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Surface Transportation System Resilience to Climate Change and Extreme Weather Events

First International Conference

September 16–18, 2015
Washington D.C.

TRANSPORTATION RESEARCH BOARD

TRANSPORTATION RESEARCH CIRCULAR E-C204

Surface Transportation System Resilience to Climate Change and Extreme Weather Events

First International Conference

Cosponsored by
Federal Highway Administration
Federal Railroad Administration
American Association of State Highway and Transportation Officials
WSP–Parsons Brinckerhoff

September 16–18, 2015
National Academies of Sciences, Engineering, and Medicine
Washington, D.C.

Rapporteurs
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Volpe National Transportation Systems Center

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Preface

Climate change and extreme weather events have become significant concerns for the global transportation sector. In collaboration with the FHWA and FTA, TRB organized the First International Conference on Surface Transportation System Resilience to Climate Change and Extreme Weather Events to promote dialogue on research, implementation, and lessons learned on this important topic. The inaugural conference, which was held September 16–18, 2015, and webcast live from Washington, D.C., convened more than 500 experts from across the world to explore state-of-the-art research and emerging practices and policies on adapting surface transportation networks to the potential impacts of climate change and extreme weather events.

Through a mix of plenary sessions, technical discussions in breakout sessions, and informal information exchanges, attendees explored the efforts of government, private sector, academia, business, and nonprofit organizations to bring the consideration of climate change and extreme weather resilience into the mainstream of all aspects of transportation decision making. Special focus was given to the development and application of climate information and innovative tools.

The conference represented one component of a larger TRB focus on climate-related impacts on transportation. As part of its strategic planning process, TRB identifies critical issues that all programs and committees should address. Addressing the serious transportation-related challenges posed by climate change likely will require interdisciplinary strategies; therefore, the TRB Executive Committee decided to make climate resiliency one of the top three strategic issues for TRB to focus on in the next several years. Now, the National Academies of Sciences, Engineering, and Medicine has initiated four major policy studies related to climate change and has established a Resilient America Roundtable, which convenes experts from all sectors to design and catalyze activities to handle extreme weather events.

This e-circular, prepared by the conference rapporteurs, follows the conference format and plenary sessions in chronological order. All research topics that speakers identified in the course of their presentations are included in the summary. The views expressed in the proceedings are those of the individual conference participants and do not necessarily represent the views of all participants; the planning team; the sponsoring committees; TRB; or the National Academies of Sciences, Engineering, and Medicine. This e-circular has not been subjected to the formal TRB peer-review process.

Leslie Stahl, Gina Filosa, Emily Lawless, and Carson Poe of the U.S. Department of Transportation's Volpe National Transportation Systems Center served as the rapporteurs for this publication.

FHWA, FRA, AASHTO, and WSP–Parsons Brinckerhoff cosponsored the conference.

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Conference Introduction and Keynote Address

Heather Holsinger from the FHWA opened the conference by thanking participants for attending and providing an overview of the conference agenda. Monica Starnes from TRB encouraged participants to engage in discussion both in person and online and reminded everyone that the sessions will be available online for a year after the conference concludes.

Neil Pedersen, Executive Director of TRB, welcomed participants and described some of the work that TRB is doing to address climate-related issues. He said climate requires an interdisciplinary approach, including science, engineering, and medicine, and said resilience is a priority topic for the National Academies of Sciences, Engineering, and Medicine. TRB committees initially identified resilience as a top priority, and it has since been included in related topics such as security, transit, and airport projects. As part of its strategic plan, TRB identifies critical issues that all programs and committees should address and resiliency rose to the top. The Executive Committee decided to make climate resiliency one of the top-three strategic issues for TRB to focus on in the next several years. This conference is critical to helping TRB set the agenda on this topic. TRB also created a new section within the Technical Activities Committee to address these issues. The Executive Committee is addressing climate resiliency in their upcoming meetings and Vicki Arroyo from the Georgetown Climate Center is serving as a member. The National Academies of Sciences, Engineering, and Medicine have four major policy studies in progress related to climate change, including geoengineering climate and developing a U.S. research agenda to advance subsidies, and have established the Resilient America Roundtable, which convenes experts from all sectors to design and catalyze activities to handle extreme weather events.

Gloria Shepherd, Associate Administrator for the FHWA Office of Planning, Environment, and Realty, stressed the importance on taking the experts and information that FHWA has gained in the past several years and making sure the solutions become a reality. Infrastructure needs to work hand-in-hand with environment to help practitioners across all disciplines to understand the importance of climate change. Climate information needs to be translated into data that practitioners can understand and use.

Katherine Hayhoe from Texas Tech University gave the keynote address, focusing on why climate change is relevant to the transportation community. Hayhoe opened by stating that no sector is as important as infrastructure. Society has thus far assumed that over the long term, all weather events average out and the range of variability can be captured by looking at the past, but such assumptions are no longer valid. Temperatures are changing globally, and strong El Niño is modifying weather patterns around the world, taking heat out of the ocean and putting it into the atmosphere. The heat content of the atmosphere and the ocean is increasing. More frequent extreme heat, precipitation, and storms, along with sea level rise, will likely impact transportation infrastructure. A confounding factor is that many scientists have been conservative about projections, and real impacts may be more extreme and frequent than anticipated. There are fortunately a number of actions that society can take to prepare for an uncertain future. Priorities, such rail transport, bridge failure, or flooding, and weather events connected to those priorities can be identified so that preparations can be made. When those two steps are not enough, downscaled data can be used to generate locally relevant information from global climate models. Making smart choices now and responding proactively will improve outcomes in the future. The key to success is incorporating climate preparedness in existing frameworks and planning.

PLENARY SESSION

Climate Data

You Can't Always Get What You Want—But How Do I Get What I Need?

This plenary session focused on the climate data needs of transportation practitioners and the degree to which climate data producers can fulfill those needs. Each panelist presented a brief overview of the data that his/her agency has identified as necessary actions to make better climate-related decisions and how they have used such data. The panel consisted of experts in climate science, hydrology, transportation planning, project implementation, and operations and maintenance, including

- Keith Dixon, National Oceanic and Atmospheric Administration (NOAA);
- Andy Wood, National Center for Atmospheric Research (NCAR);
- Karuna Pujara, Maryland State Highway Administration (SHA);
- Herby Lissade, California Department of Transportation (Caltrans);
- Jeff Perlman, North Jersey Transportation Planning Authority (NJTPA); and
- Gordana Petkovic, Norwegian Public Roads Administration (NPRA).

Herby Lissade said Caltrans is reviewing weather information, bridge designs, pavement types, flood paths, atmospheric storm exercises, and emergency response routes to determine what data Caltrans already has and what it will need in the future. Caltrans is in the process of developing WeatherShare to provide information to field staff to help improve decision making.[1] FloodCast, FireCast, SnowCast, and ShakeCast are all tools that look at the impacts of fires, floods, snow, and earthquakes on the state's transportation systems. These tools are helping Caltrans improve planning, response, and recovery efforts for climate-related impacts.

Jeff Perlman spoke about the climate data gathering and analysis that the NJTPA, the Federally mandated metropolitan planning organization (MPO) for North New Jersey, has completed with its operating partners New Jersey Transit, New Jersey Department of Transportation (DOT), and county and municipal planners and engineers. They looked at statewide, county, and local assets and are determining climate change vulnerabilities. Using funding from the FHWA climate resiliency pilot program, NJTPA is looking at how extreme temperatures and flooding will impact infrastructure in 2050 and 2100. Some of its efforts to downscale climate data are a lesson in what not to do since it selected models based on how well they could predict past events, which many climate scientists do not recommend.

Gordana Petkovic said the basis for everything NPRA has done is collaboration between different professions. The NPRA has free access to meteorological data, hydrological data, and national or regional climate projections for 2100. It also has easy-to-use interactive maps that demonstrate the effects of climate change in certain regions. Communication with experts outside of roadway engineering is important; short-term precipitation increases are something NPRA needs to collaborate on and has done so with the hydrological society. Road owners are responsible for describing what they need and explaining and understanding the uncertainty of the data that scientists supply.

Karuna Pujara talked about how sea level rise, sea level surge, and precipitation are currently the most significant climate concerns for Maryland SHA. Precipitation changes have thus far been the most challenging for Maryland SHA because engineers want accuracy and precision, but predicting

future increases can only provide ranges. The SHA has found that a tendency has been to overdesign or oversize infrastructure, which is a strategy that may not always work and may need to be adapted.

Andy Wood said NCAR has learned a lot in the past decade. There were many unknowns in climate models 10 to 15 years ago, but that has been improving. There is a move towards sector-specific practice, and there is also a "triage" happening, where agencies are making the best of what they have to understand and account for potential errors and uncertainties in the models.

Keith Dixon said that as a scientist at NOAA, he represents the upstream portion of the data chain, where the models are big, complex, and physics based. These models are getting better, but they can be biased and variable in their results. Climate scientists are interested in how they can translate and transfer climate data so that it is used wisely and can be repurposed as decision support.

BREAKOUT 1: DECISION SUPPORT FOR PLANNING

The session presented various decision-support tools to address questions such as: Where should new infrastructure be sited? how should it be designed, operated, and maintained? Michael Savonis of ICF International moderated the session, which included three presentations.

A Benefit–Cost Analysis Framework for Integrating Resilience into Transportation Planning and Operations

Sam Merrill presented a benefit–cost analysis framework for how to support site-specific analysis to inform decisions at the conceptual design stage, prior to typical preliminary design efforts. The framework calls for evaluating the relative fiscal efficiency of various conceptual designs, which is calculated by dividing the cumulative avoided damages by the construction and cumulative repair costs, in order to compare the relative savings in terms of avoided damages between designs. The approach also allows practitioners to optimize design choices across different climate change impact scenarios, which minimizes the odds that an agency either underbuilds or overbuilds infrastructure.

Gaming Adaptation: Using Role-Play Simulation Exercises to Help Decision Makers and Other Stakeholders Enhance Their Resilience

Todd Schenk presented the use of role-play exercises as a way to bring stakeholders together and deliberate on solutions to climate change problems. Schenk presented an example of a role-playing simulation project that was run in three different cities—Rotterdam, Singapore, and Boston—that brought together a multistakeholder group to evaluate potential solutions to addressing congestion in a fictional port city. The example highlighted two key takeaways: (1) in terms of addressing climate change, uncertainty is prevalent and poses not only a scientific challenge but is also a governance challenge. The most popular response from the groups was to maintain flexibility in terms of policy making, planning, and design; and (2) multistakeholder engagement is important and the process design and techniques used to engage stakeholders has implications.

The Infrastructure Planning Support System: An Introduction

Xavier Espinet presented the IPSS tool, which the University of Colorado Boulder developed as a quantitative engineering and economic analysis of climate vulnerability at a network level.[2]

IPSS can be used to identify vulnerable assets across a transportation system and then estimate the cost–benefit analysis of adaptation strategies to address those vulnerable assets. The tool supports robust decision making by developing projections for additional maintenance and repair costs associated with business as usual approaches (no adaptation) and determining the long-term benefits of adaptation strategies.

Dynamic Learning Process for Selecting Storm Protection Investments

Raymond Chan of Northwestern University presented on the dynamic learning process. Building protective infrastructure is challenging in terms of securing financing and advancing decisions. These challenges are compounded by the uncertain and evolving risks associated with climate change. The dynamic learning process allows decision makers to adjust infrastructure over time by incorporating estimates of how risk evolves throughout the life of an infrastructure in order to make changes to the system in order to maintain an acceptable level of risk policy throughout the life of infrastructure. The dynamic learning process is a shift away from thinking about infrastructure design as a single decision point and moving towards processes that for infrastructure to be flexibly deployed in order to allow for future adaptations within the lifetime of the infrastructure.

BREAKOUT 2: DESIGNING BACK TO THE FUTURE— LOOKING AT THE PAST AND TURNING TOWARD THE FUTURE

This session focused on the development of technical guidance and procedures for incorporating climate information into project designs. Engineers traditionally have looked at past recorded data to perform designs and are now being asked to incorporate climate information into future projections. FHWA's Brian Beucler presided over the session, which included four presentations.

Incorporating Climate Change, Risk, and Resilience into Hydrologic Design Procedures for Transportation Infrastructure

Roger Kilgore of Kilgore Consulting and Management presented on ways to incorporate uncertainty in climate change into hydraulic design procedures for transportation infrastructure. Although the science of climate change is not as certain as engineers would like, decisions need to be made now in terms of safety and costs. FHWA's Hydraulic Engineering Circular 17 (HEC-17) takes the least economic cost approach of looking at different scenarios.[3] The new circular, which will be called *Highways in the River Environment—Floodplains, Extreme Events, Risk, and Resilience*, should be complete by spring 2017. Chapter three will examine riverine technologies and define terms such as "extreme flood event" and consider concepts such as no stationarity and natural variability in observed data. Regression equations may be adaptable to climate change questions, but new methods may need to be established for evaluating whether watersheds can handle anticipated climate and extreme weather effects. Chapter four will examine thresholds for risks, resiliency, and failures. The circular will also focus on making sure engineers do not underprepare for future flood trends but also avoid overinvesting in preparations. Chapter five will discuss where readers can find climate models and downscaling

information and which data sources are most accessible and useful for hydraulic engineering. Chapter six will feature an analysis framework that provides guidance for different levels of effort required to assess and adapt various types of infrastructure. Chapter seven will include case studies that can help engineering designers moderate the tendency to be cumulatively conservative, meaning choosing scenarios that have a very low probability of happening.

Assessing Vulnerability of Iowa's Highway Infrastructure to Climate Change and Stream Hydrology for Implementation of Resiliency and Hydraulic Design Practices

David Claman from the Iowa DOT discussed how the Iowa DOT is assessing the vulnerability of Iowa's highway infrastructure to rain and flooding events. It recently participated in an FHWA resilience pilot project. The study examined the Skunk River and Cedar River basins. These basins were selected due to major flood events in 2008 and 2010 where the Interstates were overtopped. Iowa DOT looked at three different greenhouse gas (GHG) emissions scenarios in nine different climate models and downscaled the data, so it could be usable for the two sites. Using the asynchronous regional regression model, Iowa DOT was able to downscale the rain data to 12 mi^2 grids. When plotted over a 40-year average, there is an upward trend that will become more variable further into the future. Historically, there has been an increase in rainfall since 2000. Floods were best simulated at a 30 mi^2 drainage or greater. The annual maximum precipitation (AMP) was projected to be 30% to 40% above the mean and 50% to 60% from its maximum from 2000 to 2059 versus 1960 to 2000. Most of the climate models showed an abrupt increase in AMP from 2000 to 2040. Iowa DOT then tried to estimate peak discharges using a University of Iowa hydrologic model. A peak discharge was produced for each gauge for each year between 1960 and 2100. Iowa DOT then used a U.S. Geological Survey (USGS) estimate for determining peak discharges for the 140-year period, which resulted in a 100-year peak discharge value. A median figure was taken from the results of all 19 climate models. The results, which were more model specific than scenario specific (which is something climate scientists may be able to clarify for engineers), suggested that infrastructure may be more vulnerable due to an increase in annual flow as well as to peak discharges.

The Engineering Assessment Process Used in the Gulf Coast Study: Phase 2

Chris Dorney of WSP–Parsons Brinckerhoff and Anne Choate of ICF International presented on the engineering assessment process used in the FHWA Gulf Coast Study, Phase 2. The Gulf Coast Phase 2^4 study began with discussions about criticality, understanding climate science, deciding how to assess vulnerability, and using information to talk to stakeholders. Mobile, Alabama, was used as a test case on several assets that could then be replicable in other places nationwide. The goal was to conduct systematic analyses of different assets and develop and compare possible adaptation strategies specific to these assets. The project also emphasized the relationship of climate information to design input data using localized climate data that accommodated the data needs relevant to engineers.

The engineering assessment used an 11-step process that was designed to be broadly applicable but also considered uncertainties and fostered data gathering and production that eventually leads to decision making. Steps one and two included describing the site context and existing or proposed facility. Steps three and four identified potential impacts to infrastructure and involved decisions about which climate scenarios and magnitude of changes to consider.

Step five assessed the performance of the existing or proposed facility, and step six was to develop adaptation options. Steps seven and eight assessed the performance of selected adaptation options and conducting an economic analysis. Steps nine through 11 included evaluating decision-making considerations, selecting a course of action, and planning and conducting activities.

The process, which was applied to 10 sites throughout the Mobile region, including bridges, culverts, piers, slopes, tunnels, and rails, proved to be useful and versatile. Case studies are available on other findings and conclusions of the Gulf Coast Study, Phase 2 report.

Climate Resilience Guidelines for Transportation Infrastructure

Peter Adams of the Port Authority of New York and New Jersey (PANYNJ) presented on how resilience is being incorporated into the agency's infrastructure design practice. PANYNJ worked on adaptation issues prior to Hurricane Irene and Hurricane Sandy, but many of its assets were impacted far worse than expected. The Port Authority Trans-Hudson in particular experienced significant damage to power traction systems, signals, elevators, escalators, and other electrical devices. It took Port Authority 4 months to resume normal service. As immediate short-term solutions, stop-log barriers have been installed at many entrances as well as concrete barriers and sliding metal flooring that protects underground assets such as tunnels.

Average temperatures, precipitation, and sea levels are expected to rise in the New York–New Jersey area, so the PANYNJ has begun making changes to infrastructure guidelines and has established a set of climate-specific engineering guidelines. From design to implementation, climate considerations are being incorporated from asset-specific and systemwide perspectives. All projects that will cost more than $10 million undergo a cost–benefit assessment. The agency also established a list of infrastructure assets that have been classified as highly critical and will be protected according to their criticality. The PANYNJ Design Guidelines for Climate Resilience are publicly available and are being used regularly by the agency to protect the region's assets.

BREAKOUT 3: FLOODS STOP TRAFFIC, DOTS IMPLEMENT MANAGEMENT STRATEGIES

The impacts of flooding on infrastructure are well-studied and are a significant part of climate resilience efforts. Less well-studied are the more frequent impacts on operations and maintenance, as well as the role that maintenance plays in reducing this impacts. This session, which Paul Pisano of the FHWA moderated, examined these impacts and actions that can minimize them.

