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Transportation Resilience

Adaptation to Climate Change and Extreme Weather Events

Summary of the Fourth EU–U.S. Transportation Research Symposium

Katherine F. Turnbull
Rapporteur

June 16–17, 2016
THON Hotel Brussels City Center
Brussels, Belgium

Organized by the
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This report has been reviewed by a group other than the authors according to the procedures approved by a Report Review Committee consisting of members of the National Academy of Sciences, the National Academy of Engineering, and the National Academy of Medicine.

This project was organized by the European Commission, the U.S. Department of Transportation, and the Transportation Research Board.

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Preface

This document summarizes *Transportation Resilience: Adaptation to Climate Change and Extreme Weather Events*, a symposium held June 16–17 at the THON Hotel Brussels City Center in Brussels, Belgium. This symposium was the fourth annual symposium sponsored by the European Commission and the U.S. Department of Transportation and organized by the Transportation Research Board (TRB) of the National Academies of Sciences, Engineering, and Medicine. The goals of the symposia are to promote common understanding, efficiencies, and trans-Atlantic cooperation within the international transportation research community while accelerating transport-sector innovation in the European Union (EU) and the United States.

The two-day, invitation-only symposium brought together high-level experts to share their views on disruptions to the transportation system resulting from climate change and extreme weather events. With the goal of fostering trans-Atlantic collaboration in research and deployment, symposium participants discussed the technical, financial, and policy challenges to better plan, design, and operate the transportation network before, during, and after extreme and/or long-term climate events.

A bilateral planning committee was assembled by TRB and appointed by the National Research Council (NRC) to organize and develop the symposium program. The planning committee was chaired by Alan McKinnon from Kühne Logistics University. Richard ("Dick") Wright, University of Maryland, College Park, served as cochair. Committee members provided expertise in public road and transit systems, ports, waterways, airports, finance, risk management, and environmental concerns. The planning committee was responsible for organizing the symposium, identifying speakers, commissioning a white paper, and developing three future case scenarios to facilitate discussion. The white paper is provided in Appendix A, and the case scenarios are presented in Appendixes B, C, and D. New readers may find it advantageous to review the white paper and scenarios first to more fully understand the discussion in the breakout groups.

The future case scenarios—rising sea level, river and storm flooding, and drought and extreme temperatures—were developed by the planning committee to help frame discussions in the breakout groups. The breakout groups addressed managing risk, minimizing disruptions during extreme events, and facilitating recovery. The breakout group discussions focused on identifying challenges, managing challenges, and research topics appropriate for EU–U.S. collaboration.

The symposium's interactive format enabled ongoing input from the assembled experts. The symposium began with keynote presentations by Jan Hendrik Dronkers from Rijkswaterstaat and Donald Weubbles from the University of Illinois at Urbana–Champaign, who is currently on assignment to the Office of Science and Technology Policy, Executive Office of the President. The white paper prepared for the symposium was also presented in the opening session. The breakout sessions followed a common format. First, members of the planning committee summarized the key elements of the future case scenarios. Second, breakout group participants discussed challenges, managing those challenges, and potential research topics. Third, the rapporteurs for each breakout group summarized the key discussion points in a general session. The symposium concluded with panels that included EU, U.S. Department of Transportation, and TRB representatives.

This report, prepared by symposium rapporteur Katherine F. Turnbull of the Texas A&M Transportation Institute, is a compilation of the presentations and a factual summary of the ensuing discussions at the event. The planning committee was responsible solely for organizing the conference, identifying speakers, and developing breakout session topics. The views contained in the report are those of individual symposium participants and do not necessarily represent the views of all participants, the planning committee, TRB, the European Commission, the U.S. Department of Transportation, or the NRC.

This report has been reviewed in draft form by individuals chosen for their diverse perspectives and technical expertise. The purposes of this independent review are to provide candid and critical comments that will assist the institution in making the published report as sound as possible and to ensure that the report meets institutional standards for objectivity, evidence, and responsiveness to the project charge. The review comments and draft manuscript remain confidential to protect the integrity of the process.

TRB thanks the following individuals for their review of this report: Ángel Aparicio, Technical University of Madrid, Spain; Heather Holsinger, U.S. Federal Highway Administration; Beatriz Martinez Pastor, Trinity College, Dublin, Ireland; and Michael Meyer, WSP–Parsons Brinckerhoff, Inc. Although these four reviewers provided many constructive comments and suggestions, they did not see the final draft of the summary before its release.

The review of this summary was overseen by Susan Hanson of Clark University (emerita). Appointed by the NRC, she was responsible for making certain that an independent examination of this summary was performed in accordance with established procedures and that all review comments were carefully considered. Karen Febey, TRB Senior Report Review Officer, managed the review process. Responsibility for the final content of this summary rests entirely with the authors and the institution.

