TechBrief

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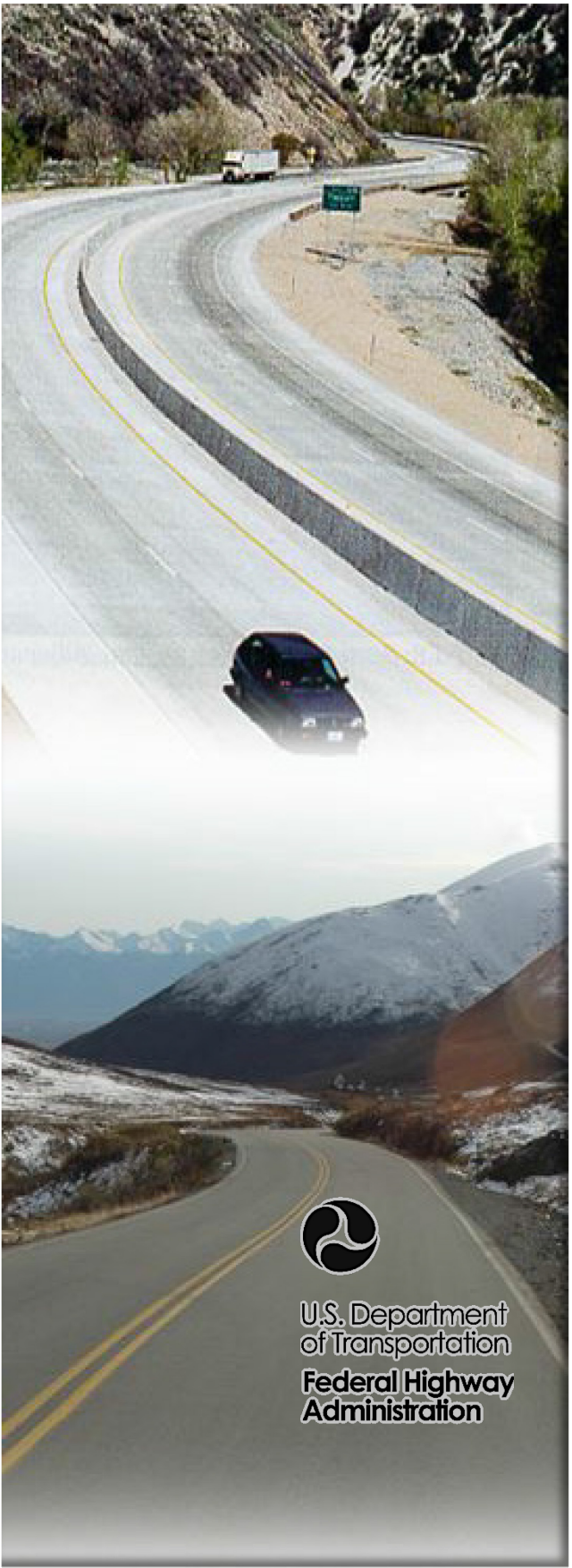
CLIMATE CHANGE ADAPTATION FOR PAVEMENTS



INTRODUCTION

Climate change can and is producing a wide array of impacts that affect infrastructure on a broad scale. An infrastructure asset's vulnerability to climate change is highly context sensitive, with its location and the adaptive capacity of local businesses, governments, and communities all being influential (EC 2013). Much has been written generally about climate change and its impacts on transportation systems, and literature is now emerging on how climate change specifically affects pavement systems and what adaptation strategies might be pursued. However, at the level of pavement systems, the state of the practice is largely limited to general observations and is lacking with regards to specific adaptation strategies. This Tech Brief provides an overview of climate change and pavement-specific impacts, and then addresses specific pavement adaptation strategies that can be implemented now and in the future.