Robustness of Roads During Flooding

Thomas Bles of Deltares presented on the robustness of embankments in the Netherlands during flooding events. The Netherlands is situated in a delta fed by many European rivers; most of the country sits below sea level and is protected by levies. Almost all highways will be affected by sea flooding or river flooding when it occurs. The Rijkswaterstaat (RWS) has outlined three phases of flooding: (1) threat, focus on evacuation; (2) acute, focus on rescue and aid; and (3)

recovery, focus on revitalization. Based on these designations, RWS conducted an analysis for the entire highway network, finding that nearly half of highways will be affected by liquefaction during the acute phase. During the recovery phase, nearly all embankments will be unstable. For each asset, RWS examined the failure mechanism, the estimated likelihood of failure, challenges and opportunities for recovery, and the effects of failure for road users. The study concluded that the highway network is not robust in response to flooding. Many embankments are unstable, and hundreds of other assets such as culverts, tunnels, bridges, and cables will likely also fail. RWS is using the analysis to plan evacuations in the threat phase and is investing in better forecasts and accelerating the decision process.

Assessment of Flood-Induced Damage in Hot-Mix Asphalt Pavements

Rajib Mallick of Worcester Polytechnic Institute presented the findings from an assessment of flood-induced damage in hot-mix asphalt pavements. There is a lack of information on how to determine the optimum time to reopen a roadway to traffic after flooding. If the road was damaged, there will likely be more damage and potentially loss of life, but if the road is intact money may be lost if people and goods are prevented from being able to move about. The primary focus of the study was to develop guidelines on how to assess flooded pavements for short-term impacts and a framework for future long-term assessments. Researchers examined changes in moisture content of pavement over time, how the material properties were affected, how the pavement performance was affected, if the results were validated with field data, and then whether the road should be opened or closed. Decision tree scenarios were developed based on operations data and testing. According to results, payoff is affected significantly by losses associated with opening the road when pavement is not sound. The research team suggests that future study on the impacts of saturation, identification of cases where accurate data on saturation level is needed, and bearing capacity analysis for one-time, short-term flooding events would likely be helpful. A tool is being developed based on the decision tree that will include reliability and probability values, as well as utility functions.

Resilience in Operations and Maintenance Activities: Lessons Learned from a Case Study of Pluvial Flooding in Norrala Railway Tunnel in Sweden, 2013

Monika Rydstedt Nyman of Karlstad University discussed the results of research into the usability of industrial accident investigation methods on climate-related events. The study, which looked at a roadway tunnel in Sweden that flooded, used fault tree analysis, man technology organization, and AcciMap (accident mapping) to demonstrate how society and government interact with or affect outcomes of different events. Well known by engineers, the models offer graphical hierarchical illustrations of events, reveal their root causes, and can build better understanding. Results suggested that the fault tree analysis is good for planning; the man technology organization has an effective feedback mechanism; and AcciMap can help depict all of the internal and external forces that can affect decision making. Drawbacks of using the models as identified in the research include, but are not limited to the following:

- Oversimplification of an event.
- Boundaries are not always clear and decision points may be hard to identify.
- They can be very technical.

Vulnerability Assessment of Critical Transportation Networks in Response to Extreme Precipitation Events: A Case Study of the 2013 Colorado Floods

Melissa Allen of Oak Ridge National Laboratory presented the results of a vulnerability assessment of critical transportation networks in Colorado in response to extreme floods in 2013. There was a 3-day extreme precipitation event that knocked out roads and rerouted rivers. The case study looked at the effects on transportation, infrastructure, and emergency evacuations. The rain occurred during September, a typically arid time of the year, resulting in mudslides and landslides given that the soil could not absorb the water. Similar circumstances are expected to occur again in the future since arctic warming may cause more blocking events like those that caused the 2013 floods.

After the floods, Oak Ridge National Laboratory used urban mobility simulations to model the flooding event's impacts on transportation network efficiency. The most-damaged roads were concentrated in mountainous areas in the northwest, and most traffic was attempting to travel to the southeast toward Denver away from the damage. Model simulations indicated that there may be more conditions in the future where similar events occur. With expected population growth in Colorado cities, there will likely be increased needs for adaptation and evacuation planning statewide.

BREAKOUT 4: BUILDING CLIMATE RESILIENCE IN DEVELOPING COUNTRIES

This session, moderated by Joshua DeFlorio of Cambridge Systematics, discussed how developing countries incorporate climate change considerations into the early stages of infrastructure development, despite the added challenges of limited financial resources and high levels of vulnerability to extreme weather events, such as how Typhoon Haiyan affected the Philippines. It highlighted strategies that the Philippines, Peru, and the Pacific Island States are using to build climate change resilience.

Costs and Benefits of Climate-Resilient Roads in the Philippines

Ben Campbell presented the successes and lessons learned from the Millennium Challenge Corporation's (MCC) Samar National Road Development Project in the Philippines.[5] The MCC built a road through Samar National Park to foster eco-tourism and to develop and attract investment in the area. To reduce the timeline and labor costs, the MCC used secondary climate literature and data, along with IPCC climate models to study the project area and develop what it calls a best value design. The $23 million project included stabilizing slopes, improving anchor and support structures, adding new seawalls, building embankment protection at new bridges, and upgrading drain pipes and bridges. MCC did not calculate the cost of incorporating climate resilience and adaptation elements. After completion, the road was tested when Typhoon Haiyan made landfall in the Philippines in 2013. The MCC structures withstood the hurricane and the road was used to transport relief supplies in the area. Campbell suggested that project planners budget the climate adaptation costs upfront and make a case to decision makers to include such measures from the start. He also stressed the importance of incorporating social elements of projects (i.e., the people who will be protected by new or improved infrastructure) early in the process to avoid overlooking them both before and after the project is approved.

Successful Strategies to Build Climate Resilience in Developing Cities

Joanne Potter from ICF International discussed the importance of building capacity within local governments to address climate change in places where extreme weather events are expected to become increasingly frequent and severe. She presented tools that the U.S. Agency for International Development (USAID) Climate Resilient Infrastructure Services (CRIS) program has implemented in Piura, Peru.[6] Potter stressed the importance of examining and incorporating climate information that is relevant to an area's development objectives (e.g., economic development or health). CRIS helped city staff in Piura to establish a sustainable community of practice that concentrated on decision-focused tools for practitioners with limited time to dedicate to using climate data and limited knowledge of it. To create easy-to-use decision support tools, CRIS took local information that would be useful for a practitioner, supplemented it with additional international climate data, created summaries, and developed a database that local practitioners can use to access the climate information they care about and need. CRIS also developed Excel-based assessment screening tool that identifies the current and future climate-related vulnerabilities of various projects. The result is a summary that can be used to identify which projects may be problematic in the future as well as where and why they will have problems. CRIS created an Adaptation Options Screening Tool that walks staff through a portfolio of potential adaptation methods including operations and maintenance, policy, planning, design, review, and engineering. Taken together, the sustainable community of practice, tools, and associated training, will improve readiness at the local level and create opportunities for new funding sources and improved dialogue with the national government.

Adapting Road Infrastructure for Climate Change and Extreme Weather Events: Experience from Small Pacific Island States

The Pacific Island States face challenges with connectivity; the islands host 2.3 million residents scattered across many widespread and remote islands. Habiba Gitay from the World Bank presented on how several Pacific Island nations have been addressing their extreme vulnerabilities to climate impacts using community-based activities since external materials and expertise are difficult to obtain. Roads in these island nations are often close to the sea, lack drainage, and do not have resources easily accessible for management—despite this, they are vital to transporting goods and people. Samoa developed asset management plans with input from the community and has begun investing in lidar equipment to update plans it developed in the late 1990s. Samoa is also prioritizing investments using these plans and spatial maps, and it is combining green approaches (e.g., planting mangroves and rehabilitating seagrass beds) with infrastructure upgrades using local materials with minimal transport costs. The country is also conducting post-disaster needs assessments after each weather event to determine short- and long-term needs and to plan using more affordable options in the future.

BREAKOUT 5: RESILIENT FREIGHT SYSTEMS AND PORTS

The presenters in this session discussed how they factored resilience into port and waterway investments and operations in response to climate change and extreme weather events. Mark Abkowitz of Vanderbilt University presided.

Monitoring Airport Resilience to Climate Change and Extreme Weather Events: Developing a Prototype Resilience Index

Thomas Budd of Cranfield University spoke about the university's ongoing research to monitor airport resilience to climate change and extreme weather events in the United Kingdom. It was noted that there are some similarities with other transportation modes in terms of risk but that there are also aspects such as temperature change, wind change, and precipitation change that are specific to air transport. Also, the air transport industry involves many stakeholders and its competitive nature hinders sharing of lessons learned or best practices.

The first step in the research project, which was done at Gatwick Airport, was to find out if accurate, comprehensible climate change projections existed for the region. An evidence-based review was performed and relevant existing data were synthesized. The team next assessed gaps in the data and consulted government, industry, and academic publications to add necessary information. Adaptive capacity—the ability of a system to enact policies, measures, and actions to improve resilience of systems vulnerable to climate change—emerged as a key concept. An urgent need for adaptation indicators and metrics was documented. These metrics should simplify, quantify, and standardize complex data from a variety of sources in a transparent way. The project team also wanted to stakeholders' perspective, therefore a survey of airport managers was administered. Most respondents indicated that extreme weather events have the most severe effect on the proper airport operations. However, it also became evident that although airport management seems to be aware that the effects of climate change are likely going to worsen, a systematic approach to adaptation planning does not exist currently. Airports that are implementing measures are doing so in a disjointed manner. The survey also found evidence suggesting that most airports are not formally evaluating adaptation measures that are being implemented. Primary reasons for the lack of formal assessments are the fact that standard baseline metrics do not exist and some airports reported that in their view the effects of climate change have not fully been defined enough to justify the cost of adaptive measure assessments. The next steps for the research project are to define what successful adaptation at airports looks like, identify available existing data to be used to develop standard metrics, define the baseline to compare future adaptation measure metrics, and develop a prototype assessment framework of metrics.

Climate Risk and Adaptation Assessment of Port Investments

Amanda Rycerz of Acclimatise presented a case study on climate risk and adaptation strategies for port investments that was done in Cartagena, Columbia at the Muelles del Bosque (MEB) port. The study was done because the International Finance Corporation wanted to better understand financial risks, costs, and benefits of adaptation measures for its assets. The objective was to identify and assess the climate change risks and opportunities for adaptation at MEB, including the effects of adaptation options on airport revenue. The study used site visits, desk-based analysis, and modeling to gather and evaluate data. Numerous value change aspects were investigated during the study but the session focused on vehicle movements inside the port. A flood risk assessment was done using a 3-D model in which two scenarios that incorporated data from future sea level rise projections were run.

MEB has a causeway that must be crossed to deliver goods from an island where ships dock to the mainland. The causeway was identified as the weakest point of the port in terms of

flood risk. The project team provided timelines and expected flooding conditions based on high and low scenarios as well as the effects on revenues that would result from the loss of vehicle movement if no adaptation measures were implemented. Two adaptation measures involving raising the causeway were presented along with cost projections and their effects on future revenues. In this case, the president of the private company that now owns MEB contributed US$10 million toward raising the causeway.

Resilience Planning and Implementation at Massachusetts Port Authority

Robbin Peach of the Massachusetts Port Authority (MassPort) spoke about current resiliency planning and implementation methods that MassPort has used during the past 18 months. MassPort's effort began in response to the aftermath of Hurricane Sandy when the agency decided that there was a need to better prepare for similar events. A resiliency program was created and a program manager hired with the goal of becoming an innovative, national model for resiliency planning and implementation within a port authority. The program's objective was to prioritize assets and analyze options and associated costs in terms of adaptation measures or total replacement. Using the Threat and Hazard Identification Risk Assessment Model, a working group identified threats and made plans to mitigate consequences of those threats. The group reviewed natural-, technological-, and human-caused threats but focused on natural threats, such as hurricanes, seal level rise, and flooding. Assets were categorized into three groups based on their assessed importance. The team then conducted a Disaster Infrastructure Resiliency Planning Study was to shed light on MassPort's vulnerabilities to climate impacts and to develop both short- and long-term strategies. A contractor was hired to apply a probability model to MassPort's assets to determine the likelihood of flooding during extreme weather situations. Based on the findings, MassPort's short-term plan is to flood proof existing assets and to design new assets based on higher flood levels. MassPort also owns approximately 500 acres of land that is rented out. Tenants of that property are being educated on suggested guidelines for existing and new structures. The team is currently in the process of creating a flood operation plan that will include flood action timelines with instructions for each MassPort department on what to do when faced with different levels of flooding.

Climate Change and Inland Waterways Operations: Experience of a U.S. Marine Carrier and Impacts on Other Modes

Craig Philip from Vanderbilt University gave a presentation on climate change and inland waterways operations. Ingram Barge Company's experience was used as an example of how the maritime sector is dealing with the effects of climate change. The industry is now taking resiliency planning more seriously than before given that extreme weather events and consequences have moved from being episodic to being chronic issues. Hurricanes, ice, and low water conditions were highlighted as the most common weather concerns; options for possible adaptation strategies for each were presented. Other modes can also be affected if maritime carrier vessels are subject to extreme weather or extreme weather occurs near active ports. Typical impacts on other modes include inaccessible terminals and consequences for truck and rail systems. Key lessons for the industry included stressing the importance of contingency plans, emergency procedures, and the need for resiliency policies to be developed and implemented.

BREAKOUT 6: DECISIONS, DECISIONS, DECISIONS

This session discussed how specific assets are analyzed for vulnerability and risk throughout the project lifecycle to inform decisions on resilient future solutions. Massachusetts DOT's Steve Miller moderated the session, which included four presentations.

Analysis of Historical Streamflow Conditions Inducing Bridge Failures in the Continental United States for Validation of Climate Change Impact Assessments

Madeline Flint from Stanford University and Virginia Tech gave an overview of a study done on historical streamflow conditions and bridge failure in the continental United States. The purpose of the analysis was to validate climate change impact assessments. Primary reasons for hydraulic bridge failures were identified as hurricanes, floods, and scour. Regarding the latter, modern scour provisions went into effect in 1991, making general assumptions about bridges and climate impact assessments difficult since bridges were held to a lower standard before 1991 than they are now.

Three major obstacles were faced in the data collection process. First, no national database on bridge failures exists. New York State DOT maintains a bridge failure database but only on a voluntary basis. A second hurdle was encountered when the project team realized that different states provide different information to the New York State DOT bridge failure database. Lastly, a stream gauge was needed to run tests, characterize flow curves, and compare return periods to a subset of bridges to draw conclusions about general bridge behavior. The data collected was used as a baseline and compared to two other data sets and run through two hydrological models. Results from the models were inconsistent, so a proxy could not be developed. However, results from each model suggested that many of the bridges in the study would not fail at a 100-year event, which could mean that the assumption that bridges fail at a 100-year or larger flood could be an underestimation of likelihood of future failure. Currently, the team is using a larger data set of 360 bridges (versus 36 previously) to create a proxy that can be used to develop better bridge failure statistics.

Considering Hazard Risk and Uncertainty for Infrastructure Decisions at the Project Level

Sue McNeil of the University of Delaware discussed decision-making techniques used in a project done with Delaware DOT to identify tools for addressing infrastructure risks due to climate change and inundation. The project, which was undertaken in response to Hurricane Irene and Hurricane Sandy events, was initially scoped as a multiobjective analysis including a heavy reliance on quantitative information. However, through discussions it became clear that Delaware DOT wanted assistance framing the issues at hand along with and in-depth qualitative analysis that could help support climate risk decision making.

When the team began, no basic problem solving mechanism had been applied. Therefore, the researchers began by identifying the problems to be addressed. The team worked with Delaware DOT to revisit most of its processes (e.g., planning, design, maintenance) to identify alternative adaptation possibilities. Analysis was performed using uncertainty models, risk assessments, and lifecycle cost analysis tools. Lastly, the team evaluated the results, and a final qualitative analysis was produced for Delaware DOT.

Specific examples of the evaluation were presented in the session, and the importance of

presenting and communicating such results clearly was noted. Since the Delaware DOT project, the team has gone on to use the framework to support other small-scale projects aimed at refining climate change decision-making processes.

Case Study of Bridge Hurricane Vulnerability and Resilience Retrofit Planning Considering Varying Sea-Level Rise Predictions

Brian Joyner and Walter Kemmsies of Moffatt & Nichol presented a case study that looked at vulnerability and resilience of bridges to hurricanes with a focus on retrofit planning that considers varying sea level rise predictions. The study was done for Virginia's Hampton Roads Bridges. First, types of bridge failure were described, followed by a review of three analysis methods the team used. Evidence was found to suggest that highway water surfaces and increased wave loads due to sea level rise will have varying impacts on bridges depending on their condition and location.

Given this finding, the research team believes the decision-making process for bridge adaptation options will be very difficult. According to Joyner and Kemmsies, cost–benefit analyses should first be applied and used to identify the potential decision options, such as bridge retrofits versus replacements, not the decision criteria. It was noted that the preservation of human life will always have priority over economic benefits, and thus data related to safety will influence funding decisions when cost benefit analyses are done. Life-cycle cost analysis was also highlighted as a useful tool for considering factors that may not be addressed in cost benefit analyses. Presenters noted that network and regional approaches are likely more appropriate when dealing with effects of climate change, given that structures are impacted by multiple factors.

Considering the Climate Impacts on and Environmental Impacts of Infrastructure Projects in Developing Countries

Dana Spindler and Michael Savonis of ICF International gave a presentation on considering climate impacts on and environmental impacts of infrastructure projects in developing countries. Implications of Executive Order (EO) 13677[7], Overview of Climate Resilient International Development, which requires that climate resilience be integrated into all international infrastructure projects, was also given The EO's goal is to enhance global preparedness for climate change.

A 2011 USAID project examined the environmental benefits and concerns, social impacts, environmental and social commitments, climate change projections and impacts, adaptation options, and systems for monitoring and evaluating six major international infrastructure projects. Two of the six examinations and the results were discussed.

The presentation ended with a discussion on the Council on Environmental Quality's (CEQ) draft guidance on incorporating GHGs in the National Environmental Policy Act. The guidance notes that the effects of a proposed project on the environment need to be considered in addition to the impacts of climate change on the proposed project. The Tongue River Railroad Corps was referenced as an example to demonstrate how cumulative impacts analysis can be used to consider both the effects a project will have on the environment and the impacts climate change can have on the project.

BREAKOUT 7: WEATHER AND CLIMATE— DIFFERENT SIDES OF THE SAME COIN

Though day-to-day weather may not be an indicator of changes in the climate, the two are inextricably linked. This session explored tools and strategies used to manage these day-to-day impacts on the surface transportation system and that can address climate challenges. Kathy Ahlenius of Wyoming DOT presided.

