REVIEW OF RECENT EFFORTS TOWARDS MORE RESILIENT PAVEMENTS

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ABSTRACT

Pavement resilience is becoming an increasingly critical consideration for highway and transportation engineers. Executive order 13990 identifies the need for the world to be put on a sustainable climate pathway and Executive Order 14008 identifies innovation, commercialization, and deployment of clean energy technologies and infrastructure in a government-wide approach as a way to increase resilience to climate change [1 & 2]. Indications from the recent United States (U.S.) Appropriation Acts 2020 and supporting Congress Reports demonstrate a growing expectation that resilience will be directly incorporated into future pavement design, construction, and maintenance processes [3]. Meanwhile, pavement asset managers have already been asked to incorporate risk to natural threats including climate change in their state Transportation Asset Management Plans [4].

It is time to incorporate resilience into the pavement design and decision-making processes. A recent report summarizing feedback from state agency design engineers and industry stakeholders on pavement design identified resilience as a factor to be incorporated into the design process [5]. Some work has already been done to examine the relationship between resilience and pavement design. Both National Cooperative Highway Research Program (NCHRP) and the Federal Highway Administration (FHWA) have examined the potential impacts of future climate conditions on pavements as well as potential solutions to increase resilience [6 & 7]. Additionally, work under the Gulf Coast 2 Study and the Synthesis of Approaches for Addressing Resilience in Project Development went a step further and examined the effects of changes in temperature and precipitation patterns on specific pavement systems in Texas, Alabama, Maine, and Alaska [8 & 9]. While several other disciplines, particularly hydraulics, have been working to address resilience concerns, this is still a relatively new concept in the domain of pavements and little guidance, or recommendations exist [5].

Recognizing the importance of resilience in the roadway sector, FHWA hosted two peer exchanges in October and December 2020 to identify best practices for assessing and

incorporating future climate conditions and resilience considerations into pavement design, rehabilitation, and maintenance. These peer exchanges are among the first United States national gatherings of pavement experts entirely focused on resilience. This paper documents the state of knowledge and best practices to improve pavement resilience, summarizes key findings from the national peer exchanges, lessons learned and research gaps, and proposes approaches to integrate resilience considerations into pavement design building on numerous FHWA resources.

1. INTRODUCTION & BACKGROUND

The effects of changing climate and extreme weather events are causing a shift in the way that state agencies consider incorporating resilience and sustainable practices for materials in pavement design and in the maintenance decision making processes. It is well known that pavement infrastructure is negatively affected by environmental conditions. In fact, according to a study using the Long-Term Pavement Performance (LTPP) Program data 36% of total damage for flexible pavements and 24% of total damage for rigid pavements was environmentally related [10]. As a result, environmental parameters such as temperature and precipitation are inputs in both material and pavement design methodologies. However, with climate change altering future environmental conditions, pavement deterioration rates may accelerate [11]. This is due to the future climate being non-stationary as opposed to forecasting historical climate data which is a common method for current material and pavement design. As the effects from climate change progress, there is growing expectation from decisionmakers that our infrastructure designs consider resilience to a changing climate and extreme weather events [1, 2, 3].

FHWA defines resilience as the ability to anticipate, prepare for, and adapt to changing conditions and withstand, respond to, and recover rapidly from disruptions [12]. Currently, pavement asset managers must incorporate risk to natural threats including climate change in their state Transportation Asset Management Plans [4]. With regards to pavement design, Title 23 Code of Federal Regulations Part (CFR) 626 establishes, “Pavements shall be designed to accommodate current and predicted traffic needs in a safe, durable, and cost-effective manner.” [13]. Regulations do not specify procedures to follow to meet the requirement. Instead, each State Highway Agency is expected to use a design procedure appropriate for its unique conditions. There are 5 simple steps that every agency can follow to approach addressing resilience which include [9]:

i. Understand Site Context and Future Climate – Determine valued assets and climate stressors that may affect them
ii. Assessing Vulnerability and Risks – Gather climate data and assess each assets vulnerability to climate stressors
iii. Investigating Options – Consider possible solutions to asset vulnerabilities
iv. Pick Strategy and Construct – Create a plan to implement the best options chosen
v. Monitor and Revisit – Continue to track results and progress

Incorporating resilience to climate change into pavement design and decision making, is a relatively new concept. As a result, FHWA hosted two peer exchanges in 2020 to identify best practices for assessing and incorporating future climate conditions and resilience considerations into pavement design, rehabilitation, and maintenance. These peer exchanges are among the first United States National gatherings of pavement experts entirely focused on resilience.