Scope

This Tech Brief is specific to hard-surfaced pavement systems (i.e., asphalt and concrete pavement) including the wearing course and all underlying layers down to and including subgrade treatment. Importantly, this Tech Brief does not address climate change adaptation issues (for transportation systems or otherwise) that are beyond the scope of pavement systems, such as (1) relocation of vulnerable routes due to storm surges or sea level rise, (2) identification and treatment of vulnerable structures (e.g., bridges), and (3) fortification of pavement systems against extreme weather events where such fortification is essentially impractical (e.g., relocation or complete reconstruction is more cost-effective than fortification). This Tech Brief also does not address climate change vulnerability assessment processes, which are more thoroughly covered in other documents such as those by the FHWA (2012) and the European Commission (Acclimatise and COWI A/S 2012). While this Tech Brief focuses on pavements alone, a complete approach to climate change adaptation should consider all of these items in concert.

BACKGROUND

Climate Change Impacts

Changes in the global climate, and the understanding that human activities have been the dominant cause, is supported by a preponderance of historical observation and climate modeling both at a national and global scale (IPCC 2013). Current climate models generally project that the climate will continue to change and do so at an increasing rate over the next century or longer (IPCC 2013; IPCC 2014). While the magnitude and speed of projected future climate change is generally dependent upon human activities, even the most optimistic scenarios project substantial climate change over the next century or longer based on what has already occurred coupled with the relatively long life and slow feedback functions of emitted heat-trapping gases (commonly grouped together as "greenhouse gases," or GHG) that drive climate change (IPCC 2013; IPCC 2014).

There are many different future scenarios for climate change, most of which depend upon the future magnitude and trends in GHG emissions. NCHRP Report 750 (Meyer et al. 2014) draws upon several climate models and future emissions scenarios to identify three broad categories of climate change impacts and their relative magnitudes, as described below.

Temperature Impacts

- General increase in temperature. Most models project some increase in average air temperature from 2010 to 2050. Among the ten specific models reported in Meyer et al. (2014), this increase is around 4 °F (2.2 °C), which is twice the rate of the previous 50 years (see figure 1).
- Higher extreme temperatures. As average temperatures increase, an increase in the frequency and duration of extreme temperatures is also projected.
- Fewer freezing days. As temperatures rise there will be fewer days below freezing. Future changes in the number of freeze-thaw cycles is still unknown.

Precipitation Impacts

- Changes in average annual precipitation. Changes will occur with some regions seeing more precipitation while others will see less precipitation.
- Wetter winters and drier summers. Results vary by model and rainstorms caused by convection are poorly simulated (see figure 2).
- Increased precipitation intensity. Increases are expected to occur for the largest single-day rain events.
- Hurricanes. Perhaps fewer in number, but more powerful category 4 or 5 storms are expected.

Sea Level Impacts

- Sea-level rise. Levels are already rising (at an average rate of 0.06 to 0.08 inches/year [1.5 to 2.0 mm/year] for the 20th century, and at an increased rate of 0.12 inches/year [3 mm/year] since the early 1990s) and will continue to do so. Projections on the amount of sea-level rise vary, and are in the range of 0.8 to 6.5 ft (0.24 to 2 m) by 2100. The amount of rise can vary from location to location based on regional differences in ocean temperatures, salinity, currents, and subsidence or uplift of the coast.

Melillo, Richmond, and Yohe (2014) discuss these impacts in more detail on a region-by-region basis within the U.S. focusing on the Northeast, Southeast and Caribbean, Midwest, Great Plains, Northwest, Southwest, Alaska, and Hawai'i and U.S. Pacific Islands.

Impacts on Transportation Systems

Many organizations have begun to plan for climate change, the impacts it may have, and the necessary adaptations needed to minimize or mitigate those impacts. For example, AASHTO's Transportation and Climate Change Resource Center catalogs State-by-State efforts and publications. At the highest level, most U.S. government and scientific organizations are in general agreement on the nature of climate change impacts and are beginning to explore how to adapt current practice to account for these impacts.