Coordinated Transit Response Planning and Operations Support Tools for Mitigating Impacts of All-Hazard Emergency Events

Vadim Sokolov presented on a project that the Argonne National Laboratory will begin with Chicago transit agencies to coordinate transit response planning and operations support tools for mitigating the impacts of emergency events. Flooding, increased snowfall frequencies and event durations, and oil spills are creating traffic delays and related challenges in Chicago. Highway systems in the Chicago region are increasingly overburdened, but technologies, such as automatic vehicle location applications, automated passenger counting equipment, and fare collection tools, are helping transit systems to be more adaptive.

The project described in the presentation will develop a decision support system that will help transit agencies respond to events on short notice and in real time. Current technology and algorithms allow real-time decision making, so incorporating them into transit agencies' existing information technology infrastructure can improve preparations for response to no-notice events. Decisions could include increasing buses on a route or re-routing buses to or from other routes. The system being developed will include a software system that communicates with bus fleets, the public, and transit operators. It will operate based on demand forecasts, fleet allocations, known constraints, and routes and schedules. An integrated transportation system model (POLARIS), which models the transportation system using census data, is already in place as is the FTA's transit operations decision-support system, which helps dispatchers manage transit systems. The Regional Transportation Simulation Tool for Emergency Evacuation Planning also helps decision makers conduct large-scale evacuations from cities.

Climate Change and Sustainability: Operational Adaptation Guide

Laurel Radow presented a new guide that FHWA developed on adapting to climate change through operations and maintenance activities. Extreme weather events are becoming more frequent and extreme across the country. It is important to convey that the past is not a good indicator of the future, so practitioners should not rely on historical data alone. Climate changes could reduce roadway capacity, reduce alternative routes, reduce mobility, and increase safety risks with rippling effects. FHWA interviewed agencies to determine what operations concerns and climate variables they are considering. Identified variables were incorporated into the scoping stage of FHWA's adaptation framework. After that, the framework suggests assessing vulnerabilities by documenting existing capabilities within the business; culture; workforce; and performance management process, systems, and technologies. Agencies should start integrating climate into decision-making processes such as performance measures and operations processes. The guide includes strategies for how to obtain buy-in from stakeholders, how to track progress over time, and ideas for conducting workshops on climate risk.

Use of a Road Surface Model Within the National Weather Service

Chris Gibson of the National Weather Service (NWS) presented on how NWS is using a road surface model to differentiate between storms that will likely cause the greatest impacts and those that will not. The NWS used the Model of Environment and Temperature of Roads (METRo) with site-specific road data, past weather observations, and weather forecast data as inputs to create "road casts." METRo road casts are displayed on an interactive map for hundreds of locations across the country, and different icons depict hazardous road conditions. To date, METRo has been tested at several sites in Montana. The NWS plans to pursue the development of a version of METRo that runs off of short-range numerical data rather than weather forecasted data.

Road Weather Information Systems and Connected Vehicle Data for Mitigation of Extreme Weather Impacts

Ralph Patterson of the Narwhal Group presented on road weather information tools and discussed lessons learned from the aviation sector. Weather can affect all vehicles through loss of friction, loss of visibility (i.e., fog, smoke, dust), and external environmental forces (i.e., avalanche, debris flow, high winds). It is important to know the operational vulnerabilities in an area. Present weather, such as satellite and radar; present climate, such as 30-year records; and long-term climate trends, such as records and models will provide insight into operations planning. Weather stations have traditionally been used to measure environmental conditions for roads, but now connected vehicles, mobile observations, crowdsourcing, and derived tools (e.g., Weather Severity Index) will begin providing more road data.

Aviation has been utilizing "connected aircraft" in the form of Aircraft Meteorological Data Relay. Planes observe wind speed, barometric pressure, and air temperature using technology standardized by the World Meteorological Organization. This type of data collection will eventually be available in connected vehicles. Managing datasets in the future will become increasingly important. Mobile data may not always be reliable, but the amount of data available could create quality assurance through statistical analysis. Instrumentation, storage, security, ownership, and public access will likely be issues in this space. Using new technology is expected to be an important part of climate adaptation, but according to the presentation, agencies should focus on cost–benefit analysis and return on investment when implementing new policies and using new technologies.

BREAKOUT 8: BUILDING CLIMATE RESILIENCE IN EUROPE AND NORTH AMERICA

Europe and North America face similar problems when it comes to adapting to climate change. This session, which NJTPA's Jeff Perlman moderated, focused on examples from both continents that are the results of recent initiatives and cooperative efforts to achieve a common goal: transportation system resilience.

Approaches and Case Studies in Transportation Resilience at a Local, State, National, and International Level

John Chow of WSP–Parsons Brinckerhoff presented a series of case studies from the journal *Network*. Following Superstorm Sandy, New York Governor Cuomo and the Metropolitan Transportation Authority began discussions to plan for ways to avoid unmanageable impacts to the system. This planning effort emphasized that system resilience requires a larger capital budget than previously available, as well as political will. The New York State 2100 Commission was assembled to help the State investigate ways to build better and smarter for the future and improve institutional coordination on climate issues at the state level. Similarly, PLANYC, which was led by former Mayor Michael Bloomberg, began long-term resiliency planning before Hurricane Sandy. Following the hurricane, Bloomberg established the Office of Recovery and Resiliency to implement resiliency projects; since that time lower Manhattan has received $100 million for flood prevention.

At the regional level, the AASHTO's Resilient and Sustainable Transportation Systems program is sharing knowledge among states and creating connections for members to share case studies and lessons learned. From a national perspective, there are now national planning grants for disaster resilience and flood prevention. The UK, for example, has implemented an adaptation program that requires climate change preparedness, particularly for airports, and the UK Highways Agency requires resilience planning and measures from its network providers. Chow emphasized that resilience is affected by people, organizations, and systems, and the extent to which they are integrated.

Adapting Roads to Climate Change: The ROADAPT Project

Thomas Bles of Deltares presented work that the collaborative Roads for Today, Adapted for Tomorrow Project[8] (ROADAPT) has done to educate road owners and operators about how climate change is affecting roads; the likelihood of impacts; the various risk levels; and preventative measures that they can take to reduce impacts. Using the ERA-NET Road method for risk analysis, the project provided road owners with seven steps for conducting risk management exercises, which were applied in four different case studies.

After the case studies, the project sponsor, the Consortium of European Road Entities (CEDR), requested more detail. The resulting revised ROADAPT method identifies cause, effect, and consequence to determine the risk evaluation, using a 10-step approach for assessing assets in the present and future. ROADAPT outputs include potential climate change threats, vulnerability factors, impacts, and risk-mitigation strategies. The ROADAPT database offers adaptation measures and maps them in stages of measures for before, during, and after weather events, and it describes the consequences of implementing various measures. ROADAPT includes a QuickScan method and action plan that uses a risk-based approach to gather experts, raise awareness, and generate action plans to address climate impacts. The tool also includes a socioeconomic impact assessment that examines the impacts of climate change on traffic and road users and the roadway system as a whole.

Joint FHWA–Rijkswaterstaat Report on Resilient Infrastructure: Assessing Vulnerabilities and Risks and Incorporating the Results into Planning, Design, and Asset Management

FHWA, RWS, and the Dutch Ministry of Infrastructure and the Environment are working together to improve infrastructure resiliency through knowledge sharing via reports, meetings, and webinars. Kees van Muiswinkel from RWS and Michael Culp from FHWA noted that the United States and the Netherlands are working together because each country is facing similar challenges regarding sea-level rise adaptation and extreme weather. Neither agency has funding set aside explicitly for climate change activities and each agency views collaboration as a cost-effective way to find innovative solutions to the challenges climate change poses. One of FHWA's focuses is minimizing impacts, while RWS has focused on preventing impacts. FHWA is seeking to learn from RWS' coastal work, and RWS would like to model some of its own pilot projects off of FHWA's experiences involving a wide variety of stakeholders.

Norwegian Roads Adapting to Climate Change

Gordana Petkovic from the Norwegian Public Roads Administration (NPRA) presented on the climate change adaptation and resiliency work that the agency has completed since 2007. Norway's infrastructure is increasingly at risk to impacts from flooding, erosion, landslides, avalanches (snow or slush), and debris flows. The NPRA released a final climate plan in 2013, which was a culmination of the research and implementation work that started in 2007. In 2009, Norway published a national framework for addressing the effects of climate change up to 2100. Although the framework rated the transport sector as having good adaptive capacity for future impacts, there are still changes that need to be made to improve resiliency. Norway currently has approximately 100 manuals for infrastructure planning, management, and design that need to be updated to take into consideration the effects of climate change. For instance, NPRA has changed many of its design standards so that new roads will be placed in the least-hazardous flood zone areas. Also, adaptation measures will become a prioritized part of routine maintenance activities. NPRA is developing new drainage manuals and new management plans for river catchments.

One of the most important lessons that NPRA has learned is that collaboration with other sectors—such as rail, water, and energy—has improved coordination on data and budgeting for all agencies. The NPRA is now working to better document current impacts in order to improve planning for future needs. All of the information NPRA and its partners have gathered are available on xgeo.no. This includes an inventory of the most vulnerable assets that should be prioritized for maintenance or upgrades.

NOTES

1. www.weathershare.org/.
2. www.innovationcenteroftherockies.com/CUIPSS.html.
3. www.fhwa.dot.gov/engineering/hydraulics/library_arc.cfm?pub_number=16&id=36.
4. www.fhwa.dot.gov/environment/climate_change/adaptation/ongoing_and_current_research/gulf_coast_study/phase2_task2/.
5. www.mcc.gov/where-we-work/program/philippines-compact.
6. www.ccrdproject.com/adaptation-partnership/cris.

7. www.whitehouse.gov/the-press-office/2014/09/23/executive-order-climate-resilient-international-development.
8. www.deltares.nl/app/uploads/2015/04/brochure-ROADAPT.pdf.

PLENARY SESSION

Transportation Resilience Policy Highway Systems Planning

Vicki Arroyo of the Georgetown Climate Center opened the Plenary Session by stating that the conference, and in particular this panel discussion session, is an opportunity to talk about the "new normal," to ask how agencies can better build infrastructure, and to ask how they can prepare for the future. A summary of the participants' questions and panelists' answers that followed is presented below.

Question: Can the panel talk about resiliency planning at state and local levels? Are there similarities?

Answer: In Arizona, sea level rise is not important, but drought is. In Rhode Island and other coastal areas like Massachusetts, there has been a realization that there is much infrastructure that will be affected by climate change, and climate considerations need to be integrated into planning processes. Rhode Island has built bridges over the past 100 years that are not necessarily designed to withstand extreme weather events. After Hurricane Irene, there was a sense of relief among Rhode Island agencies until they learned of the enormous infrastructure losses in Vermont. Two years ago this month, Colorado was hit by extreme rains and had similar flooding to that in Vermont. People from Vermont visited Colorado to help the state prepare for the evacuation and recovery. In Colorado, practitioners reviewed the I-70 corridor for alternatives but did not find viable alternatives. There are limited options to evacuate those areas served by I-70 and to move goods and services there, meaning Colorado will likely need to harden and modify infrastructure to avoid future losses to similar events. This is not just a transportation department issue. All levels and areas of government need to work together as one.

Question: Much was learned from Hurricanes Katrina and Sandy, which is captured in various reports. Some might argue the reports predicted Katrina's impacts. What studies are being done now?

Answer: There is a great deal of transit in densely populated places near water. Sandy presented New York with enormous storm surge issues for which all agencies had not prepared. In 2012, FTA was given authority to do emergency response and Congress allocated $10 billion for Sandy recovery. A process was established to work quickly through the historical and environmental issues with other federal agencies, and funding was allocated to New York and New Jersey transit. Of the $10 billion, $3.6 billion was for resiliency planning to protect transit investments. The South Ferry Station in Manhattan, which had been rebuilt after September 11, 2011, was destroyed during Sandy and had to be rebuilt at a cost of $384 million. There is a belief that through additional planning to factor climate change considerations, some of the issues of the recent past can be avoided. Planning is a venture to protect investments in transit, to make sure business as usual can resume quickly after extreme events.

Question: FHWA has been a leader in resiliency; how has FHWA incorporated adaptation and resilience planning in its work?

Answer: FHWA has been trying to identify vulnerabilities in particular areas of the country along with how the agency can draw attention to the issue of climate impacts on highways. FHWA is trying to seed good ideas to the state and MPOs, and are asking them to help FHWA figure out how to go about climate change planning. FHWA funded 19 pilots to determine where in the process climate considerations and decisions should be made. Working with and supporting the MPOs and states have helped the agency better understand what stakeholders need. A decade after FHWA started working in this area, it released FHWA Order 5520[1]. It is a much-richer policy because FHWA had built great relationships with operations and infrastructure personnel. Now, FHWA wants to use its experience as a springboard to move toward implementation. There is a real demand learning how these ideas can be manifest in specific projects as places move from research to implementation. Congress has helped by tying infrastructure funding to preservation and planning for extreme weather events, which is also part of FHWA's policy.

Question: Different levels and agencies of government have roles that sometimes conflict, especially when rebuilding after a disaster. Can the panel discuss transportation infrastructure provisions to address this?

Answer: CEQ has worked with state, local, and tribal leaders to discuss how the federal government can help them prepare for climate change impacts. CEQ recognizes the need to modernize federal programs and to consider the anticipated demands and plans in the future using current funding. For instance, the DOT TIGER grants now incorporate climate impacts. The president issued an Executive Order to require that all federally funded projects meet a new flood risk number, so infrastructure lasts much longer into the future. This is not about creating a new climate program. It is about embedding climate considerations into everything we are doing, working with partners and learning from innovative solutions happening across the country.

Question: Are there communities that can be esteemed as having done something differently with support from federal agencies? What has been learned?

Answer: Washington State DOT recently completed its FHWA pilot, where the agency picked a study area in the state where there was already an ongoing U.S. Army Corps of Engineers (USACE) study investigating what flood protection approaches would be most sensible. Washington State DOT brought a transportation component to the study, which was successful in that Washington State DOT was able to leverage more advanced analysis than it would have been able to do otherwise. These synergies of looking at transportation infrastructure and flood prevention are good examples of the creativity that is occurring through the pilots.

Question: What are communities doing regarding evacuation routes? Especially vulnerable communities that may not have access to vehicles? Are there innovative solutions?

Answer: Coordination is the single greatest difference between success and failure. It has to happen long before the extreme event. Putting energy into building relationships, evacuation plans, and contingency plans can pay off multifold. Also, transportation technologies such as vehicle-to-vehicle and vehicle-to-infrastructure advances, and cellphones provide more efficient ways of communicating with the public. In the future it will be much easier to address with

immediate information and action.

Question: In the decade since Katrina, there has been a lot of federally sponsored work for vulnerable populations, but the national response network has been a model where all locals have to respond to the state and the state responds to federal organizations. It seems like nobody owns the problem. What are the panel's thoughts on being able to take ownership of that problem?

Answer: The national response frameworks have been instrumental in providing a way to support agencies, but on the issue of climate equity there is a long way to go. To demonstrate the commitment, an AmeriCorps resilience program was launched so that people can focus on climate change disparities. When President Obama visited Alaska, he spoke about the need for frameworks to address this.

It is a tough issue. If the state approaches local agencies and says we are doing this, the reaction is negative. A similar dynamic sometimes exists between the federal and state levels. If something goes wrong, the blame is on the level that was not there to help.

At FHWA, evacuation planning does happen. That has been part of FHWA's discussion in the climate change arena, and at the same time, there has been discussion about disparate impacts.

Question: Can the panel speak to how social infrastructure might replace the physical infrastructure when it washes away?

Answer: From the state level, Michael Lewis from Colorado DOT says he has been incredibly impressed on the social infrastructure, specifically by how Colorado and Vermont came together with local affairs, budget, DOT, etc., and worked together. If a proactive attitude is taken in planning and preparation more often, agencies will likely be better off.

Practice can help, too. For example, teleworking exercises can help an agency quickly and appropriately determine whether or not it is effective for staff to work from home when they cannot get into the office.

Disasters uncover issues that agencies did not realize were there until they occur. CEQ announced a set of principles on location and migration. It speaks to temporary displacement from an extreme event, but the agency is considering permanent relocation as well.

Question: There is really no statutory basis for considering climate change. How can agencies be flexible and creative? Is there flexibility, and can it be built into legislation?

Answer: Michael Culp from FHWA said he thinks we are on the right track to make sure that this can be part of different decisions, and Congress may not necessarily need to weigh in. FHWA proposed to add a provision into the planning regulation to require states and MPOs to do some level of climate adaptation and resiliency as part of their transportation planning process. It did not make it into the Drive Act. It was not prescriptive. Instead, it was intended to say that climate adaptation should be a part of regular day-to-day business.

CEQ is working on these issues with the agencies to create flexibility where possible. A common story is that local and state governments say they want to work together but cannot integrate federal funding streams. The Partnership for Sustainable Communities and other place-based planning efforts are working to address this.

Question: In an era where extreme heat will affect driving and flying, how much focus has been given to operations and maintenance?

Answer: Drainage is really key. A lot of subway tunnels can turn into rivers and it can be prevented ahead of time by knowing what is there and what needs to be done.

One of the best methods FHWA has seen for adaptation planning is to talk to the maintenance staff because they know where the problems are and they can say where they will go first to take care of problems. Engaging them in a structured way to gain that insight is really important and valuable in a lot of states.

Question: Is there policy related to the intersection of extreme weather with hazardous materials?

Answer: A climate preparedness council has been created. There is a venue for coordination on these issues across the federal government.

BREAKOUT 9: HIGHWAY SYSTEMS PLANNING

Changing climate and extreme weather have very different impacts on infrastructure, whether flooding is from sea-level rise, surface runoff, or changing air temperature and rainfall. This session presented tools and procedures for infrastructure planning for climate impacts in different parts of the world. The U.S. DOT Volpe Center's Ben Rasmussen presided.

Working Toward Climate Resilient Highway Infrastructure in the Netherlands

Kees van Muiswinkel of RWS opened by stating that the Netherlands is accustomed to change and extreme weather. Along the coasts, the Netherlands had marshes that strong storms have washed away. From 2000 onward, the Netherlands has pumped water out of lakes to create new land. About 59% of the Netherlands is susceptible to flooding because most of the country is located below sea level. The country has a high level of water protection, which began in the 1950s with the Delta Works and Delta Program. More extreme precipitation, though, means the system cannot handle all of the water even when maintenance is good.

