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

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. 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. • 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. 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. 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. 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. 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. 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). 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

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. 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. 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. 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). 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. 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. 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.

Table 5: Knowledge or Data Gaps in Interrelated Systems

Knowledge or Data Gap	Description	Examples
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). 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. 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. 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. 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 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. 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). 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. 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. 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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