Melillo, Richmond, and Yohe (2014) describe a wide range of impacts by category and U.S. region. These impacts are many and include, among others, intensified droughts, 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 (Melillo, Richmond, and Yohe 2014). For the transportation sector in particular, Melillo, Richmond, and Yohe (2014) provide the following key points on climate change impacts:

- The impacts from sea level rise and storm surge, extreme weather events, higher temperatures and heat waves, precipitation changes, Arctic warming, and other climatic conditions are affecting the reliability and capacity of the U.S. transportation system.
- Sea level rise, coupled with storm surge, will continue to increase the risk of major coastal impacts on transportation infrastructure, including both temporary and permanent flooding of airports, ports and harbors, roads, rail lines, tunnels, and bridges.
- Extreme weather events currently disrupt transportation networks in all areas of the country; projections indicate that such disruptions will increase.

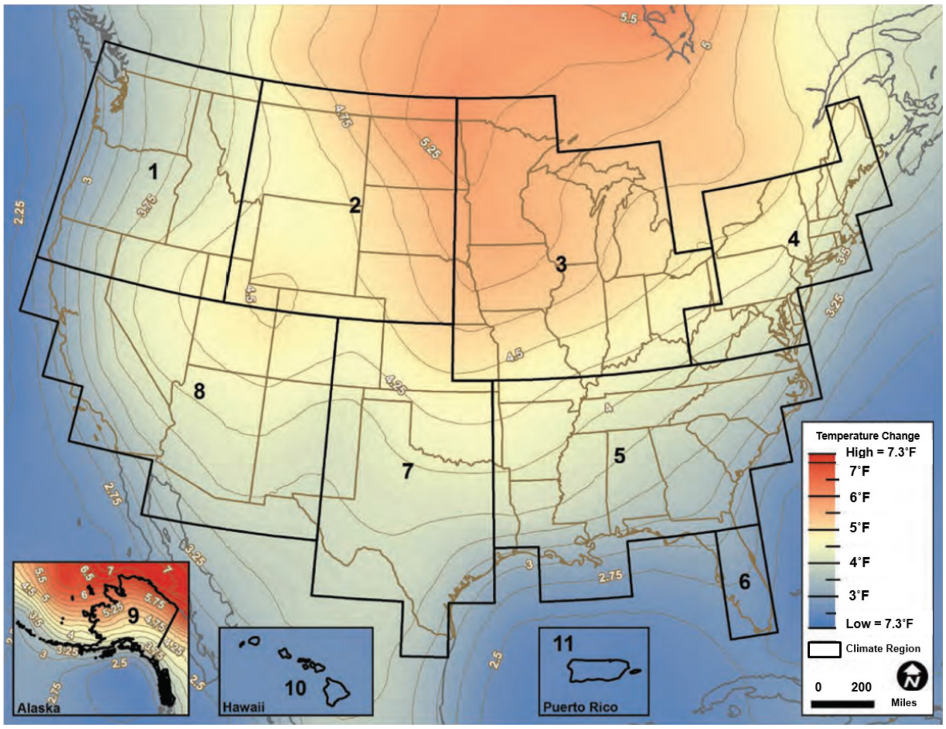


Figure 1. Estimated increases in temperature (°F) in 2050 relative to 2010 (Meyer et al. 2014). The black numbers identify the 11 broad climate regions as represented in the MAGICC/SCENGEN coupled software suites.*