RWS carries out a policy created by the Ministry that states all vital and vulnerable state functions must be resilient by 2050. This includes the transport, water, and energy sectors. The country has a National Adaptation Strategy, which is an integrated to climate change and adaptation, including all domains and different departments. RWS has taken concrete actions to prepare for and mitigate the effects of climate change through the following: conducting blue spot studies to determine where sea walls and levies are most vulnerable and will cause flooding; determining road element vulnerabilities; developing guidelines for considering climate impacts, including time, costs, and capacity; adjusting guidelines for water discharge; developing knowledge; and implementing measures such as porous asphalt. RWS is now facing challenges regarding how to implement such changes in daily operations. RWS is also working on developing an adaptation strategy for multimodal planning.

Risk Mapping Major Danish Roads with Blue Spot Identifications: Implementing Results Organizationwide with an Interdisciplinary Approach

Marianne Grauert of the Danish Road Directorate discussed the studies the agency has completed on "blue spots" throughout Denmark, which are sections of major roads that become flooded during major precipitation events.[2] Denmark is fairly prepared for flooding events but knows additional preparations are needed as flooding becomes more severe. Based on the directorate's research, the agency expects it will need to account for up to a 27% increase in drainage capacity by 2100 to keep the country's 4,000 km of roads working. The current strategy for adapting to climate change is to manage flooding when it occurs, prevent and improve where possible, and to collaborate with the relevant authorities. The blue spot project resulted in a GIS-based model that provides scenarios for present and future flooding. After mapping the entire road network, the directorate determined there are currently 11 blue spots. In 2050 there will be 17 more, and by 2100 five more will be added. The blue spots the model identified are being tested for accuracy, and they are being integrated into emergency planning, including rerouting and call-out service during floods. The model is now an obligatory tool to use in road planning, meaning project managers must consider blue spots when building roads and prioritizing resources.

Risk Analysis for the Adaptation of the German Road Network to Climate Change

Jürgen Krieger talked about how the Federal Highway Research Institute of Germany is using a risk-based approach to prepare for the climate change impacts projected for Germany's infrastructure. Starting with regional projections, the institute investigated possible vulnerabilities, derived indicators, and then developed potential consequences and risks. Roads were divided into top-level risk elements, such as tunnel, bridge, drainage, or slope, and then into lower-level damage categories, such as heat-induced damages. Indicators were developed by calculating the hazard potential and determining the risk potential (not taking into account probabilities). Vulnerability indicators were combined with climate indicators, such as heat-related damage to asphalt pavement (the risk element), and these values led to categories that were weighted to create a combined value. Seven case studies were conducted in various regions throughout Germany, resulting in a GIS risk map that road owners and operators can easily use to decide what actions to take.

Resiliency Planning at Caltrans

Julia Biggar of Caltrans noted that the agency is approaching climate impacts in the state by using regional-scale strategies. Climate change risks in California include sea level rise, rising temperatures, increasing wildfires, precipitation increases, and landslides. Caltrans is working with the California Coastal Commission to address how to handle the 3,000 mi of coastal roads that are susceptible to sea level rise and King Tide events. The state's options are defending these assets or adapting to events through planned or forced retreats. California is currently enduring the worst drought in recorded history, which will likely increase the frequency of wildfires, landslides, and washouts. More rain than snow is falling in the mountains, and the drainage systems are not designed for such heavy rainfall, which can lead to heavy flooding. Drought is exacerbating forest fires. These occurrences have been impacting and will likely

impact roadways, signposts, and guardrails. As part of the FHWA pilot studies, Sonoma County ranked and mapped its most vulnerable areas. Caltrans will now map assets statewide. The state is also reducing water consumption; implementing smart control irrigation systems that will receive weather conditions automatically and adjust levels accordingly; recycling water; increasing native drought-tolerant plantings; greening its fleet; replacing traditional lights with LED bulbs; and recycling pavement.

BREAKOUT 10: ADAPTING TO UNCERTAINTY

Presentations in this session centered on ways to make decisions that account for the uncertainty of the future and how to plan, prioritize, and adapt transportation assets to the effects of climate change. Jake Keller of WSP–Parsons Brinckerhoff moderated the session.

Increasing Resilience in Transportation Projects Through Robust and No-Regret Decision Making

Xavier Espinet of Resilient Analytics discussed a methodology that Resilient Analytics developed to address the high level of uncertainty associated with climate change impact models. Decision makers do not always understand the true nature of climate problems and sometimes find it difficult to define future standards or choose the best strategy to prepare for future weather events. FHWA developed a conceptual model several years ago to help practitioners understand asset vulnerabilities. Traditional cost–benefit analysis does not perform well for adaptation decision making. IPSS developed a robust decision-making methodology that includes: (1) identification of adaptation strategy options; (2) quantification of cost and benefit of each adaptation strategy; (3) determination of economic indicators based on perfect foresight; (4) comparison of strategies across all scenarios and build a payoff table; (5) evaluation of robustness and regret; and (6) selection of the best strategy. Resilient Analytics has taken adaptation strategies and calculated the costs and impacts of each to see which strategies have the least regret in various climate scenarios. This robust, low-regret approach to transportation adaptation investments is expected to assist planners with choosing the appropriate strategies to deal with climate impacts.

A Case Study Approach for Engineering and Economic Analysis for Climate Adaptation: Alaska's Dalton Highway

FHWA's Amit Armstrong presented the results of a case study for engineering and economic analysis for climate change adaptation on Alaska's Dalton Highway. This FHWA pilot project focused on conducting detailed case studies at three locations: Igloo Creek in Denali National Park, Kivalina along the Chukchi Sea, and the Dalton Highway. Each has a different climate impacts to address, such as thawing permafrost or sea ice melt. The Dalton Highway is a 411-mi stretch of roadway that is mostly used by freight trucks carrying oil.

Permafrost is permanently frozen water and soil beneath freeze–thaw and vegetative layers. When permafrost melts, it settles. The worst case scenario is expected to be up to 3 ft of settlement. When settlement occurs, roads can become uneven. The pilot looked at permafrost thawing and settlement along the highway and tried to calculate the effects on DOT maintenance

costs and roadway users. Using a thermal model, four cross-sections across a 2-mi area were studied to reflect varying subsurface conditions. The models indicated that up to 5 m of thaw could occur, and after 2033 there may no longer be a permafrost layer. If nothing is done, the settlement is expected to be up to 6 ft, which could result in approximately $150,000 of highway maintenance costs per year per mile. In certain sections, the cost may reach up to $325,000 per year per mile. The total present value costs over an 18-year period were calculated to be $6.9 million for the 2-mi highway segment.

NJ TRANSITGRID: Microgrid Technology as the Cornerstone of a Transportation Resilience Strategy

Eric Daleo, Steven Santoro, both of New Jersey Transit (NJ Transit), and Rima Oueid of the U.S. Department of Energy discussed the new microgrid project that NJ Transit is implementing following Superstorm Sandy. NJ Transit experienced significant water and wind damage to electric facilities. Diesel generators were found to not necessarily be a solution since fuel supply can be impaired too and generators cannot move trains or run continuously without raising air quality and emissions concerns.

As a result, NJ Transit and the U.S. Department of Energy signed a memorandum of understanding to start the process on developing NJ TRANSITGRID, which is a microgrid that will coordinate energy sources by providing energy closer to the distribution source. Microgrids provide customized, local energy, making systems requiring electricity more resilient and reliable. Sandia National Laboratory evaluated the existing system boundaries and devised a conceptual design for meeting NJ Transit's needs in the future. The microgrid system envisioned will utilize distributed energy resources including solar, microturbines, and fuel cells that provide energy to trains and facilities. NJ TRANSITGRID will provide direct energy to major substations in the network through the grid, so the transit system can be operated normally and can function off the grid in emergencies. A transportation operating plan will help NJ Transit to utilize the new system as well as add in bus infrastructure.

The project is an example of the intersection of federal policy and local needs. FTA awarded NJ Transit funding to make various portions of the transit system more resilient based on the anticipated economic impacts to customers if they will be late, or else unable to get, to work.

Arizona DOT: Mainstreaming Climate Change and Extreme Weather Resilience

Steven Olmsted discussed Arizona DOT efforts to mainstream climate change and extreme weather resilience. Arizona DOT assets operate from sea level to 8,000 ft and temperatures from below 0°F to over 120°F. Arizona DOT, which was the first state agency in Arizona to begin considering climate impacts, tested the CMIP-5[3] tool during a vulnerability climate assessment it conducted. Arizona DOT's resilience pilot was part of the Arizona DOT Sustainable Transportation Program and is now a formal program in the agency. Arizona often faces extreme weather impacts including flooding, landslides, overtopping, and extreme temperature changes. Formalizing a climate-related program has helped Arizona DOT to incorporate climate actions into existing planning, design, construction, operations, and maintenance criteria.

From a maintenance standpoint, the impacts of extreme weather events in Arizona are significant, because clean up is a costly regular occurrence, particularly from floods. Based on

pilot results, Arizona DOT has begun updating its Highway Drainage Design Manual to re-evaluate the entire risk approach for flood-related events. This has led to a clean-up of many Arizona DOT databases. Arizona DOT has also partnered with USGS to update hydrologic data in the state, which is expected to improve Arizona DOT efforts to plan and respond to incidents of flood, overtopping, system hotspots, and hydraulic-related failures. New Arizona DOT maintenance and operations projects include the Phoenix Pump Station Evaluation Plan that will refine assumptions made in developing capital projects, and the Healthy Forest Initiative which will ease roadway weight restrictions to allow timber to be removed to reduce risk of future wildfires. Arizona DOT is taking an economic approach to show how assets built in 2015 and onwards will fare into 2100. Arizona DOT is trying to move forward on climate resiliency efforts and encourages other agencies to do the same.

BREAKOUT 11: DEVELOPING CLIMATE INFORMATION

This session, which was presided over by FHWA's Robert Kafalenos, focused on examples of climate projections, information, and tools developed for planners and engineers.

Climate Products for Engineers

NOAA's Ellen Mecray opened by discussing gaps that exist between data makers and decision makers given that reports are often developed at large scales not necessarily usable by decision makers. NOAA offers a variety of tools and resources that have been tracking and continue to track climate indicators such as temperature and precipitation, which can help agencies plan and design for a different climate future. One such tool is ATLAS 14, which will be released soon.

Climate change will affect all modes, and there are many resources available to assist planners and engineers prepare. For example, the U.S. Climate Resilience Toolkit is an interagency product that the White House initiated that provides a five-step process for analyzing vulnerabilities, looking at risks and options, and then taking action. Furthermore, state climatologists are available in every state with the exception of Tennessee and Massachusetts, and there are six NOAA regional climate service directors. TRB Special Report 290[4] provided a good starting point for these discussions, and ICNet is a complementary resource that offers the tools necessary to work on assessments. ICNet offers a Climate Model Comparison Tool that shows users how to downscale each of the available climate models to determine which set of models are best for each agency's interests and needs. The website also features climate maps that display 21 indicators including temperatures and precipitation levels across different scenarios. The ICNet Research Guide and webinars explain how to approach climate assessments and specific topic areas that planners and engineers may be interested in better understanding.

Future Projections of Infrastructure-Relevant Climate Indices for Washington, D.C.

Texas Tech University's Anne Stoner described a process that the university followed to develop infrastructure-relevant climate indices for Washington, D.C. The first step was to assess all available knowledge to identify main areas of concern. In D.C., this included extreme temperatures and precipitation. The next step was to assess the extent to which robust

quantitative projections can be developed. For Washington, D.C., Texas Tech looked at observations from three weather stations and tested their data for errors. Next, the researchers assembled available data from nine different climate models that covered a range of climate sensitivity, had the appropriate outputs for the study, and were all well-established models. Climate models are improving over time, and no one model is the best or perfect. Practitioners should understand their limitations and recognize that a multimodel ensemble is nearly always closer to reality than any one model. Next, the researchers selected one high scenario and one low scenario for D.C. in the future. Results suggested that the average summer temperature in D.C. could increase dramatically as 2100 approaches.

In order to get localized climate projects, agencies can utilize statistical modeling or regional climate modeling. Statistical models are flexible, rapid, and less expensive, but they are limited by the nature of the model. Regional climate models have more output variables and detail, but they are expensive, time-consuming, and do not provide many scenarios. After running the models, the Texas Tech team looked at historical temperature and precipitation trends and determined if the models could predict those trends. The models averages were close to observed historical trends. From an infrastructure perspective, findings suggested that D.C. should expect more frequent extreme heat days and heat waves that can warp rail lanes and buckle roadways. Results also suggested that D.C. will experience an increase in heavy precipitation events that could flood roadways and cause structural damage.

European Guidelines for the Use of Climate Data for Road Infrastructure: ROADAPT and CliPDaR

Thomas Bles of Deltares discussed the European guidelines for using climate data to inform road infrastructure adaptation planning and implementation. ROADAPT and Climate Projection Data for Road Impact Models (CLiPDaR) are two projects to provide guidelines for using climate data. Landslides, avalanches, and extreme rainfall are examples of weather events that are increasingly affecting road infrastructure. Risk Management for Roads in a Changing Climate (RIMAROCC) is a framework European countries are using to begin addressing climate change and its impacts on road infrastructure. Its first step is to determine which climate parameters are relevant for assessing threats in a given area and time horizon in relation to the life expectancy of different assets. The second step is to look at how climate has changed in the past and how it may change in the future; availability and quality of data are important considerations. Step three consists of selecting climate scenarios and projections, recognized that data often needs to be downscaled to select adaptation options effectively. Mapping low, medium, and high scenarios can help practitioners compare and contrast results across the models. The fourth step is to process available data in order to use it. Observed climate data should not be compared with simulated future scenarios, but it can be verified to minimize biases of the models. Using statistical and regional downscaling methods is advised but may not be appropriate for small projects or if budget is a concern.

These guidelines are meant to provide road authorities with some information about how to manage climate impacts and to provide a starting point for having discussions internally and with climate scientists.

BREAKOUT 12: APPROACHES AND TOOLS FOR STATE AND REGIONAL ANALYSES

This session highlighted innovative tools and approaches for considering the potential impacts of climate change and extreme weather events at the state and regional level. Bob Noland of Rutgers University presided.

Vulnerability Assessment of the Maryland State Highway Network

Elizabeth Habic of the Maryland DOT presented the results of the Maryland adaptation and vulnerability assessment. The pilot focused on two counties in Maryland, which were selected based on their difference and geographic locations. The objectives of the pilot were to assess vulnerability of several assets to climate stressors including sea level change, storm surge, and precipitation. Maryland DOT used 2050 and 2100 sea level change projections for both counties to determine what future inundation the agency could anticipate. Maryland DOT created a hazard vulnerability index (HVI) to determine which parts of roadways in each study area were vulnerable. An initial screening of bridges in the study areas eliminated assets not expected to be affected by various rainfall and sea level rise risk scenarios, reducing the number of assets to be included in the analysis by nearly one-fifth. It was difficult to select roadway locations susceptible to flooding, so Maryland DOT developed HVI to take into consideration evacuation routes, flood depths, and road classifications (e.g., Interstate or local road). FHWA's Vulnerability Assessment Scoring Tool (VAST) structures were compared to the HVI roadway locations, and vulnerable areas at risk were identified. Lessons learned included data collection is easiest for bridges and there are data gaps related to small culverts and drainage pipes; VAST and HVI were useful for quantifying results and an initial screening reduced the total level of effort; adaptation measures for drainage assets have interdependencies outside of DOT's jurisdiction; and climate change needs to be incorporated into planning, design, operations, and maintenance. Next, Maryland DOT plans to review origin–destination network data to determine which roadways are the most critical before and after flood events and make plans for 2050 and 2100.

Evaluating the Vulnerability of Transportation Infrastructure to Extreme Weather Events: A Regional Approach

Mark Abkowitz of Vanderbilt University and Alan Jones of Tennessee DOT presented on Tennessee DOTs participation in FHWA climate change pilot program.[5] Tennessee, in contrast to the other FHWA climate pilots, is a landlocked state, where some new and different issues were identified.

Tennessee DOT is starting to take the results of the analysis to meet the requirements in Moving Ahead for Progress in the 21st Century (MAP-21) to develop a risk-based asset management plan that addresses extreme weather and climate change. Tennessee DOT worked with the Tennessee Extreme Weather Transportation Adaptation Partnership and regional focus groups that included the public and regional field staff. Tennessee DOT created an asset inventory (roads, rail, navigable waterways, airports, and pipelines), selected the most critical assets (based on strategic importance, emergency response routes, network connectivity, and redundant capacity), identified extreme weather impacts (extreme temperatures, heavy rain, drought, wind, snow, and ice), located relevant NWS data, and mapped the average weather event frequencies by

county. Tennessee DOT also mapped current observed climate data and future projected climate scenarios to understand where the most damage would occur. Tennessee DOT developed a survey to determine the damage and loss that an asset would incur given certain weather events. Transportation stakeholders responded to the survey, indicating whether a weather event would create nominal, moderate, significant or catastrophic effects, which led Tennessee DOT to generate impact scores for assets. The critical impact scores were overlaid on the map of extreme weather events by county. Tennessee DOT used this as a tool to determine which assets should be prioritized for adaptation measures. Conducting a statewide assessment required Tennessee DOT to group assets into generic asset categories (i.e., roads) and was time- and data-consuming. The field staffs were essential to identifying and categorizing assets. Next, Tennessee DOT plans to integrate weather risks into its policies and will select 15 to 20 of the most vulnerable assets to conduct a more targeted analysis. Tennessee DOT will also meet with the regions and provide them with accessible, user-friendly briefing books on the assessment and may develop the tool for others to use.

In the Wake of Hurricane Sandy: Creating a More-Resilient Regional Transportation System in New York, New Jersey, and Connecticut

Joshua DeFlorio of Cambridge Systematics and Jeff Perlman of NJTPA presented an assessment of the New York and New Jersey region after Hurricane Sandy. The assessment built on a pilot completed in 2011 for New Jersey conducted prior to the hurricane. FHWA led the assessment, but it involved partnership from many local and regional agencies, DOTs, MPOs, and consultants. The pilot involved four major steps:

- Conducting a damage and disruption assessment that recorded transportation damage and disruption from major weather events.
- Making climate projections based on existing climate data on precipitation, temperature, storms, and sea level rise.
- Performing 10 engineering-based assessments of transportation assets that considered a range of climate stressors and proposed a range of adaptation strategies.
- Developing a regional climate change vulnerability assessment and adaptation analysis.

