**Transportation Engineering Approaches to Climate Resilience**

# Assessment of Key Gaps in the Integration of Climate Change Considerations into Transportation Engineering

## Task 2.3

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# 1. Introduction

## 1.1. Report purpose

In many areas of the United States, climate change is bringing an increase in frequency of extreme heat and precipitation, as well as an increase in sea level rise and associated storm surge, and a host of secondary impacts. These climate stressors are taxing an already aging transportation system, and the continuation or acceleration of these trends are often not accounted for in new construction. Recent research has provided insights into how scientists believe the climate may change, and recent pilot studies have revealed anticipated vulnerabilities of transportation agencies. However, research on how transportation practitioners should use and react to this information is still limited.

The Federal Highway Administration (FHWA) is seeking to provide answers through the development of case studies and methodologies in the Transportation Engineering Approaches to Climate Resiliency Project. A first step to addressing these shortcomings is the identification of *exactly* what type of assistance practitioners need. This report:

- Reviews gaps in information and practice related to integrating climate change into transportation engineering (Section 2) and
- Recommends a select set of gaps for further investigation in the remainder of the project (Section 3).

**Key Terms and Concepts**

**Climate change:** Long term changes to the global or regional "average weather" attributed largely to increased levels of atmospheric carbon dioxide produced by the use of fossil fuels.

**Extreme weather events:** Events that are at the extremes of climatological distribution—weather that occurs only 5% or less of the time.

**Climate variable:** Parameters used to measure and describe climate. For the purposes of this report, six different climate variables were examined: temperature, precipitation, wind, storm surge, waves, and relative sea level change.

**Climate stressor:** Variation in a climate variable that may lead to a climate impact (e.g., high temperatures, heavy rainfall, cyclical variations in temperature over a period of time).

**Climate impact:** The effect that climate has on a transportation asset.

## 1.2. Methodology for Identifying Gaps

An initial understanding of these gaps was developed through a suite of strategies including the Project Team's professional experience, a literature review, and interviews with several state DOTs involved in the FHWA Climate Resiliency Pilot Projects. The pilot participants are on-the-ground practitioners who are in the midst of encountering and working through some of these gaps.

A draft version of this report was used as the basis for a 1-day meeting of transportation practitioners and climate change professionals in Washington, DC on June 17th, 2014. At this meeting, participants discussed the key challenges they faced when attempting to address climate change in their planning and design processes. These discussions provided valuable insights not only into what other gaps exist, but also which one are the most urgent to address. For a complete list of participants, please see Appendix C.

The gaps from the literature review/expert interview process and the transportation practitioner meeting are organized thematically and presented back-to-back in Section 2.

Drawn from these processes, a subset of gaps has been highlighted in Section 3 for further study in the remainder of this project. These select gaps represent critical barriers to integrating climate change into transportation engineering practices, as well as gaps that the Project Team can make substantial progress towards closing through a series of engineering case studies.

# 2. Key Knowledge Gaps in Addressing Climate Change in Transportation Engineering

A summary of the key gaps from both the literature review/interviews and the expert/practitioner meeting are presented in this section. The gaps are categorized in the following manner:

1. Translation of Climate Data to Terms that Resonate with Transportation Practitioners
2. Engineering Solutions for Preparing for Climate Change
3. Methods for Evaluating Efficacy and Costs/Benefits of Implementing Adaptation Measures
4. Organizational Processes/Decision Making[1]

This section provides a broad introduction to the topic area with specific gaps and details located in Appendix A.

Note that this section (and Appendix A) covers *all* gaps identified through the literature review and expert/practitioner meeting. This full list is narrowed down into 17 high-priority gaps to address in later stages of this project, as discussed in Section 3 and Appendix B.

## 2.1. Translation of Climate Data to Terms that Resonate with Transportation Practitioners

Although there is an abundance of climate projection data, transportation practitioners do not always know how to use this information in their work, as the data does not neatly fall within data formats or calculations that engineers use. Thus, there is a "translation" barrier between the data available and the data that is needed.

### *2.1.1. Overview of Key Literature Review Gaps*

**Consolidated and consistent guidance on addressing climate change.** There is still a need to communicate to transportation practitioners why they should be considering the effects of climate change in their transportation planning, design, and operations. Part and parcel of this gap is a lack of a clear and concise description of why greenhouse gas emission mitigation strategies, although important, will prove to be insufficient at stemming the damaging effects of climate change on transportation assets. Transportation practitioners would feel more confident about incorporating climate change into their work if they were provided clear and consistent guidance on which climate scenarios, models, and data should be used when designing and maintaining assets. All of this information needs to be contained in a single, consolidated location for ease of access and easy updating, and it needs to be written with the transportation practitioner in mind. Currently, although information on climate change is available, there is no consistent guidance on when or how it should be considered, and it is

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[1] Some gaps identified in this section are outside the scope of the engineering assessments to be conducted in later stages of this project.

often not presented in terms that are relevant to the day-to-day work of transportation engineers.

**Methodologies for translating temperature, precipitation, storm surge, and wind into data formats that engineers traditionally use, and guidance on how to incorporate the data into design**. Climate projections are often expressed in different terms than the data formats that engineers are accustomed to using. Some of this information has or can be translated to provide easy integration into traditional engineering practices, although there may not be established methodologies for doing so. For example, temperature projections can be obtained at the daily level, and from those projections, maximum annual temperature, the number of days above a certain temperature threshold, etc. can be calculated, but there is no formal established methodology for how to move from the raw data to the desired variables. Other key metrics cannot be translated and thus require the development of new engineering methodologies to account for them.

There are also several big picture concerns that transportation practitioners face when they begin to use climate model data. First, they need guidance on how to deal with the compound errors inherent in large climate models. Second, they need guidance on how to define scenarios for bounding the uncertainty across the ensemble of climate model projections. And third, there is significant confusion surrounding the appropriate use of downscaled climate data. For more information on these gaps, see Appendix A Section 5.1.1 on Climate Communication.

**Methods and models to assess changes in, and the probability of, secondary and combined climate impacts (e.g., landslides, freeze-thaw cycles, and coastal zone morphology) and their impacts on transportation infrastructure.** Often, it is not the direct climate stressor (such as temperature or precipitation), but the secondary impacts of these climate stressors that can cause the most damage and disruption to transportation. For example, increases in temperature might not have a severe effect on roadways in Alaska, but the thawing of the underlying permafrost could have significant impacts. It is therefore critical that methodologies be developed to ascertain the effects of these secondary stresses on transportation infrastructure in order to allow for the design of robust infrastructure that will continue to be operational under a wide range of climate futures. Examples of the secondary impacts that warrant further study and require the development of methodologies for their inclusion in transportation planning and design include: the effects of deforestation (due to wildfires or pests) on landslides, flash floods, and sediment/debris flows; the effect of temperature changes on freeze-thaw cycles, permafrost melt, and snow coverage/melt cycles; the effects of sea level rise and changing thermal conditions on coastal zone morphology; changes to stream morphology due to increases or decreases in higher frequency, smaller discharge flood events; the impact of changes in soil moisture content on hydrology and landslides; and information to enable prediction of changing coastal environments such as shore line erosion, changes in beach sand, and cliff recession rates.

It is also important that engineers understand the probability and impact of multiple stressors occurring concurrently or consecutively. These compounded impacts could significantly increase the vulnerability of a transportation asset. For example, there needs to be easily accessible information on the combined impact of sea level rise, land uplifting or subsidence, and sedimentation/erosion. See Appendix A Section 5.1.3 for additional gaps and information.

**Information on the impacts of losing critical infrastructure services, such as power, communications, and water control systems due to climate change stressors.** Transportation networks do not operate in isolation. They depend on a host of ancillary systems, without which there may be user delays or damage to transportation assets. Transportation practitioners need methodologies for determining the impacts of failures in the electric power supply network, the communication network, and water control systems on transportation systems and how to build resiliency to these impacts. See Appendix A Section 5.1.4 for additional gaps and information.

### *2.1.2. Overview of Key Gaps Identified at the Expert/Practitioner Meeting*

**Guidance on how to address the significant uncertainty in climate change models.** This uncertainty raises large concerns for the integration of climate data into engineering practices. It would be useful to compare climate model uncertainties to uncertainties in other prediction based models that engineers accept and use every day. For example, land use models contain significant uncertainties but they are frequently trusted more often because (a) it is the state of the practice to use them, and (b) they infrequently quantify the uncertainty associated with the model, thus providing an unrealistic sense of certainty. It would also be beneficial to provide a better understanding of how accurate the downscaled climate model data is and how useful it is for project level design.

**Federally adopted climate scenarios.** Participants agreed that it is unlikely that the federal government will endorse specific climate scenarios or climate models. Instead, FHWA could request that states include climate risk in their investment decisions, and encourage states to develop protocols for selecting scenarios, models, and other assumptions.

**Climate data provided to engineers in a format that is pre-processed for use**; however, the development of that information cannot be a black box–it should not require a background in climate science to decipher climate information. Statistically valid methods of assessing climate trends are needed. Engineers want to understand exactly what the numbers mean, how they were developed, and why they are statistically valid before they will feel comfortable using them in design.

**Assistance translating climate data into standard engineering formats.** For all climate stressors, improved information on the return interval/probability of climate events would be beneficial. There is also the need for intensity-duration-frequency (IDF) and depth-duration-frequency (DDF) curves for precipitation and hourly and sub-hourly (potentially down to 5-minute increment) rainfall data, as well as the impact of rainfall and changes in groundwater levels on soil moisture content. With respect to temperature, in addition to knowing temperature maximums and minimums, engineers need to know the duration of the high and low temperatures.

**Guidance on how to connect climate projections to the mean, standard distribution, and skew of storm events/precipitation events**. While it may not be realistic to obtain such detailed data (with a sufficient degree of confidence) directly from climate models, it may be possible to provide guidance or example methodologies of how assumptions of event characteristics could be tied to projected changes in precipitation.

## 2.2. Engineering Solutions for Preparing for Climate Change

Engineers require guidance on how to incorporate climate change information into engineering design and asset management systems. Traditional engineering guidance and methodologies do not account for future changes in climate so additional and/or complimentary approaches to engineering design need to be developed.

### *2.2.1. Overview of Key Literature Review Gaps*

More information on these gaps can be found in Section 5.2.

**Design guidance and commonly utilized data sources (e.g., FEMA Flood Plain, NOAA rainfall data) that incorporate climate change.** Although most transportation departments have written their own guidelines and specifications, they are generally based on the national guidelines published by agencies such as the Federal Highway Administration in the case of roadway work, or the National Oceanic and Atmospheric Administration (NOAA) for rainfall or other climate data. At this point, the majority of these guidelines do not account for future changes in climate. For example, FEMA base flood data, NOAA Atlas 14 rainfall tables and distributions, HEC-20 and HEC-25 (although the next version of HEC-25 will provide some guidance on how to include future climate conditions), and multiple AASHTO guidance documents do not consider future changes in climate. (Exceptions include, for example, the USACE sea level rise guidance and the California sea level rise guidance)

**Methods to determine the scale of impacts that a given transportation asset will experience during its lifetime and insufficient guidance for determining the appropriate hard or soft adaptive design measures.** There are several additional gaps that affect engineering design.

- First, methodologies are needed to determine the scale of climate change impacts that will be experienced within a particular asset's lifetime. The return intervals for various events are shifting, transportation assets are frequently used well past the end of their design life.
- Second, basic information in needed on the points in the planning and engineering process where climate change considerations should be incorporated. Transportation practitioners need specific guidance not only on *how* to incorporate climate change into their work but also *when* in the process it is most appropriate.
- Third, guidance is needed on how to determine the appropriateness of a design/construction solution versus a non-design/construction solution. In certain circumstances, alternatives to construction solutions may be more cost-effective and result in a better overall improvement with fewer negative effects. Similarly, transportation practitioners would benefit from guidance on how to consider designing for a shorter design life for infrastructure that may be increasingly subject to frequent, destructive stress. There needs to be a way to ensure that these alternatives to traditional engineering design are considered during the planning and engineering phase.
- Fourth, there is currently limited information available on damage thresholds—that is, the point at which a stressor actually causes damages, and what that damage may be. A better understanding of how resilient infrastructure is to climate stressors would help

decision makers understand whether projected changes in climate might be problematic.

For more information on these gaps, see Appendix A Section 5.2.1.

