possibility of climate change-related lower performance of current road designs.

As a measure to reduce moisture infiltration into pavement subgrade and prevent base erosion, FHWA recommends the installation of geotextiles or mulch in the shoulders to improve subsurface drainage.

4.3 Pavement Adaptation in more Robust Materials and Mix Design

As a medium-term solution to combat impact of increased frequency of intense precipitation events, [17] recommend adjustments to asphalt mix design to improve resistance to water damage by the use of special additives and fillers. It is also suggested to mitigate precipitation effects to develop hydrophobic coatings suitable for use at the micro-mechanical and/or pavement surfacing level. They expand 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.

Furthermore, to improve road strength and reduces pavement rutting and cracking resulting longer road life, sulphur extended asphalt modifier[1] which is a patented Shell additive can be used. It is added to asphalt paving mixtures as a binder extender and a mix modifier, as well as in applications with heavy and concentrated loads.

In FHWA’s study on pavements on expansive soils [18], in order to compensate for the softening of asphalt concrete and decrease fatigue damage and rutting, it is proposed to adjust the grade of the asphalt binder based on future temperature projections. Similarly, to control asphalt concrete (AC) 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.

In a different approach for adapting material and mix design, MacLeod [19] provide data and information to help establish practical parameters for using supplementary cementing materials (e.g., fly ash, slag, etc.) 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 mineral and metal in a way that meets the performance and durability requirements of a concrete pavement in the Canadian environment.

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[1] https://www.shell.ca/

4.4 Pavement Adaptation in Maintenance, Regulatory 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. [20] and Regmi and Hanaoka [21] discuss importance of more frequent maintenance represented in shortening revisit periods, and the latter also emphasize that roads along important routes would require more frequent inspection and monitoring of conditions. World Road Association [17] also discuss more frequent maintenance and rehabilitation or reconstruction as well as specifically more frequent surfacing.

With regards to regulatory standards and from the foregoing discussions on climate impacts on pavements, Enríquez-de-Salamanca, et al. [20] highlight without much discussion the ultimate need for the relaxation of design and construction standards, especially in cold regions where impact is more pronounced. As an example, to reduce material variabilities and air voids in pavement, FHWA recommends modifications to specifications to tighten pavement quality characteristics, and enforcement of more stringent acceptance tolerances for mix and materials.

Likewise, White, et al. [22] studied how pavement production and construction contributes to climate change. In the study, they developed a methodology to examine the direct CO2 emissions from pavement production and constriction but adjusting the design model parameters, adaptation measures can be optimised for a specific highway project based on climate conditions, traffic volumes, etc. Furthermore, Muench and Van Dam [3] talk about how climate change impacts may influence when paving is allowed, especially that current specifications often ban paving during the winter, and recommend short and long term solutions. The former 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. The latter include, in addition to expanding allowable paving seasons, the review worker safety and comfort requirements, particularly in areas with extreme (hot and cold) temperatures.

The authors of [17] introduce a very interesting concept related to adaptation measures that is climate analogue, which is defined simply as the current climate in location A that is similar to the projected future climate of a given location B. And the idea 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.

5.0 CONCLUSION

Climate change is impacting transportation infrastructure including pavement systems. Therefore, engineering-informed adaptation measures must be implemented and incorporated in the project development thought process early on. Although climate change is deemed slow on the existing pavement life-cycle scale and no immediate action is urged, ultimately adaptive efforts for new pavement projects, (especially long-term performance highways) must be implemented. More research is needed to identify more potential adaptation strategies, and elaborate on which ones are more impactful, cost effective and environmentally friendly

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