NJ-7, one of three assets in New Jersey that were selected, was assessed for impacts due to projected future sea level rise and increased precipitation. Based on results, New Jersey DOT identified potential adaptation strategies such as raising portions of Route 7, building a seawall to protect the most vulnerable portion, and installing new drainage features. The PANYNJ Port Jersey South was also evaluated, and New Jersey DOT found evidence suggesting that the electrical infrastructure that severely damaged by Hurricane Sandy would also likely be affected by rising sea level by 2100. To prevent future impacts associated with flooding and sea level rise, the electrical facilities will be elevated to 15 ft above the facility's ground floor. Lastly, an assessment of the Thomas A. Mathis Bridge on NJ-37 found evidence that the structure itself is sound but that approach roads are prone to flooding. Installing floodwalls or earthen berms and fender systems to deflect debris could protect the asset. Once all assessments are completed, New Jersey DOT and its partners plan to release a final regional report. The team expects to release the report in 2016.

A Robust and Open-Source Climate Change Analysis Tool for Scenario-Based Planning

Alex Epstein of the U.S. DOT Volpe Center presented on the Central New Mexico Climate Change Scenario Planning project,[6] an interagency project funded predominantly by federal agencies. The purpose was to guide the long-range transportation planning of the Albuquerque region. Heatwaves, wildfires, snow melt, and flooding are the predominant climate stressors in the region. The project team used CMIP climate projections to look at the precipitation and temperature changes anticipated for the region up to 2099. These were then analyzed to develop four different scenarios in different regions within Albuquerque. The models indicate that temperatures will increase later in the century and the number of consecutive days over 100°F will increase, especially in the models' "hot dry" scenarios. In the valleys, particularly in the south and west of Albuquerque, dramatic changes are expected. Aggregating for the entire metropolitan area would not necessarily depict these differences. As a next step, the team plans to make the tool widely available in order that other agencies can refine it and expand upon it to meet their needs. This could include time series elements that would allow for analyzing species migration and other ecological impacts.

BREAKOUT 13: MAINSTREAMING CLIMATE RESILIENCE

This session, which Allison Yeh of the Hillsborough County MPO moderated, discussed how adaptation examples from across the globe, including how agencies in select countries are evaluating and integrating climate vulnerability considerations into transportation planning and prioritization processes.

Flexible Approaches to Climate Vulnerability Assessment for Urban Public Infrastructure

Joanne Potter of ICF International presented on lessons learned from the USAID CRIS program that has been operating in developing cities worldwide. Piura, Peru, is subject to severe drought conditions and severe flooding. Nacala-Porto, Mozambique, has been struggling to stay ahead of development pressures throughout the region, which has seen an influx of investments and is facing an increase in sea level rise and inundation. CRIS has found that climate assessments should be decision focused, rather than being deeply rooted in climate science, and that they should be integrated with a region's and nation's existing processes and objectives.

CRIS developed the Climate Information Application and Risk Screening Tool in partnership with Piura, Peru. The tool provides an approach to help practitioners find the climate information they need based on the infrastructure, its intended life span, the region, the level of climate information necessary, and climate stressors. Practitioners are then directed to synthesized, compiled summary information based on their criteria. That information is fed into a vulnerability assessment that can be used to provide vulnerability rankings and potential adaptation options. Using this building block approach is working in local governments—climate data is being integrated into decision making and local capacity is increasing.

Transit System Resilience Building through Prioritization, Institutionalization, and Implementation of Identified Climate Adaptation Options

Andrea Martin of Cascadia Consulting Group discussed the results of an FTA pilot project that Sound Transit participated in to determine which of its infrastructure operations and assets are most at risk. The Pacific Northwest will likely experience extreme precipitation, temperature increases, increased flooding and mudslide risks, sea level rise and storm surge, glacial retreat, and erosion. The project assessed the risks to Sound Transit assets, identified initial adaptation strategies, and provided testing ground for the process Washington State DOT established during its participating in FHWA's pilot project on climate change vulnerability assessment methodology.

Sound Transit's pilot studied how temperature, precipitation, and sea-level rise changes will affect rails, facilities, pavement, tunnels, and landscaping. First, Sound Transit worked with the University of Washington to project potential inundation from sea level rise at its facilities and, through stakeholder meetings and workshops, agreed on a prioritized list of assets. The assessment categorized potential impacts into minor, moderate, and significant impacts with low, medium, and high probabilities. Overall, there are low to moderate potential impacts, but increased mudslides and storm surge reach are expected to be concerns in the future. Using a matrix, Sound Transit created a range of adaptation more than 70 options and sorted those into options that could apply to various departments. The options were screened into four categories: (1) already doing, (2) consider now, (3) hold for the future, or (4) not in my purview. Fifteen of the 49 options were already underway and 12 were identified for near-term consideration. The options were then categorized into strategic action categories that Sound Transit plans to use in the future: (1) monitoring and evaluation of trends and available guidance (improved landslide gages and predictive monitoring); (2) integration of climate change information into plans and systems (including resilient design standards in the Design Criteria Manual); (3) adjustment of infrastructure and processes (drought- and heat-tolerant vegetation requirements); and (4) engagement with departments, jurisdictions, and agencies (engage on resilience at regional council meetings).

From Frameworks to Action: How Three Transportation Agencies Are Integrating Climate Resilience into Their Operations

Cris Liban presented on how LA Metro is integrating climate resilience into its operations. LA Metro is the regional transit planner, builder, operator, and funder for Los Angeles County. LA Metro developed a resiliency indicator framework, which includes indicators that help prioritize and evaluation adaptation implementation priorities. The criteria inform future funding streams and help Metro incorporate resiliency into its processes. Currently, LA Metro is conducting an organizational assessment and completing design criteria strategies for transportation engineers as well as asset management, so that resiliency is included in design–build and in management processes.

Claire Bonham-Carter of AECOM presented the results of the FHWA pilot project conducted in the San Francisco Bay Area. Sea level rise in the Oakland Coliseum area could cause significant inundation events by the end of the century. The pilot project developed a strategy for mainstreaming climate change considerations into transportation decision making. It focused on (1) establishing a climate change policy from the top-down, which will influence

other departments and plans; (2) incorporating adaptation in capital development, especially in relation to addressing physical vulnerabilities; and (3) updating emergency and operations plans to incorporate projected climate changes. Bay Area Rapid Transit, for example, is in the process of developing a sustainability policy and strategic plan that places a greater emphasis on resiliency and adaptation planning and is now beginning to incorporate adaptation planning into projects that are being considered for infrastructure reinvestments. Bonham-Carter also discussed a climate change study that is being completed for the Port of Long Beach. The port is developing an overarching climate change policy and incorporating climate information in its strategic plan, risk assessment manual, design standards and criteria, and stormwater infrastructure master plan.

Combining Risk Identification Methods to Prevent Roads and Railways in Sweden from Suffering from Increased Risk Due to Climate Change

Eva Lijegren of the Swedish Transportation Administration (STA) presented on whether it is possible to predict where roads will be flooded before they actually are flooded. The STA oversees roads, railways, shipping, and aviation. The country faces permafrost melt in the north and sea level rise in the south, but the country is most concerned with flooding, torrential rain, and increased precipitation. The study discussed used two methods: (1) GIS layers of existing traffic, geotechnical, and road accident data, and (2) blue spots based on high-resolution digital terrain models that depicts where low-lying areas are flooded. Both methods use coordinates and data that can be converted into GIS-layers and have been tested before. Without a database of natural hazards, the study conducted web searches to identify media coverage of flooding events. The assessment compared the two methods against the case study sites, which included Malmo, Munkedal, and Kristinehamn. The statistics used for traffic patterns were not useful for identifying flooding events—there were too few road traffic accidents in the system to accurately inform the assessment, and flooding-related risks are not recorded in the geotechnical data. The blue spots method worked well, but the locations identified were all "false" positives because the areas had bridges and culverts. The blue spot method could be useful if the locations of all bridges and culverts are known. Better records of incidents would provide better results, and working more with maintenance and operations staffs will also improve this process.

BREAKOUT 14: GREEN AND GRAY INFRASTRUCTURE AND CLIMATE RESILIENCE

This session demonstrated the effectiveness of "green" infrastructure as one tool for adapting to the impacts of climate change. The presenters provided suggestions of ways that transportation departments can begin to develop a standardized approach to assessing culvert vulnerability, or "gray" infrastructure. WSP | Parsons Brinckerhoff's Michael Meyer moderated the session.

Green Infrastructure and Transportation System Resilience

Sara Hoverter and Matthew Goetz of the Georgetown Climate Center presented on the state of green infrastructure around the country. Intense rainstorms and localized flooding combined with sewer systems in older cities are causing problems. Climate change can exacerbate problems

given projected increases in storm intensity and the resulting flooded streets, closed roads, and damaged roadways. Agencies would previously have used concrete masses to manage these impacts, but many organizations are realizing that green and gray infrastructure can be helpful.

The River Smart Washington program in Washington, D.C., is an example of how local government is testing the benefits of green infrastructure. U.S. DOT and Department of Energy are testing solutions such as porous asphalt and vegetative bio-soil to determine the most effective strategies for managing floodwater, water quality, traffic impacts, and winter road salt applications. During roadway repairs in Prince George's County, Maryland, is leveraging green and complete streets policies, for instance, to make multiple improvements at once. The county is improving parking, upgrading transit, ensuring American Disabilities Act compliance, and adding stormwater management systems. This has saved the county money and produced environmental and social co-benefits including better water and air quality. In another example, Pringle Creek, Oregon, installed porous pavement on all of its streets, saving $250,000 in infrastructure costs related to flooding. Chicago, Illinois, has established a green alley program that replaced existing pavement with permeable pavements that re able to melt and absorb ice and snow. These materials have reduced the need for salt by up to 75%. Chicago DOT published a Green Alley Handbook, so other agencies can learn from its work.

Goetz discussed how green infrastructure can be cost competitive if not cost-saving. Hoboken, New Jersey, has broadly deployed green infrastructure using U.S. Department of Housing and Urban Development, FTA, and private capital grants funding—some of which are only made available to applicants implementing green infrastructure. They closed the session by referring participants to the Georgetown Green Infrastructure Online Toolkit, which includes resources, tools, best practices, and case studies.

Culvert Vulnerability and Prioritization: Reconciling Currently Available Approaches and Data

Thomas Wall of Argonne National Laboratory discussed the importance of assessing all of the assets within an agency's inventory and prioritizing those that are at the greatest climate change risk. Culverts, which were a particular focus of the presentation, are vulnerable to increased precipitation since flow increases create excess pressure that can cause blockages or failure. This is especially problematic given the sheer number of culverts in the transportation system (many more than bridges).

Currently, there is limited literature on culverts aside from DOT-focused inventory information. A review of culvert inspection and rating systems from Federal Lands Highway and the National Bridge Inventory generated a list of indicators related to either embankment related culvert failures or blockage related culvert failures. Washington, Oregon, Minnesota, and New York provided data on their culvert management practices, which varied widely. Washington has inventoried culverts; Oregon began expanding its inventory by looking at functional performance but not condition; and Minnesota and New York both collected statewide location, performance, and condition information on their culverts. Though there were large gaps in the data, culverts were organized into low, medium, and high scale vulnerability tables. This exercise demonstrated that available data can be used to develop a vulnerability scale for culverts that can be applied across the country. The researchers suggested that there is a need for more complete and consistent data in order to develop national guidelines.

Prevention Is Better Than A Cure: Bioengineering Applications for Climate Resilient Slope Stabilization of Transport Infrastructure Assets

Asaif Faiz of the World Bank opened his presentation by saying there is defensible evidence linking increased and more frequent precipitation to increased risks of slope instability. Slope instability involves a water-related factor and human activity, such as flawed road construction. Most natural slopes are gently concave, providing the least susceptible and most sustainable conditions for resiliency. Manmade slopes are often much steeper and more linear, causing them to take on a concave shape and break off when there is a landslide.

In Pakistan traditional gray structures such as retaining walls, Gabion walls, benched slopes, and shotcrete, are not working as they have in the past. Green practices are being used to preserve slope and prevent landslides. Soil bioengineering and biotechnical stabilization are examples of green structures that can be integrated with conventional engineering measures, which are more cost effective when combined. Bioengineering is inspired by natural vegetation stabilization mechanisms. Grass seeding, woody planting systems, and vegetative structures are low cost and sustainable solutions. Drawbacks of these strategies are that they are seasonal, require more training, need protective fencing, and may be more vulnerable than traditional approaches in the first few years.

Steady Habits (Culverts): Anticipating Increased Precipitation in the Litchfield Hills of Connecticut

Stephanie Molden of Connecticut DOT presented the results of Connecticut DOT's FHWA-funded climate pilot studying culvert vulnerabilities.[7] Connecticut DOT's pilot focused on small culverts, between 6 and 20 ft long, in areas where the populations are low and transportation infrastructure is old. The project team began by reviewing Connecticut DOT's existing bridge and culvert database to narrow down the study assets to those in poor condition and that had high traffic volumes and had not been recently rebuilt. Assets on a designated national network were given priority.

Connecticut DOT chose 52 of the 60 culverts that its engineers evaluated. The project team assessed each culvert's importance and vulnerability using a criticality matrix borrowed from Washington State DOT, modifying it to include hydraulic, spatial, and social indicators. These rankings were mapped to determine if they were spatially important. The pilot revealed that not all culverts need to be upsized or resized and that adaptation is site specific. Thirty-four met flood standards and 13 were considered vulnerable. Eighteen did not satisfy bridge design criteria and 19 were deemed in critical condition.

The presentation stressed that culverts that are well equipped may still be vulnerable due to other assets in the system. As such, Connecticut DOT has begun outlining a plan and process managing risk to its bridges. The agency is also considering reestablishing a statewide hydrology committee to work with municipalities on adaptation strategies.

BREAKOUT 15: DEVELOPMENT AND APPLICATION OF DERIVED AND EXTREME CLIMATE VARIABLES

This session explored the techniques and challenges associated with applying global climate

model information to various localities faced with specific climate stressors. Jeff Arnold of the USACE presided.

Extreme Weather Exposure Identification for the Primary Road Network in the Alpine Region

Matthias Schlögl of the Austrian Institute of Technology conducted research on how the exposure of roads to extreme weather events can be assessed. The purpose of the research was to provide a quantitative basis for assessing the exposure of the primary road network in Austria to extreme weather events. The study examined precipitation and temperature using an extreme value analysis. To provide a nationwide analysis of the various climate impacts that may take place throughout Austria, the study selected 20 "hot spot" regions that were (1) near the highway network, (2) had quality data available, and (3) were evenly spread throughout the country. The study used block maxima and peaks over threshold methods to identify extreme values in each of the hot spot regions. The models suggested that increased precipitation and temperatures will occur across Austria.

To conclude, Schlögl noted that extreme value analysis is an easily applicable methodology for estimating return levels of precipitation and temperature indicators for any hot spot, although it may be difficult to find sufficiently long (20 to 30 years) time series data. In the future, the research team plans to analyze and model the impacts of adverse weather events on road accidents and road infrastructure in Austria, include a risk mapping effort.

Developing Transportation-Relevant Historical Trends and Future Climate Projections for Decision Support in the South Central United States

Esther Mullens of the South Central Climate Science Center presented the results of a regional study that evaluated future climate projections for the south central United States, which is geographically and climatically diverse including deserts, wetlands, prairies, and mountains. Most global climate models provide coarse climate data for local areas, which is why downscaling is important. The South Central Climate Science Center is developing a tool that will help practitioners better understand how uncertainty factors into global climate model predictions and statistical downscaling. The region has gaps in freezing precipitation data, so the center is using existing data to generate a geospatial dataset that generates statistics about ice conditions for different time periods. These types of analysis should help the center develop climatological data that will inform future projections.

A Process for Efficient, Scientifically Informed Climate Data Downscaling for Large-Scale Resilience Assessments: The Arizona DOT Approach

Steven Olmstead of Arizona DOT and Timothy Grose of Cambridge Systematics presented the results of Arizona DOT's 2014 FHWA Extreme Weather Vulnerability Assessment. A key component of the project was working with academics and practitioners to understand which projections, resolutions, and models would be most useful for Arizona DOT's purposes.

During the assessment, Arizona DOT used a statistical downscaling method and a number of general circulation models that have been shown to have accurately modeled El Niño southern oscillation. The agency relied on existing tools such as the FHWA's CMIP tool to

analyze climate stressors. CMIP converts daily metrics into data useful for practitioners using inputs such as precipitation events. Arizona DOT was able to adapt the tool using a script to automate the data processing, providing an easy-to-use GIS file that showed where assets could potentially be vulnerable. Arizona DOT was interested in extreme events and wanted to look beyond conservative estimates in order to prepare better for 2025 or 2050. Findings from the assessment were included in the Arizona DOT's strategic plan, particularly in the focus areas of financial resources, innovation, and infrastructure health.

Now, Arizona DOT is beginning to familiarize engineers and planners with results of the assessment using the GIS maps resulting from the pilot. There are three upcoming construction projects where aging drainage areas could be updated using data from the pilot. Arizona DOT plans to downscale climate data for the remainder of the Arizona state highway system.

Exploration of Climate Change Impacts: Modeling Projections of Extreme Events

Lorenzo Cornejo of the Texas A&M Transportation Institute presented the results of a study that evaluated climate impacts to transportation infrastructure in El Paso and Rockport, Texas. The study examined records of observed daily rainfall and sea level rise using SimCLIM software. The El Paso study analyzed estimates of future rainfall intensity in July, August, and September, while the Rockport study centered on estimates of future sea-level rise in Rockport. Results suggested that rainfall intensity projections for a 100-year-flood event in El Paso are expected to increase between 4.5% to 21.63% by 2030. Results for the Rockport component of the project suggested that sea levels will rise between 0.85 and 1.14 ft by 2035. Recommendations for El Paso include revising design standards and guidelines, and for Rockport identifying areas expected to become increasingly vulnerable to future sea level rise.

BREAKOUT 16: VULNERABILITY ASSESSMENT AND ADAPTATION—TOOLS AND GUIDES

This session explored tools and guides for climate risk assessment developed for use across countries and contexts. FHWA's Robert Hyman moderated the session.