**Guidance on when to consider and how to coordinate planning and engineering responses to climate change.** Future changes in climate and land uses need to be discussed by engineers and planners prior to selecting an appropriate course of action. Guidance is needed on how to approach this collaboration and ensure that these conversations are taking place. For example, if a small island will be under water at 3 feet of sea level rise would it make sense to adapt the sole bridge serving it to be able to deal with 5 ft. of sea level rise? It depends if other adaptation actions will occur to protect the assets that the bridge is serving.

**Revised asset management systems that take climate change into account.** A well-designed transportation asset management program will minimize the lifecycle costs for the management, operation, and maintenance of transportation assets, such as bridges, pavements, culverts, etc. Integrating climate change into transportation asset management can support the identification and prioritization of asset repairs, improvements, or replacements based on the vulnerability and criticality of the asset. Transportation practitioners require guidance and data to fully integrate climate change considerations into their asset management plans. These gaps include methods to understand system-wide impacts of site specific asset failure and methods for understanding the impacts of non-extreme weather events on asset performance. For additional gaps and information on the integration of climate vulnerability into asset management systems, see Appendix A Section 5.2.2.

### *2.2.2. Overview of Key Gaps Identified at the Expert/Practitioner Meeting*

**Defensible approaches to alter their design practices or inputs in light of climate model uncertainty.** Transportation engineers do not want to arbitrarily increase the factor of safety or design storm. There are concerns surrounding adding substantial additional uncertainty (from climate models) to the existing, unknown levels of uncertainty. All sources of uncertainty (climate and otherwise) need to be quantified, including how to appropriately design structures with these levels of uncertainty.

**Methodologies for incorporating climate change into their design *while still* taking into account traditional engineering considerations.** Climate change can only be one of the many factors considered in engineering design; it cannot be the sole factor that dictates the design. A balanced approach should always be considered. One way to address this may be through designing assets based on desired outcomes, taking into account climate change, the environment, site characteristics, operational needs, and other factors.

**Methodologies to consider secondary impacts of climate stressors.** For example, increased sediment and debris transport due to heavier rains and increased deforestation (due to wildfires and pests) needs to be accounted for in design. It's not just rain that leads to failure but the combination of rain with unanticipated large debris flow events. Additionally, changes in the frequency of forest fires need to be accounted for in pavement design because they can increase pavement deformation.

**Methodologies that ensure that upsizing culverts is not just creating a sediment drop area.** This can lead to them becoming clogged and ineffective. Engineers need to balance the size of the culvert with the possibility for sediment deposition.

**Methodologies on incorporating climate change considerations into standard design practices that do not currently include any weather or climate inputs.** For examples, engineers cannot easily insert changing precipitation patterns into most commonly used regression equations. They need another approach for integrating climate change considerations into this frequently used design practice.

**Guidance on which design practices do not require adjustment due to the ability of existing factors of safety to accommodate climate change.** Knowing what doesn't need to change is just as important as determining what does need to change. This guidance may require a flowchart to allow engineers to self-diagnose based on the magnitude of climate changes within their region.

**Guidance on how to coordinate operations and design with surrounding asset owners.** For example, utilities frequently make changes to their systems that affect the resiliency of transportation assets. Additionally, there will be climate impacts that affect surrounding land uses which in turn affect the use of transportation assets (such as disappearing freshwater wells).

**Methods to account for the changes in wave forces due to sea level rise.** Sea level rise will change where a structure is located within a wave column which has a substantial effect on the impact forces experienced by the structure.

**Updates to the national temperature based design maps (applicable to pavement and expansion joints).** It would be beneficial to add probability to the temperature ranges on these maps.

**A transition from designing assets for service life to designing them for durability.** For example, instead of designing an asset with a service life of 75 years, you may design it to withstand specific climate stressors that could occur.

**Guidance on how to consider climate change impacts on a network of assets.** Transportation professionals cannot replace one culvert just to move the flooding problems downstream. Different solutions such as comprehensive watershed management should be considered.

**Guidance on how and when engineers should plan for an asset to fail during severe weather conditions.** For example, resisting hurricanes may be more expensive than rebuilding after the event.

**Guidance on how to conduct scenario planning/engineering; particularly on how to cost-effectively conduct scenario assessments.** It is possible that a range of scenarios should be considered for longer lived, more expensive infrastructure while only one scenario may be appropriate for short design life and low cost assets. In addition, it may be reasonable to analyze more severe climate scenarios when designing an expensive and long life.

**Guidance on how to develop operations and maintenance (O&M) in light of increasing climate vulnerability.** Budgets are traditionally developed based on recent years' expenditures but this approach may no longer be appropriate given the substantial impact that climate variability has on O&M costs.

## 2.3. Methods for Evaluating Efficacy and Costs/Benefits of Implementing Adaptation Measures

Investing resources to adapt to climate change is frequently viewed as a luxury that agencies cannot afford. However, most engineers would agree that investing a small amount of money during project design and development or during routine maintenance is more cost effective than reacting to failed and damaged infrastructure after an extreme weather event. Transportation practitioners need methodologies for capturing and communicating this effect to decision makers.

### *2.3.1. Overview of Key Literature Review Gaps*

Additional information on these gaps can be found in Appendix A Section 5.1.3.

**Guidance on how to track damage and costs of past extreme events, how to estimate the likelihood of future events, and how to monetize the cost of those events.** With each extreme weather event comes costs associated with emergency response and repair. Documenting these costs and tracking them over time allows the asset owner to understand the long-term cost of underbuilt infrastructure.

Furthermore, estimating both the likelihood of future events and monetizing the cost events can assist in determining the most cost-effective course of action.

**Methods for estimating the "cost of inaction" with respect to projected climate impacts on infrastructure.** Transportation practitioners do not have good information on the effects that losing a particular piece of infrastructure has to the general economy nor do they have a straightforward way to quantify the impacts of these events. Future guidance on calculating these costs may include economic impacts such as reduced freight transport, increased travel time and the loss of productive hours, risks to public health, costs to repair the infrastructure, and a number of other categories.

**Methods to estimate the costs of adaptation measures.** There are limited rules of thumbs regarding how much it would cost to design a structure to be resilient to extreme events. Developing detailed cost information is very project-specific, so cost information relevant to one site may not accurately portray costs (or even relative costs) at another site. Rules of thumb or example project costs could be helpful in planning.

**Appropriate approaches to minimizing the total lifetime cost of an asset.** The expected cost includes the cost to build an asset (including any adaptation measures) and potential loss of use during repairs after extreme weather events during the asset's service life (which would be reduced by any adaptation measures), as well as the costs associated with potential repairs. It takes into account the probability of the climate event and an economic analysis of the repercussions. Using this technique ensures that infrastructure is not over-built and that public resources are effectively spent. There is currently no guidance on how to use this decision making approach to select the appropriate level of engineering design.

### *2.3.2. Overview of Key Gaps Identified at the Expert/Practitioner Meeting*

**Information on integrated adaptation strategies that can be funded within existing budgets.** Resources for funding transportation projects are very limited and many agencies are already struggling to maintain their existing infrastructure. With this in mind, low cost adaptation strategies and those with many co-benefits need to be identified and prioritized.

**Guidance on how to conduct risk based cost assessments.** Transportation practitioners are concerned about overspending given the amount of uncertainty surrounding climate change timing and impacts. They need guidance on how to balance the risk of an impact with the cost of adaptation.

**Guidance on the appropriate range of benefits and costs to include in a cost benefit analysis.** For example, some analyses only consider the costs of damage to the asset itself while others may consider the ability of emergency response personnel to respond to disasters. Additionally, benefits of protecting an asset may be reduced if the surrounding infrastructure is impassible. Varying levels of detail may be appropriate for different structures.

**Guidance on how to discount future cost savings.** Frequently in cost benefit analyses, future benefits of investments are steeply discounted. This approach may misrepresent the benefits of investing in climate change adaptation strategies.

## 2.4. Organizational Processes/Decision Making

In addition to engineering gaps, the literature review identified organizational and decision making gaps that affect the ability of public agencies to implement the adaptation strategies and create non-engineering solutions such as emergency response plans. For more information on these gaps, see Appendix A Section 5.1.4.

### *2.4.1. Overview of Key Literature Review Gaps*

**Funding options for adaptation strategies, including guidance on how to document co-benefits and how to build appropriate partnerships for planning and co-financing.** The primary objection to climate change adaptation implementation is the lack of available funding. As climate change accelerates, the costs to adapt may be well beyond the current capacity of public agencies. New sources of funding and creative cost sharing approaches to addressing vulnerabilities need to be identified. Additionally, the identification of the co-benefits of adaptation could help in "selling" adaptation investment. In order to so, additional information on the co-benefits of adaptation need to be identified.

**Guidance on how to plan reactive adaptation strategies and how to integrate climate change into emergency response planning.** In some instances it may be best to take a more reactive approach to adaptation by adapting after existing assets have proven to be vulnerable and damaged or after some trigger thresholds have been reached; key considerations include asset criticality and remaining service life. A more proactive approach to adaptation requires retrofitting and designing for adaptation prior to experiencing damages. A framework for weighing these strategies against each other and selecting the appropriate response in different situations is needed.

**Consistent policy guidance from Federal and State agencies.** Almost all transportation agencies interviewed during the creation of this report requested consistent guidance from policymakers on what climate stressors they should be considering and which climate change scenarios should be used in analysis. Consistency is emphasized because transportation planners and engineers must adhere to requirements and guidance from various agencies, including U.S. DOT, FEMA, AASHTO, and state and local requirements.

**Approaches for addressing inconsistent planning horizons and integrating climate change into the environmental review process.** Planning horizons for most long-range transportation are only 25 to 30 years although the planned infrastructure will likely be in place much longer. This makes it difficult to consider the impacts climate change will have on these assets and the surrounding communities beyond the time period of the plan (GC1 2008; TRB 2014). Transportation professionals need guidance on how to marry these disparate time frames.

The Council on Environmental Quality (CEQ) has proposed guidance on integrating climate change considerations into the environmental review process but no guidance documents have been passed to require local agencies to consider it (TRB 2014). Additional guidance and examples of its application are required to ensure widespread adoption of this practice.

# 3. Select Knowledge Gaps Recommended for Further Study

This section refines and presents a subset of the gaps presented above. All gaps in this section meet two key criteria: (1) the gaps are particularly vital to address if transportation practitioners are to be well-equipped to plan for a changing climate, and (2) the Project Team believes that substantial progress can be made toward closing these gaps through a series of engineering case studies that will occur later in this project. In some cases, the gaps have been supplemented with potential strategies for closing the gaps. These strategies will be explored and refined during the case study scoping process.

Efforts to close these selected knowledge gaps will rely on analyses of specific transportation assets and climate stressors; for each asset/climate pairing, the Project Team will conduct detailed assessments and will develop recommendations for more climate-resilient designs, protections, retrofits, and/or maintenance approaches, in addition to an economic analysis of the costs and benefits of the various approaches. The knowledge gaps selected at this stage are subject to revision through a detailed case study scoping process that will marry the key knowledge gaps with the best opportunities for asset-specific assessments that could inform and promote more resilient outcomes.

A summary of these 17 gaps, along with potential engineering assessments that could be conducted to help fill the gaps, is shown in Appendix B.

## 3.1. Translation of Climate Projections into Variables/Formats Engineers Can Readily Use

1. **Selecting climate information.** Transportation practitioners should not be expected to become climate change experts; therefore, they need assistance in sorting through the plethora of data sets and models. The amount of information available contributes to the current belief that there is too much uncertainty to incorporate any climate change data into engineering design. If engineers are to integrate climate change information into their practices, this basic barrier needs to be removed and an approach to incorporating uncertainty into project decision-making developed. Guidance shouldn't necessarily be prescriptive, but rather it should narrow down the choices and perhaps explain when transportation engineers may want to choose one data set or model over another or how many climate scenarios are appropriate for the study. For example, it may be appropriate to include a very high emissions scenario in the range of scenarios considered when designing a high cost asset with a long design life.

2. **Effect of multiple conservative assumptions on asset design.** In closing this gap, we would seek to evaluate the compound effects of making multiple conservative assumptions. That is, if a more extreme emissions scenario is selected "to be conservative," and then climate models producing more extreme results are selected, and then a large margin for error is included in the design—will the resulting design be overly conservative? What context can be provided about the compounding effects of these conservative assumptions? Additionally, we will take into account the level of risk that transportation agencies are willing to accept and will focus on the desired outcome

and performance of structures rather than starting from the assumption that the design inputs must be changed.

