U.S. Department of Transportation
Federal Highway Administration

SUSTAINABLE PAVEMENTS PROGRAM

PAVEMENT RESILIENCE:
STATE OF THE PRACTICE

FHWA-HIF-23-006

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For the Federal Highway Administration (FHWA), resilience, with respect to a project, means a project with the ability to anticipate, prepare for, and or adapt to changing conditions and or withstand, respond to, and or recover rapidly from disruptions. This includes the ability: (A) to resist hazards or withstand impacts from weather events and natural disasters, or to reduce the magnitude or duration of impacts of a disruptive weather event or natural disaster on a project; and (B) to have the absorptive capacity, adaptive capacity, and recoverability to decrease project vulnerability to weather events or other natural disasters. 23 U.S.C. § 101(a)(24). As noted in FHWA Order 5520 (FHWA 2014), climate change and extreme weather events present significant and growing risks to the safety, reliability, effectiveness, and sustainability of the Nation’s transportation infrastructure. This document examines pavement resilience, a subset of transportation resilience, and describes the state of knowledge, practice, and future needs based on (1) key national and international climate documents, (2) a FHWA approach to resilience, (3) the results of an unpublished literature review, and (4) the findings from two FHWA-sponsored Peer Exchanges on pavement resilience held in late 2020.</td></tr>
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Table of Contents

List of Figures

List of Tables

1 INTRODUCTION

In the context of transportation infrastructure, *resilience* means, with respect to a project, the ability to anticipate, prepare for, and or adapt to changing conditions and or withstand, respond to, and or recover rapidly from disruptions, including the ability: (A) to resist hazards or withstand impacts from weather events and natural disasters, or reduce the magnitude or duration of impacts of a disruptive weather event or natural disaster on a project; and (B) to have the absorptive capacity, adaptive capacity, and recoverability to decrease project vulnerability to weather events or other natural disasters. 23 U.S.C. § 101(a)(24). *See also* FHWA Order 5520 (FHWA 2014). As noted by FHWA (2104), climate change and extreme weather events present significant and growing risks to the safety, reliability, effectiveness, and sustainability of the Nation's transportation infrastructure. This report examines pavement resilience, a subset of transportation resilience, as it specifically relates to climate stressors associated with climate change. Specifically, it describes the state of knowledge, practice, and future needs in the following sections:

- **Section 2: Climate change stressors**. There has been global and national work to identify an initial set of climate stressors (IPCC 2014; USGRCP 2017). This document focuses on stressors that affect pavements.
- **Section 3: Impacts on transportation systems**. Several efforts have, on a large scale, related general climate impacts into impacts on transportation systems. While these transportation impacts are informative, they are not granular enough to be actionable for the pavement community.
- **Section 4: Impacts on pavements**. This section discusses climate stressors and resulting transportation impacts into specific pavement impacts and potential adaptations in materials, design, construction, maintenance, preservation, and operations.
- **Section 5: Resilience**. This section describes a pavement-specific resilience approach based on the FHWA's *Vulnerability Assessment and Adaptation Framework* (2017).
- **Section 6: Specific research on pavement resilience**. This section discusses existing pavement resilience research as well as areas with little research to date.
- **Section 7: Peer exchange findings**. The FHWA hosted two peer-exchange sessions in 2020 with several State Departments of Transportation (DOT), academic, and industry representatives on the topic of pavement resilience. This section summarizes findings from these sessions.
- **Section 8: Overall findings**. The findings from the literature search and the peer exchanges are presented in this section, along with a summary of current gaps and research needs.

Funding issues and societal factors, while critical to resilience efforts, are outside the scope of this report.

2 CLIMATE CHANGE STRESSORS

Resilience actions are dependent upon climate stressors associated with climate change and, specifically, how they might be different than historical climate stressors. This section reviews those anticipated differences based on the following national/international summative references.

It is important to consider how climate change stressors can vary from region to region and cause impacts to differ by location.

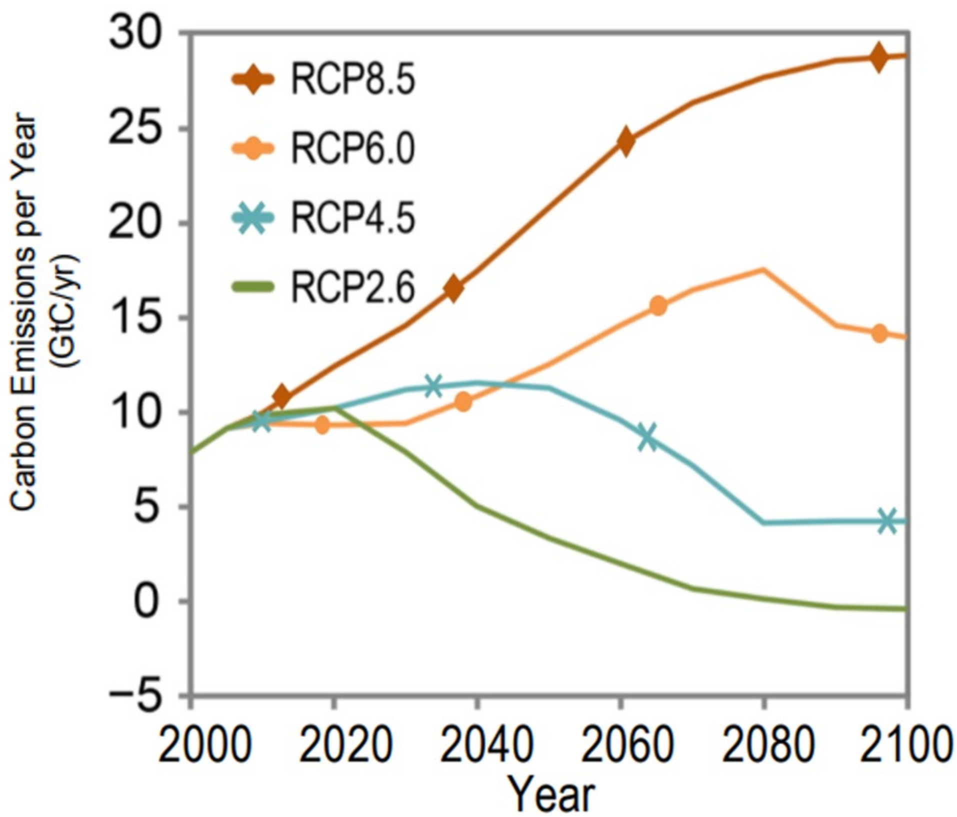
- The Intergovernmental Panel on Climate Change (IPCC) Fifth Assessment Report (AR5) *Climate Change 2014 Synthesis Report* (IPCC 2014). The IPCC is the U.N. body for assessing the science related to climate change. Since 1990, IPCC has produced comprehensive reports every 5 to 7 years.
- The U.S. Global Change Research Program's *Fourth National Climate Assessment* (USGCRP 2017; USGCRP 2018). The USGCRP coordinates Federal research and investments in understanding the forces shaping the global environment and their impacts on society. Starting in 2000, USGCRP has produced comprehensive U.S. climate assessments every 4 to 9 years on climate change science, mitigation, and adaptation. The fourth assessment has two main volumes:
  - *Climate Science Special Report* (Volume 1). Reviews the climate science used to predict climate change (USGCRP 2017).
  - *Impacts, Risks, and Adaptation in the United States* (Volume II). Provides climate change details by U.S. region and presents climate stressors, risks, and adaptation issues by national topics (e.g., transportation) (USGCRP 2018).
- The National Cooperative Research Program's *NCHRP Report 750: Strategic Issues Facing Transportation, Volume 2: Climate Change, Extreme Weather Events, and the Highway System* (Meyer et al. 2014). This report provides an overview of climate change and adaptation specifically for the transportation sector. It contains high-level treatment of pavement impacts, the only reference of these three that does.

2.1 CLIMATE CHANGE BACKGROUND

Changes in the global climate and the understanding that human activities have been the dominant cause are supported by a preponderance of historical observations and climate modeling both at a national and global scale (IPCC 2014; USGCRP 2018). Current climate models generally predict that the climate will continue to change and do so at an increasing rate over the next century or longer (IPCC 2014; USGCRP 2018). While the magnitude and speed of predicted future climate change is generally dependent upon human activities, even the most optimistic scenarios predict substantial climate change over the next century or longer based on what has already occurred in conjunction with the relatively long life of emitted heat-trapping gases (commonly grouped together as *greenhouse gases*, or GHG) and with the slow feedback functions of the atmospheric systems that drive climate change (IPCC 2014). Climate stressors with the most direct relevance to pavements extracted from USGCRP (2018) are explained in sections 2.2 through 2.7. Inclusion of stressors are limited to those considered to be medium or higher confidence of impact.

A note on climate change uncertainty. The greatest uncertainty in projecting future climate conditions is the uncertainty in future GHG emissions (USGCRP 2018). To address this uncertainty, the IPCC Fifth Assessment Report (IPCC 2014) included climate modeling over a range of projected future GHG emission scenarios. As shown in Figure 1, each scenario is labeled a *representative concentration pathway (RCP)* with the suffix reflecting the radiative forcing values, with higher forcing resulting in increased warming for the year 2100 (IPCC 2014; USGRCP 2017). Radiative forcing in watts/m^2 may be easier to envision as a scenario of when GHG emissions peak and then start to decline:

- RCP2.6: Emissions peak around 2010-2020 and then decline thereafter.
- RCP4.5: Emissions peak around 2040 and then decline thereafter.
- RCP6.0: Emissions peak around 2080 and then decline thereafter.
- RCP8.5: Emissions continue to rise throughout the 21st century.