In relationship to the 5-step generic approach to addressing resilience referenced above, this paper identifies pavement specific vulnerabilities (steps i and ii) and strategies that could be solutions investigated (steps iii-v). In doing so, this paper documents the state of knowledge of pavement resilience, summarizes key findings from the national peer exchanges including best practices, lessons learned and research gaps, and proposes approaches to integrating resilience considerations into pavement design building on numerous FHWA resources that are publicly available.

2. CLIMATE CHANGE AND PAVEMENT VULNERABILITIES (STEPS I AND II)

The occurrence of climate change is a common understanding and concern between agencies. The changing of climate is largely caused by human activity and with the activity that has already occurred, major change in climate is inevitable over the next century. The reason for this is the relatively long life of emitted heat-trapping gases (commonly grouped together as greenhouse gases, or GHG) and the slow feedback functions of the atmospheric systems that drive climate change [9]. Usually when creating projections for future climate conditions, different GHG emission scenarios are used. Each scenario is labeled a representative concentration pathway (RCP) with the suffix reflecting the radiative forcing values, with higher forcing resulting in increased warming. These scenarios reflect projections that are possible depending on changes in emission outputs and when those reductions in GHG emissions occur.

- RCP 2.6: Emissions peak around 2010-2020 and then decline thereafter.
- RCP 4.5: Emissions peak around 2040 and then decline thereafter.
- RCP 6.0: Emissions peak around 2080 and then decline thereafter.
- RCP 8.5: Emissions continue to rise throughout the 21st century.