Climate and Disaster Risk Screening Tool for Roads

Ana Bucher of the World Bank presented on work the institution completed through the International Development Association (IDA) to help impoverished countries incorporate climate and disaster risk considerations into its decision-making processes. The work involved developing a climate screening tool, which assesses exposure, potential impact, adaptive capacity, and project risk to screen all new IDA operations for climate change and disaster risks. The tool identifies risks at an early state, and when combined with user input, can help facilitate discussion that will lead to more in-depth analysis if necessary. Using the tool, a practitioner first identifies the study location and potential hazards and then rates physical components (i.e., climate hazard, time frame) with low, moderate, and high potential impacts. At this stage, the tool provides thresholds for a given climate hazard's impacts on road infrastructure. In addition to the screening tool, which is available through the Climate Change Knowledge Portal, the World Bank is developing a proposed strategic framework for integrating resilience measures

into all sectors through different mechanisms (i.e., capacity building, emergency planning, or relocating infrastructure).

FHWA Vulnerability Assessment Tools

Cassandra Bhat of ICF International presented on FHWA's suite of climate change adaptation tools developed as part of Phase 2 of the U.S. DOT Gulf Coast Study in Mobile, Alabama. FHWA hosts an online Virtual Adaptation Framework that provides tools, videos, and case studies that guide practitioners through conducting a complete vulnerability assessment. The asset criticality guidance related to the framework explains how to use various indicators (such as socioeconomic, operational, and health and safety) to identify which assets are the most critical. It includes a spreadsheet-based sensitivity matrix that describes how various climate stressors may affect different asset types. The CMIP Climate Data Processing Tool helps users find, access, and process readily available data that are relevant to transportation decision making. The CMIP Tool is already providing information on multiple vulnerability assessments in progress, but the tool can be expanded to accommodate different derived variables and sources of climate data. The final tool presented was VAST, a tool to help users interpret climate data through step-by-step guidance regarding assets, exposure, sensitivity, and adaptive capacity.

A Quickscan for Risks to Roads in Changing Climate

Thomas Bles of Deltares presented the ROADAPT QuickScan, a method for performing a preliminary climate change risk assessment. The method follows steps 1 through 5 of the RIMAROCC approach using a semiquantitative approach that is based on expert knowledge. The Quickscan method involves three desktop planning efforts and three workshops to identify consequences, probabilities, risk and location, and an action plan. The initial step in the QuickScan method is to identify threats. In the subsequent steps, the practitioner maps the probability and consequence of each threat. Consequence criteria (i.e., availability, safety, surroundings) are applied and weighted and experts are asked to score the threats and their consequences, as well as the probabilities for present and potential future scenarios. Finally, workshop participant discuss the results, which are graphed, to determine which risks are the most important to discuss and which can be eliminated. This process results in a short list of locations that will receive action plans, which can include new actions or existing activities that take place in operations and maintenance activities. Participants in the process should include transportation experts, economists, road engineers, communications experts, climate specialists, and asset operators. Agencies in Portugal, the Netherlands, Denmark, and Sweden have implemented the QuickScan method to date.

Toward Sustainable and Resilient Pavement Systems

Thomas Van Dam of NCE presented FHWA research on how increased precipitation and extreme temperatures that will likely impact pavement in the future. Both asphalt and concrete pavements will likely experience negative impacts from extreme temperatures, including increased risks of rutting or increased tendencies for curling and warping. More rainfall will likely impact texture, drainage, and visibility. When pavements are submerged it could take a long time for the roadways to recover. While historical data are important for determining how

pavements will react to future climate change, agencies should closely monitor whether and when pavement distresses are occurring and link those distresses to climate changes before implementing adaptations. Mechanistic–empirical pavement design considers historical climate data, so a next step will be to predict pavement distress using climate models. Van Dam noted that adapting critical assets to the changing climate will require changing specifications and better materials that can resist freeze–thaws, submersion, and extreme temperatures, and roadways that extreme weather events will affect may need to be relocated.

BREAKOUT 17: ASSET MANAGEMENT—STRENGTHENING OPERATIONS AND MAINTENANCE

This session, moderated by FHWA's Laurel Radow, examined the intersection of infrastructure asset optimization and efforts to broaden the scope of operations and maintenance in the context of climate resilience.

Incorporating Climate Change Impact Risks into Transportation Infrastructure Asset Management

Constantine Smaras of Carnegie Mellon University presented a new approach in asset management that incorporates climate change, minimizes life-cycle costs, and maximizes performance for the cost. Using the Markov Chain process, researchers and practitioners try to predict infrastructure conditions from very well to very poor and estimate when deteriorations will occur and when it makes the most sense to reinvest. When current climate data are added into an asset management framework, maintenance costs become uncertain. Changing the probabilities of an assets' condition based on the projected effects of climate change can generate a set of capital and maintenance decisions across a range of future scenarios. By changing the initial service life estimates, practitioners can anticipate the frequency of necessary inspections. Incentives will not necessarily be aligned to maximize performance and minimize cost, which is something that should likely be communicated to the public.

Using Asset Management Systems as a Platform for Continual Adaptation Planning

Michael Meyer of WSP–Parsons Brinckerhoff presented a template that AASHTO is developing for incorporating climate change into a transportation asset management plan (TAMP). U.S. DOT has issued a Notice of Proposed Rulemaking from MAP-21 that says state DOTs should have risk-based asset management plans. The TAMP is a mechanism that can accomplish this. The NCHRP 25-25 Task 94 Report[8] summarizes climate- and weather-related conditions that have historically affected the transportation system and particular assets. It discusses climate-related objectives, performance gaps, life-cycle costs, risks, financial plans, investment strategies, and lessons learned. The report includes the AASHTO TAMP Builder, a template for developing a TAMP. The TAMP Builder outlines questions that a user answers to determine where climate change and extreme weather considerations can be incorporated into a TAMP. Questions include: what types of assets should be considered; what are potential extreme weather specific impacts; can climate change or extreme weather performance measures be linked through aspects of the TAMP; how are assets funded after extreme weather events; and which

assets had the most funding?

Projected Impact of Climate Change on Frost-Thaw Profiles Beneath Roadways in Northern Maine

Heather Miller of the University of Massachusetts–Dartmouth discussed recent research on how climate change affects frost–thaw processes beneath roadways and how that process affects the seasonal load restrictions placed on trucks. In the late fall, the soil begins to freeze under asphalt and then moisture builds up, strengthening the frozen soil. In the spring, the soil thaws and reduces the asphalt's strength and stiffness, weakening load strengths. The research study used a USACE model that used test site data from around New England to determine projected air temperature changes in future climate scenarios. The team downscaled the data to get a higher resolution using a method from the Bureau of Reclamation. Research results showed a decrease in the depth of frozen soil, leading to an earlier and earlier end point for weight thresholds over time. The study concluded that climate change will significantly impact frost-thaw profiles beneath roadways. There will likely be a much shorter period when trucks can haul heavy loads without harming the roadways.

Emergency Management and Resilience in Transportation

Herby Lissade of Caltrans described Caltrans' processes for addressing emergency response and recovery. Caltrans has a mission in place to immediately respond to help citizens in emergency situations. California faces all natural and manmade disasters that Federal Emergency Management Agency recognizes, which means interdependencies with other sectors are essential for Caltrans to accomplish its mission. The agency uses the pre-event recovery planning guide for transportation, NCHRP 753. Caltrans activities to address climate change are included in the report. Additionally, the agency is greening its fleet, using LED lighting, and implementing new equipment methods for snow and ice management.

BREAKOUT 18: COOPERATION AND PEER LEARNING— CITIES, REGIONS, AND COUNTRIES

This session explored efficient ways to share knowledge and integrate activities across political boundaries at all levels. Kees Van Muiswinkel of RWS presided.

The Infrastructure and Climate Network: Lessons from a Regional Collaborative

Jennifer Jacobs of the University of New Hampshire and Gina Campoli of the Vermont Agency of Transportation presented on lessons learned from ICNet, a network of academics, students, and practitioners who are dedicated to accelerating climate science and engineering research in the northeastern United States. ICNet has been utilizing its experts from civil engineering, climate science, and communications to develop tools and offer assistance to agencies and practitioners in need. The network enables transportation practitioners to ask question about current infrastructure and conditions, and researchers are able to model future climate scenarios and how they will impact infrastructure. The network is producing forward-looking research,

studies on topics that have not yet been explored, and systemwide studies. ICNet has also developed advice on which climate models to choose and which agencies to contact for certain needs.

Peer Learning Across Developing Cities

Wendy Jaglom of ICF International discussed how the CRIS uses peer learning to build capacity for climate change assessment and adaptation in developing countries. Peer learning has been successful in developing countries because it builds trust, enthusiasm, and motivation among local practitioners who are responsible for adopting and advancing climate change adaptation on the ground in their cities. CRIS hosted a peer learning workshop that included participants from three Latin American pilot cities (two in Peru and one in the Dominican Republic). Agenda were developed based on participants' needs, wants, and promising practices. During the workshop, the participants developed 3- to 6-month action plans that outlined how they would use the knowledge from the event when they returned to their cities. Participants also participated in a "serious game" where they assumed the role of a city manager and made different decisions for their community based on different knowledge they were provided through the scenarios. A follow-up survey to workshop participants indicated that many had been in contact with other participants and had used the resource guide they received at training. CRIS learned that investment in post-event outreach will be useful to keep momentum and dialog going among participants in the future.

The Engineering for Climate Extremes Partnership

Mari Tye of the NCAR presented on the implications of various weather threats on transportation infrastructure from floods to freezing to wildfires to high temperatures. Bridge collapse, road and railway buckling, and toppling vehicles are occurring more frequently, which leads engineers to think about the consequences of system-wide failures. Residual risks are increasing, and failure is now likely certain. Structural engineers have been designing for graceful failure for a long time; designing for failure decreases the amount of damage and allows for faster recovery. The concept of graceful failure requires people to partner and decide where redundancies are necessary and where they are possible and desirable.

Cross-Border Cooperation on Adaptation Strategies for Roads in Europe

Marianne Grauert of the Danish Road Directorate provided examples of collaborative projects from the CEDR. CEDR is unifying member organizations behind a strategy for climate change adaptation of roads that begins at the executive level and is implemented throughout the organizations. Denmark and Sweden each developed strategies for adapting to climate change, which informed a template that CEDR developed for road authorities to use to implement the Danish and Swedish findings. The template focuses on management, improvement, prevention, and cooperation, and provides resources on communications, planning, legislation, research, and coordination.

BREAKOUT 19: DEVELOPING AND APPLYING FUTURE PRECIPITATION AND FLOWS

This session focused on the challenges and limitations of working with downscaled precipitation data and the conversion of precipitation to flow. It also included discussions about well-informed decisions that consider a range of future hydrologic scenarios. Brian Beucler of FHWA moderated the session.

Incorporating Climate Data Uncertainty into Stormwater Management Design Decisions for Transportation Infrastructure

Lauren Cook of Carnegie Mellon University began the session with a presentation on incorporating climate data and uncertainty into stormwater management design decisions for transportation infrastructure. Historical data is used to design drainage infrastructure. Annual maximum precipitation data are used to create intensity duration frequency (IDF) curve. Peak discharge curves can then be derived, which are used to design culverts. Practitioners can also use EPA's SWMM model. The model allows for analysis of multiple runoff scenarios based on various time series rainfall data. If conditions were expected to stay the same in the future, SWMM would be sufficient. Unfortunately, since the future will not look like the past, historical data cannot be used to design for the future as previous practice dictated. The question then becomes how can historical data and climate projections be used to inform rainfall as an input to drainage design?

In 2011, an extreme rainfall event caused flash flooding in Pittsburgh, Pennsylvania, that killed four people. Afterwards, a sign was erected that will flash when the road is closed due to high water. Some believe the sign to represent a low-cost solution to prevent future accidents; others believe the road should be redesigned. Rain data for Pittsburgh is high quality: there are 33 rain gauges collecting data every 15 min, with data being available for 2004–2014. To extrapolate these observed data to forecast conditions for 2040–2050 and 2060–2070, climate trends need to be incorporated into the rainfall time series. For this research, NARCCAP data with a time step of three hours and a grid cell size of 50 km^2 was used to calculate the 3-h exceedance probability. Delta change from climate models is then applied to the rainfall data based on exceedance.

The research teams believe others should "start simple," and then add layers of complexity to rainfall change models. Other take-away messages are that delta change is an easy method to use climate data to assess possible future rainfall patterns; different rainfall scenarios show varying future characteristics, for the same time period and across time periods; multiple futures means practitioners must plan for nearly all possibilities in future drainage designs.

Framework for Determining Suitable and Credible Climate Information for Hydraulic Adaptation Design and Incorporating Climate Projections into Design Metrics with Uncertainty Bounds

Chris Anderson and Ricardo Mantilla presented on FHWA's Iowa pilot to develop a framework for determining suitable and credible climate information for hydraulic design. The pilot project's problem statement was bridges will sustain greater fatigue and stress from streamflow than anticipated when designed to climate change. Setting out to test this hypothesis, the team

had to ensure credibility despite two potential error types:

- Aggregation error: climate projection data are coarse in space and time compared to measurements; and
- Sequence error: climate projection data will have storms in a different sequence compared to measurements.

Aggregation error was evaluated against historical observed data and against fine simulations. This error as a function of upstream area was also calculated. Sequence error was evaluated by within-sample flood quantile confidence intervals. Standard engineering practice uses the entire historical record to evaluation future loses. This is incompatible with using projects of future weather. For this reason, the Iowa research team then decided to define the period of record by bridge lifetime of 1960–2059. Results suggested that 12-km daily rainfall data are suitable for peak flow simulation in big basins (>100 mi^2) and big floods (twice the annual peak flow). Other takeaways from the pilot project are that climate projections do not indicate consistent patterns of change in flood frequencies, however not all models and scenarios agree on the magnitude of future flood levels.

BREAKOUT 20: SEA-LEVEL RISE, STORM SURGE, AND FLOODING TOOLS

This session centered on innovative tools and technologies being used to model, map, and manage sea level rise and storm surge risks across the United States. FTA's Adam Schildge presided.

Sea-Level Rise Inundation Mapping and Shoreline Vulnerability Analysis for California SR-37

Justin Vandever of AECOM presented on sea level rise inundation mapping done for California's SR-37 in the northern part of the San Francisco Bay Area.[9] The highway is constructed in low-lying areas across four counties. It is vulnerable to inundation and flooding now and is expected to be so in the future. The goal of study was to determine possible future planning solutions for SR-37 and its human and natural environment. The study comprised a stakeholder involvement process, sea level rise inundation mapping, shoreline and highway vulnerability assessment, and conceptual engineering design and cost estimates.

Regarding the sea level inundation mapping component, the project team relied upon topographic data (5-ft lidar-based digital elevation model), water level data (2-D hydrodynamic model results), and stakeholder input from federal, state, and local agencies and land managers. The project team used mid- and high-range projections for sea level rise that the NRC developed in 2012 for San Francisco, and then combined them with the daily high tide and extreme high tide scenarios. The results were a series of maps showing the depth and extent of regional inundation and overtopping of highway and shoreline protection assets. Other study products included a high-level sea level rise vulnerability and risk assessment for each highway segment in the area, including exposure, sensitivity, and adaptive capacity.

The Sea-Level Scenario Sketch Planning Tool: A Planning Tool for Assessing At-Risk Transportation Infrastructure

Crystal Goodison and Alexi Thomas of the University of Florida's GeoPlan Center presented on a sea level sketch planning project that the center has been working on with Florida DOT. In 2012, Florida Atlantic University completed a comprehensive analysis of SLR projections, studies, models, and methodologies used in Florida. One of the recommendations from the study was to develop a sketch planning tool to identify potentially vulnerable infrastructure. Since then, the GeoPlan Center has worked with Florida DOT to develop the tool.

Phase 1 of the effort focused on mapping where and when inundation is projected to occur in Florida and developing a GIS planning tool to facilitate the identification of transportation infrastructure potentially at risk to projected sea level changes. Data inputs for the mapping exercise included USACE's sea level change projections, NOAA tide gauge data and sea level trends, and a digital elevation model for Florida. Florida DOT data layers, particularly the strategic intermodal system, were included in the model to determine how many miles of infrastructure are susceptible to inundation. For the sketch planning tool, the team developed three tools: (1) a map viewer that allows users to visualize areas of inundation and affected infrastructure, (2) GIS data layers that GIS specialists can use in their own analyses, and (3) a sea level rise inundation surface calculator for GIS experts who want to create their own custom inundation layers. Now municipalities across the state are interested in learning about or using the sketch planning tool, which the project team plans to continue to enhance.

Use of Innovative Technology to Identify Flood Vulnerabilities and Mobilize Response for New York City Transit

David Kinskey-Lebeda of Arup discussed how innovative technologies to identify flood vulnerabilities and organize responses were applied for transit in New York City in the aftermath of Hurricane Sandy. Three projects were described. The first was a project to identify ways to protect and adapt fan plants. Fan plants are critical ventilation facilities on either side of underwater crossings. The second project focused on stations in the Canal Street area of lower Manhattan. The third project spanned stations and other transit infrastructure spread across New York City. Each project aimed to identify vulnerabilities at hatches, manholes, doors, conduits, entrances, ventilation buildings, and vent bays among other infrastructure components. Strategies for adapting them were also devised. For example, vent bay flood mitigation design solutions that were identified include mechanical closure devices (MCDs) and deployable covers—both of which are innovative and quickly installed protections. MCD design and development was discussed in depth. As part of the three projects, Arup also utilized iPads to inventory and track vulnerabilities and the status of armoring them.

State-of-the-Art Flood Modeling: World Trade Center Water Intrusion Protection Plan

Anna Lantin and Mark Olser of Michael Baker International presented on surface and subsurface flood modeling that Michael Baker International has done for the World Trade Center. The purpose of the flood modeling was two-fold: to determine flood risk and to raise public and decision-maker awareness. Typical approaches used to communicate results are 1-D, static text tables or output files conveying showing the extent of inundation. The project team decided to

communicate results using 2-D color exhibits and 3-D animations to help make complex model results readily comprehensible to laypeople and to gain trust from decision makers.

After conducting a risk and vulnerability analysis, devising mitigation alternatives, and modeling both, animations were creating using .kmz files that could be merged with Google Earth to show time-varying flooding scenarios at street level, as well as 3-D animations of subsurface portions of the World Trade Center. Regarding the latter, emergency escape routes, critical rooms and flood paths, interior flood mitigation strategies were outlined for stakeholders.

ROUNDTABLE DISCUSSION

Lessons Learned from Recent Climate Change Adaptation Pilot Projects and Initiatives

Becky Lupes, who is leading the FHWA climate change pilot program, which is nearly complete, said 11 of the 19 pilot projects are participating in the roundtable discussion. FHWA planned to fund 10 to 12 projects, but the agency funded 19 given the high response rate. The program included peer exchanges and webinars for the participating agencies, and the development of final research reports that will be summarized in a report available in 2016. Lupes asked each agency representative to briefly summarize the work that his agency completed during the pilot.