Source: USGRCP

Figure 1. Representative concentration pathways (RCPs) as they relate to global annual greenhouse gas (GHG) emissions. Each RCP scenario results in a different predicted GHG emissions profile. Figure is a portion of Figure 4.1 from USGRCP (2017).

Predictions of climate stressors are dependent upon which RCP is assumed. Some climate stressors are true for all RCPs (only varying in magnitude, with more radiative forcing resulting in larger impacts) while others are dependent on the assumed RCP such that the prediction may change based on the RCP used.

2.2 TEMPERATURE CHANGE

General increase in temperature (USGCRP 2017). Annual average temperature over the contiguous United States is projected to rise by about 2.5 degrees F (1.4 degrees C) for the period 2021 to 2050 (relative to 1976 to 2005), no matter which RCP scenario is considered. This is about twice the rate of the previous 50 years. Temperature rises by the late century (2071 to 2100) range from 2.8 to 11.9 degrees F (1.6 to 6.6 degrees C) depending upon the RCP scenario.

Higher extreme temperatures (USGCRP 2017). Extreme temperatures are predicted to increase even more than average temperatures. Cold waves will become less intense whereas heat waves will become more intense. These changes may also lead to fewer days below freezing, potential changes in the number of freeze-thaw cycles experienced, and reduced frost penetration into soil.

2.3 PRECIPITATION CHANGE

Changes in annual precipitation will vary across the United States (USGCRP 2017). Seasonal changes will also occur, with some regions seeing less precipitation (for example, the Pacific Northwest seeing less summer precipitation) while other areas will see more precipitation (for example, the Northeast will see more winter precipitation) (USGCRP 2017).

More frequent and intense heavy precipitation events (USGCRP 2017). Increases are expected to occur for the largest single-day precipitation events. Regional and seasonal differences exist.

Changes in snow patterns (USGCRP 2017). Large declines in snowpack are expected in the west, as well as shifts to more precipitation (less in the form of snow, more in the form of rain) during the cold season in parts of the central and eastern United States.

2.4 DROUGHTS, FLOODS, AND WILDFIRES

Possible increasing chronic, long-duration drought (USGCRP 2017). Under higher RCP scenarios, the potential for an extended drought in some parts of the country is more likely by the end of the century.

Decrease in surface soil moisture (USGCRP 2017). Increased evapotranspiration caused by higher temperatures will reduce soil moisture**.**

Some classes of flood frequency have changed, but it is difficult to connect future flooding to human-induced climate change (USGCRP 2017). The emergence and timing of any future change in flooding that can be traced to human-induced climate change is unclear.

Increased large forest fire incidences in the western United States and Alaska (USGCRP 2017). The annual number of large forest fires have been increasing in number and intensity since 1980. This trend is likely to continue.

2.5 EXTREME STORMS

Increase in tropical cyclone intensity and frequency (USGCRP 2017). This is consistent with the observed upward trend in North Atlantic hurricane activity since 1970.

Tornado activity has become more variable and confidence in future predictions is low (USGCRP 2017). Models generally predict an increase, but confidence in the details is low.

Projections in winter storm frequency and intensity are varied and prediction confidence is low (USGCRP 2017). Agreement amongst models is poor.

2.6 ARCTIC CHANGES

Permafrost in Alaska is thawing and becoming more discontinuous (USGCRP 2017). Air temperatures in Alaska and the Arctic have increased over the last 50 years at a rate of over twice that of the global average.

2.7 SEA LEVEL RISE

Sea level rise (USGCRP 2017). Global mean sea levels are already rising (7 to 8 inches since 1900 and about 3 of those inches occurring since 1993) and will continue to do so. Projections on the amount of global mean sea level rise are in the range of 1.0 to 4.3 ft. by 2100. Rise can vary from location to location based on regional differences in ocean temperatures, salinity, currents, and subsidence or uplift of the coast.

Sea level rise will increase the depth, frequency, and extent of tidal floods that cause minor impacts (USGCRP 2017). Higher sea levels may result in more flooding issues associated with high tides.

Sea level rise will increase the frequency and extent of flooding during coastal storms (USGCRP 2017). Higher sea levels may result in more flooding, which may be severe, for a given storm intensity and duration.

3 IMPACTS ON TRANSPORTATION SYSTEMS

Some organizations have begun to plan for climate change, the impacts it may have, and the adaptations to consider avoiding or mitigate those impacts. At the highest level, most U.S. government and scientific organizations are in general agreement on the nature of climate change and its environmental stressors and are beginning to explore how to adapt current practice to account for these impacts (FHWA 2014; FHWA 2017; FHWA 2017a). The *Fourth National Assessment, Volume II* report (USGCRP 2018) describes a wide range of climate impacts, risks, and adaptation by category and U.S. region. These impacts are many and include, among others, compromised coastal freshwater aquifers, increased electricity consumption, transportation network disruption, declining crop production, increased tree mortality, ecosystem alteration, increased respiratory and cardiovascular disease, and changing land use (USGCRP 2018). For the transportation sector in particular, the report offers the following key messages (USGCRP 2018):

- **Climate change poses a risk to U.S. transportation infrastructure**. The impacts from heavy precipitation, flooding, heat, wildfires, sea level rise, storm surge, extreme weather events, Arctic warming, and other climatic conditions are affecting the reliability and capacity of the U.S. transportation system.
- **Extreme events can cause strong and varied impacts to transportation networks**. These impacts can have broad societal and economic consequences and can disproportionately affect vulnerable populations.
- **Practitioners are beginning to address climate risks through vulnerability and risk assessments and implement adaptive measures**. Tools that measure climate change impacts at both the project and system level are becoming more widely available, but there is more to be done to develop additional tools and methodologies.

Table 1 provides examples of climate stressors and the impacts these changes may have on pavements. The table further provides examples of how those impacts could change how pavement assets are managed in the future.

Table 1. Potential impacts of climate change on transportation assets (from Childress et al. 2015).

Climatic Event	Impacts of Current Climate Variability and Future Climate Change	Examples of Potential Vulnerabilities
Sustained extreme heat	• Causes road and runway buckling. • Stresses bridge integrity. • Limits construction crew schedules. • Results in loss of lift for airplanes. • Causes rail deformation as well as derailments.	• The possibility of increased future need for road maintenance and road closures for heat-related problems makes the **road** system vulnerable given current adaptive capacity. • **Airports** unable to extend runways may find themselves vulnerable to reduced cargo capacity due to warmer air, which can make passenger flights less cost effective. DIA may experience summer cargo losses as high as 19% by 2030. • **Rail lines** are particularly vulnerable to increased heat due to the very high cost of installing more heat-resistant tracks.
More frequent and intense drought which increases wildfire risk	• Causes road closures, reduces visibility, and a greater risk of mudslides; decreases safety. • Threatens airport facilities directly and impairs visibility.	• All elements of the transportation system, especially **roads**, are vulnerable to closures due to increased wildfires. Communities and travelers are vulnerable to safety hazards from wildfire.
Continued flooding events and increased intensity of winter storms	• Can lead to submerged roads; flooded underpasses; road and bridge scouring; increased landslides and mudslides; overloading of drainage systems; compromised structural integrity of roads, bridges, and tunnels; adverse impacts on road bases; the need for larger bridges and culverts; road closures; increased maintenance costs. • Can cause flooding of airports as well as damage to runways and drainage systems. • Can cause flooding of rail lines and damage to rail bed support structures; winter snows can damage rail track and cables and block tracks.	• The State's **road** network could be vulnerable to closures and infrastructure damage due to intense precipitation, even under the current climate, and traffic accidents are linked to extreme weather. • Communities with limited **road** access are highly vulnerable to being cut off by floods or winter storms. • **Airports** could be vulnerable to damage to runways and drainage systems from flooding events and winter storms that overwhelm their existing capacity to respond. • **Railroads** could be vulnerable to damage from flooding and winter storms that overwhelm their capacity to respond.

4 IMPACTS ON PAVEMENTS

Meyer et al. (2014) provides a list of climate stressors for pavements and potential adaptation strategies. In 2015, the FHWA (2015a) modified and expanded that list, which describes the range of climate stressors and their impacts relevant to pavements. Table 2 expands further on the table presented in the FHWA (2015a) document, supplemented with additional pavement-specific information presented by FHWA (FHWA 2017a).

Table 2. Climate stressors related to specific pavement impacts and potential adaptation strategies.