Acronyms

AASHTO	American Association of State Highway and Transportation Officials
BCA	benefit–cost analysis
CCCEF	Center for Climate Change and Environmental Forecasting
CEDR	Conference of European Directors of Roads
CH_4	methane
CO_2	carbon dioxide
F	Fahrenheit
EU	European Union
FAA	Federal Aviation Administration
FAST Act	Fixing America's Surface Transportation Act
FHWA	Federal Highway Administration
GHG	greenhouse gas
ICS	incident command system
IPCC	Intergovernmental Panel on Climate Change
IT	information technology
NCA	National Climate Assessment
NCHRP	National Cooperative Highway Research Program
N_2O	nitrous oxide
NRC	National Research Council
NWS	National Weather Service
OST-R	Office of the Assistant Secretary for Research and Technology
ppm	parts per million
RBTAM	risk-based transportation asset management
R&D	research and development
SHA	Maryland State Highway Administration
STA	state transportation agency
TRB	Transportation Research Board
U.S. DOT	United States Department of Transportation

Contents

Welcome and Introductory Remarks

The symposium welcome featured comments from Clara de la Torre of the European Commission, Directorate General for Research and Innovation; Kevin Womack of the U.S. Department of Transportation (U.S. DOT), Office of the Assistant Secretary for Research and Technology; and Neil Pedersen of the Transportation Research Board (TRB) at the National Academies of Sciences, Engineering, and Medicine. Alan McKinnon of Kühne Logistics University and chair of the symposium planning committee provided an overview of the symposium goals and the program.

Clara de la Torre provided a welcome from the European Commission, Directorate General for Research and Innovation. She reviewed the EU, U.S. DOT, and TRB partnerships, the goals for the symposium, and the desired outcomes.

De la Torre reviewed the EC, U.S. DOT, and TRB partnerships established in 2012 to conduct four symposiums addressing common transport challenges. Although each symposium has addressed a different topic, they have all focused on enhancing trans-Atlantic transportation research, communication, and cooperation. She noted that the symposiums have provided excellent methods for sharing information on critical issues, best practices, and research gaps. She reported that initial promising outcomes from the symposiums have included early learning, expanded networking, and collaborative research opportunities. The symposiums succeeded in fostering greater trans-Atlantic interaction among researches and practitioners. She described the twinning research approach, which includes the EU and the U.S. DOT issuing separate, but compatible, calls for research. The selected researchers are able to meet and collaborate with funding for travel provided as part of the individual projects.

De la Torre emphasized the importance of this symposium examining the impact of climate change and extreme weather events on the transport system and approaches to reduce the frequency and severity of related disruptions. She noted that the symposium included sharing information, discussing issues, and identifying trans-Atlantic research opportunities. She invited participants to adopt a cross-modal perspective on the adaptation of transport infrastructure and operations to changing climatic conditions. She reported that exploring public- and private-sector responses to weather-induced disruptions was important, as was discussing needed research and innovation to support climate adaptation in the transport sector.

De la Torre stressed that a major goal of the symposium was to foster trans-Atlantic collaboration in research and development across a wide range of disciplines, including transport planning, engineering, design, operations, finance, economics, insurance, risk assessment, risk balance management, public outreach, and public policy. Key activities for the symposium included reviewing the current state of research in transport adaptation, identifying research gaps and hot topics, and discussing methods to stimulate future research innovation. She noted that the symposium results will be used to inform future research agendas, foster trans-Atlantic collaboration, and promote cross-disciplinary research. She stressed the importance of increasing the relevancy and the impact of research, as well as identifying take-up measures for trans-Atlantic technology deployment. She challenged participants to engage in frank discussions, to learn from others, and to enjoy the symposium.

Kevin Womack provided a welcome from the U.S. DOT Office of the Assistant Secretary for Research and Technology. He recognized and thanked the other sponsoring agencies, the planning committee, and the white paper authors. He noted the benefits from previous symposiums and stressed the importance of identifying opportunities for ongoing research collaboration.

Womack expressed appreciation to the EU for hosting the symposium. He extended greetings from U.S. DOT Secretary Anthony Foxx and Assistant Secretary for Research and Technology Greg Winfree. He thanked Alan McKinnon, chair; Dick Wright, cochair; and members of the planning committee for organizing an excellent program for the symposium. He also recognized white paper authors Gerry Schwartz and Lori Tavasszy.

Womack noted that examining transportation resilience and climate change and extreme weather events is an important and timely endeavor. The June 2016 flooding in Paris; Houston, Texas; and southern Oklahoma provided the most recent examples of extreme weather events. These events damaged the transportation infrastructure and resulted in fatalities.