3. **Climate model precipitation data at the sub 24-hour level.** 24-hour based precipitation estimates are a useful data format for hydrologic modeling of mid-range to larger watershed basins; however, discharge estimation for smaller catchments, such as those supplying stormwater management facilities, small drainage pipes, catch basins, etc., is dependent on sub-24 hour precipitation intensities, with durations ranging from 12-hours down to 5-minutes. One way to close this gap would be to develop new Intensity-Duration Frequency (IDF) or Depth-Duration Frequency (DDF) curves for climate change conditions. These curves would need to be developed in collaboration with respected science organizations. These curves would be developed through peer-reviewed methods which recognize the uncertainty inherent in climate data.

4. **Rainfall distribution type curves for future climate scenarios**. Currently, these curves are only available for historic climate conditions. Rainfall distribution curves are utilized to develop synthetic rainfall hyetographs for use in theoretical hydrologic models such as TR-20 (NRCS), HEC-HMS (ACOE), or SWMM (EPA). The curves are used to distribute the selected duration storm event (24-hour or other) down to the selected computational interval of the theoretical model, commonly on the order of 6-minutes. This data gap is related to the 24-hour data format gap and would be similarly addressed through the development of new IDF or DDF curves for climate change conditions. Theoretical storm distributions could be developed from IDF or DDF curves following the alternating block method as described by Chow (1988) and others.

5. **Changes in temperature and precipitation patterns and soil moisture conditions.** Soil moisture conditions can have a significant impact on the hydrologic process. Future temperature and precipitation patterns may result in substantially wetter or drier soils in a particular region, which will impact the initial abstractions from the rainfall runoff cycle and thus impact stream flow rates. This data gap may be addressed through the development of detailed water budget models for particular areas by utilizing climate inputs for temperature and rainfall. However, more practically the gap would likely be addressed through large scale water budget modeling that results in scaling factors that may be adopted for use by other individual hydrologic studies.

6. **Incorporating sea level rise and changing storm surge in absence of probabilities.** Sea level rise is documented through numerous studies for all locations along the coasts of the US; however, varied levels of rise are predicted by the numerous studies commonly available. Many agencies have adopted ranges of rise, quantified on a basis of low, medium, and high for the use in design studies. However, probabilities of occurrence for each value in the range are not definable. Selection of the appropriate level of change is a gap in need of addressing. Similarly, storm surge models can predict surge levels, but do not predict if, when, or with what frequency those storms might occur.

7. **Combining historical climate data with projected future climate changes.** Engineers are comfortable using historical data sets for their designs. A complete departure from this

approach is unlikely; therefore, it would be advantageous to develop a method to meld the local historical trends with future projections.

8. **National temperature based design maps**. Many engineering design processes (e.g., pavement design) utilize nationwide mapping of design temperature data. Often these maps are included in specific publications that outline the design process for the asset, but may not be the primary focus of the publication. There is an apparent need for an update to both the maps and the design methodologies for these types of assets that both incorporates future projects and allows for flexibility in working with a range of possible future projections.

## 3.2. Engineering Solutions for Preparing for Climate Change

9. **Secondary impacts of climate stressors.** For example, increased sediment and debris transport due to heavier rains and increased deforestation (due to wildfires and pests) needs to be accounted for in design. Experience has shown that sediment and debris loading on structures may be responsible for just as many failures as intense rainfall and high runoff. Additionally, changes in the frequency of forest fires need to be accounted for in pavement design because they can increase pavement deformation.

10. **Incorporating climate change into design practices.** For example, engineers cannot readily include changing precipitation into commonly used hydrologic regression equations, which inherently rely upon historical climate patterns. The need exists for a modified approach that allows for integrating climate change considerations into this frequently used design practice.

11. **Climate change impacts on a network of assets.** Transportation professionals cannot replace one culvert just to move the flooding problems downstream. Rather, they need to evaluate different solutions such as comprehensive watershed management and to determine when a broader view of the affected area needs to be considered.

12. **Climate change and the design of lower-cost assets.** Transportation engineers rely upon varied levels of detail in the development of their designs. Generically, the level of analysis detail could be viewed as scalable to the cost/value of the structure under design. For instance the design of a bridge could involve highly detailed hydrologic computations using models such as TR-20 or HEC-HMS along with detailed hydraulic modeling using HEC-RAS, while the design of a small highway pipe could be designed using the rational equation and a pipe nomograph. Therefore, it would be useful to develop a simplified process to incorporate climate change/asset adaptability for lower cost/value assets and forego the more rigorous analysis and/or design.

13. **Phased adaptation strategies.** This would include information on selecting trigger points for implementing the next phase of adaptation as well as designing the various phases. This could be studies in the second half of two complementary case studies where one case study could look at an asset-stressor combination to understand vulnerabilities and

then the next case study would assess phased adaptation options to address those vulnerabilities.

14. **Loss of auxiliary infrastructure services.**[2] Transportation networks do not operate in isolation. They depend on a host of ancillary systems, without which there may be user delays or damage to transportation assets. Transportation practitioners need methodologies for determining the impacts of failures in the electric power supply network, the communication network, and water control systems on transportation systems and how to build resiliency to these impacts.

15. **Resilience to simultaneous climate events.** For example, information on the combined impact of heightened storm surge and riverine flooding on bridges is needed. Traditionally, these impacts have been evaluated independently of one another as the combination of two extreme events (e.g. the 100-year storm surge and the 100-year precipitation) is viewed as producing an overly conservative storm condition (akin to the 1,000-year storm). While the joint probability of the example occurrence may indeed represent a lower probability event, the combination of different intensity events may present a more realistic occurrence for the design probability condition (e.g. the 100-year storm surge and 10-year precipitation representing a 100-year combined storm event).

## 3.3. Methods for Evaluating Efficacy and Costs/Benefits of Implementing Adaptation Measures

16. **Climate change uncertainty and cost of adaptation.** Resources for transportation projects are limited and there are concerns about responsibly allocating funding for climate change adaptation given future uncertainties. In the Gulf Coast Phase 2 project, a Monte Carlo analysis was conducted for the culvert case study that looked for cost-effective solutions in light of climate change uncertainty. This approach could potentially be refined and built upon to provide additional guidance to transportation practitioners.

17. **Costs and benefits of adaptive measures.** This guidance should include considerations such as common co-benefits of adaptation, the boundaries for the analysis (e.g., impacts to the economy, emergency services and health, physical damage to the asset), how to incorporate risk into the assessment, how to use historic costs of severe weather events as well as projected costs of future events, and approaches to using the benefit cost analysis to inform funding decisions and minimize the lifetime cost of an asset. There is also a need for guidance on how and when engineers should plan for an asset to fail during severe weather conditions. For example, resisting hurricanes may be more expensive than rebuilding after the event.

[2] If this gap is selected for further analysis, the scoping process will be very important to ensure appropriate boundaries are placed on the analysis. This kind of analysis could quickly become quite broad, so we would recommend focusing on a specific aspect of ancillary services, such as loss of use of pumps in a tunnel.

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# 5. Appendix A: Supporting Information on Gaps Identified through the Literature Review

## 5.1. Translation of Climate Data to Terms that Resonate with Transportation Practitioners

Global climate change models were developed to allow scientists to assess the impacts of a range of possible increases in concentrations of greenhouse gases on Earth's climate and weather. These changes occur over a long time horizon and scientists generally look at changes in long-term annual or seasonal averages and their associated uncertainty. Meanwhile, engineers usually work with climate information focused on much shorter-term events, such as the amount of precipitation that might fall in 30 minutes, or the maximum temperature that could be reached. In addition, engineers regularly base designs on "recurrence intervals" (e.g., the 1-in-25 year event). This mismatch of data formats – changes in annual or seasonal precipitation versus maximum water flow and hourly or sub-hourly precipitation levels – needs to be addressed either through the translation of climate model outputs into formats that engineers can readily integrate into their projects, or through the development of new methodologies to provide engineers with ways to consider how to change their design to make it resilient to climate stresses.

This section identifies gaps in the translation of data from global climate models to project-level information.

### *5.1.1. Climate Communication*

Climate change is a complex topic, even for people who immerse themselves in the details on a regular basis. For planners and engineers, sorting through the science and technical information is time-consuming at best, highly polarized and confusing at worst. Expectations that planners and engineers become experts in the latest climate science in addition to their current responsibilities are unrealistic. Instead, engineers need to be provided concise, targeted information on climate data and resources; the focus should be on scientifically proven facts minus editorialization that tends to polarize audiences. They need to be provided with clear information on why they need to adapt the way transportation infrastructure is designed and specific methodologies on how to do so. This call for change can be supported with better information on observed changes in climate trends, easy access to clear information on projected future changes in climate, and guidance on using projected future climate change changes based on climate model outputs.

The key gaps that have been identified related to communicating about climate change to engineers and planners are documented in Table 1.

| Table 1: Key Climate Communication Knowledge and Data Gaps | | |
|---|---|---|
| **Knowledge or Data Gap** | **Description** | **Examples** |
| **Information that clearly describes why climate change should be addressed in engineering design and explanations as to why greenhouse gas emission mitigation efforts are not sufficient** | Transportation engineering and design will not take climate change into account if the individuals making design and planning decisions do not understand the need to do so. Communication of this information will require documentation of existing changes, projections of current trends into the future, and information on the accelerated degradation of infrastructure due to these stresses. An additional emphasis should be that mitigation alone is insufficient at eliminating increased climate stresses on transportation infrastructure.<br><br>Many engineering designs still rely on the concept of "stationarity", an assumption that historical weather data is a good indicator of future climate (FHWA, 2013). However, in many areas, DOT staff have noticed that the climate has been perceptibly shifting to more frequent and intense weather events; for example, a flood that was once considered to have a 2% annual likelihood of exceedence (a 50-yr event) may now occur every few years. Thus, engineers designing a structure to withstand this type of flood may not being using climate assumptions that adequately portray the magnitude of the event. In many cases, these changes are also leading to increased O&M costs and additional stress on aging infrastructure. It must be communicated that reliance on assumptions of stationarity are increasingly inappropriate. | |
| **Clear climate projection data including guidance on which climate** | Given the long design life intended for many transportation assets, relying on current trends is insufficient to deal with the accelerated rate of change | In California, Caltrans adopted specific sea level rise scenarios and advised local agencies to use these scenarios in their own work |

| Knowledge or Data Gap | Description | Examples |
|---|---|---|
| **scenarios, models, and data should be used when developing adaptation strategies** | projected by climate change models. Access to climate change model outputs and the availability of downscaled climate data have improved tremendously in recent years; however, there still is not, nor will there ever be, a single model ensemble or future climate scenario deemed the ultimate source. Instead, an abundance of models, each representing multiple scenarios based on future economic and social changes, may render all but the most savvy climate experts confused about how to process and use the information. Demystifying this information on projected climate and uncertainties associated with climate model outputs will inform engineers' efforts to consider how single point values used in design and planning may need to be evaluated through sensitivity testing or scenario analysis to mitigate future risks.<br><br>Guidance on which climate scenarios, models, and data should be used (and why) could be addressed by providing engineers with more guidance on which assumptions they should use, and/or by explaining the pros and cons of numerous decision points (which models, single models v. multi-model ensembles, most extreme/least extreme scenarios, how many scenarios, which time frames, dry v. wet models, etc.). This information has the potential to reduce one of the largest barriers to mitigating climate risks in engineering design – selecting appropriate climate futures - by allowing engineers to leverage climate model information and scenario choices that have been approved and vetted locally or by the state. | (Caltrans, 2011). Because the state determines the sea level rise scenarios, individual agencies no longer need to make assumptions about the "right" climate futures. A similar approach is used in Washington State where all climate work relies upon scenarios developed by the University of Washington.<br><br>Communicating the effects of future climate change to engineers has been undertaken several times. In 2010, FHWA produced a report titled *Regional Climate Change Effects: Useful Information for Transportation Agencies* to provide transportation professionals with a summary of regional climate change effects (FHWA, 2010). This resource provides an overview of the effects of climate change on transportation assets and delves into forecasted changes in major climate stressors by region. In 2014, the National Cooperative Highway Research Program produced a special guidance report on adaptation strategies that should be considered through 2050 (and 2100 for sea level rise). Included in the report is a section on climate models – what are they, what can they do, what can be modeled, and to what level of detail can they be used? Both of these |