Category	Climate Stressor	Pavement Vulnerabilities	Materials Adaptations	Design Adaptations	Construction Adaptations	Operations Adaptations
Temperature	Higher average temperature	• Increased maximum pavement temperature • Increased rate of age hardening of asphalt binder • Increased concrete temperature-related curling and associated stresses • Increased concrete moisture-related warping if accompanied by lower relative humidity.	• Raise high-temperature asphalt binder grade • Polymerized binder in surface course • Increase required rut/deformation resistance for asphalt mixes • Concrete mixes with lower drying shrinkage, reduced coefficient of thermal expansion	• Higher stiffness asphalt mixes selected for surface to resist rutting at higher temperatures • Consider concrete pavement design holistically to reduce environmentally induced damage • Smaller concrete slabs with enhanced load transfer • Increased reinforcement in continuously reinforced concrete pavement to resist cracking	• Adjust construction season to reduce construction during hotter months and extend more into cooler months • Shift to more night work for lower temperatures and less evaporative environment	*
	Higher extreme maximum temperature	In addition to what is listed above: • Concrete pavement blow-ups due to excessive slab expansion. • More construction scheduling limits due to high temperature working hour restrictions	Same as above	Same as above, plus: • Reduce concrete joint spacing to reduce slab stresses • Modified concrete joint design to reduce slab stresses	In addition to what is listed above: • Construction health considerations to work in extreme heat (mid-day breaks, air-conditioned break areas, health monitoring, etc.)	• Increased efforts to maintain (seal/clean) concrete joints • Include concrete expansion joints in existing pavement if blow-ups become a recurring problem
	Warmer extreme minimum temperature	• Shallower frost depth • Reduced risk of frost heave • Warmer minimum pavement temperature	• Adjust low-temperature asphalt binder grade	• Accommodate warmer minimum temperatures and reduced frost depth in structural design	*	*
	More freeze-thaw events in some locations	• Increased thermal cycling • Increased need for deicing	• Asphalt binders that are more resistant to thermal cracking • Concrete materials more resistant to freeze-thaw cycling and chemical deicers	• Concrete joint design that ensures activation allowing drainage and keeping concrete below critical saturation	*	• Changes in frequency and occurrence of spring thaw load restrictions where they exist

* No available information.

Table 2. Climate stressors related to specific pavement impacts and potential adaptation strategies (continued).

Category	Climate Stressor	Pavement Vulnerabilities	Materials Adaptations	Design Adaptations	Construction Adaptations	Operations Adaptations
Precipitation	Higher average precipitation	• Reduced pavement structural capacity of unbound sublayers, and subgrade • More construction delays due to precipitation events	• Reduce moisture susceptibility of unbound base/subgrade by modifying or using different materials	• Improved pavement drainage including elevated pavement structures • Incorporate moisture insensitive base/subbase materials in design	• More allotted construction times to accommodate precipitation events that may impact schedule	*
	Wetter winters and drier summers	• Increased potential for soil shrinkage and swelling • Increased concrete saturation during critical freezing cycles • More construction delays due to precipitation events	• Reduce swelling potential in susceptible soils through treatment, replacement • Improve freeze-thaw/chemical deicer resistance of concrete	• Incorporate soil modification/stabilization into design • Concrete joint design that ensures activation allowing drainage and keeping concrete below critical saturation	• More allotted construction times to accommodate more rain that may impact schedule	*
	Low summer humidity in places	• Increased evaporation rate during construction • Increased long-term concrete slab warping • Increased asphalt binder aging	• Reduce drying shrinkage of concrete mixes • Improve asphalt binder aging resistance using additives	• Consider concrete drying shrinkage in design, potentially reducing slab length or using thicker slabs	• Improve concrete curing practices	• Use asphalt pavement preservation techniques that reduce asphalt binder aging in the surface course (e.g., fog or chip seals)
	More extreme rainfall events	• Reduced surface friction • Surface drainage may be overwhelmed, therefore more flooding incidents • Sublayers may be more frequently saturated, reducing support • Reduced visibility (splash/spray, pavement markings) • Threats to embankment stability	• Maintain adequate skid resistance using materials properties (e.g., more skid resistant aggregates) or materials (e.g., open-graded friction course) • Reduce moisture susceptibility of unbound base/subbase • Improve moisture resistance in asphalt mixtures	• Design and maintain subdrainage • Improve surface drainage capacity • More erosion resistant embankment design • High friction pavement surfaces	*	• Maintain high friction pavement surfaces

* No available information.

Table 2. Climate stressors related to specific pavement impacts and potential adaptation strategies (continued).

Category	Climate Stressor	Pavement Vulnerabilities	Materials Adaptations	Design Adaptations	Construction Adaptations	Operations Adaptations
Drought, Floods, and Wildfires	Decreased subgrade moisture	• Potential for soil shrinkage	• Reduce soil susceptibility to shrinkage	• Design to address soil shrinkage	• May require more over excavation	*
	Increased large forest fire incidences in western United States. and Canada	• Increased heavy vehicle use of low-volume pavements in affected areas	*	• Design pavement to anticipate heavy vehicle use during emergencies	• Rebuild damaged pavement	*
	Changes in classes of flood frequency	• Loss of structural support while inundated • Reduced pavement structural capacity of unbound sublayers, and subgrade that may remain saturated for long periods of time	• Reduce moisture susceptibility of unbound base/subgrade • Improve moisture resistance in asphalt mixtures	• Incorporate moisture insensitive base/subbase materials in design • Design and maintain subdrainage and improve surface drainage capacity • More erosion resistant embankment design	• Emergency repair procedures including evaluation, triage, and rapid contracting	• Nondestructive methods to determine pavement strength in inundated/flood condition • Restrict pavement loading (including closure) after inundation events.
Arctic Change	Changes in subgrade support for Alaska roads on permafrost	• Rapid loss of serviceability • Heaving and settling	*	• Substantially more robust design potentially involving piles or bridge-like structure	*	*
Sea Level Rise	Sea level rise and increased frequency and extent of flooding during coastal storms	• Loss of structural support while inundated • Reduced pavement structural capacity of unbound sublayers, and subgrade that may remain saturated for long periods of time	• Reduce moisture susceptibility of unbound base/subgrade • Improve moisture resistance in asphalt mixtures	• Incorporate moisture insensitive base/subbase materials in design • Design and maintain subdrainage and improve surface drainage capacity • More erosion resistant embankment design	• Emergency repair procedures including evaluation, triage, and rapid contracting	• Nondestructive methods to determine pavement strength in inundated/flood condition • Restrict pavement loading (including closure) after inundation events.

* No available information.

Willway et al. (2008a; 2008b) produced a similar list for climate stressors on pavements and mitigation efforts for the United Kingdom and concluded the three major impacts are temperature, precipitation, and soil moisture.

5 RESILIENCE

The United Nations (UN 2016) describes resilience as:

> The ability of a system, community or society exposed to hazards to resist, absorb, accommodate, adapt to, transform and recover from the effects of a hazard in a timely and efficient manner, including through the preservation and restoration of its essential basic structures and functions through risk management.

To focus more narrowly on the U.S. transportation system, FHWA defines resilience, with respect to a project, as:

> … a project with the ability to anticipate, prepare for, and or adapt to changing conditions and or withstand, respond to, and or recover rapidly from disruptions, including the ability: (A) to resist hazards or withstand impacts from weather events and natural disasters, or reduce the magnitude or duration of impacts of a disruptive weather event or natural disaster on a project; and (B) to have the absorptive capacity, adaptive capacity, and recoverability to decrease project vulnerability to weather events or other natural disasters.

23 U.S.C. § 101(a)(24). In 2014, FHWA Order 5520 specifically referred to *transportation system preparedness and resilience to climate change and extreme weather events*. Therefore, based on the definition in statute and FHWA Order 5520, for FHWA resilience is focused on: (1) transportation systems, (2) changing conditions including climate change impacts, (3) disruptions to transportation systems, (4) weather events, and (5) natural disasters. This report uses the FHWA Order 5520 definition and focuses on how pavement systems contribute to transportation system resilience.

5.1 RESILIENCE SCOPE

Disruptions and changing conditions addressed by FHWA in this report in the context of analyzing resilience are limited to natural hazards (i.e., extreme precipitation and temperature, and sea level rise) and their impacts (e.g., pavement rutting). Specifically, the following key resilience characteristics should be remembered:

- **Resilience addresses disaster risk reduction and adaptation to climate change impacts** (Arup 2014). While longer-term climate change impacts are considered, current action often focuses on extreme weather events (e.g., hurricanes, floods, droughts, heat waves), as well as other disaster events (e.g., earthquake, wildfire, tsunami).
- **Resilience is a system characteristic.** Resilience is an expression of how a system (e.g., pavement, road, network) plans for, responds to, and recovers from changing conditions and disruptions. This implies it is a composite measure and is not specific to a single hazard or condition. This also includes resilience as it is incorporated into the design of the individual assets.

- **Resilience should consider the effects on interacting systems**. Optimal resilience for one asset or system may have detrimental effects on others. Consideration of other assets and system components are important to include in analysis of resilience alternatives.
- **Resilience goes beyond traditional engineering qualities**. While strength, durability, and function are important, resilience also considers finance, leadership, security, community support, public health, and more (Arup 2014).
- **Resilience is not an absolute quality**. The resilience of an infrastructure asset can be described in relation to another or against a set of metrics. Decisions on tolerance for risk to an asset can guide adaptation measures and design to incorporate resilience into assets or systems.
- **Resilience strategies are used in risk management**. The actions associated with resilience align closely with traditional risk management actions: risk reduction, transfer/share risks, improving preparation, and responding and recovering effectively (Mitchell and Harris 2012).