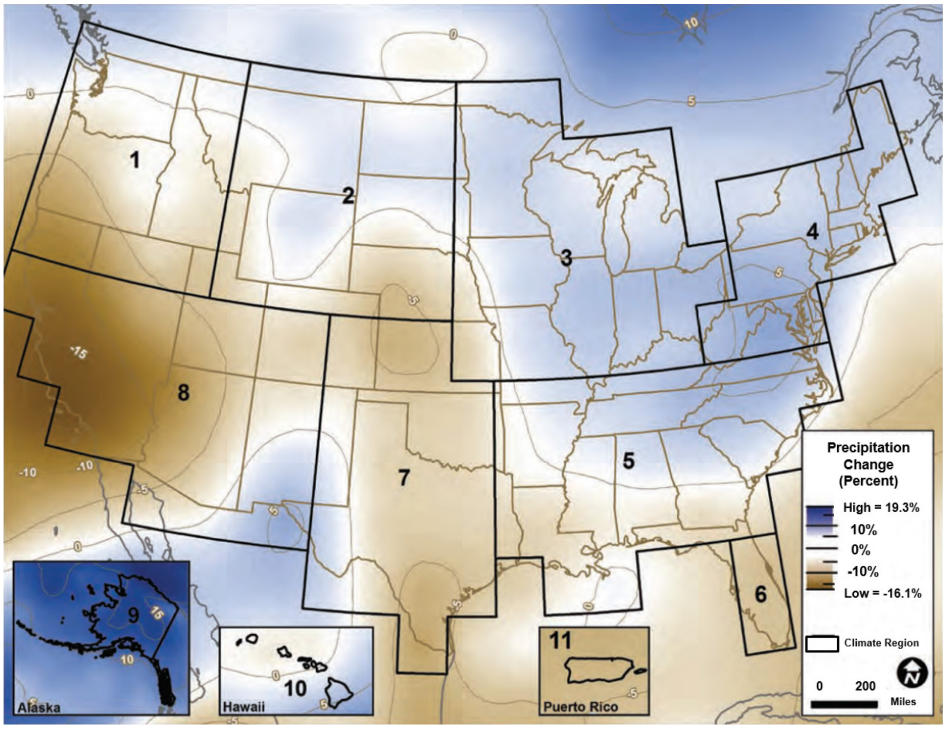


Figure 2. Estimated percentage change in summer precipitation in 2050 relative to 2010 (Meyer et al. 2014). The black numbers identify the 11 broad climate regions as represented in the MAGICC/SCENGEN coupled software suites.*

*Estimates were developed using A1FI scenario, 3°C (5°F) sensitivity. Data are smoothed, so transitions between different changes in precipitation (and temperature) should not be taken as being exact model output.

- Climate change impacts will increase the total costs to the nation's transportation systems and their users, but these impacts can be reduced through rerouting, mode change, and a wide range of adaptive actions.

The level of detail provided by Melillo, Richmond, and Yohe (2014) is where most major work on climate change adaptation in the transportation sector stops, reflecting the current state of the practice in climate change adaptation work. To date, most transportation climate change adaptation work at the DOT level or above has focused on:

- Anticipated large-scale impacts.
- Incorporating climate change into the planning process.
- Assessing climate change vulnerability of transportation assets (e.g., FHWA 2012).

Impacts on Pavements

Work on specific adaptation strategies for pavements remains general in nature. Meyer et al. (2014) provide one of the more comprehensive lists of pavement adaptations published to date. Tables 1a and 1b are adapted from that list with modifications to include construction items.

Detailed pavement implications for climate change are scarce but growing in number and include work on the effect of rising average temperatures, changes in precipitation patterns, and increasing freeze-thaw cycling on pavement performance (Mills et al. 2009). The focus of these efforts is to integrate climate change into pavement design (e.g., Mills et al. 2009; White et al. 2010; Wistuba and Walther 2013) and predict pavement performance based on future climate scenarios (e.g., Bilodeau et al. 2013). Most work has offered general advice or predictions but has stopped short of recommending immediate changes in practice.

PAVEMENT ADAPTATION STRATEGIES

Most climate change impacts are projected to occur slowly over a long period of time (e.g., increases in average temperature of 4 °F [2.2 °C] over 40 years, slow changes in precipitation patterns, and sea level rise of 0.8 to 6.5 ft [0.24 to 2 m] over nearly 100 years). In general, those few efforts that have focused on specific pavement adaptations (e.g., Mills et al. 2009; Li et al. 2013; USDOT 2014) have generally found climate change to be slow on the scale of the typical 20 to 40 year pavement life cycle (albeit fast on a geological time scale), requiring no immediate changes to current practice but likely requiring changes at some point over the next century. For instance, Mills et al. (2009) found that, for Southern Canada, the development of pavement distresses will change over time due to the impacts of climate, with required changes being within the range of current material properties, but "…the key adaptation issues will pertain not on how to deal with potential impacts but rather on *when* to modify current design and maintenance practices." (italics added for emphasis).