Womack reported that the three previous symposiums were very successful in generating opportunities for additional trans-Atlantic research collaboration. He thanked participants for taking the time to attend the symposium. He challenged participants to engage in the breakout group discussions and to share their experiences and ideas for research. He also noted that the symposium provided an excellent opportunity for networking, developing new contacts, and initiating potential research collaborations.

Neil Pedersen provided a welcome from TRB and the National Academies of Sciences, Engineering, and Medicine. He thanked the EU and U.S. DOT personnel, the planning committee members, and participants. He highlighted the importance of the symposium topic to TRB and discussed his experience at the Maryland State Highway Administration (SHA) in dealing with extreme weather events.

Pedersen thanked the EU for hosting the symposium in Brussels and noted that TRB was pleased to provide support for the four EU–U.S. symposiums. He acknowledged the hard work of the planning committee and recognized the chair, cochair, white paper authors, and scenario authors. He thanked Monica Starnes of TRB and Frank Smit of the European Commission for their assistance in organizing the symposium. He noted that Starnes was moving to a new position at TRB, where she would be working on a major policy study on the future of the Interstate Highway System, and that resilience would be one of the topics examined in the study.

Pedersen noted that resilience was one of three strategic issues identified by the TRB Executive Committee. The symposium results will help guide key research issues and potential trans-Atlantic cooperation. He commented that resilience has been an important topic at TRB since the 9/11 terrorist attacks and that what began as a focus on security has expanded to a more holistic approach. He noted that Vicki Arroyo and Katie Turnbull are members of the TRB Executive Committee and would be providing a summary of the symposium at the Executive Committee the following week in June 2016.

Pedersen discussed the global interest in the impact of climate change and extreme weather events on transportation resilience. The symposium provides the opportunity to think holistically, examine common issues, and advance the state of knowledge and the state of the practice.

Pedersen shared some of his experience with extreme weather events when he was Director of the Maryland SHA. The state experienced its single largest recorded snowfall during the Presidents' Day blizzard of 2003. The snow caused significant disruptions for the road, rail, transit, and air systems in the state. There had not been a major snowstorm in the previous 10 years. A year later, a hurricane caused extensive flooding in the state. The following year the state experienced record high temperatures, with the heat causing rail tracks to warp and resulting in a major commuter rail crash. He noted that speed reductions were instituted for the rail system.

Pedersen commented that these extreme weather events affected all the transport modes in the state—road, transit, rail, air, and water. He noted that SHA sought information and guidance for addressing the issues encountered from these events. He commented that the agency did not have the resources to respond to all needs. As a result, SHA recognized that a risk-based approach for making intelligent decisions to keep the system operational, or return it to operation as soon as possible, was needed. This approach has been expanded to include risk-based asset management, which is now recognized in federal legislation. He suggested that discussion of risk-based asset management in the breakout groups would be beneficial.

Pedersen reported that the American Association of State Highway and Transportation Officials (AASHTO) has established a Committee on Resilience and Sustainability. He noted that this symposium was discussed at the committee's spring meeting and that committee members expressed interest in the outcomes related to best practice guidance and ideas for beneficial research. He further noted that state departments of transportation are involved in selecting projects for the National Cooperative Highway Research Program. He suggested that the symposium results will be of help to AASHTO and TRB committees in developing research problem statements.

Alan McKinnon provided a welcome from the symposium planning committee. He thanked members of the committee for their hard work organizing the symposium and reviewed the symposium goals and program. He recognized Dick Wright, University of Maryland, who served as cochair of the planning committee.

McKinnon reviewed the goals of the symposium identified by the planning committee. These goals included reviewing the current state of research in the field and identifying research gaps and hot topics. A second goal focused on stimulating more research, including addressing the mitigation and adaptation imbalance. Other symposium goals included suggesting research for adaptation studies, fostering trans-Atlantic research collaboration, promoting cross-disciplinary research to break down subject silos, and increasing the relevance and impact of research through expanded practitioner engagement.

McKinnon discussed the importance of the symposium topic in addressing the impact of climate change and extreme weather events on the transport system. He noted the interest on the part of both researchers and practitioners. He commented that approximately 80% of the participants at the first symposium were from academic institutions, whereas 80% of the participants at this symposium were practitioners from a range of public- and private-sector organizations.

McKinnon reported that symposium participants came from across the United States and 13 European countries. All transport modes—roads, railroads, public transit, aviation, ports, inland waterways, and shipping—were represented. Further, he noted that participants had expertise in a broad range of subjects, including climate science, civil engineering, transport planning, logistics, infrastructure design, construction, operations, maintenance, and management. Other disciplines represented were decision theory, risk analysis, economics, insurance, public policy, hydrology, and coastal protection.