Table 1: Key Climate Communication Knowledge and Data Gaps

| Table 1: Key Climate Communication Knowledge and Data Gaps<br>Knowledge or Data Gap | Description | Examples |
|---|---|---|
| | | reports provide an excellent resource to engineers, however, they are published papers that are difficult to update with new information and resources. There is currently no comprehensive nationwide database of data and approaches to adaptation for transportation planners and engineers. |
| **There is currently no "one-stop-shop" for climate change data sets and tools for engineers and planners** | A tremendous amount of climate information is housed in a wide variety of online locations. Additionally, the body of knowledge on climate change is continuously growing and changing. Engineers cannot be expected to hunt down all of these disparate resources. They need the information consolidated in an easy to access location so the most recent guidance and data is only a click away whenever they need it.<br><br>This resource would serve as a consistently updated clearinghouse for climate data and resources available to transportation planners. It would serve to house the information identified in the first two gaps as well as additional data sets, methodologies, and tools available to engineers. It would be organized into an easy to access format and be consistently updated as new information is released. It could also serve as a forum for engineers to discuss how they are addressing climate change in their work. | There are several examples of climate data repositories that efficiently display and provide access to climate information; however, they still lack the specificity of information that engineers require. These website formats could be replicated to house the specific types of information engineers need. The California Energy Commission, for example, has produced an interactive web portal, cal-adapt.org, which allows for the easy exploration of climate exposure data through a series of interactive maps. It synthesizes volumes of downscaled climate data for presentation in this graphical layout; however, the data only includes information on changes to monthly averages which is too broad to be useful in engineering design. The source data and additional resources are available for download to anyone who wants access it (CEC, 2014).<br><br>Another excellent example of an easy-to-use |

| Table 1: Key Climate Communication Knowledge and Data Gaps | | |
|---|---|---|
| **Knowledge or Data Gap** | **Description** | **Examples** |
| | | website that collects and synthesizes data, tools, and trainings is the NOAA Digital Coast website (NOAA, 2014). This website collects all information relevant to addressing coastal issues. Its ease of navigation and transparent data tools makes it a frequently used and referenced site (NOAA, 2014). These resources could be collected and organized in such a way as to create a one-stop shop for climate change data and resources that are relevant to transportation planners and engineers. |
| **Information on how to deal with the compound uncertainty inherent in climate projections, downscaling, flood modeling, and engineering analyses** | Uncertainty is included in each step of the climate forecasting process. These uncertainties can compound and increase the total uncertainty of the data that is needed for design purposes. This gap frequently leads to inaction. | This gap was noted early in the Gulf Coast Phase 2 research on adaptation. It was also identified during the Connecticut and Minnesota DOT interviews as being a barrier to considering climate change in design. |
| **Guidance on the appropriate use of downscaled data to aid in understanding the minimum, valid spatial resolution for establishing forecast precipitation totals for a given duration and temperature changes** | When working with rainfall and temperature data, it is important to know the valid spatial resolution used for modeling in a specific area. Guidance on how to use downscaled data and their caveats is needed. | Connecticut DOT, Minnesota DOT, and Washington DOT interviews included this as an issue. In particular, they mentioned the need for downscaled data that captures the geographic differences across their large areas of jurisdiction but they were concerned and unclear about the uncertainty of the data at that resolution. |

| Table 1: Key Climate Communication Knowledge and Data Gaps | | |
|---|---|---|
| **Knowledge or Data Gap** | **Description** | **Examples** |
| **Guidance on defining scenarios for bounding the uncertainty across the ensemble of climate model projections** | For a given set of assumptions, different climate models generate different projections. Similarly, changing input assumptions will yield different model results. Thus, there is uncertainty surrounding climate projection data.<br><br>One approach to dealing with an uncertain future is to use a "scenario approach" – develop possible climate or other stressor scenarios and plan for each scenario. General guidance on the considerations involved in developing scenarios is needed. | This approach was used in the Gulf Coast Phase 2 study. Three emission scenarios, three timeframes, and ten climate models yielded a large number of projected data points. This project therefore developed a "Warmer" and "Hotter" scenario to bound the temperature futures, and a Drier and Wetter scenario to bound the precipitation futures. |

### *5.1.2. Atypical Data Formats and Climate Data Processing of Primary Stressors*

Not all information from climate models has been (or can be) translated into the metrics that engineers are accustomed to using in their analyses. This disconnect in data formats has contributed to a lack of understanding of how to account for climate change during engineering design. This section identifies gaps between standard engineering data formats and climate model outputs, as well as gaps associated with climate data processing such as down-scaled precipitation data. Table 2 provides detail on the specific climate variables where climate projection translation has been identified as an issue.

| Table 2: Typical Engineering Data Formats and their Availability from Climate Models | | |
|---|---|---|
| **Climate Stressor** | **Typical Engineering Data Format (in US Customary Units unless noted otherwise)** | **Appropriate Data Available From Climate Models?** |
| **Precipitation** | • Projected rainfall depths for 24-hour period with a 0.2%, 1%, 2%, 5%, 10%, 20%, and 50% occurrence in any one year<br>• Intensity-duration-frequency (IDF) curves for the 0.2%, 1%, 2%, 5%, 10%, 20%, and 50% probability storms with durations ranging from 5-minutes to 24-hours.<br>• Rainfall distribution curves with incremental values for $P_i/P_{24}$ (where $P_i$ is the incremental precipitation value and $P_{24}$ is the 24 hour total), typically at a 15 minute time step. | Projected 24-hour precipitation for a given RCP with recurrence intervals can be calculated, but post-processing of raw climate model data needs to occur to obtain information in this format and some agreement on providing the associated uncertainty. Use of scenarios / RCP's without a set probability is not directly compatible with the engineering process, but adaptation of the design process is warranted.<br>While climate models can produce outputs at the sub-daily level (such as at the hourly level, as would be necessary for generation of IDF curves and rainfall distribution curves), the uncertainty associated with these data points is too large for these data to be useful for applied purposes. |
| **Temperature** | • Forecast minimum air temperature during a 20-year period (°C)<br>• Maximum 7-day average air temperature during a 20-year period (°C) | Yes, but post-processing of raw climate model data needs to occur to obtain information in this format. |
| **Storm Surge** | • Peak stillwater elevation for return periods of 0.2%, 1%, 2%, 5%, and 10% coastal surges.<br>• Vector wind fields and central pressure for individual coastal storms. | Information like storm surge depths can be calculated, but return intervals are not as straightforward. There are some hurricane modelers that provide future probabilities of various storms occurring in various basins. These models represent the change in likelihood of the occurrence of a particular category of hurricane |

| Table 2: Typical Engineering Data Formats and their Availability from Climate Models | | |
|---|---|---|
| **Climate Stressor** | **Typical Engineering Data Format (in US Customary Units unless noted otherwise)** | **Appropriate Data Available From Climate Models?** |
| | • Hourly average wind speeds for an individual coastal storm event or for return periods of 0.2%, 1, 2%, 5%, and 10%; for determination of wind set-up and design wave conditions. | occurring. However, these models require experts to run and are therefore not readily available for use by transportation engineers.<br><br>It is possible to translate surge depths to levels associated with flooding return intervals, but clearer methodology is needed.<br><br>The vector wind fields and central pressure data are used to define the intensity of historic coastal surge events modeled in ADCIRC. In the Gulf Coast 2 study, these data sets were combined using the Empirical Simulation Technique (EST) to predict return period based coastal flood conditions. Methods for scaling of storm intensities or skewing the Empirical Simulation Technique would seemingly be an appropriate and realistic method for inclusion.<br><br>The Sea, Lake and Overland Surges from Hurricanes (SLOSH) model is a computerized numerical model developed by the National Weather Service (NWS) to estimate storm surge heights resulting from historical, hypothetical, or predicted hurricanes by taking into account the atmospheric pressure, size, forward speed, and track data. |
| **Sea Level Rise** | • Base sea level elevation (or mean higher high water (MHHW)). | Sea level rise is readily available from various sources as a range of possible future sea levels based upon various methodologies including the use of climate |

| Table 2: Typical Engineering Data Formats and their Availability from Climate Models | | |
|---|---|---|
| **Climate Stressor** | **Typical Engineering Data Format (in US Customary Units unless noted otherwise)** | **Appropriate Data Available From Climate Models?** |
| | | models driven with different scenarios and model assumptions. One source of this data is the NOAA Sea Level Rise Viewer. Use of a range of sea level base conditions is not directly compatible with the engineering process, but adaptation of the design process is warranted.<br><br>The U.S. Army Corps of Engineers has released guidance on how to consider sea level rise in design but their methodologies may not be applicable to all project types. |
| **Wind** | • Maximum 3-second gust speeds.<br>• Maximum sustained wind speeds.<br>• Return interval of various wind speeds. | Wind speeds can be modeled over certain time periods (significantly longer than 3 seconds), but depend on user assumptions. From climate models, the daily texture of wind can be obtained and the maximum speed achieved during a day can be extracted.<br><br>Hurricane models are driven by changes in projections for wind shear and warm temperatures and may be an appropriate data source.<br><br>Rough estimates of the return intervals of specific wind speeds or projected likely maximum gusts could be obtained from climate models with post processing. |
| **Wildfires** | • Atypical input in the standard transportation engineering process. | No. Climate models do not provide information on projected wildfire occurrence. Wildfires are an indirect result of changes in climate and are more difficult to |

| Table 2: Typical Engineering Data Formats and their Availability from Climate Models | | |
|---|---|---|
| **Climate Stressor** | **Typical Engineering Data Format (in US Customary Units unless noted otherwise)** | **Appropriate Data Available From Climate Models?** |
| | | model. It is possible that precipitation and temperature proxies could be developed to provide some indication of changes in wildfire likelihoods. Additionally, the likelihood of wildfires is highly tied to ongoing wildfire management practices which are not included in climate models.<br><br>LANDFIRE is a model that provides geospatial layers on fire regimes, vegetation, wildfire fuel, and disturbance. Although this data is not forward looking it is updated every two years and therefore may be able to accurately represent changes in areas likely to experience wildfires frequently. |
| **Dust Storms** | • Atypical input in the standard transportation engineering process. | Climate models represent dust particles to the extent that they affect the radiative balances in the model. It is unclear if this information can be processed to obtain useful information on the return interval of dust storms. |
| **Freeze-Thaw Cycles** | • Daily temperatures (high and low) over a future period of time dictated by the specific design requirement.<br>• Probability of occurrence. | Daily temperature highs and lows can be obtained from climate models. However, the probability of occurrence requires additional post processing. |
| **Snow Coverage and Melt** | • Atypical input in the standard transportation engineering process. | Climate models do not provide direct information on snow coverage and melt but the modeled occurrence of precipitation and low upper air temperatures can provide some information on snowfall. This information |

| Table 2: Typical Engineering Data Formats and their Availability from Climate Models | | |
|---|---|---|
| **Climate Stressor** | **Typical Engineering Data Format (in US Customary Units unless noted otherwise)** | **Appropriate Data Available From Climate Models?** |
| | | would need to be post processed to provide useful information to engineers. There are some limited models on snowpack but they do not predict annual changes in snow coverage and melt. |

Information on climate processing gaps identified through the literature, professional experience, and the FHWA Climate Resiliency Pilot interviews are in .

| Table 3: Knowledge or Data Gaps on Climate Data Processing | | |
|---|---|---|
| **Knowledge or Data Gap** | **Description** | **Examples** |
| **Probability of projected rainfall intensity, duration and frequency** | The engineering design of drainage and stormwater management facilities and the evaluation of flood conditions have been based on the probability of exceedance of a particular rainfall intensity, frequency, and duration. There is less agreement and more skepticism towards model outputs and other techniques that project rainfall depths at the sub-daily scale.<br><br>Climate models are generally based on various emission scenarios for which the probabilities are unstated, forcing decision makers to use surrogate events, a scenarios approach that ultimately requires subjective probability, or the application of some factor of safety. | This issue was cited in the interviews with Connecticut DOT, New York State DOT, Maryland SHA, and Minnesota DOT.<br><br>New York DOT has funded Cornell University to provide detailed information on future precipitation levels across the state. Without investing their own resources to obtain this information they could not design appropriate adaptation strategies. |

