Progress and Challenges in Incorporating Climate Change Information into Transportation Research and Design

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Abstract: The vulnerability of our nation's transportation infrastructure to climate change and extreme weather is now well documented and the transportation community has identified numerous strategies to potentially mitigate these vulnerabilities. The challenges to the infrastructure sector presented by climate change can only be met through collaboration between the climate science community, who evaluate what the future will likely look like, and the engineering community, who implement our societal response. To facilitate this process, the authors asked: what progress has been made and what needs to be done now in order to allow for the graceful convergence of these two disciplines? In late 2012, the Infrastructure and Climate Network (ICNet), a National Science Foundation–supported research collaboration network, was established to answer that question. This article presents examples of how the ICNet experience has shown the way toward a new generation of innovation and cross-disciplinary research, challenges that can be address by such collaboration, and specific guidance for partnerships and methods to effectively address complex questions requiring a cogeneration of knowledge. **DOI: 10.1061/(ASCE)IS.1943-555X.0000377.**

Introduction

In 2011, the United States experienced 16 distinct billion-dollar-disasters, namely weather and climate related events with damages exceeding US$1 billion, adjusted for inflation (NCEI 2017), totaling over US$50 billion (Smith and Katz 2013). Many of these events affected transportation infrastructure. For example, Hurricane Irene disrupted transportation services in the northeast United States, especially in Vermont [where more than 800 km (500 mi) of roads and approximately 200 bridges were damaged or destroyed] and eastern New York, ultimately costing at least 45 lives and US $7.3 billion. In February of the same year, the city of Chicago was brought to a virtual standstill and hundreds of motorists stranded for 12 h on Lake Shore Drive by over 0.5 m (nearly 2 ft) of snow, the city's third largest snowfall on record. In 2012, the United States experienced the warmest year and the warmest July on record (Diffenbaugh and Sherer 2013); July 2016 became the warmest month ever recorded on Earth. On one day in July 2012, a U.S. Airways regional jet was delayed in Washington DC because its tires were stuck in the tarmac and a subway train derailed because of buckled tracks, both due to record-high temperatures (Wald and Schwartz 2012). The exclamation point on a disastrous warm season was Hurricane Sandy in October 2012, which devastated New York City with a record 2.87 m (9.42 ft) storm surge, flooding over 80 km (50 mi) of subway tunnels and costing 117 lives (CDC 2013) and an estimated US$71.4 billion

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in damage (NOAA 2016). In 2014, heavy precipitation caused deadly mudslides in Oso, WA and landslides in Colorado that blocked roadways. The record-setting snowfall of early 2015 in Boston, MA brought the city and its public transit system to a complete halt, costing approximately $1 billion in lost wages alone, with total economic losses expected to be up to US$50 billion (Weather Channel 2016).

Attribution of individual extreme events to anthropogenic climate change, once considered impossible, is now occurring with probabilistic attribution being conducted for certain events that have appropriate observational data for comparison to model output (Peterson et al. 2012; NASEM 2016). Since 2011, the *Bulletin of the American Meteorological Society* has devoted a special supplement to this subject each year. At the same time, the spatial and temporal resolution of climate projections is increasing, with experimental global model simulations at 25 km resolution and empirical-statistical downscaling to individual weather stations (Wuebbles et al. 2014). As the field of climate extremes matures, this information will increasingly be incorporated into engineering design for the future. To facilitate this process, the authors asked: what needs to be done in order to allow for the graceful convergence of these disciplines now and in the future?

In late 2012, the Infrastructure and Climate Network (ICNet), a National Science Foundation–supported research collaboration network, was established to answer that question. The Infrastructure and Climate Network is a network of climate scientists and engineers comprising over 60 academics, students, and engineering practitioners dedicated to accelerating new research in transportation infrastructure related to climate change impacts and adaptation. Since its inception, ICNet has made progress in bridging the gap between the climate science and transportation engineering communities. Members of ICNet have also learned how to better articulate the challenges in incorporating climate information in engineering design. The objectives of this paper are to provide the engineering community with (1) insights from ICNet's work at the intersection of the climate science and transportation infrastructure sectors that go beyond those widely available in transportation agency reports and review papers, which tend to synthesize the technical literature; and (2) suggested pathways forward.