5.2 RESILIENCE IN RELATION TO SUSTAINABILITY

Climate change and extreme weather events present significant and growing risks to the safety, reliability, effectiveness, and sustainability of the Nation's transportation infrastructure and operations. It is FHWA's policy to strive to identify the risks of climate change and extreme weather events to current and planned transportation systems.

Programs and activities that facilitate appropriate consideration of environmental, economic, and social values support the triple bottom line of sustainability. The FHWA describes sustainability as considering three primary values or principles: social, environmental, and economic (FHWA 2022b). The goal of sustainability is the satisfaction of basic social and economic needs, both present and future, and the responsible use of natural resources, all while maintaining or improving the well-being of the environment on which life depends. For FHWA, a sustainable highway project satisfies basic social and economic needs, makes responsible use of natural resources, and maintains or improves the well-being of the environment.

Because sustainability is so broad and encompasses the needs of the present without compromising the needs of the future, resilient practices can contribute to sustainability. The Sustainable Pavement Program includes assessment methods and metrics for each aspect of sustainability. Life Cycle Assessment (LCA), Life Cycle Cost Analysis (LCCA), Life Cycle Planning (LCP), Sustainability Rating Systems (SRS), and Social LCA (SLCA) are all examples of sustainable pavement assessment methods.

Another approach to pavement resilience and risk reduction includes natural and nature-based features in addition to structural and non-structural measures adjacent to vulnerable pavement. These are not necessarily solutions for the pavement itself but can provide protection where vulnerable assets are threatened by climate stressors. Nature-based features mimic characteristics of natural features and processes but are created by human design and engineering. Examples include dunes, wetlands, maritime forests, beaches, and reefs. These features can protect coastal highways from the brunt of storm surges and waves. Some can adapt to sea level rise by accreting sediment or migrating inland. They can also provide benefits such as recreation opportunities, habitat needed for commercial fisheries, and a healthier environment. These sustainable practices are examples of approaches that contribute to resilience.

Related to the concept of natural and nature-based solutions, Section 11103 of the Bipartisan Infrastructure Law (BIL), enacted as the Infrastructure Investment and Jobs Act, Pub. L. 117-58 (Nov. 15, 2021), added a definition of natural infrastructure under Section 101 of Title 23 of U.S. Code as follows:

> The term "natural infrastructure" means infrastructure that uses, restores, or emulates natural ecological processes and —
> (A) is created through the action of natural physical, geological, biological, and chemical processes over time;
> (B) is created by human design, engineering, and construction to emulate or act in concert with natural processes; or
> (C) involves the use of plants, soils, and other natural features, including through the creation, restoration, or preservation of vegetated areas using materials appropriate to the region to manage stormwater and runoff, to attenuate flooding and storm surges, and for other related purposes.

Executive Order 13690 "Establishing a Federal Flood Risk Management Standard and a Process for Further Soliciting and Considering Stakeholder Input" also promotes such NBS and natural infrastructure by requiring agencies, where possible, to use natural systems, ecosystem processes, and nature-based approaches when developing alternatives for consideration.'' (80 FR 13690 (Jan. 30, 2015), revoked by EO 13807 (Aug. 15, 2017), but reinstated by EO 14030 (May 20, 2021)). NBS and natural infrastructure are important to consider as FHWA and others seek to ensure the transportation network is resilient in the face of the risk associated with climate change.

5.3 RESILIENCE IN DESIGN

Selecting an appropriate design approach for climate change stressor impacts can address resilience aspects. Traditionally, engineering design parameters are selected to ensure infrastructure function given a certain threshold for risk within the historic spectrum of environmental stressors; for instance, the flood level associated with a 100-year storm recurrence. However, given the expected significant changes in climate forces over the next century (IPCP 2014a; USGCRP 2018), the use of historic climatic data to predict future events, their severity, or their recurrence interval may not ensure the anticipated life of the asset.

5.4 RECENT FEDERAL POLICIES ON TRANSPORTATION INFRASTRUCTURE RESILIENCE

Requirements to address resilience can be found in several directives associated with transportation infrastructure.

- **Statutory Definition of "Resilience" at 23 U.S.C. § 101(a)(24)**. Section 11103 of the Bipartisan Infrastructure Law, enacted as the Infrastructure Investment and Jobs Act, Pub. L. 117-58 (Nov. 15, 2021), added a definition of "resilience," which applies throughout Title 23 of the U.S. Code. With respect to a project, "resilience" means a project with the ability to anticipate, prepare for, and or adapt to changing conditions and or withstand, respond to, and or recover rapidly from disruptions, including the ability: (A) to resist hazards or withstand impacts from weather events and natural disasters, or reduce the magnitude or duration of impacts of a disruptive weather event or natural disaster on a project; and (B) to have the absorptive capacity, adaptive capacity, and recoverability to decrease project vulnerability to weather events or other natural disasters. 23 U.S.C. § 101(a)(24).

- **23 CFR 515: Asset Management Plans (FHWA 2016a)**. Requires development of a risk-based Transportation Asset Management Plan (TAMP) to include minimum standards for developing and operating highway bridge and pavement management systems. The TAMP must describe how roadways will be managed to meet system performance effectiveness and targets for asset condition. Assets must be managed to consider risks, in a financially responsible manner, and at a minimum practicable cost over the life cycle of the asset. The TAMP requires conducting life-cycle planning and risk analysis that includes, among other things, information on future environmental conditions including extreme weather and climate change.[1]

  In addition, BIL Section 11105 amended 23 U.S.C. Section 119(e)(4) to require State DOTs to consider extreme weather and resilience as part of the life-cycle planning and risk management analyses within a TAMP.

- **23 CFR Part 667: Periodic Evaluation of Facilities Repeatedly Requiring Repair and Reconstruction Due to Emergency Events (FHWA 2016b)**. A FHWA regulation requiring State DOTs to periodically evaluate transportation facilities (roads, highways, bridges) that have involved repair and reconstruction activities on two or more occasions due to emergency events and consider these evaluations when developing projects.

- **FHWA Order 5520: Transportation System Preparedness and Resilience to Climate Change and Extreme Weather Events (FHWA 2014)**. This order established FHWA policy on preparedness and resilience to climate change and extreme weather events.

5.5 RESILIENCE APPROACH

5.5.1 General Approach to Transportation Resilience

Climate change literature contains much information about planning for, executing, and integrating resilience into organizations, functions, or topics. For instance, FHWA's *Vulnerability Assessment and Adaptation Framework* (FHWA 2017) provides information on how to conduct vulnerability assessments and develop adaptation options. And, at the project level, FHWA's *Synthesis of Approaches for Addressing Resilience in Project Development* (FHWA 2017a) provides specific examples on how to incorporate resilience into the project development process through what it calls an "engineering-informed adaptation study." As shown in Figure 2, this approach includes five key steps:

1. **Understand site context and future climate**. Determine how climate stressors may impact a given location and transportation asset and determine what future climate scenarios will be addressed.
2. **Test the project asset(s) against future climate scenarios**. Determine how the assets perform under the selected climate scenarios. This determines if/how the asset(s) are impacted.

[1] See FHWA 2022, "FHWA State Asset Management Plan Under BIL," May 5, 2022, Federal Highway Administration, Washington, DC.

3. **Develop, evaluate, and select adaptation measures**. If a project asset is impacted by climate stressors, identify and develop plausible adaptation strategies. These may involve the asset in question or may include broader resilience efforts that may change or eliminate the need for asset-specific solutions.
4. **Review additional considerations**. Consider how the asset(s) interact with the broader transportation network, socioeconomic situation, and surrounding environment. These interactions may influence selected adaptation measures.
5. **Monitor and revisit as needed**. Determine if the adaptation actions improve resilience and adjust as needed.