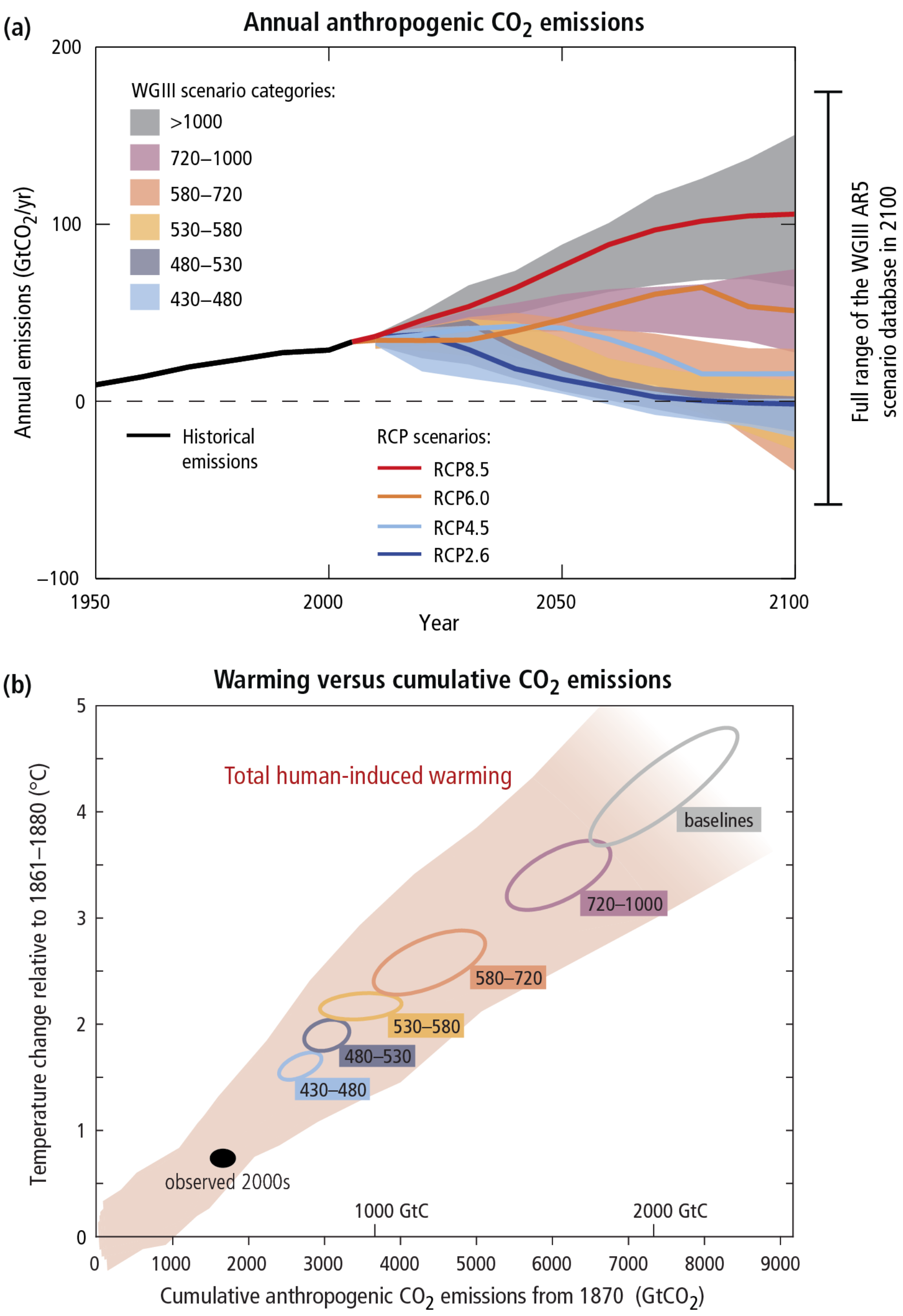

Figure 1 - Representative concentration pathways (RCPs) from the IPCC Fifth Assessment Report [14]

The effects of climate stressors are dependent upon the scenario that is assumed, with RCP 8.5 being the worst-case scenario. Unfortunately, RCP 8.5 is also the current path for GHG emissions. If this continues to hold true, changes in climate will happen at an increasing rate and assets will be at risk during major extreme weather events.

2.1. Temperature

Temperature rise is a common concern for all agencies. Current models show that, regardless of the scenario used, average annual temperature over the contiguous United States is expected to increase by 2.2°F in the next few decades, relative to 1986–2015. Projected temperature increases for the end of the century is much larger in that temperatures could rise by 2.5°F to 11°F depending on the emission scenario [15]. The projected temperature changes will come with both higher maximum and minimum temperatures as well as less days below freezing with more days in extreme heat (>90°F). Increased temperatures could lead to an increase in the rate of pavement deterioration from cracking and rutting as well as decreased overall pavement performance if design standards are not adjusted [16]. Table 1 identifies the temperature climate change impacts expected and their potential impacts to pavements if climate change is not considered in the design [7].

Table 1 – Potential Temperature Climate Change Impacts on Pavements [7]

Climate Change Impact	Vulnerabilities	
	Flexible Pavement	**Rigid Pavement**
Higher Average Temperature	Increased potential rutting and shoving	Increased potential for curling and moisture warping
	Increased age hardening	
Higher Extreme Maximum Temperature	Construction delays or limitations	Construction delays or limitations
		Concrete pavement blow-ups
Warmer Extreme Minimum Temperature	Degradation of ride quality in areas with permafrost which is anticipated to melt	
More Freeze-Thaw Events in Some Locations	Increased thermal cracking	Decreased durability due to the freeze-thaw cycling and chemical deicers

As temperatures increase, there is a growing concern for melting permafrost in the arctic. Air temperatures in Alaska and the Arctic have increased at a rate of over twice that of the global average over the last 50 years [15]. Permafrost is melting, causing reduced sub-grade support and as freeze thaw cycles change, pavement designs may have to change as well.

2.2. Precipitation

Precipitation changes are also a common concern among all agencies. Some regions such as the Pacific Northwest are seeing less precipitation while many other areas are seeing more precipitation. These changes are also seasonal and change with geography. For 2070–2099 relative to 1986–2015, precipitation increases of up to 20% are projected in winter and spring for the north central United States and more than 30% in Alaska, while precipitation is projected to decrease by 20% or more in the

Southwest in spring [17]. Increased precipitation can lead to inundation and reduced structural capacity of pavement infrastructure. Table 2 identifies the potential impacts to pavement that are associated with changes in precipitation due to climate change [7].