Monitor Key Performance Parameters

If the key issue is *when* to modify current practices, then a critical first step is to identify and monitor key pavement performance parameters and search for trends that develop over longer periods of time to reveal slow shifts in these parameters. For instance, current work in Washington State shows that for a majority of well-constructed, high-volume asphalt pavements, rehabilitation is eventually triggered by rutting distresses, while for most low-volume pavements, rehabilitation is eventually triggered by cracking distresses. In general, changes in these trends (whether in the rate and/or type of distress development) over time may be influenced by climate change and may instigate a strategic change to more rut resistant materials, such as stone matrix asphalt (SMA) and polymer-modified binders in surface courses. Table 2 lists key pavement indicators that should be monitored for asphalt and concrete pavements.

Table 2. Key pavement indicators to monitor for climate change impacts.

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

Table 1a. Climate change adaptation and pavement design–temperature items (adapted from Meyer et al. 2014).

Climate Change Impact	Affected Components and Strategies
Higher Average Temperatures	**Flexible Pavement** • Increased maximum pavement temperature increases the potential for rutting and shoving, requiring more rut resistant asphalt mixtures – May require raising high-temperature asphalt binder grade and/or increasing the use of binder polymerization and/or improved aggregate structure in asphalt mixes – Increased use of rut resistant designs including thin, rut resistant surfaces • Increased age hardening of asphalt binder – Use binders that age more slowly – Expanded use of asphalt pavement preservation techniques to address binder aging **Rigid Pavement** • Increased potential for concrete temperature-related curling (and associated stresses) and moisture warping – Greater consideration of concrete coefficient of thermal expansion and drying shrinkage – Incorporation of design elements to reduce damage from thermal effects including shorter joint spacing, thicker slabs, less rigid support, and enhanced load transfer
Higher Extreme Maximum Temperature	In addition to strategies listed above: • Higher extreme temperature may impact construction scheduling, requiring work to more often be conducted at night • If accompanied by drought, increased potential for subgrade shrinkage **Flexible Pavement** • Increased potential for asphalt rutting and shoving during extreme heat waves – See strategies above, but recognizing that the historical basis for selecting binder grades may no longer be valid **Rigid Pavement** • Increased risk of concrete pavement "blow ups" due to excessive slab expansion. – Use shorter joint spacing in new design – Keep joints clean and in extreme cases, install expansion joints in existing pavements
Warmer Extreme Minimum Temperature	• For all pavements, expect the depth of frost to decrease thus reducing the risk of frost heave – May be able to require less depth of frost protection – In areas with permafrost (e.g. Alaska) significant melting is anticipated resulting in serious impacts on ride quality **Flexible Pavement** • Warmer minimum pavement temperature may allow for raising the low-temperature asphalt binder grade requirement
Potential for More Freeze-Thaw Events in Some Locations	**Flexible Pavement** • Increased thermal cycling may require more careful consideration of the thermal fatigue characteristics of asphalt binders **Rigid Pavement** • Potential increase for deicing may require concrete materials that are more resistant to freeze-thaw cycling and deicer applications, particularly as related to joints.

Table 1b. Climate change adaptation and pavement design–precipitation items (adapted from Meyer et al. 2014). (continued)