Progress and Challenges to Integrating Climate Change Effects in Transportation Engineering

Extreme events, as well as more subtle and pervasive changes in long-term temperature and precipitation regimes from climate change, will interrupt the use of transportation infrastructure, increase maintenance and repair costs, and alter the deterioration process of the materials used in its construction. Over the past decade, the United States transportation sector has published over 50 state, national, and regional agency reports on climate change and infrastructure vulnerability, impacts, and adaptation strategies that collectively demonstrate the sector's increasing knowledge and capacity about climate change. (e.g., NRC 2008; CCSP 2008; FHWA 2010, 2013; GAO 2013; ASCE-CCAC 2013; TRB 2014; among others). The community largely agrees that the nation's transportation systems and networks are vulnerable to the changing climate. In particular, the transportation sector consistently points to the following set of potential climate change impacts as being most relevant to transportation infrastructure: (1) increases in intense precipitation events, (2) increases in Arctic temperatures (leading to permafrost melting), (3) rising sea levels, (4) increases in very hot days and heat waves, and (5) increases in hurricane intensity (USDOT 2014; CNA Military Advisory Board 2014; Caltrans 2013; MacArthur et al. 2012; Burbank et al. 2012). The transportation sector has largely obtained their information from national climate reports (e.g., Mellilo et al. 2014; Meyer et al. 2014; IPCC 2014) and sea level rise assessments. Some studies rely on climate change information generated by regional and local climate scientists (e.g., Wake et al. 2014; Kirshen et al. 2015).

It is well understood that impacts to transportation infrastructure from climate change will manifest themselves in bridge, rail, air, maritime and port facilities, and pavement systems, as well as transportation networks via a wide range of performance impacts that include component damage, rapid deterioration, system failures, travel delays and disruptions, and public safety risks (USDOT 2015; TRB 2014; CNA Military Advisory Board 2014; Caltrans 2013; Meyer et al. 2013, 2012; Johnson 2012). A subtle, but significant, recent advancement is that state transportation agencies are reframing impacts and strategies to match their units and programmatic hierarchies (e.g., Caltrans 2013). Table 1 outlines the relationship between climate impacts and state department of transportation (DOT) operations. The bad news is that climate stressors affect all aspects of DOT activities from operations and maintenance to long-term planning. Fortunately, some of these impacts can be accommodated within the current DOT structure. For instance, more frequent extreme events may require a concomitant increase in the frequency of culvert maintenance and pavement rehabilitation. However, climate change will impose additional burdens on DOTs, many of which are already stretched thin within the current funding environment. For instance, in the absence of additional sources of revenue, more frequent maintenance and replacement of system components may erode resources that would normally be set aside for system upgrades.

The transportation community as a whole has identified numerous strategies to potentially mitigate climate change impacts (USACE 2015; Wilbanks et al. 2014; White House 2013;

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Table 1. Representative Hierarchy of Climate Impacts That Affect State-Level DOT Programs and Operations (Courtesy of Ann M. Scholz, Research Engineer, New Hampshire Department of Transportation)

Group	Operation	Impact of climate stressors
Programs	• Pavement and paving • Bridge maintenance • Bridge rehabilitation and replacement • Culvert replacement • Asset management performance strategies	• Patching and frost heaves • Erosion of stream beds and scour of susceptible bridge piers/abuttments • Funding for local roads and bridges • Managing risks
Policies	• Design level for storm frequency • Culvert upgrade and replacement • Drainage design • Project development • Maintenance funding	• Updating design standards • More frequent culvert monitoring • Construction season • Funding for winter maintenance
Activities	• Communication with utilities, state police, local planning agencies • Seasonal maintenance • Transportation infrastructure	• Emergency events • Invasive species • Work schedules • Increased maintenance and repairs
Other	• Aging vehicles and equipment • Reduced staffing levels • Emergency planning	• Wear and tear during all seasons • Reduced efficiency • Establish evacuation routes

USDOT 2014; Meyer 2008). These strategies include (1) increased resistance (e.g., strong and taller structures, critical route protection, and larger culverts/bridge openings) (Claman et al. 2014; Thomson et al. 2012); (2) development of advanced information technologies (internal asset management systems, advanced weather and mobile observations, crowd sourcing, and big data analysis tools) (Muller et al. 2015; Drobot et al. 2014; Mahoney and O'Sullivan 2013); and (3) novel approaches and designs that are readily adaptable as environmental loads change (e.g., soft engineering supported by ecological and geomorphic principles, drought-tolerant vegetation, dynamic load restrictions) (Bigford 2015; Strauch et al. 2015).