Table 2 – Potential Precipitation Climate Change Impacts on Pavements [7]

<table>
<tr><th rowspan="2">Climate Change Impact</th><th colspan="2">Vulnerabilities</th></tr>
<tr><th>Flexible Pavement</th><th>Rigid Pavement</th></tr>
<tr><td rowspan="2">More Extreme Rainfall</td><td colspan="2">Reduced skid resistance</td></tr>
<tr><td colspan="2">Reduction in structural capacity of unbound bases and subgrade when pavements are submerged</td></tr>
<tr><td rowspan="2">Higher Average Precipitation</td><td colspan="2">Reduction in pavement structural capacity due to increased levels of saturation</td></tr>
<tr><td colspan="2">Construction delays</td></tr>
<tr><td>Wetter Winters and Dryer Summers</td><td colspan="2">Increased potential for soil shrinking and swelling due to moisture changes, particularly in times of drought</td></tr>
<tr><td rowspan="2">Low Summer Humidity</td><td rowspan="2">Increased volatization and aging of binder</td><td>Increased long-term concrete slab warping</td></tr>
<tr><td>Impacts concrete curing during construction</td></tr>
</table>

2.3. Drought and Wildfires

With temperatures increasing all over the country and some areas receiving less precipitation, droughts and wildfires are a major concern. Parts of Alaska and western U.S. have seen larger wildfire events and, under some RCP scenarios, will experience longer periods of drought in years to come, which could lead to damage to pavements. During the FHWA Highway Resilience to Wildfire Events peer exchange held in 2020, there was discussion that pavements are less likely to be damaged by the actual fire itself but instead are damaged from the heavy vehicles traveling on the roads to help manage the fires and aftermath clean up. Also, it was reported that in some isolated cases, the pavement surface was severely damaged due to the fire.

2.4. Sea-Level Rise and Flooding

Sea-level rise and flooding are growing concerns for many agencies and stakeholders especially for coastal areas. Global sea levels are projected to rise 1 to 4 feet by 2100, which is much more than what historical measurements have shown being as though the global sea level has risen by only 7 to 8 inches since 1900 [18]. Studies have shown that flooded pavements lose structural capacity and are less resilient to deterioration [19].

2.5. Climate Forecasting Tools

Projected data which considers climate change would provide more accurate value inputs when determining design/operating parameters. There are currently resources available for obtaining climate projections and sea level rise. Below is a list of some data sources available.

Table 3 – Data sources for future climate projections and see level rise [9]

Resource	Description	Link
Downscaled CMIP3 and CMIP5 Climate and Hydrology Projections (DCHP) database	A database that contains publicly available, downloadable, downscaled climate projection data for temperature and precipitation in the contiguous United States.	Available in reference section: [25]
USGS Geo Data Portal	A web portal that provides access to a suite of climate data sets for temperature and precipitation, including climate projections using different downscaling techniques.	Available in reference section: [26]
U.S. DOT CMIP Climate Data Processing Tool 2.0	An excel-based tool to process data from the DCHP database to provide temperature and precipitation projections for climate variables relevant to transportation planners. Updated version uses the LOCA dataset and incorporates several new variables.	Available in reference section: [25]
U.S. Army Corps Sea Level Change Curve Calculator	A web-based tool that accepts user input to produce a table and graph of the projected sea level changes at the project site which includes vertical land movement.	Available in reference section: [27]
National Oceanic and Atmospheric Administration's Sea Level Rise Viewer	Web mapping tool to visualize community-level impacts from coastal flooding or sea level rise which contains downloadable sea level rise data for many locations.	Available in reference section: [28]

Although there are resources available for projected data, there are sometimes limitations to how some of the data can be used. Tools to obtain projected data that better suits pavement design needs such as hourly projected data rather than daily could be beneficial to agencies but is not available. This type of information would require some additional research and development.

3. STATE OF PRACTICE OF PAVEMENT RESILIENCE STRATEGIES (STEPS III-V)

The best way to address resilience is to consider climate change impacts and adaptation early in the project development process which commonly consist of planning, scoping, preliminary design/engineering, environmental analysis, final design/engineering, right-of-way acquisition, and construction. It is during the first three stages—planning, scoping, and preliminary design/engineering—that engineering-informed adaptation studies can have the greatest impacts on the design features of the project [9]. It should be noted that there are opportunities to incorporate resilience during the design process as well.