Climate Change Impact	Affected Components and Strategies
More Extreme Rainfall Events	• Increased need for surface friction meaning potentially more focus on surface texture and maintaining adequate skid resistance – Maintain positive cross slope to facilitate flow of water from surface – Increase resistance to rutting – Reduce splashing/spray through porous surface mixtures • Increased need for surface drainage to prevent flooding – Increase ditch and culvert capacity – More frequent use of elevated pavement section • Increased need for functioning subdrainage – Ensure adequacy of design, installation, and maintenance of subdrainage • Need to improve visibility and pavement marking demarcation • High levels of precipitation may threaten embankment stability • Reduction in structural capacity of unbound bases and subgrade when pavements are submerged – Develop a better understanding of how submergence affects pavement layer structural capacity and strategies to address it
Higher Average Annual Precipitation	• Reduction in pavement structural capacity due to increased levels of saturation – Reduce moisture susceptibility of unbound base/subgrade materials through stabilization – Ensure resistance to moisture susceptibility of asphalt mixes • Improved surface and subsurface pavement drainage – Use strategies mentioned previously • Will likely negatively impact construction scheduling – Investigate construction processes that are less susceptible to weather-related delays
Wetter Winters and Drier Summers	• Must address increased potential for soil shrinking and swelling due to moisture changes, particularly in times of drought – Incorporate soil modification/stabilization into design Flexible Pavement • Use stiffer/improved pavement designs that are less susceptible to changes in subgrade properties incurred due to changes in moisture Rigid Pavement • Increase risk of concrete saturating during critical freezing cycles and increased deicer use – Concrete joint design should ensure that the concrete remains below critical saturation – Improve freeze-thaw resistance of concrete
Low Summer Humidity	Flexible Pavement • In combination with hotter summer temperatures, aging of asphalt binder likely to increase due to increased volatilization • Use asphalt pavement preservation techniques that reduce asphalt binder aging – Use binders that age more slowly – Expanded use of asphalt pavement preservation techniques to address binder aging Rigid Pavement • Increases long-term concrete slab warping • Impacts concrete curing during construction and thus good curing practices must be followed – Reduce drying shrinkage of concrete mixes by decreasing paste volume – Consider concrete drying shrinkage in design by reducing slab length, if needed

Recommended adaptation strategies:

- Short-term
  - Monitor key pavement performance indicators and climate metrics (e.g., freeze-thaw cycles, average temperatures, temperature extremes) on an annual basis. To begin with, monitor the distresses that typically trigger rehabilitation efforts and their frequency of occurrence in relation to traffic levels.
  - Incorporate summary statistics of this monitoring in periodic (e.g., annual) pavement management system reports.
- Long-term
  - If longer-term trends are not attributable to another identifiable cause, consider the impacts of climate change as a cause. Specifically, a general increase in temperature, higher extreme temperatures, decrease in depth of frost penetration, increased freeze-thaw cycling, and changes in precipitation patterns may impact pavement performance. The USDOT (2014) provides an 11-step framework for determining vulnerabilities of a specific transportation facility that can guide this consideration.
  - Make necessary changes in pavement materials, design, and management to compensate for identified climate impacts.

Pavement Design: Approach and Flexibility

The use of a mechanistic-empirical (ME) design approach, such as the AASHTOWare Pavement ME Design software, offers the opportunity to directly incorporate anticipated changes in climate into the pavement design software, as well as the ability to incorporate improved or new materials (with appropriate calibration efforts). A key concept in climate adaptation is to use environmental design parameters derived from predictive models (that account for climate change) rather than purely relying upon historical data that does not reflect future trends. Currently, all pavement environmental design inputs (e.g. the climatic data used in the AASHTOWare Pavement ME Design for the prediction of pavement temperature and moisture conditions through the Integrated Climatic Model) are based only on projecting repeated cycles of historical information, some of which goes back many decades. Further, the calibration of the empirical models used to predict pavement performance (ride quality, rutting, fatigue cracking, slab cracking, faulting, and punch-outs) are all based on historical data as well, reflecting how pavement designs and materials interacted with an environment that is now changing. Modifying this approach will take a major effort in research and implementation.

For asphalt pavements, in time it may be found that designs consisting of a thick asphalt layer (i.e., long-life pavement) composed of multiple lifts with varying levels of stiffness provide greater flexibility with regards to rehabilitation. Supporting layers are largely moisture insensitive and the surface (which is most dramatically affected by temperature) can be maintained through cold-milling (or micro-milling) and replacement. Thus, over time the rut resistant surface can be readily modified to accommodate climate change impacts without affecting the underlying structure.

Similarly for concrete pavements, robust designs that rely on low shrinkage concrete, moisture insensitive supporting materials, good load transfer, shorter joint spacing, and additional thickness that will accommodate multiple future diamond grindings to address functional requirements such as roughness, surface friction, and noise, are a good alternative.