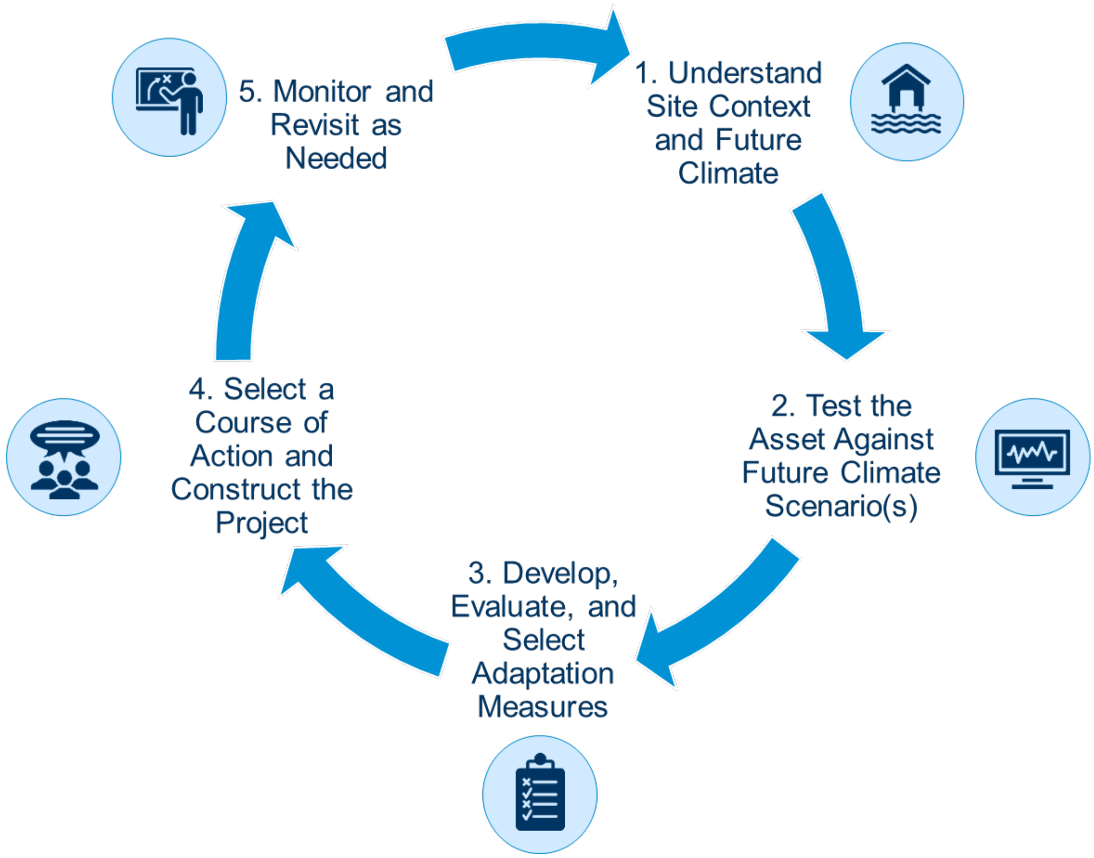


Figure 2. Key elements of an engineering-informed adaptation study. (FHWA 2017a as updated)

5.5.2 Pavement-Specific Approach

Applying this approach specifically to pavements provides the following:

1. **Understand site context and future climate**.
   a. Determine which assets are included and how they are valued. For this report, addressed assets are limited to pavement structures, including all supporting pavement layers down to but not including the untreated subgrade. Pavement performance is typically established by function and context that, in turn, determines acceptable damage, recovery time, and recovery methods. For instance, those pavements on identified critical links (e.g., those that provide sole access to an area, or on evacuation routes) may have a higher value placed on their serviceability. Many

transportation organizations have begun classifying assets according to climate risk, but there have been limited efforts to prioritize pavements specifically.

b. Identify climate stressors that affect pavement, especially those that are expected to change significantly in type or magnitude. Current climate conditions should already be accounted for in pavement design, construction, operations, and maintenance. Therefore, it is important to highlight how conditions may change in the future to those that may not be accounted for in current design, construction, operations, and maintenance. Table 2 provides examples of the climate impacts that could be considered.

c. Obtain asset data. Pavement asset data are typically available at the DOT level via pavement (or asset) management systems. Including vulnerability-specific data fields (e.g., future flooding) in these data sources may help identify vulnerable assets.

d. Obtain climate data. Find key projections of future climate conditions from predictive models that have been scaled down to the local level for use as inputs to models, design standards, or materials specifications. Determining appropriate climate data sets and how to downscale them to a local level is still an active area of research and may vary by location. Many States and DOTs have adopted climate change projections that can be utilized for determining impacts to pavements. The *CMIP Climate Data Processing Tool* (FHWA 2021) can be used to access and process readily available downscaled climate projection data at the local level.

2. **Test the project pavement(s) against future climate scenarios**.

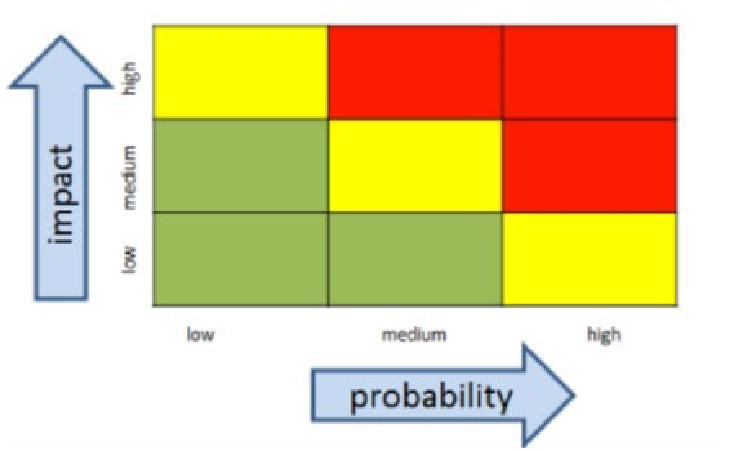
   a. Determine which pavements are exposed (climate stressors may vary by location), how sensitive they are (each asset has individual physical conditions due to factors such as material and age), and what their adaptive capacity is (ability of the network to accommodate potential impacts). Collectively, exposure, sensitivity, and adaptive capacity determine vulnerability. Individual research efforts have done this for specific pavements, geographic areas, or hazards. Approaches to determine pavement vulnerability and risk can vary:

      i. Stakeholder input. Use the institutional knowledge of stakeholders to identify and rate potential vulnerabilities (qualitative approach to vulnerability).

      ii. Indicator-based. Use data on pavements (e.g., elevation, location, age, distance from the shoreline, maintenance staff knowledge) as indicators for computing a relative score to determine potential vulnerability across a large area or number of assets.

      iii. Engineering-informed assessments. Use detailed engineering assessments to evaluate vulnerability and risk following the procedures outlined by FHWA (FHWA 2017a).

   b. Estimate the risk to each asset. This includes identifying the probability (likelihood) and cost (impact/consequence) of predicted impacts, see Figure 3.



http://longtailrisk.com/2013/04/01/creating-simple-information-risk-management-heat-maps/

Figure 3. Risk Heat Map

3. **Develop, evaluate, and select adaptation measures**.
    a. Consider possible solutions and investigate a wide range of actions. Include alternatives that involve different budgets (high down to zero) and even partial or phased solutions. Research to date generally assumes a few solutions (e.g., increase pavement thickness, change PG grade, reduce joint spacing) and then calculates the impact of those solutions. Additional research on alternatives and actions to resolve impacts in saturated coastal locations or to evaluate, prioritize, and restore pavements to service after damage could be beneficial.
    b. See what others have done. Some communities have documented their strategies for adaptation (for example, Miami-Dade County [2021] has developed a strategy to address sea level rise), and these can be valuable resources for agencies or communities just getting started with their resilience program. State DOT Planning Offices or other State agencies may have climate projection data that is useful for determining impacts to pavement. Because this is an emerging topic, information will often be shared through peer exchanges and conference presentations and papers.
    c. Analyze using appropriate methods. Analysis of risk reduction (across a range of qualitative and quantitative criteria) and economics (e.g., benefit-cost analysis) can be done. Evaluation of pavement design procedure outputs that are determined by using future climate inputs could more accurately project future asset needs.
    d. Prioritize. Evaluate the value of possible actions under future climate scenarios. Account for the context identified in Step 1. Determine whether actions can reduce risks and what trade-offs may be necessary in light of limited resources.
    e. Implement the prioritized solutions. Implementation can range from planning and project selection to specific engineering alternatives for pavements. For instance, a critical evacuation route increasingly subject to flooding may warrant a thicker pavement design to support traffic levels and better maintain structural integrity for use during flood events.

4. Review additional considerations. Consider how a pavement and its function contribute to the broader transportation network, as well as socioeconomic and environmental considerations.
5. Monitor and revisit as needed. Monitoring can be built into asset management. For instance, a pavement management system could be expanded to (1) include climate change vulnerability information such as time and duration of flood events, and (2) aggregate and analyze condition data to better detect long-term changes. As flood events can increase asset's deterioration rates, this information could provide better projections for future maintenance needs.

6 SPECIFIC RESEARCH ON PAVEMENT RESILIENCE

This section summarizes research on pavement resilience. Pavement-specific research summarized in this section includes (1) assessing pavement vulnerabilities to climate change (item 2 in the resilience approach of Section 5.5.2), and (2) considering possible solutions (item 3.a in the resilience approach of Section 5.5.2), with most work a combination of the two.

6.1 PAVEMENT VULNERABILITIES

This section broadly characterizes work on pavement vulnerability. Vulnerability assessments for temperature increases and flooding are the most commonly studied climate stressors.

6.1.1 General Transportation Infrastructure Vulnerability Assessment

Many State DOTs have conducted vulnerability assessments (e.g., Anderson et al. 2015; Childress et al. 2015; FHWA 2015b; Abkowitz et al. 2016; Blandford et al. 2018; Caltrans 2018a; FHWA 2022) and have covered a variety of topics. Most State DOT efforts are network-level studies, use specific local data (including local climate data) as much as possible, and involve a wide range of stakeholders. Some studies used projected climate conditions to assess vulnerability, while others used a more qualitative historical approach (e.g., local transportation officials were asked to identify areas that had historically experienced flooding or landslides, for which changing climate conditions could worsen). Of note, the Gulf Coast Study (FHWA 2015b) developed an indicator-based tool for scoring and ranking multiple assets called the Vulnerability Assessment Scoring Tool (VAST). This is a spreadsheet-based tool designed to help agencies perform a quantitative vulnerability assessment covering multiple asset types and climate risk factors, including pavements. A few additional vulnerability studies focused on pavements in the pilot program for Asset Management, Extreme Weather and Proxy Indicators (FHWA 2022, Figure 4).