3.1. Resilience in Design

In the context of pavement design, there have been many strategies to enhance the performance of long life pavement. Roadways could be elevated or porous materials could be used in certain areas in terms of storm water management. Stiffer pavement mixes or modified asphalt binders are being tested to determine their resilience to increased heat and pavement loads [7]. Table 4 shows various pavement resilience strategies that are available to strengthen pavement against climate stressors.

Table 4 – Possible solutions for pavement vulnerabilities [7]

Climate Change Impact	**Strategies**
More Extreme Rainfall	-High friction surface treatments -Porous pavements or open graded friction courses
Higher Average Precipitation	-Reduce moisture susceptibility of unbound base/subgrade materials through stabilization -Ensure asphalt mixtures resistance to moisture susceptibility
Wetter Winters and Dryer Summers	-Incorporate soil modification/stabilization into design -Use stiffer/improved pavement designs that are less susceptible to changes in subgrade properties -Ensure concrete freeze-thaw resistance -Concrete joint design should ensure that the concrete remains below critical saturation
Low Summer Humidity	-Addition of asphalt binder antiaging additives -Pavement preservation to address binder aging -Reduce drying shrinkage of concrete mixes by decreasing paste volume -Consider concrete drying shrinkage in design by reducing slab length
Higher Average Temperature	-Raise asphalt binder grade or consider polymer modified binders -Greater consideration of concrete coefficient of thermal expansion and drying shrinkage -Incorporation of design elements to reduce damage from thermal effects in concrete pavements including shorter joint spacing, thicker slabs, less rigid support, and enhanced load transfer
Higher Extreme Maximum Temperature	-Consider polymer modified binders -Use shorter joint spacing in concrete designs -Keep joints clean and in extreme cases, install expansion joints in existing pavements

More Freeze-Thaw Events in Some Locations	-Increase consideration of the thermal fatigue characteristics of asphalt binder

Many states already use climate data in their pavement modeling and decision-making processes but in doing so, historical data is typically used rather than future projected data. The issue with this approach is that historical data is now becoming less reliable for predicting the severity and recurrence of future events, making it obsolete. All pavement design methods and tools which use environmental inputs base them off historical climate data including the currently used Mechanistic-Empirical Pavement Design Guide (MEPDG) and supporting software (i.e. AASHTOWare Pavement ME™ design). AASHTOWare Pavement ME™ design is a design software that is commonly used by engineers in the pavement industry that calculates pavement responses based on traffic, climate, and materials parameters to predict the progression of key pavement distresses and performances over pavement life time [21]. A study was done to determine how climate change could affect pavement performance based on the current pavement design models and one result was that localized calibration coefficients could be used to incorporate the effect of climate change into the pavement design process [22]. Obtaining local calibration coeficciencts is a difficult task but once completed would provide more accurate results for pavement design.

The porous pavement allows rainwater to absorb into the pavement then flow laterally out from the roadway surface onto the shoulder section, where the runoff is infiltrated [23].Texas and California added the use of porous pavement to their stormwater best management practices and the North Carolina Department of Transportation (NCDOT) highway stormwater program supervisor anticipates the same. NCDOT is updating their stormwater design manual to include nature-based solutions such as “Bio-embankments” to control stormwater runoff and is in search of other mitigation strategies to be added. Officials have already started creating, installing, and testing the bio-embankments as well as other nature-based solutions [23].

To provide an example of proactive approaches toward resilient pavement and its benefits, Virginia did a case study on three of its districts to determine the Life Cycle Cost Assessment (LCCA) to determine the economic impacts of using a modified asphalt binder (Performance Grade PG 76-22). The study concluded that pavements using the modified binder perform better over time and are also economically advantageous [20]. As more adaptation methods are being developed it is important to use tools like LCCA to evaluate the strategies life cycle benefits and impacts (step iv).

Although we can quantify climate change effects, it may be better option to use an adaptive design where assets could easily recover from major climatic events rather than be undamaged. No matter which adaptation method is used, it will always be important to incorporate projected data in addition to other data into the design processes.