Recommended adaptation strategies:

- Short-term
  - Investigate the climatic data that form the basis for current designs and revise as necessary to adjust for recent and short-term projected changes.
  - Review current calibration of pavement performance models and determine their sensitivity to changes in climatic input.
  - Evaluate existing pavement network and assess how robust it is to potential climatic changes anticipated to occur over the short-term, and set priorities within the network based on findings.
  - Initiate studies to evaluate the costs and benefits of modifying existing pavement designs to be more robust in the face of climate change.
- Long-term
  - Modify climatic data used in design based on updated climatic trends and the results of advanced climatic modeling.
  - Recalibrate pavement performance models reflecting trends in performance resulting from climate change.
  - Ensure pavement designs are such that they consider anticipated climate change over a 40-year design life.

Investigate More Robust Paving Materials

As the environment changes, so must the materials used to construct pavements. The effects of high temperatures on asphalt materials are well known. Decreasing asphalt binder temperature susceptibility through increased polymerization will enhance mixture stability under higher temperatures and keep the mixture pliable under cold temperatures. Increased stripping resistance may also be desirable. Conventional unbound subbase and base materials are known to be susceptible to changes in moisture condition, becoming weaker and less stiff as their moisture content approaches saturation. As a result, there will likely be an increased use of stabilized subbase and base materials in regions in which additional precipitation is forecast to help address some of this impact.

For concrete, mixtures that are more volumetrically stable under changes in temperature and moisture are desirable. This will reduce the potential for increased temperature curling and moisture warping. Further, increased freeze-thaw durability will likely need to be sought in some regions to partially offset impact of increased winter moisture, increased number of freeze-thaw cycles, and the commensurate increase in the use of chemical deicers that are known to accelerate damage due to freezing and thawing.

Recommended adaptation strategies:

- Short-term
  - Review current pavement materials, evaluating their robustness with respect to changes in environmental conditions (temperature and moisture).
  - Initiate studies to evaluate the costs and benefits of modifying existing materials to be more robust.
- Long-term
  - Implement new material specifications that are directed at mitigating the impact of climate change.
  - Investigate new materials with properties that are less susceptible to temperature and moisture than today's materials.

Changes in Construction Activity Periods

Most transportation organizations place weather limitations on pavement construction. Usually these limits involve (1) minimum surface temperatures for asphalt paving, (2) protection from extreme temperatures and dry, windy conditions during concrete placement and curing, and (3) prevention of paving during heavy rainfall. In areas with pronounced seasonal weather changes, specifications often ban paving during the winter except in special circumstances. Climate change impacts such as a general increase in temperature, higher extreme temperatures, changes in annual precipitation, and increased precipitation intensity may impact when paving is allowed, potentially extending the construction season in some cases or potentially decreasing allowable days for construction in other cases.

Recommended adaptation strategies:

- Short-term
  - Investigate the need for or desire to expand the construction season (if one exists).
  - Investigate whether changes are justified to extend existing temperature limitations for paving.
  - If a need exists, investigate the use of existing technologies to enable expanded construction seasons. Specifically, the use of warm mix asphalt (WMA) for asphalt pavement can improve compaction and allow for paving in colder temperatures (e.g., Kristjánsdottir et al. 2007; Manolis et al. 2008; Goh and You 2009). Improved hot-weather and cold-weather concrete paving technology can be used for concrete paving and curing in extreme temperature/humidity conditions, including the use of precast slabs.
- Long-term
  - Where appropriate, expand allowable paving seasons if currently limited by specification to certain dates.
  - Review worker safety and comfort requirements in extreme temperatures. Such requirements are covered under the OSHA General Duty Clause, with specific heat and cold stress guidelines provided by a variety of organizations including OSHA and the Center for Disease Control (CDC). Typical requirements include not only health and safety precautions and equipment but also worker training.