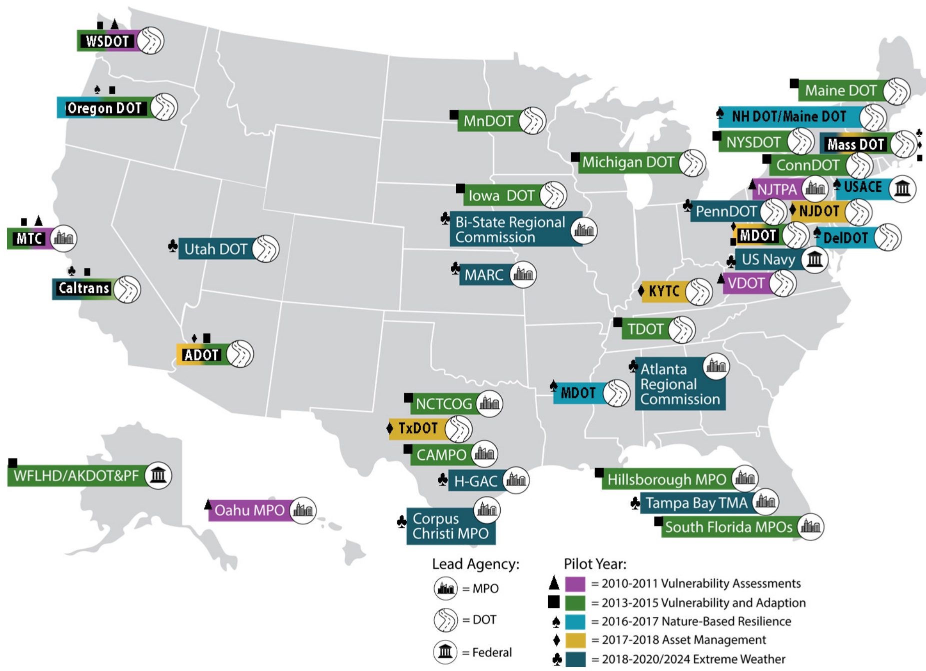


Figure 4. FHWA Climate Resilience Pilot Studies

6.1.2 Temperature Increase

Several studies (e.g., FHWA 2016c; FHWA 2016d; Underwood et al. 2017; Sharma et al. 2018; Knott et al. 2019; Stoner et al. 2019) have examined the impact of temperature changes (either annual averages or extremes) on pavement performance. Most analyses are done by modeling future climate change projections in mechanistic design software and then interpreting output for specific routes or networks. General conclusions are that, without any action, increasing temperatures lead to more damage, shorter pavement surface life, and additional pavement life-cycle costs. It appears that some basic actions can be used to mitigate the largest concerns (e.g., periodically choosing higher PG binder grades for overlays), but this conclusion is not present in all studies.

6.1.3 Flooding Impacts

Pavement response to flooding seems to be a high-interest area in research. Studies (e.g., Helali et al. 2008; Zhang et al. 2008; Sultana et al. 2014; Lu et al. 2017; Mallick et al. 2017) tend to find that flooding saturates pavement sublayers rather quickly, weakening pavement structural components that are susceptible to increases in moisture content. Hence, making pavement more susceptible to damage during and shortly after the flood event. Some studies (e.g., Khan et al. 2017; Oyediji et al. 2019) conclude that stronger pavements (i.e., generally thicker structures) are more resistant to flooding instances.

6.1.4 Wildfires

Wildfires are another climate stressor impacting pavement with much still unknown or undocumented on the topic. One of the most noted impacts, for rural local roads, is that the significant increase in weight loads due to truck traffic to fight the fires themselves and for recovery (e.g., debris removal) that could potentially reduce pavement life. Also, wildfires could create landscapes vulnerable to high runoff and erosion from subsequent rainfall due to a lack of vegetation, increased debris, and changes to soil permeability.

Some work has been done considering the fire risks of asphalt pavements in tunnels (Schartel et al. 2010). Generally, this work shows that asphalt pavements can burn in extreme fire scenarios, but common asphalt types can be considered "intrinsically flame-resistant materials." However, polymer-modified asphalt shows a "pronouncedly greater fire risk." On a limited basis, some work has been done to address flame-retardant asphalt pavement by adding aluminum trihydrate (ATH) to the mixture (Hu et al. 2008).

6.2 POSSIBLE SOLUTIONS

Recent research has investigated possible solutions to pavement impacts due to climate change stressors.

6.2.1 Performance Monitoring

The FHWA Tech Brief *Climate Change Adaptation for Pavements* (FHWA 2015a) suggests pavement performance monitoring can contribute to pavement resilience. While a significant amount of climate change can occur over the next 50 to 100 years, the annual change in climate is generally small. Therefore, it is important to consider the life-cycle of the pavement and possible future conditions when considering materials and design to address long-term changes in climate. Determining when they are needed involves monitoring key pavement performance indicators (see Table 3) over time and applying corrections in design, construction, and maintenance when warranted. There may be merit to tracking these indicators year-to-year and to monitoring overall trends. This may be challenging with current capabilities in current pavement management systems.

Table 3. Pavement performance indicators affected by climate (FHWA 2015a).

Asphalt Pavement Indicators	Concrete Pavement Indicators
Rutting of asphalt surface	Blow-ups (for jointed plain concrete pavement)
Low temperature (transverse) cracking	Slab cracking
Block cracking	Punch-outs (for continuously reinforced concrete pavement)
Raveling	Joint spalling
Fatigue cracking and potholes	Freeze-thaw durability
Rutting of subgrade and unbound base	Faulting, pumping, and corner breaks
Stripping	-

6.2.2 Pavement Design

Currently, all pavement design procedures and design assistance tools/methods (e.g., frost depth determination) that depend on environmental inputs base those inputs on historical climate data. Given the impacts of climate change, these data may not be accurate predictors of future environmental conditions (USGCRP 2018). This has created an active area of research into how pavement designs might change if predictive climatic model data are used instead of historical climatic data (e.g., Li et al. 2011; Knott et al. 2017). In general, these models predict generally higher temperatures and sometimes more moisture, which (when used with a pavement design methodology) typically results in accelerated pavement damage and a shorter pavement life. Much of the literature overviewed in Section 6.1.2 rely on such efforts. What follows are research examples using pavement design software with normal historical climate data replaced by model-based predictive climate data.

6.2.3 Pavement Materials

It may be possible to modify the materials used to construct pavements to improve overall pavement resilience. In general, the literature is limited to smaller local studies and sometimes concludes that a change in PG binder grade is necessary for asphalt pavements to address a warmer climate in the future (e.g., Sharma et al. 2018; Caltrans 2018a). Some studies (e.g., Underwood et al. 2017) quantify the potential economic impacts if no action is taken.

6.2.4 Recovery Activities

Emergency repairs include how quickly and to what degree service can be restored once a pavement asset is damaged. Emergency repair methods appropriate for the rapid restoration of pavements are reviewed in this section.

7 PEER EXCHANGE FINDINGS

The FHWA conducted two virtual peer exchanges on the topic of pavement resilience, the first on October 7–8, 2020 and the second on December 16–17, 2020. Each was a 2-day event with 3-4 hours of online content per day. The objective of these peer exchanges was to identify strategies and barriers for designing, constructing, and maintaining more resilient pavement systems. Technical presentations, surveys, and breakout sessions were used to elicit responses from the participants. In total, 92 individuals participated in the two peer exchanges, representing Federal, State, and local transportation agencies, associations and institutes, academic institutions, suppliers, and consultants.

This section summarizes the findings from these events without analysis. The results do not constitute FHWA policy or transportation agency guidance; rather, they provide information on what organizations around the country are thinking and doing regarding pavement resilience. The FHWA may or may not take the information into account in formulating policies.

7.1 EVENT HIGHLIGHTS

The peer exchange explored three broad topics: issue identification, role of pavements, and gaps and needs. Breakout sessions with self-reporting and polling were used to capture participant thoughts, which are summarized in the next sections.

7.1.1 Top Issues Identified

In both peer exchanges, the top issue identified by attendees was climate change related pavement inundation because of:

- Tidal flooding resulting from sea level rise.
- Flooding due to higher intensity coastal storm events/storm surge coupled with sea level rise.
- Riverine flooding due to higher intensity inland storm events.
- Riverine flooding many miles inland from the coast due to the damming effects of higher sea levels due to sea level rise and storm surge from coastal storms.

Other specific issues related to pavement inundation that were identified include:

- Uncertainty as to when a pavement can be reopened to traffic following an inundation event to avoid further damage or shortening pavement life.
- Incorporating flooding concerns and future climate conditions in pavement design.
- Increases in extreme storm event intensity and frequency that can result in significant damage beyond inundation including erosion, washout, and scour. Repeated occurrence of such events at the same location was also a concern.