McKinnon reviewed the symposium scope, which focused on the nature of the risk of climate change and extreme weather events and the nature and extent of the impacts on all transport modes. The scope covered the potential impacts in short-, medium-, and long-term time frames, as well as on urban, interurban, regional, and national geographies. He noted that the types of extreme weather events included excess rainfall and flooding, extreme heat and drought, hurricanes and storms, and sea level rise. He also noted that the impacts of these events on the transport infrastructure, other critical infrastructures, and transport operations would be addressed in the symposium, as would possible socioeconomic impacts. He commented that participants would have the opportunity to discuss conceptual and analytical frameworks, methodologies, technologies, and governance structures. He reported that the results of the symposium discussions would assist in developing and refining research agendas on these topics, including projects appropriate for trans-Atlantic collaboration.

McKinnon reviewed the symposium format. After the opening welcome session, Jan Hendrik Dronkers of the Rijkswaterstaat and Donald Wuebbles of the University of Illinois, currently on assignment to the Executive Office of the President of the United States, would provide keynote addresses. Lori Tavasszy of the Delft University of Technology would summarize the white paper prepared for the symposium. McKinnon explained that the planning committee had decided to organize the breakout session discussions around the three phases of preparing for climate impact, minimizing transport disruptions during an extreme weather event, and recovering from these disruptions.

McKinnon reported that members of the planning committee developed scenarios for each phase based on a different type of extreme weather event. The first scenario focused on preparing the transport system for sea level rise, and the second examined the management of disruptions to the transport system during abnormal precipitation and flooding. The third scenario considered how a transport system would recover from extreme heat and drought conditions. Members of the planning committee would present the scenarios and facilitate discussions in the breakout groups. The rapporteurs in each breakout group would provide a summary report to the full group about the main topics discussed. The closing session would feature a panel discussion with comments from symposium sponsors and participants. In closing, McKinnon encouraged participants to actively engage in the discussions and to share their experiences, ideas, and suggestions for research.

Opening Plenary Session

Jan Hendrik Dronkers, *Rijkswaterstaat, Ministry of Infrastructure and the Environment, Netherlands*
Donald Wuebbles, *University of Illinois at Urbana–Champaign, currently on assignment to the Office of Science and Technology Policy, Executive Office of the President of the United States, Washington, D.C., USA*
Lori Tavasszy, *Delft University of Technology and TNO, Delft, Netherlands*

Keynote Presentation 1

Resilient Transport System: An Ongoing and Multistakeholder Responsibility

Jan Hendrik Dronkers

Jan Hendrik Dronkers discussed transport resiliency in the Netherlands. He described the role of the Rijkswaterstaat, the executive agency of the Ministry of Infrastructure and the Environment in the Netherlands, and highlighted examples of transport vulnerability to extreme weather events and adaptive approaches.

Dronkers described the importance of resilience in the Netherlands, which is a country reclaimed from the sea. He stated that without the system of dykes, dams, and storm-surge barriers, two-thirds of the country would be underwater. He noted that Netherlands citizens have over eight centuries of experience working together to transform a vulnerable area into a safe and prosperous river delta. He suggested that the port of Rotterdam is Europe's port of access and that the Netherlands is a key element in Europe's transport system.

Dronkers described the role and function of the Rijkswaterstaat related to the transport system in the country. He noted that the Rijkswaterstaat has played a crucial role in keeping the country's delta secure, accessible, and habitable since 1798. The infrastructure includes the highway, waterway, and main water networks. He reported that the main highway network comprises approximately 3,100 kilometers of motorways, including 2,500 viaducts, 15 tunnels, and 700 bridges. The main waterway network extends over almost 8,000 kilometers. He noted that it is the busiest waterway network in the world, with a total of 83 locks and more than 400 bridges. The main water system includes over 65,000 square kilometers of surface water, a range of damming dunes stretching over 44 kilometers, and over 250 kilometers of dykes and dams.

Dronkers discussed the challenge of protecting the Netherlands from flooding. He noted that climate change was resulting in rising sea levels, with a projected sea level rise of up to 1.3 meters (4.25 feet) by the end of the century. High-water levels in the country's rivers will also increase significantly. He commented that the country is coping with more extreme weather events, such as more storms, drier summers, and wetter winters.

Dronkers described the Rijkswaterstaat's ambition of creating a resilient and sustainable transport system that would allow for managing disruptions and switching to other modes or routes, if necessary. He noted that seamlessly linking the transport modes is important to achieve a resilient and sustainable system. Changing from road to rail and then to the internal waterways would be an example of this modality. He further noted that information and communications technology, intelligent transportation systems, and connected smart mobility are assuming an increasingly prominent role in the Netherlands to accomplish this ambition.