Table 3: Knowledge or Data Gaps on Climate Data Processing

| Knowledge or Data Gap | Description | Examples |
|---|---|---|
| **An accepted technique for projecting precipitation at the temporal scale** | The time of peak rainfall within a "design" storm has a large effect on the determination of peak runoff. Knowledge of the distribution of rainfall amounts within a 24-hour duration storm would provide valuable information in determining the rainfall amounts to use in design. However, climate models cannot, with any degree of confidence, project precipitation levels at a scale less than 24-hours. | This issue was the topic of discussion with the Maryland DOT. The Gulf Coast Phase 2 report required working around this issue by making assumptions regarding rainfall distribution. |
| **A robust methodology for adjusting existing rainfall data to account for future climate changes** | With the unavailability of downscaled, projected rainfall data, engineers might consider appropriate scaling of existing precipitation data, if a defensible method were available. | The Connecticut DOT pilot staff noted this gap. NYSDOT and other agencies are considering a "factor of safety" approach. |

| Table 3: Knowledge or Data Gaps on Climate Data Processing | | |
|---|---|---|
| **Knowledge or Data Gap** | **Description** | **Examples** |
| **Better methodologies to predict wave intensity / wave run-up** | This information would assist in the prediction of damage to shore-line roadways and how to protect them during typical and extreme events. Wave modeling and run-up as associated with coastal extreme events is commonly analyzed using a coupled hydrodynamic and wave modeling system such as ADCIRC & SWAN. SWAN computes random, short-crested wind-generated waves in coastal regions and inland waters. The coupled versions of these models have limited availability, require a very high degree of technical knowledge for use, and require a very detailed modeling and analysis process (i.e. a substantial project budget). Wave run-up can be post-processed with models such as RUNUP 2.0 using inputs from a surge model (ADCIRC) or analysis, however, the dynamic nature of waves and interaction with run-up lends itself towards coupled wave and surge modeling. | Oregon DOT mentioned that they are beginning to use wave run-up models but it is difficult to obtain results that are detailed enough for engineering analysis.<br><br>The Gulf Coast Phase 2 study also ran into challenges in predicting wave intensity and wave run up due to budgetary constraints. The Gulf Coast Phase 2 study did include run-up as a backend computation in the Battlefield Parkway sea level rise / wave impact study.<br><br>FEMA uses a coupled hydrodynamic and wave modeling system in flood insurance studies that are currently underway. |

| Table 3: Knowledge or Data Gaps on Climate Data Processing | | |
|---|---|---|
| **Knowledge or Data Gap** | **Description** | **Examples** |
| **Methods on how to determine future hurricane and coastal storm frequency, intensity, and tracks** | Dynamic coastal storm models are available for determining storm surge, wave height, and wave run-up conditions. The procedure for these models typically involves use of historical storm intensity and tracks. Insufficient information is available on the conversion of these techniques to work with storm frequency based events and for increases in storm intensity due to changing climate. This additional information will help the planning and design of a variety of facilities to accommodate these events. | The Gulf Coast 2 study utilized variations in Hurricane George and Hurricane Katrina in lieu of working with projected intensified hurricanes due to climate change. The Gulf Coast 2 work was intended to quantify the impacts of intensified coastal storms, which were developed with the realistic basis of historical events, while recognizing that projections tied to specific time horizons and climate change scenarios were not readily available. |
| **Methodologies or guidance for determining future peak wind speeds** | Bridges, traffic signs and signals, and other transportation structures are built to withstand certain wind speeds. The wind speed threshold is usually determined by wind speeds historically experienced in the area, plus a margin of safety, or the wind speeds associated with potential storms. As the climate changes, peak wind speeds may change as well. However, there are few resources available to assist in determining how wind speeds may change. | The New York State DOT noted that they are facing this challenge. They need information on sustained wind speed and peak wind speeds for designing traffic signals and signs. |

Table 3: Knowledge or Data Gaps on Climate Data Processing

| Knowledge or Data Gap | Description | Examples |
| --- | --- | --- |
| **Models of drought impacts on settlement, vegetation and floods, dust storms, and wildfires.** | Drought has many implications for soil erosion and the hydrologic cycle as well as on normal variations in groundwater levels. Additional information is needed on: the compression of aquifers due to decreasing pore water pressure (from decreasing groundwater levels) that will cause settlement of foundations, etc; hydrologic properties of an individual catchment which can be impacted if increasing droughts alter the vegetative landscape coupled with severe rainstorms, by causing flashier floods with higher peak flow rates (due to loss of plant interception); and implications on the frequency of dust storms (from decreases in latent soil moisture and defoliation) and wildfires. | Software developer, SimCLIM, is working on incorporation of new climate predictions that include considerations for changing drought conditions. |
| **Empirical data, models, and methods to help estimate the impacts of climate stressors on facilities** | Changing precipitation, temperature, and forces in the riverine/coastal environment will damage transportation assets. However, there is no easy way to determine specifically *how* these changes in climate stressors would impact individual facilities. Data, models, or methods to determine the impacts and failure thresholds for specific assets are needed for the development of effective adaptation strategies. | |

### *5.1.3. Secondary Impacts of Climate Change on Transportation Facilities*

The effects of climate stressors on infrastructure must be well understood in order to design resilient infrastructure. Methodologies to estimate impacts in specific geographic locations are needed to develop appropriate response strategies.

Any given climate stress or event can trigger a range of secondary events such as landslides and permafrost melt. These secondary events may cause far greater damage to transportation assets than the original event. Information on these impacts are harder to extract from climate models and therefore require additional methodologies to ascertain the effects they will have on infrastructure in any given location. Defining the secondary impacts caused by climate change and the effect on highways is critical for designing a robust system that will continue to operate under a wide range of future conditions.

Additionally, transportation systems do not operate in isolation; they are dependent on systems such as electricity, communication, and water management structures that are owned and maintained by separate entities. Being resilient to climate change also requires building resiliency to failures in these support systems. An understanding how these systems are vulnerable to climate change and how to operate in emergency situations without them is necessary.

Some of the secondary impacts and simultaneous stressors that require further investigation are included in Table 4.

| Table 4: Secondary and Combined Climate Events Knowledge and Data Gaps | | |
|---|---|---|
| **Knowledge or Data Gap** | **Description** | **Examples** |
| **Information on increases in deforestation due to wildfires or pests and the resulting increases in landslides, flash floods, and sediment/debris flow** | Climate change could affect vegetation through drought, pests, and wildfires. If an area is deforested, there are several subsequent events that can damage transportation infrastructure. Heavy rains can carry excess sediment and dead tree branches downstream which can clog or blow out culverts. Without vegetation to hold soil in place, there is an increased risk of landslides. Without vegetation to help absorb water during periods of heavy precipitation flash flooding is more likely to occur.<br><br>Although the potential for these secondary impacts to affect transportation is known, there currently are no established methodologies to tie changes in precipitation or temperature to actual impacts on particular transportation systems. | In some parts of the United States climate change models forecast that there will be wetter winters and drier summers. This combination of climate stressors makes areas particularly vulnerable to wildfires—the wet winters lead to increased vegetation growth which turns into dead brush that provides fuel for wildfires during the hot summers (TRB, 2014).<br><br>Deforestation can also be caused by pests; the pine bark beetle outbreak has killed off millions of trees from Alaska to California. The life of a pine bark beetle is highly controlled by temperature, and as temperatures continue to rise, it is likely that more frequent and severe outbreaks of these beetles will further reduce tree coverage (Bentz, 2008). |
| **Information on the combined impact of heightened storm surge and riverine flooding on bridges** | Many bridges span waterways adjacent to the coast. These bridges are vulnerable to both storm surge and riverine flooding due to precipitation. Increases in storm intensities can lead to simultaneous coastal storm surge stresses and upstream riverine flooding stresses. Engineers require guidance on how to calculate the probability of these simultaneous events and how to design adaptation solutions that are resilient to both stresses. | Gap was identified at several of the regional peer exchanges in the development of HEC-25 Volume 2. |

| Table 4: Secondary and Combined Climate Events Knowledge and Data Gaps<br>Knowledge or Data Gap | Description | Examples |
|---|---|---|
| **Information on increased flooding due to the combined impact of sea level rise and land subsidence/ uplifting and sedimentation/ erosion** | Climate change models project increases in global sea levels due to melting of the polar ice caps, but at any given coastal location there are additional factors involved in the calculation of *local* sea level rise (LSLR). LSLR takes into account global seal level rise in addition to uplift and subsidence from land settling and tectonic forces, and sedimentation and erosion (FHWA, 2012). Alaska is experiencing substantial uplifting while the Gulf States are rapidly subsiding due to the pumping of groundwater and damming of rivers (TRB 2014). Additionally, there are regional variations in sea level rise due to currents and other natural forces. For example, rates of sea level rise are projected to be higher along the mid-Atlantic even without changes to the land elevations due to subsidence. Without accounting for these compounding factors, the effects of flooding on transportation infrastructure may be grossly miscalculated. Engineers require a clear methodology for accounting for the combined effects of these various factors. Although there are methodologies for all of these stressors, there is no comprehensive data set that combines these stressors in a prepackaged way for use by engineers. | The most detailed and comprehensive data set on sea level rise is the NOAA Digital Coast Sea Level Rise and Coastal Flooding Impacts Viewer. However, this data set does not take into account subsidence/uplifting or sedimentation/erosion. A version of this tool with these additional features would allow engineers to fully understand the impacts of future sea level rise on their assets. |
| **Information on how changes in temperatures will affect structures through changes in freeze-thaw cycles, permafrost melt, and snow coverage/melt cycles** | Increasing temperatures are already having significant effects on roads and bridges constructed in cold locations. The permafrost is thawing, freeze/thaw cycles are changing in frequency, and snow melt rates are increasing.<br><br>The freeze-thaw cycle can be much more damaging to | Michigan DOT is witnessing shifting freeze-thaw cycles – the northern parts of the state are being affected by more frequent fluctuations in the freeze-thaw cycle, similar to those previously seen in the southern parts of the state. These changes in cycles impact pothole creation which in |

| Table 4: Secondary and Combined Climate Events Knowledge and Data Gaps | | |
|---|---|---|
| **Knowledge or Data Gap** | **Description** | **Examples** |
| | infrastructure than extreme cold temperatures that remain stable. Warming temperatures could increase the frequency of freeze-thaw cycles in some areas; however, there is limited information on how freeze-thaw cycle frequency might change in specific areas. Local agencies will be able to obtain information on these changes from the CMIP Data Processing tool once it is released to the general public.<br><br>Thawing permafrost is leading to increased slope instability, landslides, shoreline erosion, and the damaging of bridge and road foundations due to settling (TRB 2014). However, there is very little understanding of when and where permafrost will melt to the point of becoming unstable. The instability is determined by more than just air temperature, it requires information on the depth of the permafrost which is commonly unknown. Information on the "trigger points" which leads to unstable permafrost is needed.<br><br>Snow cover and snow melt are strong influencers on the rainfall runoff rates, base stream flow, and groundwater amounts. Changing snow melt may lead to increased flooding and landslides but may also reduce snow clearing costs. Traditionally, the snow pack slowly melts over the course of the spring and summer months, but climate change could lead to a more rapid snow melt in some areas, sending excess water to downstream communities. | turns impacts their O&M costs. There is limited historical record of freeze-thaw cycles and currently no information on how the freeze-thaw cycles will change in different parts of the state with changing temperatures (MDOT 2014).<br><br>Alaska is experiencing melting permafrost which is creating unstable bridge and roadway conditions. |