Non-flooding related pavement issues that were identified include:

- Impact of increasing temperatures on pavement condition due to materials and design.
- Vulnerability assessment and risk analysis and prioritization approaches to identify pavements in need of improved resilience.
- Strategies to rapidly respond to an extreme event to maintain or restore pavement operations.

7.1.2 Gaps and Research Needs

The top gaps and research needs identified include:

- Need for models to account for vulnerability and address predicted impacts of climate change in design.
- Need for improved design options of base and subbase layers to increase structural integrity, especially in areas subject to inundation.
- Incorporation of pavement vulnerability to climate change in asset management systems.
- Rapid evaluation/assessment criteria for pavement potentially damaged by extreme events.
- Guidance on improving resiliency of existing pavements.

Other gaps and research needs identified include:

- Tools to communicate to upper management and the public the importance of pavement resilience.
- Incorporation of project specific future climatic data into design methodology (i.e., Pavement ME).
- National effort that makes pavement resilience a priority.

7.2 SUMMARY OF AGENCY PRACTICES

Based on the peer exchange breakout sessions reports, the major concerns regarding pavement resilience were primarily related to inundation due to flooding and/or groundwater rise and, to a far lesser degree, temperature change. These are discussed below, along with design concerns and some other issues that were raised in the meetings. The comments were made by individuals from agencies and organizations around the country and do not necessarily represent the views or policies of their agencies.

7.2.1 Concerns Related to Inundation

The participants indicated that flooding is becoming more frequent, resulting in increased occurrences of pavement inundation. Flooding was divided into two categories: coastal flooding and riverine flooding. Coastal flooding due to sea level rise tends to be slow moving and non-turbulent, leading to negative impacts on pavement layers from frequent daily high-tide flooding or nuisance flooding to long-term inundation. Nuisance flooding, also referred to as "sunny day flooding," is caused by an increase in sea level so that high-tide and high winds bring water inland to flood coastal areas that historically did not flood unless there was a storm event. If coastal flooding is coupled with a major coastal storm event/storm surge, this flooding can result in high velocity, turbulent flow, leading to immediate erosion and washouts and destruction of pavement and other infrastructure.

Several coastal States have also experienced such an increase in saturated soils that roads are sinking while sea level rises. While there is not a particular design or material solution for this issue, frequent overlay is commonly used to maintain service in these locations.

Inland riverine flooding is most often associated with a major storm event. At or immediately downstream of the event, the flow velocity is high and turbulent, resulting in erosion and washouts in addition to inundation. Further downstream, the flooding may be similar to coastal flooding due to sea level rise, being generally low velocity and non-turbulent.

Riverine flooding can also occur because of sea level rise, which compounds effects of high tide by creating even higher tide ranges than historically recorded. Under these conditions, the high tide acts as a "dam" that can causes flooding many miles upstream resulting in reoccurring pavement inundation.

Some agencies are beginning to track flood data to identify locations where pavements are being adversely impacted by reoccurring flooding, inundation, and rising groundwater tables.

7.2.2 Concerns Related to Increasing Temperatures

Increasing temperatures appeared to be of less concern than flooding and inundation. Some agencies mentioned that they are considering increasing the asphalt binder grade, especially if significant warming occurs or if rutting begins to impact performance. For concrete pavements, blow-ups were considered a risk, especially for older pavements that may not have been adequately maintained.

7.2.3 Concerns with Design

Various comments made during the peer exchange focused on limitations that exist within the current pavement design methodologies. These concerns fell into two broad categories: the inability of current design methodologies to adequately consider the impact of pavement inundation and the inability of pavement performance models to incorporate future climate conditions rather than projecting historical climatic data into the future.

It was noted that pavement design does not take inundation and loss of support into account and agencies are being reactive instead of proactive towards potential risks. A designer can increase reliability to make pavements more resilient, but this does not necessarily address inundation. It was further noted that the Pavement-ME climate models are based on historical data and future sea level rise and extreme weather events are not accounted for in the model.

A non-coastal southwestern State felt that its big issue is elevated temperatures. Incorporating pavement resilience concepts for extreme heat into what they are already doing to address resilience could be easily incorporated into the design process.

7.2.4 Other Concerns

There were several other concerns raised through the peer exchanges that could not easily be categorized as related to flooding/inundation or temperature. One concern was drought impacting the structural integrity of pavement due to high shrinkage and swelling of subgrade soils. One agency observed during a recent drought that the soils shrank and fissured to the extent of creating deep and wide longitudinal cracks in pavements. When rains returned, soil swelling could be extensive.

Another concern was that an increase in the number of freeze-thaw cycles in areas that normally receive a hard freeze may increase damage to the pavement. Related to this are fluctuations in the date to apply spring load restrictions and winter load premiums when the pavements are frozen as few tools are available to identify the timings.

Rockfalls were an issue in mountainous areas made worse by loss of trees due to droughts and bark beetles, which has contributed to wildfires and debris flows. Wildfires have impacted pavements in several ways including directing heavy traffic onto low-volume road detour routes and additional heavy loads caused by firefighting equipment and post-fire truck traffic for debris removal and reconstruction.

The impact of permafrost thawing in Alaska resulted in roadway embankment and pavement failures.

7.3 PEER EXCHANGE RESILIENCE TECHNIQUES

This section summarizes the results of the peer exchange regarding strategies being used and considered to improve the resilience of pavements. These strategies are presented in the same order as the concerns previously discussed. Again, this feedback is representative of the thoughts and practices of the participants and may not reflect their agencies' official policies or procedures.

7.3.1 Resilience Techniques to Address Flooding and Inundation

It was the consensus of the peer exchange groups that, when possible, areas with high risk of inundation should be avoided during the construction of a new roadway or the reconstruction of an existing roadway. If alternative routes are unavailable, or the alignment of an existing roadway cannot be changed, the risk of inundation should be accommodated in the pavement section. This includes:

- Raising road elevation above projected flood waters (it was noted that this could cause damming and make flooding worse). In some instances, agencies have used causeways or bridges especially for evacuation routes.
- Armoring roadways to make them less susceptible to erosion when overtopping occurs. One agency has found that using non-erodible shoulders on routes subjected to inundation can help preserve travel lanes from erosion and scour.
- Using stabilized subgrade and base materials in areas prone to inundation to increase resilience. This is a strategy being employed by several States.

- Using thicker and/or stiffer pavement surfaces that will increase resilience in areas prone to inundation, including the use of rigid pavements or HiMA (highly modified asphalt) to help with load distribution if supporting layers are saturated. It was commented that concrete-surfaced pavements and pavements with bound layers tend to perform better, particularly in terms of flooding washout and inundation, and can also be returned to service much sooner, if not damaged. It was suggested that concrete overlays of HMA in areas subject to inundation could be considered to further help distribute or reduce stresses on subgrade/base materials.
- Using more robust drainage to facilitate the removal of water from flooded pavements once water recedes. This includes incorporation of drainage in new design, including the use of geosynthetics. Some felt that the use of permeable pavements would reduce flooding impacts
- Minimizing pavement damage through the application of established protocols to assess when flooded pavements can be reopened to traffic. It was felt that a better understanding of the length of time that a pavement's structural integrity is compromised by inundation or rising groundwater table is needed to help make these decisions. One State has developed a protocol based on nondestructive testing to assess the structural capacity of the pavement during and after inundation and found that it can take weeks before full structural capacity is restored.

7.3.2 Resilience Techniques to Address Temperature Increase

The peer groups also reported on their efforts to address temperature increases. Some said that the use of premium materials (e.g., polymer-modified asphalt) may be useful at some locations and that pavements may be under-designed based on historic temperatures. Others have made or are considering changes to their asphalt binder grade and/or mix design primarily to address higher temperatures. One group also felt that nighttime work will likely increase because of the potential for elevated daytime temperatures that impact worker safety.

7.3.3 Resilience Techniques to Address Design Deficiencies

Most of the pavement design deficiencies noted previously focused on limitations within current design approaches and methods to address inundation and, to a lesser degree, increases in temperature. Some specific suggestions to address deficiencies in design include the development of tools to assist agencies in abating issues caused by inundation and saturated subgrades in the pavement design process. This included identifying more moisture-resistant base layers that would likely involve stabilization and increased permeability and considering the use of thicker pavement sections to mitigate structural failures that occur due to reduced support from saturated base/subgrades. It was felt that tracking flooding data to identify vulnerable locations where pavements are being adversely impacted by inundation and rising groundwater tables would be helpful.

8 OVERALL FINDINGS

8.1 CLIMATE STRESSORS

Information from the literature (e.g., IPCC 2014; USGRCP 2017) suggests that the climate is changing and will be different in this century compared to the last. Key differences predicted by climate models with medium or greater confidence are:

- Temperature change.
  - General increase in temperature.
  - Higher extreme temperatures.
- Precipitation change.
  - Changes in annual precipitation will vary across the United States.
  - More frequent and intense heavy precipitation events.
  - Changes in snow patterns.
- Droughts, and wildfires.
  - Possible increasing chronic, long-duration droughts.
  - Increased large forest fire incidences in the western United States and Alaska.
- Extreme storms.
  - Increase in tropical cyclone intensity and frequency.
  - Tornado activity more variable.
  - Varied projections for winter storm frequency/intensity.
  - Increased inundation for both riverine and coastal areas.
- Arctic changes.
  - Permafrost in Alaska is thawing and becoming more discontinuous.
- Sea level rise.
  - Increased depth, frequency, and extent of tidal flooding that causes minor impacts.
  - Increased frequency and extent of flooding during coastal storms.
  - Increased inundation due to higher tides.