According to Dronkers, a resilient transport system is efficient, good for the economy, and good for society. It is also environmentally friendly and sustainable as it results in the efficient handling of raw materials. He noted that the Netherlands had agreed to follow the EU's objective to reduce greenhouse gas (GHG) emissions by 60% by 2050 (compared with 1990 levels), even with the projected growth in the transport system.

Dronkers described some of the uncertainties facing the Netherlands and Europe, including the global economy, the impacts of technology on the transport system, and the social acceptance of new technologies and their effect on mobility patterns. He noted that connected smart mobility, which applies to both passenger and freight transport, is one of the major technological developments on the horizon. It includes other modalities, such as shipping and inland navigation, and the potential for unmanned ships and trains. He suggested that the effect of the Internet of Things on mobility and cybersecurity are other issues requiring attention. He commented that although these developments will make the transport system as a whole more efficient, they will also make it more vulnerable. Further, the transport system will be much more dependent on other networks, such as telecommunications and electricity. He suggested that it is vital to incorporate this vulnerability effectively into the development of a resilient transport system.

Dronkers discussed the effect of climate change and extreme weather on the transport chain. He noted that the cost of transport as a percentage of income will increase if action is not taken. He suggested that although the actual costs associated with climate change are uncertain, costs will increase markedly and will probably affect certain groups of citizens disproportionately. For example, not all people in vulnerable areas are able or willing to move. They accept the risks, but they can lose everything in one extreme event.

According to Dronkers, initiating a strong policy of adaptation and mitigation would restrict the long-term costs of climate change. Countries in Europe have developed or are developing national adaptation strategies to address this need. He noted that these strategies will assist in achieving a coherent approach toward the climate change issue by reducing vulnerability and increasing resiliency in the face of increasing extreme weather events.

Dronkers described some of the vulnerabilities of the different transport modes and the approaches being used in the Netherlands to reduce these vulnerabilities. Road and rail transport are affected adversely by heavy rainfall and flooding, but inland waterways are less sensitive. A long period of drought, however, can force inland navigation to a virtual standstill, while road transport remains unaffected. A severe storm would bring virtually all modes to a halt. As a result, he suggested that it is important to examine the system as a whole, with a focus on the local and regional context, as many of the effects of extreme weather are local in nature.

Dronkers discussed the use of a stress test to assess the vulnerability of the transport system. This stress test examines the different components and modes individually, as well as their interdependencies. He noted that this approach helps develop measures that guarantee the long-term robustness of the transport system. Examples of criteria used in stress tests include the effect on the transport capacity of the system, the availability and flexibility of the infrastructure when it is affected by extreme events, and the costs associated with system unavailability and recovery. He highlighted questions that can be examined during the stress test analysis. For example, what are the consequences of a long period of drought for inland shipping, and for the transport system as a whole? What measures are necessary to guarantee system availability for transport, and is extra capacity needed for the other modes? How can the Port of Rotterdam keep operating? Where will the needed funding come from?

Dronkers provided examples on different levels to illustrate the necessity for adaptation. He noted that materials need to be resilient to a wide range of extreme weather circumstances. Physical infrastructure, like road embankments and bridges, must meet functional requirements in a changing climate, without increasing costs, or it should be designed in such a way that it can be easily adapted to changing circumstances such as rising water levels. The transport system as a whole has to be less vulnerable to climate change and extreme weather. He said that the stress test was used to assess these conditions.

The material example presented by Dronkers occurred during a period of hot weather in 2015 during the renovation of the Galecopperbrug (a bridge), which is located on a busy arterial road. The underlying steel was left bare during a heat wave, which led to a distortion of the steel. He noted that this incident led to a modification of the maintenance strategy. The second example concerned trench roads, which are roadways constructed at low levels. Insufficient capacity in the drainage system results in a trench road filling with water during heavy rainfall. The trench road design criteria were adapted on the basis of the new climate scenarios provided by the meteorological institute to address this concern. The adaptation will result in low-level sections being able to withstand 30% more rain without flooding. The third example was a recent collapse of an embankment next to the A74 motorway, located near the Dutch border with Germany, resulting from torrential rain. Immediate action was taken, the road was reopened within a day, and the embankment was repaired. Emergency measures such as sandbags and pumps have also been made available in case comparable problems arise again. The event also resulted in investigating the integrity of road structures in more detail throughout the country.

Dronkers noted that climate change is often not the only reason for modifications to the infrastructure. He described the current reconstruction of the Afsluitdijk, a 30-kilometer dyke originally built in 1932, that protects the central part of the country against flooding. He noted that the project includes reinforcing the dyke to cope with sea level rise, and, at the same time, improving opportunities for road haulage, recreation, and nature. A passage to aid fish migration has also been added. Sustainability is being improved, and opportunities for hydroelectric power and solar power are being explored.