The first step in reducing climate change impacts is to identify vulnerable assets. State and federal transportation agencies have made significant progress in assessing the vulnerability of transportation systems around the country. The Federal Highway Administration (FHWA) Climate Change Resilience Pilot Program (FHWA 2016) provided critical leadership in which FHWA partnered with state DOTs and metropolitan planning organizations to identify the vulnerability of transportation systems to climate change and extreme weather events (see Douglas et al. 2016b as an example). Moreover, the FHWA compiled the pilot findings and developed tools to enable the broader community to understand best practices in vulnerability assessment. These efforts helped communities and private organizations to also evaluate the vulnerability of their transportation infrastructure (e.g., Massport 2014; Douglas et al. 2016a, b).

The next challenge is to reduce or eliminate those vulnerabilities. This effort is still in its infancy. The FHWA provided the opportunity for progress by specifically making adaptation activities eligible for funding available through the federal-aid program (FHWA 2017). However, while the transportation sector's knowledge base is considerable and rapidly advancing, there are few, if any, national or statewide design standards that incorporate climate change. A critical challenge is to cast this knowledge in a manner that allows infrastructure engineers, asset managers, and transportation officials to modify planning, operation, and design guidelines to consider future climates. To some extent, the lack of federal and state policies requiring action is a barrier. But arguably progress on policies is moving more rapidly than sound technical guidance as exemplified by the recent requirement that the effects of climate change be considered in National Environmental Policy Act reviews (CEQ 2016).

Even if policies exist, the engineering community of practice is challenged to implement effective design standards, regulation, and standards of practice because more mature cross-disciplinary fundamental and applied knowledge, tools, and evidence of vulnerabilities are critically needed before these can be robustly and quantitatively revised to incorporate the impacts of climate change (Wilbanks et al. 2013; Baglin 2014; ASCE 2015). Communities of practice struggle with translating climate model output to engineering design values. Design standards that include environmental loads (e.g., wind loads on bridges), consider long-term exposure to water and heat (e.g., pavements), or rely on environmental states that will likely change in the future (e.g., foundations in permafrost or roads in coastal zones) need to be reconsidered in light of the range of variability used in behavioral response studies. While adaptive management often uses strategies that include *prepare and monitor* actions (Kirshen et al. 2015), these strategies rely on monitoring systems that do not yet exist and triggers or thresholds that still need to be established. Furthermore, tools are needed to quantify the costs and performance of adaptation over the expected lifecycle of the asset under transient environmental conditions.

Challenges to the Maturation of the Climate Science and Engineering Collaborations

The challenge of ensuring that existing and new transportation infrastructure are resilient to a changing climate cannot be met when approached solely from the perspective of, and with the tools of, a single discipline. Research on cross-disciplinary efforts is now at the stage of articulating the obstacles and of searching for innovative solutions for addressing those obstacles (Gardner 2013; McGreavy et al. 2013). For instance, there are institutional barriers that must be overcome such as the fact that cross-disciplinary work can be slow, producing fewer publications, and research tends to be applied, both of which are disincentives in certain sectors. Ambiguity in team expectations and project outcomes is inherent in the nature of cross-disciplinary work (Dewulf et al. 2007). McCoy and

Gardner (2012) and Gardner (2013) found that those with a higher tolerance for ambiguity were also more likely to feel satisfied with interdisciplinary collaboration and continue to participate in such efforts. Amey and Brown (2004) found individuals in early stages of collaborative projects tend to see only their own disciplinary perspectives but become more open to other perspectives as the research developed.