These climate stressors may have direct impacts on pavements. While these impacts have not been prioritized based on pavement impacts, the peer exchange participants identified pavement inundation resulting from sea level rise and increased intensity and frequency of extreme storm events as their top impact of concern. Other concerns in the peer exchanges were the impact of drought on shrinking soils, changes in the number of freeze-thaw cycles, increase in rockfalls and wildfires, increased temperatures, and melting permafrost contributing to pavement instability.

8.2 RESILIENCE KNOWLEDGE AND PRACTICE ASSESSMENT

The literature and two peer exchanges hosted by the FHWA show the state of knowledge and practice in pavement resilience. Key findings follow.

8.2.1 State of the Practice

- **DOT pavement resilience concerns are most commonly flooding (from coastal storm events, precipitation, and sea level rise) and, to a lesser extent, temperature rise (extreme heat events)**. While other concerns exist, these topics, especially flooding, dominated both peer exchanges. Other concerns identified include damage induced by droughts due to shrinking soils, loss of permafrost layers, increasing number of freeze-thaw cycles in areas the previously underwent a long hard freeze, and damage induced by increased truck volumes in response to fighting and recovering from wildfires.

- **Pavement resilience research is more concerned with pavement impacts rather than a debate over climate data sources**. While sources and models of appropriate climate data are not yet at consensus in climate research, pavement research concentrates on pavement impacts rather than which source or model to use to project climate impacts. A consensus decision on appropriate data sources could be useful in moving research forward.
- **Pavement resilience research has focused mostly, but not exclusively, on assessing vulnerabilities (step 2 project approach) and possible solutions (step 3)**. There is substantial emphasis in the literature and during the peer exchanges on the pavement vulnerabilities associated with a general increase in temperature and roadway inundation (flooding from storm events or sea level rise).
- **There is general consensus on pavement vulnerability to climate stressors**. Research tends to agree that pavement is vulnerable to the following:
  - *Temperature increases*. Without adaptation strategies, there will be significant loss in pavement life and added expense in the future. Much of this research focuses on the temperature-dependent properties of asphalt binders, and some work addresses concrete warping and thermal expansion.
  - *Flooding*. Flooding can damage pavement in different ways due to the increased flow and volume of water on the pavement. Inundation saturates pavement sublayers quickly, weakens pavement structural components that are susceptible to increases in moisture content, and makes them more susceptible to damage during and shortly after flood events. Inundation includes groundwater saturation which is an area in need of more study to understand impacts of the rising groundwater and solutions. Generally, thicker pavement structures survive flooding and inundation events with less damage.
- **There is general consensus on possible solutions in some areas**. Research tends to agree on the following pavement solutions:
  - *Pavement design*. Climate projections should replace some or all historic observed data used in pavement design modeling. Doing this may lead to selecting designs and materials that are different from those considered normal by today's standards.
  - *Robust materials*. Materials exist today that can be used to provide more resilient pavement structures, such as higher PG binder grades and/or additives for warmer temperatures and more moisture-resistant base materials for pavement structures at higher risk of inundation.
- **The two peer exchanges provide insight into seeing what others have done (step 3b)**. Participants discussed some adaptation options that have been tried but that are not widely applied, including: raising road elevations, stabilizing base layers, testing base layers for susceptibility to inundation, thicker/stiffer pavement surfaces, improved drainage, and protocols for deciding when to reopen flooded pavements.

8.2.2 Needs

Comparing the state-of-practice (Section 8.2.1) with the pavement-specific resilience approach (Section 5.5.2) yields a list of suggested needs or items in the pavement resilience approach not yet fully understood or implemented (see Table 4). In general, these needs agree with the "knowledge gaps" discussed in the FHWA report *Assessment of Key Gaps in the Integration of Climate Change Considerations into Transportation Engineering* (FHWA 2014). These needs are many and significant, largely a result of resilience being a new field of pavement engineering with initial efforts being limited and local. Broad categories of needs are:

- **Research**. Research can address needs for additional data on impacts of temperature, permafrost, inundation, and flooding. For example, research may be able to incorporate climate projections into pavement design, more precisely describe pavement responses to inundation, calculate risk based on vulnerabilities, and develop new designs processes/standards. While fundamental research is needed, some shortcuts can be found by applying existing knowledge within the climate change context. For instance, while pavement flooding is a new research area, the effects of moisture saturation on pavement systems are well known and may be accounted for in pavement design.
- **Tools and methods**. While some models may be modified to integrate future climate projections, additional tools and methods may be needed to better analyze pavement performance under future conditions. Utilizing better predictive tools to determine pavement performance could improve asset management and financial planning to maintain pavement in the future.
- **Consensus and information sharing**. As pavement resilience efforts advance, community consensus based on shared information is important because guidance tends to be based on it. Evidence from the peer exchanges suggest there are a few groups of concern that most States have (e.g., coastal States are concerned with sea level rise, all States are concerned with riverine flooding and temperature rise, northern States are concerned with frost depth and freeze-thaw). Information sharing and consensus in these groups is part of the most efficient path to better guidance.
- **Training**. While not directly listed in Table 4, most items would involve training.

Table 4. Pavement resilience needs related to resilience approach steps.

Step	Item	State of Practice	Needs
Understand site context and future climate	Determine which assets are included and how they are valued.	High-level (more general than pavements) assessments have been done by multiple DOTs. Some were early pilot efforts, others more recent and driven by policy.	Prioritization protocol for pavements. This may come from prioritization of transportation assets in general or may be done specifically for pavements.
	Identify climate stressors that affect pavement, especially those that are different in type of magnitude from the present.	Table 2 identifies climate variables. There is no national consensus yet.	National consensus or guidance from a national leader in transportation (US DOT, FHWA, AASHTO, etc.).
	Obtain asset data	Data are usually available in some form (e.g., pavement management system) but needed data can be from disparate sources or has not yet been aggregated.	Guidance on data to include beyond basic pavement management information.
	Gather appropriate climate projections data (Agency or State may have adopted projections)	Pavement research has used down-scaled climate projections, but there is no consensus or guidance on data requirements or quality.	Consensus or directed use of acceptable/practical downscaled climate data sets.
Test the project pavement(s) against future climate scenarios	Determine what assets are exposed, how sensitive they are, and what their adaptive capacity is.	High-level (more general than pavements) assessments have been done by multiple DOTs. Some were early pilot efforts, others more recent and driven by policy. In many cases determinations are by region and not a full asset-by-asset inventory. Research efforts and some agencies have assessed some vulnerabilities (e.g., flooding, temperature). However, not all vulnerabilities have been investigated (e.g., droughts, wildfires).	More specific inventories of assets and their exposure. Some DOTs are doing things like inventorying culverts and bridges, but there is no evidence of pavements inventoried at the same level of detail yet. Guidance on how to assess pavement vulnerability so organizations can be consistent with one another. Incorporate vulnerability into asset management systems as 23 CFR 515 requires. Update design software/processes to include predictive climate models and better treatment of inundated layers so that vulnerabilities can be identified in design.
	Estimate the risk to each asset	Some high-level work has been done (e.g., risks to transportation assets based on regional climate characteristics) and some asset risk has been quantified (e.g., bridges). No significant work on pavement networks noted.	Standard risk assessment method for pavements, including how composite risk relates to singular impact risk.

Table 4. Pavement resilience needs related to resilience approach steps (continued).

Step	Item	State of Practice	Needs
Develop, evaluate, and select adaptation measures	Consider possible solutions	Some solutions are explored in research (e.g., materials adjustments to adapt to rising temperatures).	Full inventory of possible solutions, perhaps regionally specific. Emergency repair guidelines. Monitor pavement assets for resilience metrics.
	See what others have done	A few meetings/workshops have explored this informally. Currently, many agencies are discovering impacts, but have not fully explored options.	After pavement resilience becomes more mature, meetings/workshops could better facilitate idea sharing. Currently, there are not many mature ideas to share.
	Analyze using appropriate methods	Isolated scenarios have been evaluated (e.g., some agencies have raised or closed roads specific roads).	Benefit/cost of possible solutions. Develop rapid evaluation/assessment criteria for pavement damage after an extreme event. Monitor pavement assets for resilience metrics.
	Prioritize	Research suggests analysis approaches and offers some prioritization, but no prioritization guidance is available to organizations.	Develop rapid evaluation/assessment criteria for pavement damage after an extreme event. Determine when/how resilience interventions can be made.
	Implement the prioritized solutions	Plans have been implemented in isolated situations for singular climate risks (e.g., raising street levels in Miami Beach).	None. Most organizations have not yet reached this step.
Review additional considerations	Review additional considerations	Consider how a pavement and its function contribute to the broader transportation network, as well as socioeconomic and environmental considerations.	Key factors to be considered for specific locations and environments.
Monitor and revisit as needed	Monitor and revisit	Most completed projects have been done rather recently and have not had enough time to be checked and improved.	Recommended monitoring procedures and frequencies.

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