- Massachusetts DOT analyzed vulnerabilities of the central artery tunnel system to extreme sea level rise and hurricanes.
- Maryland SHA started a climate change program in 2008 but had not been able to integrate it into the organization. The FHWA pilot helped jumpstart the program.
- Arizona DOT was interested in climate change impacts on the state's diverse biotic community, including both the natural and built environments. The DOT wanted to do vulnerability assessments across the state to cover eight different biotic communities and a wide range of temperatures. The pilot helped Arizona DOT start a formal resiliency program.
- Connecticut DOT completed a study on small culverts in a rural part of the state. The pilot helped the DOT better understand vulnerabilities and critical assets, as well as how to develop a statewide methodology. The DOT is now more willing to incorporate climate change data from an asset management perspective.
- Tennessee DOT has recently experienced several extreme weather events that have had significant impacts on infrastructure, including the 2010 flooding in Nashville. The DOT completed a statewide vulnerability assessment that identified the state's most critical assets. A lesson learned is that field staff are valuable partners because they know a lot about the vulnerabilities in their regions.
- Michigan DOT performed a statewide vulnerability assessment. The agency identified data gaps as they pertain to conducting climate-related work. The agency entered new data resulting from the pilot into a database and plans to query the regions to see if it aligns with what staff are seeing on the ground.
- Maine DOT studied a culvert, a road, and a bridge along the coast of Central Maine. The agency designed alternatives to three different sea level rise projections and looked at the kinds of damage the assets would sustain under different design decision scenarios. The information is expected to help the DOT establish a cost efficient defense mechanism.
- Alaska Department of Transportation and Public Facilities (DOT&PF) performed a detailed economic analysis for three locations with different climate variables—one coastal, one inland permafrost, and one inland with slides. The analysis is still underway.
- Caltrans District 4 completed a second pilot with FHWA. (The first was a risk and vulnerability assessment of the Alameda County shoreline where the effects of climate change are already visible on King Tide and high tide days.) The most recent pilot focused on

developing and analyzing adaptation strategies. The agency also refined the sea level rise inundation mapping in combination with storm surge and analyzed a variety of different scenarios. Mapping proved to be a better way to communicate the potential impacts to stakeholders and decision makers.

- Iowa DOT used the pilot to determine what the peak discharge would be in 2100 assuming current bridges will last into 2100. The study ran 19 models to explore rainfall amounts and what future peak discharges might be.
- Broward MPO analyzed superstorm and storm surge issues from a long range planning perspective. The analysis revealed gaps within the local road network. The agency integrated different datasets to create a regional model that has since been deemed sufficient for making policy decision. Broward MPO is now looking to add climate change criteria to its funding mechanisms.

BREAKOUT 21: ASSET MANAGEMENT

Presiding over the session, ICF International's Michael Savonis started the breakout by commenting that asset management can be thought of as an important tool for planning. Asset management and planning complement one another as both involve life-cycle analysis, performance system development and administration, and budget management with the goal of better informing decision makers. In this session, presenters Paul Thompson and Hani Farghaly discussed ways that asset management can succeed in quantifying the effects of climate change.

Geotechnical Asset Management for Improved Highway Resilience in Alaska

Paul Thompson of Shannon and Wilson, Inc., presented on how Alaska DOT&PF is using an asset management plan to manage the issue of climate change. The Chief Geologist at Alaska DOT&PF began a project three years ago to manage geotechnical assets improved highway resilience. The project was founded on the idea that an asset management process plan could give the department the ability to better quantify and manage issues that climate change presents.

The first steps in the asset management process for a project like this are documenting the objectives of the asset management plan and the policies that should guide it. Afterwards, an inventory of geotechnical assets should be created in order that their conditions can be evaluated. The condition assessment can also be a resilience assessment and includes additional ways that this asset could disrupt a transportation system. Using information from the model developed, alternatives can be explored and the overall program can be optimized for implementation, evaluation, and modification, if necessary. One of the advantages to using an asset management plan to manage climate change is that it provides a clear performance measure. The asset inventory and its condition assessment can be used as a concrete baseline to track progress.

Alaska DOT&PF plans to make continuous improvements to the process but now has a solid foundation. Completing the asset inventory is top on the list of priorities for the very near future. Additionally, Alaska DOT&PF is focusing on beginning to track geotechnical asset management projects on their own rather than as a part of bridge or corridor projects, documenting performance versus target results on its public website, and continuing to improve risk and life-cycle cost analysis to better support priority setting.

The Resilience of Ontario Highway Drainage Infrastructure to Climate Change

Hani Farghaly, Ministry of Transportation Ontario, presented on a recent study completed on the resilience of Ontario's highway drainage infrastructure to climate change.[10] The main focus of the study was to determine whether the current drainage design standards and practices provide resilience to possible effects of climate change. Design standards in Ontario are typically based on 10- to 100-year return periods. However, impacts of historic extreme events are also considered and more stringent models might be implemented if certain parts of the infrastructure could be severely affected by such an event.

The research began with the task of finding existing case studies that provided applicable data that could be used to compare to the current infrastructure in Ontario. The next step was to compare the models in the chosen studies to the IDF curve that the Ministry uses. Base-year values for each study (1960–1990), were compared and adjusted to 2007, as 2007 data is the most recent available in Ontario. Variability of the results ranged from 10% to 30% depending on the location in the province. The Ministry of Transportation Ontario has now incorporated the values of the most consistent comparison into its current highway drainage infrastructure to make future predictions. The Ministry found that in many cases, adaptive measure could be taken to preserve the existing infrastructure in lieu of replacing major components. It was noted that the research findings are specific to Ontario and that results would vary greatly throughout the province.

Incorporating Climate Change Adaptation into Routine Bridge Preservation Decision Making at Florida DOT

Paul Thompson of Florida State University discussed routine bridge preservation and climate change adaptation efforts based on Florida DOT's bridge inventory. Florida DOT's research goal was to develop and implement a framework for bridge risk assessments. Using risk analysis, 31,000 bridge structures were prioritized in terms of life-cycle cost. A challenge faced was identifying appropriate funding levels for preservation projects, as the risk models consulted did not provide much insight. To overcome this challenge, very clear priorities were set to estimate both the likelihood and the consequences of 10 types of extreme weather events. Using these estimates, a dollar amount can be tied to the risks and then fully integrated into Florida DOT's planning, programming, and asset management processes. Florida DOT also has a project level analysis tool that can be used to consider individual structures. The tool incorporates deterioration models as well as risk analysis of the 10 extreme weather event types.

BREAKOUT 22: TWO CASE STUDIES—BIG AND WICKED BIG

Ellen Mecray of NOAA gave a brief introduction to start the session. The idea of climate change and its effects can be quite overwhelming. However, if consequences of climate change can be better understood and predicted, efficient adaptation measures can be designed and implemented. During the session, by Patrick Obrien, Kirk Bosma, and Ellen Douglas presented case studies on models and frameworks that can be used to predict and plan for specific climate change impacts.

Climate Vulnerability Assessment for a Water Resources Infrastructure Project

Patrick O'Brien of the USACE presented on the Climate Preparedness and Resilience Register (CPRR), which is a framework that was developed as a part of the USACE's Climate Vulnerability Assessment for Water Resources Infrastructure project.[11] The main goal of the project was to evaluate the accuracy of vulnerability assessments being done to prepare for climate change, focusing on sea level change in particular. The project also looked at how vulnerability assessments are being used, noting that one of primary purposes of a vulnerability assessment is to find thresholds. For the project, a scenario approach was used and three equally plausible scenarios were applied (low, medium, high). The CPRR was developed by combining key concepts such as linking tidal–geodetic datum, identifying coastal design performance factors, applying coastal force–total water level approach, applying future scenarios, and scaling analysis and decision making. According to O'Brien, all of these principles should be applied to successfully create design performance. The CPRR breaks performance factors into categories then evaluates vulnerability, defines the rate at which performance will be lost, and offers options for adaptive measure that can be introduced.

A Detailed Assessment of Climate Change Vulnerability and Adaptation Options for the Central Artery-Tunnel System in Boston, Massachusetts: The Good, the Bad, and the Wicked Difficult

Ellen Douglas, University of Massachusetts–Boston; Steven Miller, Massachusetts DOT; and Kirk Bosma, Woods Hole Group, Inc. discussed a case study done on storm surge risk modeling for a transportation project in Boston's Central Artery.[12] The project started when Massachusetts DOT and FHWA set a goal of finding the true vulnerability and probability of flooding in Boston and then making a plan based on that information.

Massachusetts DOT needed to assess the vulnerability of the Central Artery because of its importance to the transportation system in Boston. The objectives of the project were to evaluate the Central Artery, develop adaptive measure to address vulnerabilities, and support the creation of a new emergency evacuation plan.

The team started by trying to use existing information to perform a vulnerability assessment. However, the team soon discovered that existing information served other very different purposes and would not be sufficient for a reliable assessment. Massachusetts DOT requested a new more enhanced model, prompting the team to develop a high-resolution hydrodynamic model that includes all of the pertinent physical processes necessary to assess dynamic flooding in a coastal area. The model grid covers most of Atlantic coast, the Gulf Coast, and the Caribbean, and the resolution can be changed to view specific areas in as detailed as 2- to 3-m spacing. Five global climate change models were used to generate hurricane sets—20,000 hurricanes in the 20th century climate and 20,000 in the 21st century climate. The resulting change in hurricane frequency over time can be applied in the model to make predictions. The model was tested using weather events in the past, and the results were within 3 in. of the water levels recorded in flooded areas. Ultimately, exceedance probability maps were created to provide information on the percent chance of flooding in a given area. The maps have scenarios for present day conditions through 2100 and can be used as a useful planning tool for prioritizing both existing and new assets.

Some unexpected challenges the team faced included defining the scope of the project

due to its complicated nature, identifying most relevant data sets, developing a way to best organize an inventory of assets, and blending probability outcomes to include both hurricanes and nor'easters. These tasks turned out to be much more complex than originally thought and took more time than expected. Lessons learned during the project were noted as allowing for a sensible amount of time for the discovery phase for this type of project, recognizing that institutional knowledge of the people in the field can be more valuable than information found in records, accounting for additional time for computation when working with models because the scope is often expanded throughout a project. The approach used in the model can be applied to both coastal and inland areas.

BREAKOUT 23: BENEFIT–COST ANALYSIS TOOLS AND METHODS

This session presented a variety of benefit–cost analysis (BCA) tools and approaches that transportation agencies are using to incorporate climate and extreme weather risks in their planning, design, and investment decisions. Adam Stephenson of FTA presided.

Incorporating BCA Approaches into Adaptation Planning: Approaches and Applications from Recent Studies

Michael Flood of WSP–Parsons Brinckerhoff discussed approaches for incorporating BCA into adaptation planning that are described in recent research. In terms of climate adaptation, BCA can establish the idea of criticality and can help agencies take another step toward decision-making. One particular study discussed compared the differences between two different methods for conducting BCAs: the Monte Carlo method and the "Area Under the Curve" method. The key takeaways from the research were that the two methods should give the same result if done correctly; however, the Monte Carlo method may provide a more robust BCA approach.

A Dynamic Restricted Equilibrium Model to Evaluate the Traffic Network Resilience under Extreme Weather Events

Transportation is a vital element that is vulnerable to both natural hazards and human-made perturbations. As such, it is important to develop tools that explicitly consider the impacts of extreme weather events on this critical infrastructure. Beatrix Martinez-Pastor of Trinity College Dublin presented the Dynamic Equilibrium-Restricted Assignment Model, which allows the simulation of the network behavior when a disruptive event occurs. The model measures effects on travel costs and changes in route choices that result from a disaster. The model creates a quantifiable answer to the measure of resilience and allows the identification of weaknesses in the network to help in the design process.

An Engineering Based Approach to Risk Based Asset Management

Colorado experienced a significant weather event in 2013 that resulted in $500 million in damage. Aimee Flannery of Applied Engineering Management (AEM) Corporation presented research that her firm is doing to take the work done in the aftermath of the Colorado emergency and apply it to asset management. AEM is applying the Risk Analysis and Management for

Critical Asset Protection (RAMCAP) process in Colorado to help state agencies make decisions on what infrastructure to rebuild as part of their flood recovery efforts. RAMCAP may provide a process in which to apply the FHWA conceptual adaptation framework to asset management.

FTA Hazard Mitigation Cost Effectiveness Tool and Flood Recurrence Interval Calculator for BCA of Transit Resilience

Hurricane Sandy had immense impacts on transit systems in the northeast. FTA established a $3-billion grant program to fund transit resilience projects. FTA's Adam Schildge presented the customized hazard mitigation cost effectiveness tool (HMCE) that FTA developed to evaluate the projects to determine which will likely have the greatest benefit to transit riders and communities. The HMCE tool estimates the preresiliency project costs, including design and construction; operation and maintenance; and loss of passenger service. It also assesses the benefits of projects after resiliency measures are incorporated, including the reduction in physical damages, lower response and recovery costs, and reduced economic impacts of lost service, among others. The tool also has a built-in capacity to estimate the impact of sea level rise based on USACE's climate change adaptation sea level change curves or a user-specified methodology.

BREAKOUT 24: INTEGRATING TRANSPORTATION SYSTEM RESILIENCE

This session explored how transportation system resilience to climate change and extreme weather events can align with climate adaptation efforts in other sectors—at both the local and state level—as well as broader resilience initiatives. FHWA's Heather Holsinger moderated the session.

New Transportation Research Board Transportation System Resilience Section

Tom Wakeman of Stevens Institute of Technology and Brian Wolshon of Louisiana State University introduced a new TRB section called the Transportation System Resilience Section. The section will advance research, identify policies, protocols, and operational practices, and communicate best practices related to resilience. The goals of the section are to (1) promote communications among the "lifeline sectors," such as transportation, energy, communications, waste water, and waste; (2) build understanding of the sources of risk and potential mitigation options—regional and local; (3) develop an integrated and conceptual framework and guidelines for physical and social infrastructure; (4) identify transportation requirements for raising awareness; (5) identify and promote new research; and (6) support the needs of end users. The section is already working on a Transportation Resilience Guide to help promote and discuss resilience with managers, planners, and engineers at the local level, so that is becomes integrated into their routine activities. The section will host a Resilience Day on January 11, 2016, at the TRB Annual Meeting and invites anyone interested to provide input and be involved with the section. More information is available on MyTRB.org and will be released through *TRNews*.

Evaluating Urban Resilience to Climate Change Across Transportation and Seven Additional Sectors

Julie Blue and Emily Seyller of the Cadmus Group, Inc., and Susan Julius of the EPA presented the results of a multisector project that created a tool to evaluate urban resilience to climate change. The project explored how climate change will likely affect critical functions and services and what can be done to preserve them. The team selected 10 indicators per sector, a list that totaled 1,500 in its initial iteration. The team then selected the indicators most relevant for urban resilience where data were available. Stakeholders at study sites (Washington, D.C., and Worcester, Massachusetts) then responded to questions from the project team to score climate stressors they believed were impacting their respective cities. City managers answered questions and the sectors broke out at workshops to answer additional questions and review the assigned scores.

Results from Washington, D.C., which were communicated to the participants and have been tracked over time, suggested that the city scored high for resilience, likely due to the federal expertise that is uniquely available there. Other results suggested that parts of the transportation system are in need of being upgraded given that they were designed and constructed based on a past climate different than that which is projected.

Successes in Transportation System Resilience Through Statewide Adaptation Planning

Vicki Arroyo and Annie Bennett provided a summary of climate change mitigation and adaptation work that the Georgetown Climate Center has completed. The center recently launched a new tracking tool that shows the progress states are making on their adaptation work as well as innovative strategies that others can use. At least 15 states have documented statewide adaptation plans, and a number of others are developing plans. The idea of the website, which is home to more than 150 case studies, is to promote a race to the top for adaptation and resiliency. The center also has an adaptation clearinghouse that provides information on specific policy areas and materials and tools for planning and implementation assistance.

Arroyo and Bennett highlighted four of the case studies:

- The Florida Sea-Level Rise Sketch Planning Tool visualizes risks from sea level rise. Users can choose different rates of sea level rise and infrastructure types and can download the data in more detail to integrate into decision supports systems.
- The Mukilteo Multimodal Terminal Project in Washington state evaluated the ability of the Mukilteo Ferry Terminal's ability to withstand impacts from sea level rise. As a result, the terminal will be relocated outside of the 100-year flood plain and will address other economic and safety requirements.
- The Caltrans Erosion Control and Water Conservation project discussed Caltrans' 30,000 acres of irrigated landscaping. Following a workshop in 2013 to discuss investments to preserve these landscapes, Caltrans added mulch, limited tree pruning to increase tree cover, added more smart irrigation, and identified plants that require less water. This has reduced water usage by 32% between 2013 and 2014.
- The Emergency Response FuelNY Initiative required gas stations within half a mile of NYC to install generators. This included grants of up to $13,000 per station to implement.

BREAKOUT 25: CRISIS MANAGEMENT PLANNING

Effective crisis management can help transportation agencies prepare for extreme weather events and effectively respond as they occur. This session provided examples of how transportation agencies can identify and assess vulnerabilities, develop policies to improve resilience, and implement practices to reduce the impacts of extreme weather events on surface transportation infrastructure. Ben McFarlane from the Hampton Roads Planning Commission presided.

Minnesota DOT Flash-Flood Vulnerability and Adaptation Assessment Pilot

Bryan Anderson of Minnesota DOT presented the results of the agency's flash-flood vulnerability and adaptation assessment pilot project.[13] Heavy precipitation has increased in Minnesota due to greater thunderstorm activity. For this reason, Minnesota DOT used the pilot project to try to understand the highway network's risk from flash flooding and to determine how to best address those risks. Minnesota DOT did a high-level screen of state highway networks in two districts where heavy rainfall has been impacting the roadways, looking at sensitivity, exposure, and the adaptive capacity of assets of interest, such as culverts, bridges, pipes, and roads paralleling floodplains. Many assets received a negative rating because they were not designed to withstand the stresses the current climate is presenting. The project team created five tiers of vulnerability by district, but the districts had similar vulnerabilities. Minnesota DOT used FHWA's recommended approach to reduce vulnerability at culvert locations in two of its districts. Minnesota DOT now has plans to complete assessments in other parts of the state and to research ways to avoid slope failure.