The differing cultures of climate science and engineering reflect different orientations to, and therefore responses to, ambiguity and uncertainty. Engineering as a design-based discipline must develop plans that reduce and hold uncertainty to a minimum because most systems that infrastructure engineers design and build provide key services to millions of people and anchor regional economies. Additionally, even when applying accepted practices and proven techniques, legal liability exposures represent an ever-present threat (NSPE 2017). Conversely, climate science often focuses on not only understanding but broadening the knowledge of uncertainties in the interaction between humans and their environment and quantifying the potential for nonstationarity in the climate system as a result of human emissions, both of which have important implications for the future performance, conditions, and contexts of infrastructure. It is no easy task to constrain this uncertainty and translate climate model output into information that is useful to engineering practice at the appropriate scale. In some cases (e.g., the 3 s wind speeds required to calculate bridge stress), this information will more than likely never be forthcoming, and collaboration must focus on mitigating vulnerabilities rather than quantifying risks. In others, climate science may challenge standard engineering practice (e.g., application of frequency analysis), and both approaches can offer quantitative information. The literature on cross-disciplinary research shows that if such efforts are to succeed, recognition of the differences in approaches must be followed by attempts to find ways to integrate these approaches so as to take into account the fundamentals of the individual disciplines (Golde and Gallagher 1999; Frost and Jean 2003; Amey and Brown 2004; van Kerkhoff 2005; Holley 2009; Gardner 2013).

ICNet-Identified Pathways for Progress on Current Challenges

Drawing from the two proceeding sections, climate change resilient infrastructure is challenged both by transportation agencies' ability to institutionalize climate change in practice and the disconnect between climate scientists and engineers. While the former appears to be the most pressing need, without the latter the necessary tools and information will not consistently be available to support adaptation strategies. In light of this, progress in both of these areas is critically needed. Through ICNet activities, the authors have recognized disciplinary differences in understanding and communicating, identified areas where improved communication strategies are needed to integrate these differences, and produced a number of pertinent insights in how to develop and sustain collaboration between climate scientists and infrastructure engineers, including the following:

- The necessity of regular interactions to start the conversation, maintain the energy and enthusiasm, generate and advance ideas, and build trust between the disciplines. Participation in regular network meetings and smaller working groups creates an environment of trust and collegiality between participants from a variety of backgrounds (academia, government agencies, private practice) so that new information can be embraced and tough questions candidly debated;
- The breaking down of barriers between governmental agencies, scientific disciplines, and individual perspectives. Collaboration and buy-in is required at all levels, from basic research at universities and government labs to application by federal and state transportation agencies. Also needed are ground truthing and implementation initiatives by local public works departments and engineering consultants; and
- The impetus for moving engineering design forward lies at the level of professional societies (i.e., ASCE) and national organizations [i.e., Transportation Research Board (TRB), AASHTO] that influence the design methods used by practitioners. Climate science and meteorological organizations at both the national [e.g., National Oceanographic and Atmospheric Administration (NOAA), American Meteorological Society (AMS)] and regional (e.g., NOAA Regional Integrated Sciences and Assessments Centers, Department of Interior Climate Science Centers) scale need to engage with these engineering societies in order to accelerate the process.

While the ICNet thus far has not come up with the right answers, participants from each discipline have listened and learned enough to begin to ask more meaningful questions and to set more achievable objectives in addressing the impacts of climate change. In fact, a survey of the ICNet members in April 2016 found that 84% of respondents have worked with new colleagues as a result of their participation in the ICNet. Additionally, the annual ICNet workshop, which brings together members from academia, government, and private practice, was ranked the most useful service provided by the network. The next two sections offer examples of how collaboration among ICNet members has led to innovative research outcomes and research topics that require more collaborative investigation, respectively.

Progress in Incorporating Climate Information into Engineering Design

To design transportation structures such as bridges and roadways, bridge and pavement engineers rely on design guidance and manuals published by AASHTO, TRB, and state departments of transportation. Beyond design, infrastructure engineers also understand how these systems will perform over time as well as when, how, and what components should be inspected and what maintenance should be performed. This section presents a specific example of the progress and process by which climate information is being integrated into existing design methods. Meyer (2008) provides another example on bridge design.