| Table 4: Secondary and Combined Climate Events Knowledge and Data Gaps | | |
|---|---|---|
| **Knowledge or Data Gap** | **Description** | **Examples** |
| **Information on changes in precipitation and temperatures affecting annual snow coverage** | If more precipitation falls as rain rather than snow in winter and spring, there is an increased risk of landslides, slope failures, and floods from the runoff, causing road washouts and closures as well as the need for road repair and reconstruction. However, GCMs do not directly provide this kind of precipitation information. | |
| **Information on how coastal zone morphology will change due to sea level rise and changing thermal conditions and vegetative cover** | It is unknown how sea level rise will affect the long-term stability/elevation of marshes, wetlands, beaches, shoals, barrier islands, etc. due to changes in the sediment transport cycle. There will also be thermal changes in the coastal zone that may impact submerged aquatic vegetation, marsh and other vegetation and the long-term sustainability of these coastal areas. Implications of these changes may include a decrease in the coastal zone protection and attenuation of storm surge provided by these coastal structures. | Changes in storm surge due to changes in marsh vegetation was identified in the Gulf Coast/South Atlantic regional peer exchange in the HEC-25 Volume 2 development process. |
| **Methods and models to assess changes to stream morphology due to increases or decreases in higher frequency, smaller discharge flood events (i.e. bankfull events), which change the sediment load/yield to streams** | Although there is information on projected changes in precipitation, there are no established methods for calculating how those precipitation changes result in changes in sediment loads. Changes in sediment loads may result in overall destabilization of roadways and slope failure along the stream due to increases in meandering and erosion/undercutting. | |

| Table 4: Secondary and Combined Climate Events Knowledge and Data Gaps | | |
|---|---|---|
| **Knowledge or Data Gap** | **Description** | **Examples** |
| **Methods for calculating the joint probabilities of climate stressors affecting a region concurrently or consecutively** | As weather of all types becomes more extreme and more frequent, it is likely that multiple stressors could coalesce to create an operations nightmare. Understanding how to design for not just one stressor, but multiple stressors in tandem will result in a more resilient system that is better equipped to deal with the increasingly likely scenario of a "perfect storm' of climate events. Currently, there is a lack of research and guidance on how to account for these joint probabilities. | As the permafrost melts these areas are particularly vulnerable to liquefaction during an earthquake. The joint probability of these events may be useful in seismic design (WFL, 2014). |
| **Methods to model future soil moisture content and the impact of soil moisture content on hydrology (base flow and storm flow)** | Periods of drought or intense precipitation are expected to increase; both of these conditions will affect soil moisture content. Trends in soil moisture content under future climate conditions are needed for comprehensive modeling of future changes in direct runoff. The amount of moisture in the soil has a direct relationship to the amount of runoff resulting from a rainfall event. A comparative difference in the "antecedent moisture condition" (a characterization of the soil moisture content prior to the design event) is a component of predicting future changes to runoff rate and volume. | The Gulf Coast Phase 2 project considered these impacts [future soil moisture content] by using a monthly water budget model that was calibrated for Mobile, AL. The findings suggested that summer months will become increasingly dry under the moderately-high (A2) and high (A1Fi) emission scenarios over time. Drier conditions traditionally experienced during the summer months are projected to extend into late spring and through the fall. The low (B1) emission scenario does not demonstrate large differences from simulated baseline conditions. |

| Table 4: Secondary and Combined Climate Events Knowledge and Data Gaps | | |
|---|---|---|
| **Knowledge or Data Gap** | **Description** | **Examples** |
| **Information to enable prediction of changing coastal environments such as shore line erosion, changes in beach sand, and cliff recession rates** | Changes in beach sand quantities (erosion or augmentation) are not predictable, but they have an impact on roadways adjacent to beach areas and influence the design of erosion protection measures or beach nourishment measures.<br><br>Information that would include all of the forces acting on cliffs (groundwater, rainfall, wind erosion, etc.) is needed to predict cliff stability and recession rates. | This was brought up in the Oregon DOT interview but is relevant to most all roadways adjacent to beach areas in coastal areas around the US. |
| **Information on groundwater as it relates to landslides** | Rainfall data and groundwater are key elements of landslides. Better monitoring and forecasting of these conditions will help correlate these elements and help forecast landslide events | Oregon DOT pilot interview regarding its areas subject to landslides and cliff erosion. |
| **Information on the effects of climate change on freshwater lake levels and, for the Great Lakes, how lake-affected weather patterns will be altered** | It is still being debated if lake levels in the Great Lakes will rise or continue to fall over the long term. Other smaller lakes have received even less study on future lake levels.<br><br>The changes to lake effect snow are highly uncertain. In the winter of 2013-2014, lake effect snow was minimized because the lakes froze over, but in general, it is projected that there may be an increase in lake effect snow due to warmer surface temperature levels but still cold air conditions. In the longer term, as land and air temperatures rise, there could be a shift from snow to rain. These changes will have significant effects on transportation assets but cannot be planned for without a better understanding of the science. | This gap was identified during the interview with the Michigan DOT. |

### *5.1.4. Interrelated Systems*

Proper operation of the transportation system is dependent on the maintained operation of supporting systems such as electricity, communications, and water control systems. Information on how the failure of these ancillary systems affects the transportation network is needed for integrated emergency response planning. Table 5 presents information on the key data and knowledge gaps with respect to interrelated systems.

| Knowledge or Data Gap | Description | Examples |
|---|---|---|
| **Table 5: Knowledge or Data Gaps in Interrelated Systems** | | |
| **Methodologies for determining what electric power investments are necessary to maintain critical assets during extreme weather events** | The electrical grid supplies necessary power to a wide range of transportation assets including mechanical components on moveable bridges, traffic signals, Intelligent Transportation Systems (ITS) (e.g., ramp meters, roadway sensors), and pumps that keep sub-grade equipment and tunnels clear of water. There is currently no methodology for estimating the extent of disruption in the transportation network due to power failures. In order to minimize the damages of power failures, the installation of power redundancy is necessary for the rapid restoration of transportation services (TRB 2008). There is a need for methods to determine the investments in power redundancy that are necessary to maintain critical assets during extreme weather events and associated power outages. | |
| **Information on which communication system investments are critical for the transportation system** | Following a major climate event, the communication network is critical for managing a response. If the communication system is knocked out, repair and recovery efforts will be significantly delayed. Information on the criticality of the communication system for the operation of the transportation network and the interconnectedness of these systems would inform investments in emergency communication networks and facilitate emergency response planning (TRB 2008). | In interviews with the Alabama DOT as part of the Gulf Coast Phase 2 Study, the focus has moved from cell phones to specialized communication equipment that can function independent of cell service. This has become critical to maintain coordination across and between divisions in the event cell towers are down. |

| Table 5: Knowledge or Data Gaps in Interrelated Systems | | |
|---|---|---|
| **Knowledge or Data Gap** | **Description** | **Examples** |
| **An understanding of how sea level rise will affect performance of water control systems** | Impacts of sea level rise and precipitation on man-made hydrologic systems such as storm sewer system, ditches, levees, dikes, etc. needs to be further researched to determine their impact on transportation systems. Integrated planning that considers the adaptation of these structures in addition to the transportation assets will result in the most secure investment. Additionally, these water control structures are frequently owned by separate agencies or private land holders, which makes coordination harder. Without integrated planning, the impacts of changes to the water control structures could have significant unintended consequences for the transportation network. | In Washington, the Army Corps of Engineers is considering adapting water control features to protect communities, but they are not necessarily considering the upstream and downstream affects these projects will have on the through traffic corridors (WSDOT, 2014).<br><br>NYSDOT is specifically concerned about the wastewater systems ability to drain and remove water from the roadway. |

## 5.2. Engineering Solutions for Preparing for Climate Change

Once engineers are provided the appropriate data they still require guidance on how to incorporate that information into engineering design and asset management. This section addresses the remaining gaps in guidance, methodologies, and design standards for integrating climate change adaptation strategies into planning, design and operation of the transportation network.

### *5.2.1. Project Design*

Transportation engineers rely on several select resources for credible information on design guidelines and design data. Although most transportation departments have written their own guidelines and specifications they are generally based on the national guidelines published by the federal agencies such as the Federal Highway Administration in the case of roadway work or the National Oceanic and Atmospheric Administration (NOAA) for rainfall or other climate data. The state and local agencies use the data from these sources and supplement and otherwise tailor the information to better meet the agencies' specific context and needs. The American Association of State Highway and Transportation Officials (AASHTO) is the leading authority on detailed roadway, pavement, and bridge design and produces the industry-accepted practices in these areas. The Transportation Research Board provides a wealth of information on all aspects roadway planning and design through the National Cooperative Highway Research Program (NCHRP). Table 6 identifies common design data sources and the additional information that is needed for them to be effective when designing for conditions that are not expected to follow historic trends.

| Table 6: Knowledge or Data Gaps in Engineering Design | | |
|---|---|---|
| **Knowledge or Data Gap** | **Description** | **Examples** |
| **FEMA base flood data do not reflect potential future rainfall changes nor effects of sea level rise** | Flood maps and Flood Insurance Studies published by FEMA are used to plan roadway locations and elevation, drainage structures and bridge openings. Flood mapping that does not account for future changes can adversely affect design decisions. | During the development of the Gulf Coast 2 project case studies, the FEMA mapping was used to identify existing flooded areas, but the data could not be used to reflect the effects of sea level rise at specific sites. |
| **NOAA Atlas 14 Rainfall Tables do not account for predicted changes in precipitation** | The rainfall data contained in the atlas are the results of statistical analyses of past events and do not reflect future, predicted changes. | During the development of the Gulf Coast 2 project case studies, the Atlas 14 data was useful as a comparative bench mark but could not be used to design an adaptive solution.<br><br>Connecticut, New York State, and Minnesota DOTs reported this as a gap during the interviews. |
| **SCS rainfall distributions / NOAA Atlas 14 rainfall distributions** | Current commonly used SCS rainfall distribution and new NOAA Atlas 14 rainfall distributions are based upon historical rainfall patterns. The distributions do not include considerations for future changes in rainfall patterns due to changes in rainfall intensity. | New York State DOT reported this as a gap during the interviews. |

| Table 6: Knowledge or Data Gaps in Engineering Design | | |
|---|---|---|
| **Knowledge or Data Gap** | **Description** | **Examples** |
| **Regional regression or stream gauge data to account for impacts of changing climate** | Current regional regression equations (commonly developed by the United States Geological Survey (USGS)) are used to predict intense storm flows as a function of drainage area and often other factors (rarely inclusive of precipitation). Regression equations are based upon historical data and do not currently include methods for scaling of the equations to account for future climate conditions; or scaling of the precipitation component of the regression equations (in most cases). | State DOT's are increasingly relying upon the USGS StreamStats program for the development of design discharges, based upon stream gauge data and regression equations. The typical use of this data as encountered on the MNDOT pilot project has caused the analysis team to redevelop hydrologic studies using theoretical models (TR-20) to replace documented analysis for an individual asset.<br><br>Washington State DOT, New York State DOT, and Connecticut DOT reported this as a gap during the interviews. |
| **HEC-20, AASHTO Guide for Bridges Vulnerable to Coastal Storms, AASHTO Model Drainage Manual, HDS 2, HDS 6, and HDS 7 lack guidance on incorporation of climate change data in engineering studies** | The reference documents are industry standard guidance documents developed by FHWA and AASHTO. The documents are generally viewed as policy level documentation on the engineering process for preparation of hydrologic and hydraulic study models for design of highway systems. The referenced documents do not currently include discussion of or procedures for inclusion of climate adaptation analysis in the engineering design process. | New York State DOT cited the lack of guidance from overseeing agencies as a gap and a necessary future step in the inclusion of climate adaptation into design projects. |

| Table 6: Knowledge or Data Gaps in Engineering Design | | |
|---|---|---|
| **Knowledge or Data Gap** | **Description** | **Examples** |
| **AASHTO LRFD does not include a factor of safety or a load combination to include climate adaptation** | AASHTO Load and Resistance Factor Design (LRFD) is the reference for the structural design of bridges and other roadway related structures. The guide book relies upon combinations of loading factors and varied environmental conditions (scour, wind speed, etc.) to guide the design and analysis of structures. In its current format, LRFD does not include factors of safety or other scaling factors for incorporation of climate change into structural design practices. | New York State DOT stated during the interviews that the development of a factor of safety to incorporate climate change may provide a more readily incorporated design method for inclusion of climate change. |
| **HEC-25 does not include guidance on the incorporation of intensified coastal storms into design** | HEC-25 provides FHWA's guidance for the analysis of transportation infrastructure in the coastal environment. While the guidance document does include discussion of sea level rise, guidance on the development of projected changes or scaling of coastal storm surge conditions are not available. Additionally, implications of potential changes to wind and related impacts of waves should be considered in the guidance document.<br><br>HEC-25-Volume 2: Highways in the Coastal Environment: Assessing Extreme Events is currently being developed. It will specifically include some guidance on how to include future climate conditions in the assessment and some limited discussion of climate adaptation but this will remain a gap. | |