Crisis Management of Unusually Severe or Sustained Snow Events

FHWA's Gabriel Guevara presented information from a World Road Association (WRA) report currently being developed on crisis management of unusual or sustained snow events. WRA defines a crisis as any event that threatens a system or organization, is unpredictable, and needs clear, rapid decisions. The report is evaluating risks in France, Spain, Iowa, and Illinois. It will also discuss ways to improve communication and processes as presented in cases from across Europe. Scotland and Latvia provide examples of how multiagency cooperation improves responses. In England, practitioners use a sliding scale for escalating crisis management through various levels of authority when necessary. The report asserts that good crisis management evaluates risk; establishes organization arrangements; and involves multiagency cooperation, escalation, communication, and preparedness practices. It involves technical subject matter experts across disciplines.

Cases from South Korea, Italy, the Philippines, and Boston, Massachusetts, are discussed as examples of effective ways to communicate with road users through signage, alerts, mobile data, and social media. Cases from Japan and Norway provide examples of how to connect experts to practitioners. The report will be available for download after November 2016.

NJ Transit Incorporates Resilience into Planning, Engineering, and Emergency Management Processes

Ayesha Dolasa of BEM Systems discussed the planning and engineering resiliency

improvements that New Jersey Transit has implemented at one of its Hoboken facilities since Superstorm Sandy. NJ Transit developed a resiliency framework that is now included in the prioritization process for capital projects and is part of a storm loss mitigation plan and a coastal storm surge emergency warning system. The system is not only more resilient, but it will improve funding and grant opportunities for NJ Transit and will manage insurance premiums. NJ Transit used a risk-based approach based on FHWA guidance to develop the framework. Now, FTA is investing in a project that will fill a canal near NJ Transit facilities and add elevated tracks to protect assets from damage. The rail yard and terminal will likely still be vulnerable, so the agency is investing in a Coastal Storm Surge Emergency Warning System that will inform workers of storms and surges up to 96 h before an event. In the future, the tools track data that can help decision makers to determine how accurate the projections were and to know how long it took to secure assets before storms.

Transportation System Disaster Response: Resilience Planning and Implementation

Pete Hankovszky of David Evans and Associates, John Susino of FTA, and Mike Marino of the Port Authority Trans-Hudson Corporation discussed the importance of collaboration, communications, and cooperation for successfully recovering from an extreme weather event. Superstorm Sandy caused $10.8 billion in transit damage, which was repaired in phases. According to Hankovszky, Susino, and Marino, agencies need to think of resilience beyond capital improvement and asset management. Resilience also involves emergency planning and management. Presenters believe that leadership, innovation, and collaboration are important parts of enhancing the state of practice. Social infrastructure is also important for pulling together efforts as is maintaining a regional perspective so as to not inadvertently move water from one area to another.

BREAKOUT 26: INTERNATIONAL AND REGIONAL FRAMEWORKS FOR ADAPTATION AND RESILIENCE

The session, which Annie Bennett of the Georgetown Climate Center moderated, included presentations about various frameworks and tools that practitioners are using to help with planning vulnerability assessments at different geographic scales.

An International Climate Change Adaptation Framework for Road Infrastructure

April Marchese of FHWA presented on the international climate change adaptation framework for road infrastructure that the World Road Association developed. The framework, which is based on the collective experience of countries in assessing climate change impacts on road infrastructure, outlines a four-phase decision-making process to identify vulnerable assets and then adapt them to accommodate the impacts of climate change. Two outcomes of the framework were the creation of a communications guide and a template for briefing senior management on climate adaptation issues. The products are designed to be useful to a variety of agency across a spectrum of adaptation planning experience levels.

North Atlantic Coast Comprehensive Study: Applicability to Regional Adaptation Planning

Amy Guise spoke about the USACE's North Atlantic Coast Comprehensive Study.[14] The study, which was part of the agency's Sandy Recovery Program, addresses the flood risk of vulnerable coastal populations within 10 states from Virginia to Maine, including Washington, D.C. The study formalizes a consistent approach for conducting more detailed, site-specific coastal evaluations and provides data and tools to support making informed coastal risk management decisions. The study identified vulnerable areas based on three exposure indices: population and infrastructure density, socioeconomic factors and trends, and ecosystems adaptive capacity. Sea level changes for 2018, 2068, 2100, and 2118 were evaluated to help practitioners determine structural and natural measures to protect against vulnerability. The applicability of the measures given different shoreline types was also assessed.

String of Pearls: Balancing Risk and Benefits of Considering Resiliency by Corridor or Asset

Maine DOT's Judy Gates presented an example of how highly technical discussions on climate change can be translated into agency decisions. The presentation discussed the challenges associated with integrating climate change impacts into decisions about infrastructure design. Challenges include fully understanding the uncertainties and risks that climate change presents, as well as a changing political climate and embedded organizational processes.

The Maine DOT is addressing these challenges in numerous ways. For example, it has integrated adaptive management practices into infrastructure decisions to account for evolving science. The DOT is recommending changes to its organization processes, specifically adding an alternatives analysis and integrating BCA into the planning stage versus at the design stage. The agency does not plan on changing its focus on safety, condition, and service to inform priorities, but instead is using design standards that address multiple factors, including climate change, to help inform and rank asset priorities.

BREAKOUT 27: INTEGRATING RESILIENCE INTO EXISTING MANAGEMENT TOOLS

The last breakout session highlighted approaches to integrating climate change and extreme weather resilience into existing management tools from planning to asset management and operations. FHWA's Rebecca Lupes presided.

Applying the Sea-Level Scenario Sketch Planning Tool to Enhance the Resilience of Long-Range Transportation Plans: Lessons Learned from Two Florida MPOs

Joshua DeFlorio of CambridgeSystematics began the session by describing the problems that sea level rise presents Florida. The state has the second most extensive coastline of any state, behind only Alaska. Given its low-lying geography, it is already subject to recurring tidal flooding and is on the front lines of sea level rise and coastal inundation exposure. The University of Florida GeoPlan Center developed a Sea Level Scenario Sketch Planning Tool (see Breakout Session 20) to help

MPOs assess Florida transportation infrastructure potentially at-risk to projected sea level rise.

Allison Yeh of Hillsborough County MPO described the MPOs experience using the sketch planning tool. The MPO started with a simulated Category 3 storm surge, which was based on the trajectory of a 1921 storm, along with 2040 projected sea level rise from the tool. Potential network disruption impacts were analyzed for the "typical day" to derive hours of travel delay, miles traveled, and trips lost. These figures were then used to approximate economic impacts and to estimate how transportation projects in the long-range plan might be affected.

James Cromar of Broward MPO briefly described the MPOs involvement in FHWA's vulnerability assessment pilot program. The process began with a data collection effort that relied on a variety of sources, including the GeoPlan sketch planning tool. While developing base maps, the MPO realized that the roadway data were not in their correct locations and therefore began using Navtec mapping data. The team also was returning false inundation locations, for example on road embankments and bridges. After making elevation adjustments, the team applied different climate stressors from the sketch planning tool to create adaptive capacity maps for transportation decision making.

The Long and Short of It: Climate Change for Asset Managers

Srirama Bhamidipati from Delft University demonstrated a GIS layer-based simulation model for assessing the impact of climate change on infrastructure. In Bhamidipati's conceptual framework, there were three stages. Stage 1 reflects climate conditions of the past and a typical asset management approach of repairing as funding cycles allow. Stage 2 introduces one climate event (e.g., snow, rain, heat) of different durations, sizes, and distances from city centers to one asset category, while stage 3 involves one climate event and multiple, interconnected asset categories (e.g., roads, sewer, utility). The resulting model allows users to view the cumulative effect of various climate stressors.

Asset managers' climate problems are that there are limited combined short- and long-term tools; there is generally reduced funding; and uncertainty about climate futures. The simulation framework presented attempts to address these problems by combining short- and long-term objectives and integrating asset management disciplines associated with urban areas in order that the most-effective investment decisions possible can be made.

Using Park and Refuge Asset Management Systems to Screen for Extreme Weather Vulnerability

Susan Asam of ICF International spoke about two tools that have been used to screen for extreme weather vulnerability at National Parks and refuges, specifically the National Park Service Coastal Facilities Risk Screening Tool and the Federal Land Management Agency (FLMA) Southeast Region Climate Change and Transportation Tool.[15] The tools were developed in the context of parks and refuges already facing infrastructure stresses from increased visitation, aging facilities, and a backlog of maintenance, among others. Climate change is expected to exacerbate these stresses, leaving FLMA asset managers with a question of how to adapt facilities to ensure that access to parks and refuges is preserved for future generations.

The approach used to develop the vulnerability assessment tools was designed to be complex enough to capture vulnerability and transparent enough to enable effective engagement

of unit staff. By using measurable indicators from existing datasets (e.g., inland flooding exposure, facility condition index, current replacement value), the project team eliminated the need for unit staff to collect data and enter them into the tools. Staff participation in tool refinement process helped to deepen the understanding of vulnerabilities and provided a solid foundation for adaption planning.

The resulting Southeast Region Climate Change and Transportation Tool assessed every transportation asset's vulnerability to coastal flooding, inland flooding, and wildfire. For the U.S. Fish and Wildlife Service, vulnerability scores are generated for 5,197 transportation assets within the Southeast Region's 121 refuges. For the National Park Service, the tool provides vulnerability scores for 5,858 transportation assets across one region's 58 parks. With this information, park and refuge staffs are now more empowered to incorporate climate change concerns into day-to-day decision making, especially regarding potential adaptation actions.

Enhancing System Operations Through Improved Reliability and Resiliency of Traffic Signals in an Urban Environment

Soumya Dey from the Washington, D.C., DOT presented on system operations strategies that the DOT has used to improve the reliability and resiliency of traffic signals. Washington, D.C., has an area of 68.3 mi^2 and is part of the country's seventh largest metropolitan area. The population is approximately 650,000, and there are 500,000 daily commuters along with more than 125,000 daily visitors—effectively doubling the daytime population. Less than 1% of the roadway lane miles are freeways, meaning that the roadway system's efficient operation relies on the effectiveness of its traffic signal system.

Power outages account for roughly 5% of traffic signal disruptions in D.C. However, power-related outages represent over 86% of total disruption duration (approximately 4,000 h total, less than 50% of which are longer than 6 h). To improve traffic signal reliability, the DOT is working with the Potomac Electric Power Company on a multiyear project to move power lines, particularly the high voltage lines, underground. Resiliency is being improved by implementing emergency back-up generators and uninterruptable power supplies (UPS) for traffic signals. The effort began in 2005 when the DOT received a $1.6-million grant from the Department of Homeland Security to procure back-up generators and develop standard operating procedures for maintenance and deployment. When Recovery Act funds became available, DOT began procuring UPS for its signals. Currently, 350 intersections have been fitted with UPS, which can operate up to 6 h at a time. Data show that 69% of the times that UPSs have been triggered, they have operated for less than 1 min. Without a UPS, the signals would have gone into flash mode, necessitating signal maintenance or repair.

Data suggest that the use of generators has saved the Washington, D.C., DOT nearly $30 million over 6 years, while UPSs saved $1.4 million in 2014.

NOTES

1. FHWA Order 5520, Transportation System Preparedness and Resilience to Climate Change and Extreme Weather Events, established the FHWA policy on preparedness and resilience to climate change and extreme weather events. www.fhwa.dot.gov/legsregs/directives/orders/5520.cfm.
2. http://tra2014.traconference.eu/papers/pdfs/TRA2014_Fpaper_19594.pdf.

3. The Coupled Model Intercomparison Project (CMIP) is a standard experimental protocol for studying the output of coupled atmosphere-ocean general circulation models (AOGCMs). CMIP Phase 5 (CMIP-5) is a set of coordinated climate model experiments that provide a multi-model context for assessing various questions that have been raised from previous models. http://cmip-pcmdi.llnl.gov /cmip5/.
4. *TRB Special Report 290: Potential Impacts of Climate Change on U.S. Transportation*, describes the nature of the potential impacts of climate change most relevant for U.S. transportation and suggests appropriate adaptation strategies and organizational responses. http://onlinepubs.trb.org/onlinepubs/sr /sr290.pdf.
5. www.fhwa.dot.gov/environment/climate_change/adaptation/publications_and_tools/vulnerability _assessment_framework/.
6. www.volpe.dot.gov/transportation-planning/public-lands/central-new-mexico-climate-change -scenario-planning-project.
7. www.fhwa.dot.gov/environment/climate_change/adaptation/publications_and_tools/vulnerability _assessment_framework/.
8. NCHRP 25-25 Task 94, Integrating Extreme Weather into Transportation Asset Management Plans, suggested a process and template the DOT officials can use to consider extreme weather events and climate change when developing or updating the Transportation Asset Management Plan. http://onlinepubs.trb.org/onlinepubs/nchrp/docs/NCHRP25-25(94)_FR.pdf.
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13. www.dot.state.mn.us/climate/pdf/ExecutiveSummary2.pdf.
14. www.nad.usace.army.mil/Portals/40/docs/NACCS/NACCS_main_report.pdf.
15. www.fhwa.dot.gov/environment/climate_change/adaptation/case_studies/southeast_region/index.cfm.

CLOSING PLENARY SESSION AND CLOSING TOWNHALL

Bringing It All Together

In this closing session, which Michael Culp of the FHWA moderated, speakers from the Netherlands and Massachusetts DOT drew linkages between the state-of-the-art research and practices presented during the conference and implementation in their own agencies and communities.

Kees van Muiswinkel of RWS opened the plenary by sharing top lessons learned during the conference:

1. Transportation planning has to do with vulnerable people;
2. Adaptation pays back in returns on investments; and
3. Now action is needed in addition to planning.

Breakout session discussions agreed that the more mitigation occurs now, the less adaptation will be required in the future. European Union (EU) policy balances mitigation and adaptation. The EU adaptation strategy from 2013 promotes climate-proofing actions at the EU level, as well as action by member states. An Adaptation Futures Conference will be held in the Netherlands and projects such as those presented at this conference (i.e., Climate-ADAPT portal, CEDR projects, the Delta Program) will be discussed. The challenge is integrating climate into daily operations. The Netherlands is working to raise awareness, add climate change considerations to key decision moments, and relate maintenance to planning activities.

Massachusetts DOT's Steven Miller said the conference is helping his agency take its vulnerability studies and turn them into actual adaptation options. The Boston Harbor flood risk model can be used to help both Massachusetts DOT and its partners. There could also be more coordination on technical and stakeholder issues, concerns, and needs. As a result of the Massachusetts DOT–FHWA pilot study, Massachusetts DOT is considering a number of adaptation projects, and there are possible regional adaptation strategies being considered. The Massachusetts DOT climate pilot report has not been publicly released yet, but universities and municipalities are using its preliminary findings to better plan their communities, assets, and infrastructure for expected climate impacts.

What We Heard and Next Steps

In the conference's last session, members of the Conference Planning Committee presented the key findings, initiatives, and ideas brought forward from a number of different participants during the conference. Conference participants were invited to join a facilitated discussion on their individual ideas for potential next steps for improving their communities' resilience to climate change and extreme weather events. This section lists the highlights from this last session.

Project Level Adaptation Track

- An update to the highways and riverine environment hydraulic circular will talk about join probability and combining conditions that could happen within the same timeframe.
- Historical and projected data will change, and agencies do not want to over-design, but there is now guidance on how to use climate and historical data together.
- Some agencies require a BCA on any project over $10 million.
- Delaware was considering buying property near a road to abandon the road if necessary or possible, but it is not legal to do so; agencies should consider legal options and opportunities as conditions change.
- Discussions about how to predict and protect populations from large-scale and extreme weather events are increasing.
- Combining green and gray infrastructure, such as pervious pavements that reduce salt usage and plowing frequency, may create useful cost savings.
- Property tax increases or Partnership for Sustainable Communities grants provide good financing opportunities for climate projects.
- Culverts are mostly being treated as individual pipes, but they should be considered as a whole in the drainage network.
- Data agencies such as USGS are great partners.

Resilience in Operations and Maintenance Track

- Climate models are not useful unless there is funding to use them.
- Maintenance staff often know where problem areas are and may have solution suggestions.
- Electrical technologies that are relied upon can be compromised during storm events; agencies should have back-ups in place for when communication towers go down or when variable speed limit signs are not working.
- Severe weather event impacts can last for months or even years from an operations and maintenance standpoint.
- Managing and using data are critical tasks; there need to be usable formats on the road and data needs to translate into implementable actions.
- FHWA is a resource, but agencies should start working on solutions now without being required to do so.

Climate Science and Data Track

- Scientists are interested in discussing the entry points for including climate information in the engineering process.
- Assemble multidisciplinary teams early in the project–planning process.
- Climate projections are interpreted differently from historical data.
- Decision-making proceeds in the absence of perfect information, so practitioners should use multiple climate models and consider moving ahead with the best information available at the time.

International and Cross-Cutting Track

- Countries are creating networks to communicate across disciplines, organizations, levels, and borders.
- CEDR has a history of cooperating across national boundaries.
- Developing countries are finding solutions that use local materials and meld with local cultures and that can be completed on a smaller scale and for a lower cost.
- There is no time to develop new models; developing countries need to use existing data.
- Norway is deploying climate factors at the project level.
- Cooperation is important in Europe through information-sharing and data-warehousing.
- Europe is pursuing different national strategies using common guidelines such as RoadADAPT and blue spots.
- The United States and the EU do not have statutory requirements; motivation is driven from within individual agencies.
- Asset management and incorporating climate change information is essential for reporting and handling vulnerabilities.
- Maintenance staff know about past problems and can help determine where future issues could occur.

Planning for Resilience Track

- Mainstreaming climate change into daily decisions using interdisciplinary and stakeholder engagement techniques is moving from frameworks into implementation.
- Numerous tools, pilot studies, and reports have become available in the past 7 years to assist practitioners, including:
  - TRB Special Report 290;
  - New TRB section on resilience;
  - BCA tools;
  - Structured asset management decision support tools; and
  - FHWA pilot projects.

Tools and Techniques Track

- Know what information is needed before using a tool and match data to the question being asked.

- Ground-truth data and models with field staff.
- Understand how results will inform future actions and outreach efforts.
- It is important to document efforts and share knowledge.
- FTA will publish a transit asset management proposed rule soon.
- A mechanism may be need for mitigating residual risks.
- May need tools for considering social resilience capacity.

Heather Holsinger from FHWA closed the session and the conference by stating that 550 people attended the plenary session remotely. She encouraged participants to continue the conversation. TRB planned to solicit feedback on the event and to hold a session at the TRB Annual Meeting in January 2016.

APPENDIX

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