3.2. Resilience in Asset Management (step v)

In the context of system performance and asset management, there are currently no standard practices between agencies that specifically address pavement resilience to climate change. One reason is due to the fact that climate change resilience for pavements is a fairly new concept that has limited amounts of research. Another reason is because climate change impacts every region differently so what works for some may not work for others. That being said, asset management can be key in identifying if climate change stressors are negatively impacting the performance of the assets through monitoring environmental pavement distresses.

Recent requirements to address climate change in asset management plans are causing states to not only think about possible ways to address resilience overall management processes. Although incorporating resilience may require additional funding, using best practices may present cost savings when considering the life cycle costs which help ensure financially sustainable implementations to the asset management systems as discussed in reference [20].

Hawaii is changing the way funding is allocated from a district approach to a prioritization approach. Instead of using formulas to allocate to funds to each district, have them make work plans, and do maintenance alone, Hawaii Department of Transportation (HDOT) is focusing on improving computerized programs to determine which projects need to be prioritized, collaborate with administration to come up with work plans, then have funds allocated to each district based on investment priorities agreed on by administration [24].

4. CASE STUDIES

The Federal Highway Administration's (FHWA) Transportation Engineering Approaches to Climate Resilience (TEACR) study is designed to help identify best engineering practices for evaluating project-specific vulnerabilities to climate change impacts and extreme weather events, and for developing adaptation solutions to address those vulnerabilities. Lessons learned for project-level adaptation assessments are summarized in the Synthesis of Approaches for Addressing Resilience in Project Development. Below are some TEACR engineering case studies that have been done addressing pavement climate change resilience.

4.1. Pavement Study Projects

The following studies involved lessons learned regarding the effects of climate stressors on pavement, and pavement subgrades

4.1.1. *Texas Study - Temperature and Precipitation Impacts to Pavements on Expansive Soil*

Texas study focused on pavements constructed over expansive soils and the effects of rising temperature and precipitation due to climate change. Proposed State Highway 170 (SH-170) that is located in the northern part of the Dallas-Ft. Worth metropolitan area was selected for the study. The geologic settings within the corridor is located in the Woodbine Sandstone formation and near the eagle Ford Shale sedimentary formation. Both formations are known to have highly expansive plastic clays. Since pavement type was not yet selected for the project both flexible and rigid pavements were analyzed using TMI-Matric Suction models, LTPPBind 3.1, Texas Transportation Institute's (TTI) Potential Vertical Rise (PVR) method using WINRES for prediction of Roughness in Expansive Soils. Temperature and precipitation projections were obtained from CMIP5 data. Soil moisture was calculated using the USGS Modified Thornwaite Monthly Water Balance Model (TMI).

The analysis found that under all future scenarios increase in temperature could be beneficial as a result of increased subgrade support and pavement smoothness for both pavement types due to less intense soil shrink swell cycles which result from lower soil moisture and clay subgrade drying. Detrimental effects could also result from the increased ambient temperature resulting in increased cracking, rutting, and overall reduced performance of the pavement itself.

Adaptation strategies included using stiffer asphalt binders for flexible pavements, stiffer binders in overlay and increased steel content for rigid pavements. Since increased temperature happens over such a long period of time, the switch of pavement materials does not have to be done immediately and can be done as needed over time.

4.1.2. *Maine Study – Temperature and Precipitation Impacts on Cold Region Pavement*

Maine study focused on how changing temperature and precipitation patterns will alter freeze thaw cycles and its impact on pavement performance in cold climates. The focus was on the change in the timing and duration of winter weight premiums (WWPs) and spring load restrictions (SLRs). CMIP5 data was used to obtain future temperature and precipitation projections. The study analyzed the effect of climate change and environmental stressors and scenarios at State Route (SR)-6/SR-15/SR-16 in Guilford, Maine.

Future projections show a clear upward trend in temperature and gradual upward trend in precipitation. The increase in temperature will reduce frequency of frost heave which will reduce pavement smoothness loss, but warming trend will cause softening of bituminous pavement layers which will result in increased load fatigue damage, subgrade rutting, and AC rutting. The analysis found that shorter freezing seasons will result in fewer opportunities for WWPs and earlier posting of SLRs and a reduction in the time period for WWPs at an approximate rate of one week per two decades.