Pavement Design Example

Climatic conditions, particularly temperature and moisture, play an important role in the properties of pavement materials and affect pavement response and performance. A changing climate raises the possibility that the rate at which damage (such as rutting and cracking) accumulates and the frequency or severity of sudden catastrophic failures (i.e., washouts) may increase, which in turn increases the cost to maintain a safe and effective road network. Existing pavement design methods allow an engineer to vary pavement design parameters (structure, materials, and prevailing site conditions) to limit the amount of damage in a pavement over a specified design period. Pavement studies represent the evolution of research that, taken as a whole, quantify forecasted climate change impacts well beyond focused component impacts, provide guidance needed to assess and address the potential design changes and costs of incorporating climate change driven rainfall events or extreme heat in practice (Mills et al. 2009; Meagher et al. 2012; Mallick et al. 2014).

The earliest quantitative analyses of climate change impacts on pavement performance were conducted by Mills et al. (2007, 2009). They concluded that forecasted temperature and precipitation changes are important considerations in several deterioration processes related to pavement performance: rutting, thermal cracking, and frost heave and thaw weakening. Following on that work the ICNet members presented a methodology to assess the impact of future climate change on pavement deterioration (Meagher et al. 2012). Based on the recommendations from climate scientists, Meagher et al.'s (2012) methodology used the North American Regional Climate Change Assessment Program's (NARCCAP) products. They were the first to identify biases between model output and the required *Mechanistic-Empirical Pavement Design Guide* (MEPDG) site information. Statisticians engaged in climate change research identified a cumulative distribution function transformation method (Michelangeli et al. 2009) appropriate to adjust the model temperature data to site-specific data prior to its use in the MEPDG. The importance of this probabilistic transformation was underscored by the shift in historical and future temperature forecasts once the observed statistical characteristics were matched. Mallick et al. (2014) leveraged this work to develop a framework to answer one of the most relevant questions: what will be the impact of future climate on pavement life and maintenance costs? Their work showed that changing air temperature, rainfall, sea water level rise, and number of hurricanes will significantly impact pavement performance with costs increasing nonlinearly by more than 160% in 100 years. An interdisciplinary group combined these studies and used them to guide future research needed to determine how climate nonstationarity differentially impact transportation infrastructure design, performance, and life span (Daniel et al. 2014). Based on these recommendations, Hayhoe et al. (2015) conducted directed work on climate projections for the transportation sector while Mallick et al. (2016) developed a simulation tool that analyzes climate change induced impacts on hot mix asphalt pavements and applied the tool at seven cities across the United States. This collective effort provided systematic, incremental advancements for pavement engineering that included impact assessment, the development of analysis framework, contributions from the climate community, and timely identification of knowledge gaps. The effort is also notable for communicating its findings to the engineering community through consistent publication record in mainstream transportation engineering journals.

Challenges Still to be Faced in Incorporating Climate Information into Engineering Design

The biggest opportunities for both collaboration and innovation at the intersection of climate science and transportation engineering research may reside in (1) constraining future uncertainty in the short term, and (2) defining transportation resilience over the long term through continuous, coordinated knowledge sharing between the disciplines that allows successful adaptation to occur. Rather than attempt to capture all the research needs, the following two examples familiarize the reader with infrastructure practices, provide some depth regarding specific research needs, and identify the roles of climate and engineering partners in challenges that transcend the capacity of disciplinary approaches.

Example 1: Addressing Uncertainty

Transportation infrastructure design standards provide well-defined specifications that account for uncertainties (e.g., material properties, environmental loads, and physical loads). For instance, roadways and bridges are designed to meet the projected traffic demands and maximum physical (i.e., large trucks) and environmental (i.e. wind, temperature) loads expected within the service life of the structure. Engineers typically accommodate these uncertainties as well as uncertainties outside the standard (e.g., design and construction errors, long-term maintenance, and model adequacy) by applying a factor of safety to their designs. A multiplier is used to scale-up the calculated limit state design (i.e., that which would be on the verge of failure) to an assumed safe level. Effectively, the system is built stronger than our best estimates of what is needed. Institutional knowledge and engineering experience also plays a crucial role in accommodating uncertainty in design and construction.