| Table 6: Knowledge or Data Gaps in Engineering Design<br>Knowledge or Data Gap | Description | Examples |
|---|---|---|
| **AASHTO Standard Specifications for Structural Supports for Highway Signs, Luminaires, and Traffic Signals does not account for changing wind conditions** | The reference design manual provides guidance for the development of structural designs and local design codes for transportation signage. The manual provides regional values for maximum sustained wind speeds and gust factors to be used for structural analysis of signs, etc. Wind data provided in the design guidance should be updated to provide projections or a scaling factor to incorporate potential climate change impacts on transportation related sign designs. | |
| **Methodology for determining the scale of climate change impacts that will be experienced during a particular assets lifetime** | Infrastructure elements are generally designed for an expected design life, for example, bridges are typically designed for a 75-year life. However, infrastructure is frequently used well beyond its original design life. Being able to estimate the timing of the changes in the climate stressors that affect the infrastructure would enable better planning of adaptive design development. | A facility may be engineered to withstand a 500 year flood but not a 1,000 year flood event. In this case, it has been determined that the costs of building for the 1,000 year event are not justified for the facility. However, with climate change, the intensity of the 500 year storm may be increasing and therefore it may be necessary to reassess the design practices for allowable risk. |
| **Information on the specific points in the planning and engineering process where climate change considerations should be incorporated** | Transportation practitioners need specific guidance not only on *how* to incorporate climate change into their work but also *when* in the process it is most appropriate. Climate change is frequently considered too late to be effectively integrated into the design of a piece of infrastructure.<br><br>The next step in disseminating the information gained from studying climate change adaptation is to consolidate the recommendations into an authoritative guide. | The Gulf Coast 2 project contains some guidance on this topic but is not comprehensive. However, it is a step in the right direction and may be useful in the interim. |

| Table 6: Knowledge or Data Gaps in Engineering Design | | |
|---|---|---|
| **Knowledge or Data Gap** | **Description** | **Examples** |
| **Guidance or direction on the appropriateness of a design/ construction solution versus a non-design/ construction solution** | In certain circumstances, alternatives to construction solutions may be more cost-effective and result in a better overall improvement with fewer negative effects. Procedures for evaluating alternatives to constructed solutions and proof of the effectiveness of green infrastructure would be helpful to transportation practitioners. | This gap became apparent when studying a major culvert crossing in Mobile, AL. A watershed management approach may have provided a better solution with fewer negative consequences than culvert replacement. |
| **Guidance on when to consider designing for a shorter design life for infrastructure that may be increasingly subject to frequent, destructive stress** | The traditional guidance has been to design durable infrastructure that can withstand all stresses placed upon it, but with climate change, roadways are being exposed to more frequent and severe stress. Given the uncertainty and potential severity of these climate stresses it may make more sense to design some pieces of infrastructure for a shorter than traditional design life and replace it as necessary. Guidance is needed on when this approach is appropriate and how to design for it. | |
| **Guidance on early integration of planning and engineering on climate-related issues** | Future changes in climate and land uses need to be discussed by engineers and planners prior to selecting an appropriate course of action. Guidance is needed on how to approach this collaboration and ensure that these conversations are taking place. | If a small island will be under water at 3 feet of sea level rise does it make sense to adapt the sole bridge serving it to be able to deal with 5 ft. of sea level rise? It depends if other adaptation actions will occur to protect the assets that the bridge is serving. |

### *5.2.2. Transportation Asset Management*

The American Association of State Highway and Transportation Officials (AASHTO) defines transportation asset management as:

> *A strategic and systematic process of operating, maintaining, upgrading and expanding physical assets effectively throughout their lifecycle. It focuses on business and engineering practices for resource allocation and utilization, with the objective of better decision-making based upon quality information and well-defined objectives.*

A well-designed transportation asset management program will minimize the lifecycle costs for the management, operation, and maintenance of transportation assets, such as bridges, pavements, culverts, etc. Additionally, a well-designed transportation asset management program will consider the condition of physical assets and any risks to the performance, safety, or reliability of that asset to deliver the level of service required. Risk factors that can impact an asset's performance can range from age (e.g., many assets have surpassed their design lives) to natural environment factors (e.g., flooding, extreme temperatures, climate stressors, etc.). Integrating climate change into transportation asset management can support the identification and prioritization of asset repairs, improvements, or replacements based on the vulnerability and criticality of the asset.

Knowledge or data gaps identified in the broader application of climate change risk in transportation asset management programs and systems are outlined in Table 7.

| Table 7: Knowledge and Data Gaps in the Broader Application of Climate Change Risk in Transportation Asset Management | | |
|---|---|---|
| **Knowledge or Data Gap** | **Description** | **Examples** |
| **Revised methods of cost planning for O&M of assets** | Some DOTs, like Michigan DOT determine winter O&M budgets by averaging expenses over the previous five years. However, with increasing variability in weather patterns, revised cost planning methods are needed to account for the abnormality mild to very severe winters experienced. | Gap identified in interview with Michigan DOT pilot. |
| **Better geographic understanding of climate impacts to understand which types of assets could be affected** | Better geographic understanding of climate impacts would benefit not only asset management planning but emergency response planning and project design. Understanding climate impacts across a region can help DOTs understand the types of assets or projects that would be impacted by a particular type of climate stressor(s), and therefore be able to better plan for the resilience of that asset. | Gap identified in interview with Michigan DOT pilot. |
| **Data gaps related to environmental context in asset management systems** | Some DOTs, as stated in the case of the Michigan DOT resilience pilot, do not have data related to asset elevation, flood plain location, or any hydrologic information in their asset management systems. Understanding the environmental context of the asset would help flag assets vulnerable to climate impacts. | Gap identified in interview with Michigan DOT pilot. |
| **Methods to understand system-wide impacts of site specific asset failure** | Studies within agencies are emerging that evaluate the impacts of failure of one asset or asset type on the performance of the transportation system or network, but processes are not yet in place to evaluate this in a way that prioritizes asset needs in a way that reduces risk across the system. | Examples include FHWA Resilience Pilots - Michigan DOT and NYSDOT DOT. |

| Table 7: Knowledge and Data Gaps in the Broader Application of Climate Change Risk in Transportation Asset Management | | |
|---|---|---|
| **Knowledge or Data Gap** | **Description** | **Examples** |
| **Understanding of impacts of non-extreme weather events on asset performance** | In many cases, it is not just an extreme weather event that will cause an asset to fail. Heavy precipitation, for example, can cause a drainage systems to fail if the system is already aged and past its design life. A drainage backup could cause road flooding in some areas and/or soil saturation of adjoining land. | Examples experienced in Minnesota and Maine; and also documented in *Design Standards for US Transportation Infrastructure: The Implications of Climate Change*. |

## 5.3. Methods for Evaluating Efficacy and Costs/Benefits of Implementing Adaptation Measures

Resources are extremely tight across all public agencies; many are barely managing to meet the ongoing operation and maintenance needs of the existing transportation system. Investing resources to adapt to climate change is frequently viewed as a luxury that agencies cannot afford at this point in time. Every single FHWA pilot that was interviewed emphasized the need for justification for allocating resources to climate change adaptation. Engineers understand that investing a small amount of money during project design and development or during routine maintenance is more cost effective than reacting to failed and damaged infrastructure after an extreme weather event, however, they need help producing documentation of this. Table 8 highlights information that is needed for cost-benefit assessments.

| Table 8: Knowledge and Data Gaps on Adaptation Efficacy and Cost/Benefit Data | | |
|---|---|---|
| **Knowledge or Data Gap** | **Description** | **Examples** |
| **Methods to track the damage costs associated with extreme weather events to build the case for investing in resiliency projects** | With every extreme weather event comes costs associated with emergency response and repair. Documenting these costs and tracking them over time allows the asset owner to understand the long-term cost of underbuilt infrastructure. While this information is sometimes recorded in FEMA worksheets there are many climate events that don't qualify for FEMA or FHWA aid but are equally relevant costs of extreme weather. | The Federal Transit Administration (FTA) recently released a funding opportunity for transit operators affected by Hurricane Sandy to enhance the resiliency of their transit network. In order to apply, an analysis of the hazard mitigation cost effectiveness had to be completed. One of the easiest ways to document the costs of not adapting was by citing recorded costs of historical damages. In most cases, these damages were either not recorded or they were documented in formats that were hard to track down and not easy to use |
| **Methods to assess the risk of damage/ failure from future extreme weather events** | Similar to challenges in integrating climate change considerations into project design, data on the likelihood and consequence of climate stressors on an asset or asset type is needed to be able to assess the risk of damage/failure. | One example is the incorporation of more intense rainfall and the associated likelihood of bridge failures due to scour action as documented in "Impacts of Climate Change on Scour-Vulnerable Bridges: Assessment Based on HYRSK"; also identified in an interview with the Minnesota DOT pilot staff. |

| Table 8: Knowledge and Data Gaps on Adaptation Efficacy and Cost/Benefit Data | | |
|---|---|---|
| **Knowledge or Data Gap** | **Description** | **Examples** |
| **Methods to monetize the impacts of future extreme weather events on transportation systems** | Transportation practitioners do not have good information on the ripple effects that losing a particular piece of infrastructure has to the general economy nor do they have a straightforward way to quantify the impacts of these events. Future guidance on estimating these "costs of inaction" may include the economic impact of reduced freight transport and the loss of productive hours, risks to public health, costs to repair the infrastructure, and a number of other categories. | |
| **Information on the cost of implementing common adaptation strategies** | There is limited information on how much it would cost to design a structure to be resilient to extreme events. Costs are very project-specific, but rules of thumb or example project costs could be helpful. | |
| **Methods to minimize the total lifetime expected cost of a transportation asset** | The total expected cost is a sum of the costs of the adaptation measures plus the costs of the expected damages and the monetized cost of the loss of facility use during repair following an extreme weather event over the lifetime of the asset. It takes into account the probability of the climate event and an economic analysis of the repercussions. Using this technique ensures that infrastructure is not over-built and that public resources are effectively spent. There is currently no guidance on how to use this decision making approach to select the appropriate level of engineering design. | This gap is documented in *A Risk Based Approach to Flood Management Decisions in a Non-Stationary World* (Rosner et al. 2014). |

## 5.4. Organizational Processes/ Decision Making

In addition to engineering gaps, there are organizational and decision making gaps that affect the ability of public agencies to implement the adaptation strategies and create non-engineering solutions such as emergency response plans. Developing case studies to fill these gaps is currently outside of the scope of work for this project; however, it is important to identify and recognize that these gaps will exist as remaining barriers to adaptation implementation. Therefore, as gaps were discovered in the literature or identified by the project team they were recorded in this section. Over time, these gaps will need to be addressed to ensure that the planning and engineering community is comprehensively and proactively planning for the effects of climate change. Table 9 provides details on gaps related to organizational processes and decision making.