Dronkers reported that the Rijkswaterstaat is not the only investor in the physical domain in the Netherlands, as the use of space is very intensive in this country. As a result, many parties are active in the same area, and working on infrastructure often requires cooperation with numerous stakeholders. He used the Botlek area in the Port of Rotterdam to illustrate the complexity of projects. The area includes roads, railroads, inland navigation, and pipelines. It also includes the Hartel barrier, managed by the Rijkswaterstaat, which is an important link in Dutch flood protection. He reported that the Rotterdam Port Authority, the City of Rotterdam, and the state government are working together to examine the possible consequences of climate change for the Botlek area. Consideration is being given to innovative approaches to keep it safe from rising water in the long term. He noted that this integrated approach is preferred, if possible, over a sectoral approach. Dronkers reported that although direct damage to the road in the event of flooding appeared to be relatively limited, the indirect consequences for the economy could be considerable due to lack of access to industries and other parts of the country. The road would also not be available for evacuation. He noted that the agencies were currently developing a preferred strategy for climate adaptation.

Dronkers described MEGO, or Module Evacuatie bij Grootschalige Overstromingen, the Dutch approach to evacuation management in response to large-scale flooding from the sea and rivers. The aim of this approach is to make the best possible use of major infrastructure for evacuation purposes when there is a threat of flooding. A key element of the plan for successful evacuations is effective cooperation and sound information. Preparing citizens and making the public aware of the risk of flooding, the evacuation routes, and sheltering in place are important parts of the process. Making full use of traffic management strategies, including adjusting routes by closing off entrances and exits and reversing lanes, improves the effectiveness of the evacuation. Large-scale interventions in the infrastructure are not cost-effective, but regional modifications on the national highways might be beneficial, especially if the modifications are useful in the event of other disasters. Dronkers presented a video on risk awareness to illustrate the MEGO concept. The video was targeted toward educating the public on the risks of flooding and response options.

Dronkers outlined three key points from the examples presented. First, he noted that taking climate change into account is important when working on transport missions and objectives. He suggested, however, that taking action is not always necessary. Costs, benefits, and effectiveness all need to be carefully considered and evaluated against other priorities and other responsibilities. For example, adapting a road in an area where the probability of a major flood is very low may not be necessary. Improvements may also be unneeded in situations in which, for example, it is considered acceptable for a road to be blocked once every few years for a few hours because of extreme rainfall. Second, he stressed that system resilience requires adaptation on three levels: on a material level, on an infrastructure element level, and on the level of the system as a whole. He noted that scenarios should be prepared for the phases before, during, and following extreme weather. It is essential that transport agencies are fully aware of the vulnerabilities, risks, costs, and benefits of different measures to be as successful and as cost-effective as possible. He also noted that the behavior of target groups is another key factor. Third, Dronkers commented that adaptation of infrastructure design to climate change is most effective during times of change, such as during planning, designing, constructing, replacing, and renovating phases. He reported that substantial cost savings can be made during these periods, with additional costs for design and realization kept as low as possible.

In conclusion, Dronkers suggested that in considering the current state of the practice with resilience there is a lot of commitment, a good level of knowledge, and many viable instruments. At the same time, he suggested that there appears to be reluctance to take concrete action due to political, financial, and organizational factors, as well as uncertainty concerning the future. He called on participants to work together to share experiences, research topics, and research results.

Dronkers noted that adaptation sometimes requires short-term investment, with benefits only being visible in the future. For example, the benefits of building better dykes now may only be realized many years from now during an extreme storm. The benefits of investing in new evacuation routes may also not be realized until well into the future. He commented that these investments are still justified. He noted that infrastructure providers and road operators must make the case now for a robust multimodal traffic system that promotes economic development and is resilient to climate change and extreme weather, with a goal to prevent social disruption. He suggested that a clear vision and strong leadership are needed to meet the challenges of climate change and more frequent extreme weather events. He further suggested that an astute, risk-controlled, adaptive, and flexible approach is needed that is aware of, but free from, political trends.

Keynote Presentation 2

The Changing Climate: The Science and How It Affects Transportation

Donald Wuebbles

Donald Wuebbles provided an overview of the science of climate change and how climate change could affect the transportation sector. He suggested that climate change was one of the most important issues facing humanity. He expressed interest in communicating information on climate change science in a way that assists transportation professionals in assessing the vulnerability of the transportation system.