For the environmental factors, the established practice in transportation engineering is to assume a stationary climate and to use historical observations to estimate future environmental loads during the design process. While long recognized as potentially incorrect (Knox 1984; Hirschboeck 1987, 1988; Knox 2000; Jain and Lall 2001; Franks and Kuczera 2003), this assumption has nonetheless allowed engineers to design infrastructure that has been remarkably reliable to an acceptable level of failure risk largely because climate change and natural variability have been sufficiently small and effective means for hedging against them (i.e., factor-of-safety design) have been available (Stedinger et al. 1985; Matalas 1997; Milly et al. 2008; Lins and Cohn 2011). However, climate change has raised the concern that future extremes will exceed historical excursions (Milly et al. 2008), and hence the design community should no longer rely solely on historic datasets and single-valued design parameters. And given the potential cost of adapting to climate change, "reducing uncertainty in climate predictions is potentially of enormous economic value." (Hawkins and Sutton 2009, p. 1102) and represents an area of collaboration between engineers and climate scientists.

A recent ICNet workshop strongly recommended that to bridge the uncertainty gap, joint research be conducted by interdisciplinary teams. The team should identify and quantify the likely sources of uncertainty, including environmental, materials, engineering models, and maintenance, for various transportation planning, design, and operations processes. The results should be synthesized to determine the relative order of magnitude of these uncertainties and associated system sensitivity, risks to existing and planned assets, and to identify critical vulnerability from the decision makers' perspective (i.e., Brown and Wilby 2012). This would highlight areas where climate science information can augment the resilience of a structure and where reduction in climate uncertainty could have the most benefit. A better understanding of the complete temporal evolution of all uncertainties including climate uncertainty (Hawkins and Sutton 2009) could inform design life and failure risk estimation. Some additional uncertainty related research questions identified in the 2015 annual ICNet workshop are:

- How can engineering and climate modeling experience be coupled with statistical analysis (i.e., a Bayesian approach) to reduce predictive uncertainty?
- Which aspects of climate projection confidence are increasing most rapidly and do these match the measures of uncertainty that are most useful to the engineering community? and
- Are there time horizons where stationary estimates are adequate for DOT planning and design purposes and beyond which nonstationary methods are needed and what role does climate uncertainty play in establishing those horizons?

Much like the pavement example discussed previously, the ICNet recommends tackling the important questions by breaking the grand challenges into manageable questions and engaging diverse team of research engineering, climate scientists and statisticians. The ICNet researchers have identified a simple transportation engineering challenge, namely climate change impacts on winter road performance. Prior to addressing uncertainty questions, an

interdisciplinary team conducted and vetted the foundation work that links climate change to winter road impacts (Daniel et al. 2017). The path forward is for this team to use this readily understandable analysis to consider complex questions around uncertainty posed earlier.

Example 2: Long-Term System Resiliency. How Parameters and Processes Change in Response to Climate

Research is needed to address the most critical gaps in our understanding of physical processes and parameters, e.g., how moisture changes within the pavement structure during freeze/thaw cycles and how new materials hold up to climate over time. Climate change needs to be effectively incorporated into evaluations or predictions of pavement performance. Cross-disciplinary collaboration is needed to examine how climate factors act in combination with increased traffic demand and new types of materials and construction methods, while recognizing and accounting for the uncertainties in materials, models, traffic, and operations/maintenance under today's climate as well as that of the future. One question that often arises is how extreme events under climate change will impact catastrophic road failures such as washouts. However, there are very few existing models for predicting the failure of roads because of the action of moving water and there is no database that contains adequate information for understanding and studying the factors that contribute to these failures. Hence, collaborative research could lead to a better understanding of this pervasive problem.

The effect of climate change on the entire lifecycle of pavements (and pavement systems) including maintenance costs may be best evaluated through a systems dynamics approach. A system dynamics model linking climatic changes to pavement maintenance and costs was developed by members of the ICNet group (Mallick et al. 2014). The effects of climate change that are considered include increases in average annual rainfall, maximum air temperature, hurricane frequency and sea level rise. These parameters will affect the pavement systems by increasing the pavement temperature and number of months during which the subgrade is saturated. Pavement state variables were linked to material responses (i.e., stiffness) and the effects on pavement performance was represented by simulating rutting to illustrate the framework.

The model was run for a time span of 100 years for two cases, with and without climate change. The average pavement life decreased from 16 (without climate change) to 4 years (with climate change) as a result of reduced effective subgrade and hot mix asphalt modulus due to climate change. The maintenance costs increased after 20 years for both cases; a linear increase was observed when climate change was not considered whereas consideration of climate change resulted in a nonlinear increase. At the end of 100 years, the cost of maintenance considering climate change increased 160%, as compared to the less than 60% increase without the impact of climate change. The study illustrates that there is a critical need for accurate and reliable data regarding climate changes, particularly those that will have significant effects on pavement performance.