Adaptation measures for addressing climate change effects included Increasing pavement thickness, proactive pavement maintenance, continual monitoring of temperature changes, and more frequent re-evaluation of pavement design and load restrictions.

5. GAPS AND NEEDS

To identify best practices for assessing and incorporating future climate conditions and resilience considerations into pavement design, rehabilitation, and maintenance, FHWA hosted two peer exchanges during the last quarter of 2020. These peer exchanges gathered pavement experts from all sectors across the nation and was entirely focused on pavement resilience. The key topics discussed during the peer exchange as well as gaps and future needs of agencies and stakeholders are summarized below.

5.1. Discussion of Key Topics

- Preservation choices are limited due to the funding requirements
    - Based on the guidelines, the preservation projects are intended to restore the pavement conditions to its original level. Therefore, funding is not granted to preservation projects that add structural capacity even if the added structural capacity is the best option to preserve the infrastructure through future events.
- Pavement inundation frequencies due to climate change
    - Higher intensity storms and sea-level rise are causing coastal and riverine flooding which increases the risk of pavement inundation
    - There is uncertainty as to when pavements can be reopened after inundation events without significantly damaging the pavements.
- Resilience and sustainability aspects to be added to the pavement design policy
    - Many states believe that resilience and sustainability should be added to the design policy but there are mixed feelings as to when this should be made a requirement due to a lack of knowledge and resources to address such issues at this time.
    - Some states believe that if added, it should be broad enough to let states address it in a way that suites each state's needs and knowledge, mainly because some states are further along in this subject area than others.

5.2. Gaps and Future Needs

- FHWA Guidance
    - FHWA needs to provide additional guidance, training, and technical support on pavement design, asset management, and use of tools to include climate change resilience and adaptation.
- Expand Collaboration Opportunities
    - There needs to be more collaboration between departments through conducting more frequent events such as peer exchanges to share practices and knowledge amongst states.

- Pavement ME™ Upgrade
  - To incorporate climate change into pavement design, software such as Pavement ME needs to incorporate climate projections and then be locally calibrated to fit the needs of specific projects at different locations.
- Research
  - More Research works need to be done to obtain more accurate climate projections and models to use the projections to make better decisions with pavement design and asset management in terms of future needs.
- Enhance Climate Projection Resolution
  - Future projections of some critical climate variables used for pavement design and management purposes need smaller temporal resolutions. (From daily to hourly)

6. SUMMARY OF FINDINGS

Pavement resilience is a growing topic that is an essential part to have a sustainable pavement infrastructure. From reviewing literature, peer exchanges, and discussions the state of knowledge of pavement resilience is limited. Federal requirements and growing concerns over climate stressors from agencies and stakeholders are pushing the agenda to incorporate resilience into decision making processes. There are 5 simple steps that every agency can follow to approach addressing resilience which include:

i. Understand Site Context and Future Climate – Determine valued assets and climate stressors that may affect them
ii. Assessing Vulnerability and Risks – Gather climate data and assess each assets vulnerability to climate stressors
iii. Investigating Options – Consider possible solutions to asset vulnerabilities
iv. Pick Strategy and Construct – Create a plan to implement the best options chosen
v. Monitor and Revisit – Continue to track results and progress

Although initial resilience efforts may need additional funding, overall life cycle cost will likely be reduced due to the amount saved on maintenance needed from damage caused by future climatic events. Using the simple 5-step process for considering resilience in project design, this paper identified various vulnerabilities (steps i-ii) and strategies specific to pavement resilience (steps iii-v). The major vulnerabilities of concern are:

- Flooding
- Sea-Level Rise
- Increased Temperatures (Minimum & Maximum),
- Increased Precipitation (Intensity & Frequency),
- Droughts & Wildfires

Strategies to enhance pavement resilience against these climate stressors include changes in material, changes in pavement structural design, and other multifunctional approaches.

Different tools are available to help understand future climate projections and sea level rise which can be useful to inform the design process. However, it should be noted that one gap in some of the design tools is the use of historical climate data to predict future conditions which is becoming obsolete as future climate is non-stationary. Further development of pavement design software in which climate projections can easily be applied is needed. It is important to note that this would significantly help pavement design and materials selection. However, based on this paper discussions, it is observed that more innovations are welcomed in the area of pavement resilience design.

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