| Table 9: Organizational Processes/Decision Making Gaps | | |
|---|---|---|
| **Knowledge or Data Gap** | **Description** | **Examples** |
| **Frameworks for determining appropriate proactive and reactive adaptation strategies** | In some instances it may be best to take a more reactive approach to adaptation by adapting after existing assets have proven to be vulnerable and damaged or after some trigger thresholds have been reached. Reactive strategies can also include increasing proactive warning systems to improve safety. A more proactive approach to adaptation requires retrofitting and designing for adaptation prior to experiencing damages. By doing so, infrastructure is more resilient to future changes, but it runs the risk of being overbuilt for the level of climate change that it will actually experience. If this occurs it means that excessive public resources may have been spent on the projects. A framework for weighing these strategies against each other and selecting the appropriate response in different situations is needed. | |
| **Funding options for adaptation projects** | Public agencies operate in a highly resource constrained setting where operating and maintaining the current transportation network frequently exceeds budgets. This situation leaves few resources to allocate to adapting infrastructure to climate change. As climate change accelerates, the costs to adapt will likely be well beyond the current capacity of public agencies. New sources of funding and creative cost sharing approaches to addressing vulnerabilities need to be identified. | |

| Table 9: Organizational Processes/Decision Making Gaps | | |
|---|---|---|
| **Knowledge or Data Gap** | **Description** | **Examples** |
| **Ways to address the disparate time frames for planning horizons and assets useful life** | Planning horizons for most long-range transportation are only 25 to 30 years although the infrastructure they are planning will likely be in place much longer. This makes it difficult to consider the impacts climate change will have on these assets and the surrounding communicates beyond the time period of the plan (TRB 2014). | Sea level rise may not inundate a planned roadway until after the horizon year of the long-range transportation plan, but it will certainly be impacted before the end of its useful life (TRB 2008). |
| **Identification of partnerships for holistic adaptation planning** | Transportation systems do not operate in isolation; they are intrinsically tied to the surrounding communities. Holistic planning with a wide range of stakeholders is necessary to develop cost effective adaptation plans that consider the entire transportation system, its users, and the utilities it depends upon. Guidance is needed on the local partnerships that are necessary to create comprehensive adaptation plans and how to go about fostering those relationships. | For climate stressors such as sea level rise, it would be cost prohibitive to protect all vulnerable transportation assets but investing in a regional adaptation strategy that includes targeted levees and other water management strategies could protect key transportation links, neighboring communities, and other vital services. |
| **Integration of climate change considerations into the environmental review process** | The Council on Environmental Quality (CEQ) has proposed guidance on integrating climate change considerations into the environmental review process but no regulations have been passed to require local agencies to consider it (TRB 2014). Additional guidance and examples of its application are required to ensure widespread adoption of this practice. | The Metropolitan Transportation Commission (MTC), the MPO for the San Francisco Bay Area, included a chapter in their Environmental Impact Report (EIR) on the effects of future sea level rise on proposed land use development and transportation investments. As mitigation measures, a suite of adaptation options were provided for consideration (MTC 2013). Frameworks for addressing additional climate stressors need to be developed. |

| Table 9: Organizational Processes/Decision Making Gaps | | |
|---|---|---|
| **Knowledge or Data Gap** | **Description** | **Examples** |
| **Identification of adaptation co-benefits** | Adaptation measures frequently provide many co-benefits and may even be the co-benefit in a larger project (FHWA, 2013). By implementing adaptation strategies as a co-benefit or being able to document the ways in which adaptation strategies help achieve additional agency goals, it may be easier to allocate resources to a project (TRB 2014).<br><br>Alternatively, adaptation measures can be the co-benefits of other projects. Being able to "sell" adaptation projects in this way frequently makes the investment an easier sell in locations where adaptation strategies are not yet popular investments.<br><br>More information on how adaptation can result in co-benefits would be useful. | The state of Washington installed wider culverts for the primary purpose of enhancing fish passage but those larger culverts are also less vulnerable to increased stream flow due to future climate change (FHWA 2012b). |

| Table 9: Organizational Processes/Decision Making Gaps | | |
|---|---|---|
| **Knowledge or Data Gap** | **Description** | **Examples** |
| **Consistent guidance from policymakers on climate change scenarios** | Transportation planners and engineers must adhere to requirements and guidance from various agencies, including U.S. DOT, FEMA, AASHTO, and state and local requirements. If one agency tells them to take climate change into account, but another one doesn't, there may be ambiguity about what to do. | During the Gulf Coast Study, Phase 2, some stakeholders noted that they receive conflicting guidance on how to address climate change. For example, they are told to use FEMA flood maps, and they know that FEMA has no plans to update these maps to account for climate change. Meanwhile, the U.S. DOT is encouraging transportation officials to account for future climate change. The stakeholders felt that they were receiving conflicting guidance from Federal agencies, and that the agencies will need to be more coordinated if real action is to take place.<br><br>Additionally, several DOTs that were interviewed for this work identified a need for consistent guidance from federal agencies. They were quick to state their desire to address climate change but they consistently requested guidance from the federal agencies on which climate scenarios to use and a mandate to do so. |

| Table 9: Organizational Processes/Decision Making Gaps | | |
|---|---|---|
| **Knowledge or Data Gap** | **Description** | **Examples** |
| **Improved weather information systems including an increased number of gauges or sensors** | Early warning systems, including weather information systems, cameras and sensors, can support emergency response planning efforts, particularly in the deployment of emergency equipment, communicating critical traveler information, or even for necessary road closures to protect public safety (e.g., in the event of flash flooding). A greater understanding of how these systems could be used as adaptive measures is needed. | In the Gulf Coast Phase 2 study, it was noted that Road Weather Information Systems (RWIS), typically employed in snow-belt states, may be applied for year-round use to monitor precipitation and flooding. |

# 6. Appendix B: Crosswalk of High-Priority Gaps and Potential Engineering Analyses to Conduct

The tables below present a cross walk between climate stressors, potential engineering assessments, and the 17 priority gaps identified in Section 3. The analyses noted in the tables are potential analyses that could be conducted in later tasks of this project to help fill the gaps identified in this report.

| | | | #1. Selecting climate information | #2. Compounding effects of uncertainty | #3. Climate model precipitation data | #4. Developing rainfall distribution type curves | #5. Changes in temperature/ precipitation patterns and soil moisture conditions | #6. Incorporating sea level rise and changing storm surge in the absence of probabilities | #7. Combining historical climate data with projected future climate changes | #8. National temperature based design maps |
|---|---|---|---|---|---|---|---|---|---|---|
| Precipitation | Bridge | Riverine watershed study, riverine flooding and impacts, and bridge scour (determination of failure points) | X | X | | X | X | | X | |
| | Culvert | Small catchment watershed analysis, hydraulics and flooding impacts. Changes to stream morphology due to increases or decreases in bankfull events and sediment transport | X | | X | X | X | | | |
| | Stormwater Facility/ Interior Drainage System | Watershed based study of peak flows, with multiple existing facilities. Evaluate watershed performance of BMPs over individual BMPs | X | | X | X | X | | | |
| | Pavement | Effects of drought on settlement and soil erosion | X | | | | X | | | |
| | | Methods to model future soil moisture content and its effect on water flows | X | | | | X | | | |
| | Slope Stability | Effects of heavy precipitation on slope stability [potentially focus on a rock cut to differentiate from the post-fire slope stability study below] | X | | X | | X | | | |
| Sea Level Rise | Drainage Canal | Effect of rising groundwater table on surface water management | X | | X | X | | X | | |
| Precip + Sea Level Rise | Storm Drain System | Analyze loss of efficiency due to sea level rise and the associated upstream flooding impacts | X | | X | X | X | X | X | |
| Storm Surge /Waves + Sea Level Rise | Bridge -Wave Deck Impact | Coupled surge and wave modeling focused on projected changes to wave loading resulting from changes to coastal storm surges | X | | | | | X | | |
| | Bridge - Scour | Perform combined watershed runoff and storm surge/wave modeling to evaluate scour potential | X | | | | | X | | |
| | Natural Systems | Effect of climate change on natural systems and coastal erosion | X | | | | | X | | |
| | Tunnel | Coupled storm surge/wave modeling and wave runup and overtopping modeling. Analyze tunnel portal characteristics, interior storage and drainage, and pump sufficiency | X | | | | | X | | |
| | Pavement – undermining | Changes to coastal zone morphology – cliff erosion, bluff recession, etc. | X | | | | | X | | |
| | Pavement – overwashing | Damage by overwashing processes as storm surge and waves move across pavements | X | | | | | X | | |
| | Power-Dependent Infrastructure | Effects of power outages on emergency operations based on proximity of electrical equipment to projected flood zones | X | | | | | X | | |
| Temperature | Pavement/ Concrete | Map change in performance grade asphalt binder specifications under climate scenarios | X | | | | | | X | X |
| | Bridge Deck/ Joints for Movable Bridges | Analyze expansion/failure of concrete bridge members due to extreme temperatures | X | | | | | | X | X |
| Wind | Highway Signage | Sign stability analysis under increased wind conditions | X | | | | | | X | |
| | Long-Span Bridges | Long-span bridge stability under increased wind loadings | X | | | | | | X | |
| Freeze-Thaw Cycles | Pavement | Long-term durability of pavements under increased freeze-thaw cycles using the MEPDG software | X | | | | | | X | |
| Snow Coverage / Melt | Culvert / Bridge | Watershed hydrology study with extreme events simulation. Associated impacts to selected structure | X | | | | | | X | |
| | O&M | Impacts of increased snow fall volume on O&M procedures | X | | | | | | X | |
| Wildfire | Slope Stability | Slope stability study after deforestation due to decreased stability and increased soil moisture | X | | | | X | | | |
| | Culvert | Hydrologic response study of the effects of deforestation and the associated debris/sediment on a culvert | X | | X | X | | | | |

| | | | #9. Secondary impacts of climate stressors | #10. Incorporate climate change into design practices | #11. Climate change impacts on a network of assets | #12. Integrating climate change into the design of lower cost assets | #13. Phased adaptation strategies | #14. How losing auxiliary infrastructure services will affect an asset | #15. Engineering structures to be resilient to simultaneous climate events | #16. Balancing climate change uncertainty with cost of adaptation | #17. Costs and benefits of adaptive measures |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Precipitation | Bridge | Riverine watershed study, riverine flooding and impacts, and bridge scour (determination of failure points) | | | | | X | | X | X | X |
| | Culvert | Small catchment watershed analysis, hydraulics and flooding impacts. Changes to stream morphology due to increases or decreases in bankfull events and sediment transport | X | X | | X | | | | X | X |
| | Stormwater Facility/ Interior Drainage System | Watershed based study of peak flows, with multiple existing facilities. Evaluate watershed performance of BMPs over individual BMPs | | | X | X | X | | | X | X |
| | Pavement | Effects of drought on settlement and soil erosion | X | | | X | | | | X | X |
| | | Methods to model future soil moisture content and its effect on water flows | X | | | X | | | | X | X |
| | Slope Stability | Effects of heavy precipitation on slope stability [potentially focus on a rock cut to differentiate from the post-fire slope stability study below] | X | | | | | | | X | X |
| Sea Level Rise | Drainage Canal | Effect of rising groundwater table on surface water management | X | | | X | X | | | X | X |
| Precip + Sea Level Rise | Storm Drain System | Analyze loss of efficiency due to sea level rise and the associated upstream flooding impacts | | | X | X | X | | X | X | X |
| Storm Surge /Waves + Sea Level Rise | Bridge -Wave Deck Impact | Coupled surge and wave modeling focused on projected changes to wave loading resulting from changes to coastal storm surges | | X | | | | | | X | X |
| | Bridge - Scour | Perform combined watershed runoff and storm surge/wave modeling to evaluate scour potential | X | X | | | | | X | X | X |
| | Natural Systems | Effect of climate change on natural systems and coastal erosion | X | | X | | X | | | X | X |
| | Tunnel | Coupled storm surge/wave modeling and wave runup and overtopping modeling. Analyze tunnel portal characteristics, interior storage and drainage, and pump sufficiency | | X | | | X | | | X | X |
| | Pavement – undermining | Changes to coastal zone morphology – cliff erosion, bluff recession, etc. | X | X | | X | | | | X | X |
| | Pavement – overwashing | Damage by overwashing processes as storm surge and waves move across pavements | | | | | X | | | X | X |
| | Power-Dependent Infrastructure | Effects of power outages on emergency operations based on proximity of electrical equipment to projected flood zones | X | | X | | X | X | | X | X |
| Temperature | Pavement/ Concrete | Map change in performance grade asphalt binder specifications under climate scenarios | | X | | X | | | | X | X |
| | Bridge Deck/ Joints for Movable Bridges | Analyze expansion/failure of concrete bridge members due to extreme temperatures | | X | | | | | | X | X |
| Wind | Highway Signage | Sign stability analysis under increased wind conditions | | X | | X | | | | X | X |
| | Long-Span Bridges (cable stay / suspension) | Long-span bridge stability under increased wind loadings | | | | | | | | X | X |
| Freeze-Thaw Cycles | Pavement | Long-term durability of pavements under increased freeze-thaw cycles using the MEPDG software | X | X | | X | X | | | X | X |
| Snow Coverage and Melt | Culvert / Bridge | Watershed hydrology study with extreme events simulation. Associated impacts to selected structure | X | | | | X | | | X | X |
| | O&M | Impacts of increased snow fall volume on O&M procedures | X | | | | | | | X | X |
| Wildfire | Slope Stability | Slope stability study after deforestation due to decreased stability and increased soil moisture | X | | | | | | | X | X |
| | Culvert | Hydrologic response study of the effects of deforestation and the associated debris/sediment on a culvert | X | | | X | | | | X | X |

# 7. Appendix C: June 17, 2014 Climate Change and Engineering Gap Assessment Meeting Attendees

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