Wuebbles reported that scientists continue to reevaluate the understanding of the science of climate change. He noted that two recent reports provide current assessments of climate change. The first report, *Climate Change 2013: The Physical Science Basis*, by the International Intergovernmental Panel on Climate Change (IPCC), is available online at http://www.ipcc.ch/report/ar5/wg1/. Wuebbles was a coordinating lead author of Chapter 1 in this report. The second report, *Climate Change Impacts in the United States*, is the third U.S. National Climate Assessment (NCA), sponsored by the U.S. Global Change Research Program; it is available online at http://nca2014.globalchange.gov.

Wuebbles summarized the current assessments of the science of climate change based primarily on these documents. He reported these assessments indicate that climate change is happening, that it is happening now, and that it is happening extremely rapidly. He further noted that climate change occurs largely because of human activities, but that many actions can be taken both to reduce future climate changes and to adapt to those changes that cannot be prevented.

Wuebbles noted that observational records clearly indicate that the global climate is changing. He observed that increasing temperatures were just one of many indicators of climate change. Other indicators include sea level rise and the decline in glaciers, snow cover, and sea ice. The two reports document temperature increases in both the atmosphere and the oceans. He noted that three major groups worldwide monitor temperatures on a daily basis and analyze changes independently. All three groups have observed an increase of almost 1°C over the past century. He noted that 2015 was the warmest year on record and 2014 was the second-warmest year, followed by 2010, 2013, 1998, and 2009.

Wuebbles discussed the importance of examining temperature on a decadal time scale, as climate change is the long-term variation in weather. He noted that each of the past three decades has been successively warmer at the Earth's surface than any preceding decade since 1850. Further, in the northern hemisphere, 1983–2012 was likely the warmest 30-year period in at least the past 1,400 years. The IPCC report further illustrates global temperature differences from 1901 to 2012. He noted that almost all areas of the world are experiencing warmer temperatures, with the Artic countries facing the largest warming changes. As a result, the IPCC concluded that warming of the climate system is unequivocal.

Wuebbles also described global trends in annual precipitation from 1951 to 2010. He noted that there has been a slight, but not significant, increase in precipitation overall. In a general sense, wetter areas are tending to become wetter and dryer areas are tending to become dryer. He commented that these trends are evident in the southwestern United States and in the Mediterranean region in Europe.

Wuebbles reported that since 1980, events that affect the U.S. economy by $1 billion or more have been tracked by the National Oceanic and Atmospheric Administration. The number of $1 billion events related to weather and climate has increased. Weather-related events include droughts and heat waves, hurricanes and tropical storms, winter storms and crop freezes, flooding, wildfires, and severe local storms. There were 151 weather-related events exceeding $1 billion from 1980 to 2013. According to Wuebbles, based on Munich Reinsurance Group (Re)analyses, similar trends are occurring worldwide. The number of weather-related events (on climate time scales) is increasing, as are the costs associated with those events.

Wuebbles described the basics of the Earth's climate system as illustrated in Figure 1. He noted that the survival of life on Earth is based on solar radiation, which penetrates through the atmosphere. The sun's radiation is absorbed by the Earth's surface. Greenhouse gases (GHGs) keep some of the radiation from escaping into space, or the Earth would be approximately 30°C cooler, a frozen planet. He commented that GHGs can be thought of as providing a blanket around the Earth, keeping it warm to sustain life as we know it. He noted that the increase in some GHGs, including carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O), results in even less radiation going to space, which results in the warming of the Earth.

Wuebbles noted that natural variability also affects the Earth's climate, but that the variability is not large compared with the changes in climate being observed. Natural factors influencing climate include variations in the Earth's orbit and energy received from the sun, as well as stratospheric aerosols from volcanic eruptions. Human factors also influence changes in GHGs and the Earth's temperature.

Wuebbles described the process of examining the bubbles in ice core samples from Antarctica to measure