Pavement Resilience in Extreme Weather Events

Given the recent rise in extreme weather events (e.g., hurricanes Katrina, Sandy, Ike, Wilma, Charlie, Ivan, Rita, and Frances, all occurring within the last 10 years), which has long been predicted (e.g., Easterling et al. 2000), one topic of increasing concern is the ability of infrastructure to

withstand such events in serviceable condition or be repaired to serviceable condition over a period of time (termed "resilience"). Most efforts have focused on the ability of transportation systems to function immediately before (for evacuation) and after (for emergency services) extreme weather events. And most of these efforts have focused on key structures (such as bridges) and largely ignored pavements. However, there have been a few efforts that attempt to identify pavement performance in such situations, most commonly where pavements are overtopped with water. Useful information includes:

- Wave action during storm surges near the coast can damage highway embankments and pavement (Douglass, Webb, and Kilgore 2014). However, addressing this issue is largely a coastal engineering question concerning revetment armor, and not pavement engineering.
- Weir-flow (storm surge water flowing across a roadway) damage can occur to embankments and pavement structures (Douglass, Webb, and Kilgore 2014). There is some evidence to suggest vegetated shoulders and embankments of compacted soils can better resist mild weir-flow damage (Douglass, Webb, and Kilgore 2014).
- Pavements submerged due to storm events tend to lose strength (Gaspard et al. 2006). The duration of submergence is generally not a factor (Gaspard et al. 2006) because moisture susceptible materials within and underlying the pavement structure quickly come to equilibrium saturated conditions. The FHWA is currently funding work at the University of New Hampshire to develop guidelines for short-term assessment of flooded pavements.

Recommended adaptation strategies:

- Short-term (these strategies are theoretical and have not been extensively researched)
  - Consider lowering roadway profiles to limit wave action and weir-flow damage for coastal pavements. This may result in more frequent inundation.
  - Consider vegetated or compacted soil embankments to resist weir-flow damage for coastal pavements.
  - Consider the use of moisture insensitive materials (stabilized materials versus unbound materials) throughout the pavement structure to minimize the reduction in structural capacity that occurs when pavements are submerged.
- Long-term
  - Same as short-term.

CONCLUDING REMARKS

Climate change is resulting in a broad array of impacts that affect transportation systems including pavement systems. It is generally projected that the global climate will continue to change and do so at an increasing rate into the next century or longer. While climate change mitigation efforts are necessary, adaptation to the change that has already happened and is nearly certain to continue to happen in the future is also needed. For pavements, investigation into climate change impacts and adaptation is in its infancy. Most work to date provides general guidance based on the effects of climate change impacts (mainly temperature and precipitation changes) on pavement materials and performance. Efforts that have gone beyond general guidance tend to converge on two general findings:

- Climate change is slow on the scale of current pavement life-cycles (e.g., 20-40 years) so (1) in most cases immediate adaptation responses are not yet warranted, but (2) ultimately some adaptive efforts must occur.
- Design efforts that rely on long-term predictive models (e.g., 40 or more years of performance prediction) should adapt such models to incorporate current climate predictive models rather than rely solely on historical records.

These findings imply the following pavement adaptation strategies:

- Monitor key pavement performance parameters. Search for trends that develop over long time periods that can be used to determine when design, materials, construction, or preservation efforts should be changed.
- In pavement design, use predictive climate models in place of historical climate data, and opt for design strategies that allow flexibility in responding to future adaptation needs.
- Investigate the use of more robust paving materials and designs that perform better in more extreme temperature, precipitation, and flooding scenarios.
- Adjust construction seasons and temperature limitations as needed while concurrently reviewing worker safety and comfort requirements.

- Understand that pavement systems can be severely damaged by extreme weather events, but that resilience efforts should focus more on embankment height/construction considerations and relocation of roads rather than fortifying pavement structures against these events. Fortification should be a last-resort option where no feasible relocation exists.

Finally, pavement climate adaptation is a new research area. This Tech Brief summarizes climate impacts and pavement adaptation strategies that have been suggested to date and proposes several other broad actions that have yet to be extensively investigated. The strategies discussed in the Tech Brief only represent a starting point for necessary future work. It is anticipated that such future work will identify more potential adaptation strategies and clarify which ones are most impactful, and the time scales over which they should be implemented.

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