Pathways for Moving Forward

There is no shortage of opportunities for the application of climate science information in transportation engineering projects or vice versa. To date, when this has occurred it has not always drawn from the other disciplines' best methods or been presented in a relevant context. Examples from the transportation infrastructure community include studies that use bias correction incorrectly, use the output from too few climate models to be credible, or draw from readily available but inappropriate information sources. Examples from the climate science community include studies that aggregate model output to summary statistics with limited value or lack discrimination based on transportation relevant units. The challenges inherent in working across climate change and transportation disciplines means that selection of research questions and framing of those questions must be carefully considered; there is no time to waste.

To address knowledge gaps in a credible and meaningful manner, the authors recommend cross-disciplinary partnerships be created through involvement in small, focused research projects involving one discipline as a service provider. For example, intercomparison studies that propagate climate projections and encompass a range of timescales, models, and scenarios through carefully selected transportation models would provide insights into the relative importance of various sources of uncertainty, and under what conditions that uncertainty matters to engineers and which conditions alter the decisions that must be made. These narrower questions also provide the basis for productively identifying, prioritizing, and engaging in more complex questions requiring cogeneration of knowledge. Furthermore, cross-disciplinary partnerships should not be limited to research but should also extend to action oriented adaptation policies and practice employed by federal, state, and local transportation agencies.

This recommendation for partnerships comes from the ICNet experience. Over the last four years, ICNet members have developed and sustained collaboration and built trust among climate scientists, infrastructure engineers, and agency decision makers. Numerous and increasingly deeper conversations over that period are now yielding new knowledge, interesting research questions, and insights about communication between these communities. The ICNet has demonstrated how climate science and engineering researchers and practitioners enthusiastically embrace the paradigm of joint collaboration. To augment the engineer's ability to work with nonstationarity and the complexity of climate model outputs, the authors recommend that relevant transportation infrastructure projects have a climate scientist embedded in it, one who is invested in supporting the design process and who understands the constraints engineers face. Moreover, funders need to be convinced of the value of this collaboration. The ICNet has demonstrated that there is intense interest and willingness between members of both the engineering and climate science disciplines; the authors believe other similar initiatives such as that recently mandated in California (CLI 2006) will prove this true disciplinewide.

The current focus on addressing very large, societally relevant challenges such as how to improve the resilience of society and critical infrastructure to future extreme weather often highlights the role of viable transportation networks. Research questions in these studies tend to be broad, crossing many sectors and drawing from the latest systems and big data advances. The complexity of these challenges too often necessitates simplification of system responses from individual sectors. This is reasonable if those systems are well understood and the dominant response pathways and feedbacks to environmental forcings can be identified. However, for transportation infrastructure this is often not the case and new knowledge from cross-disciplinary research is needed to understand how a changing climate will impact the frequencies and magnitudes of infrastructure failures in the future. But existing knowledge is also important; bringing the ICNet members to a common baseline of understanding about climate science and engineering fundamentals was an important first step. And the resulting collaboration of climate scientists and engineers through ICNet can both foster new applications of climate model output in engineering practice and influence how engineering standards

and policies accommodate nonstationary climate implications. Thus, while federal funding agencies have increasingly offered significant support for large multidisciplinary research, the authors believe opportunities that specifically target climate science and infrastructure need to be initiated.

Concluding Remarks

The challenges to the infrastructure sector presented by climate change can only be met through collaboration between the climate science community, who evaluate what the future will likely look like, and the engineering community, who implement our societal response. The collaboration of these two communities also draws on social science perspectives for resources in advancing cross-disciplinary research. The opportunities have only begun to be tapped, and the ICNet experience has shown the way toward a new generation of innovation and cross-disciplinary research that will define the resiliency of the existing and future United States transportation infrastructure. As one DOT engineer stated during the 2014 annual ICNet workshop, civil engineering "*may have to move from design services to risk management*." This can only occur through deliberate integration of and investment in climate science and engineering research to plan for a changing—and a safer—future.

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