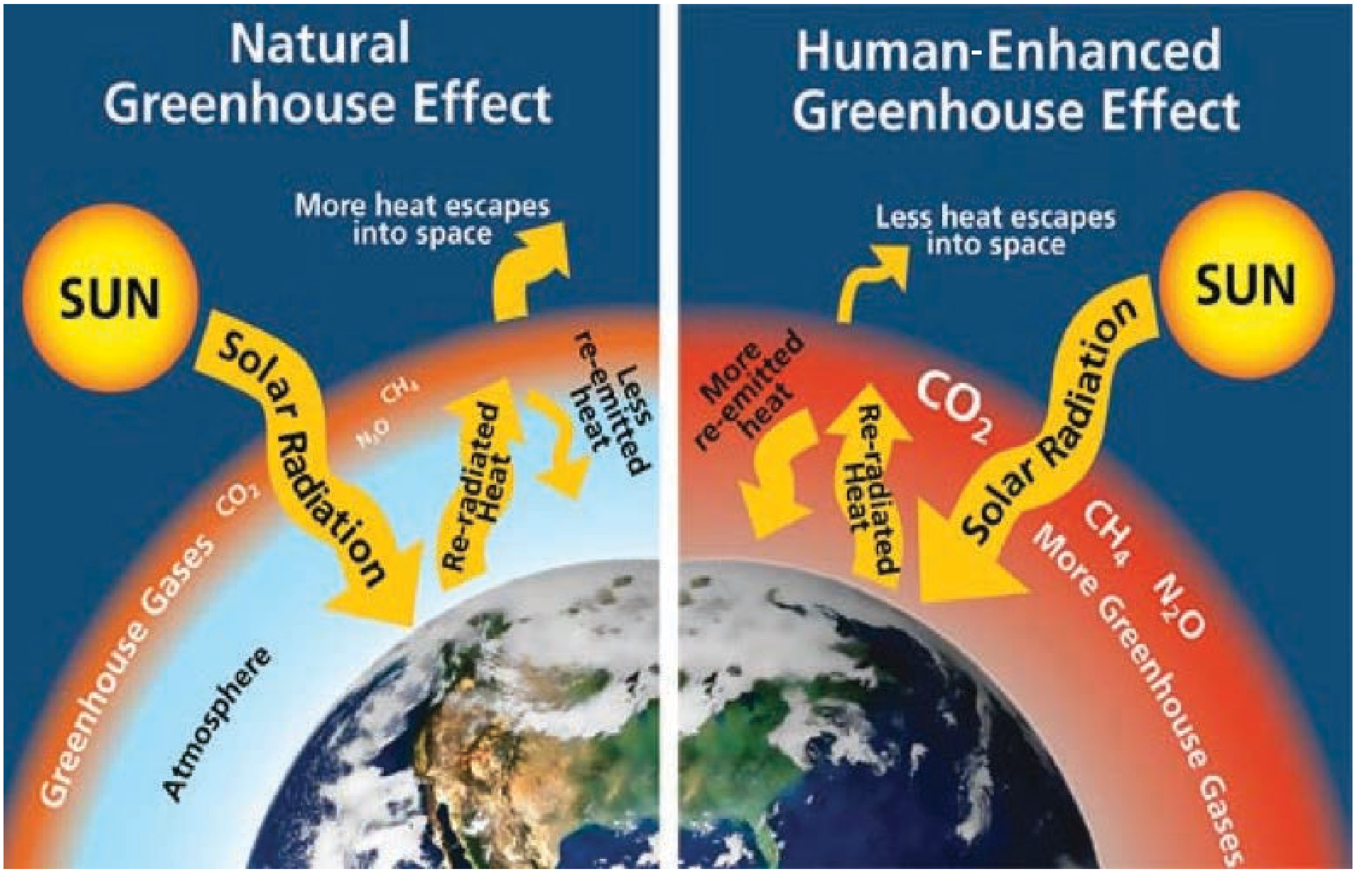

FIGURE 1 Earth's greenhouse effect (*1*).

changes in CO_2 over the past 800,000 years. He highlighted some of the typical oscillations, but noted that the atmospheric concentrations of CO_2, CH_4, and N_2O have recently increased to levels unprecedented in at least the past 800,000 years.

Wuebbles discussed an analysis by the IPCC showing the influence of human behavior on the increase in temperatures. The observed global mean temperature warming from 1951 to 2010 is approximately 0.6°C to 0.7°C. He noted that accounting only for the changes in GHGs and their effect on the climate system would probably overestimate the change. He reported that there is a net cooling effect from certain particles in the atmosphere emitted from human activities, however, and combining both into the anthropogenic forcing results in the change in temperature that would have been expected. Because changes in solar flux or from natural variability are too small to explain the observed temperature change, the IPCC concluded that it is extremely likely (greater than 95% in certainty) that human influence has been the dominant cause of the observed warming since the mid-20th century.

Wuebbles discussed projections for future average global surface temperatures. He noted that continuing heavy use of fossil fuels could result in at least another 4°C increase in temperature by the end of the century, in addition to the 1°C increase that has already occurred. Major reductions in the use of fossil fuels would be needed to realize an increase of only 2°C by 2100 (relative to the preindustrial climate). He noted that the recently developed agreement in Paris calls for 2°C, but that we should aim for a 1.5°C target, if possible. He added that the GHG emissions that have already been generated will influence changes over the next 20 years, but that the choices made today are important for influencing trends by 2100.

Wuebbles described changes in the average precipitation from 1986 to 2005 and then for the future low- and high-precipitation scenarios for 2081 to 2100. The scenarios indicated that the contrast in precipitation between wet and dry regions and between wet and dry seasons will increase. Wuebbles described trends in extreme weather events. He noted that there is high confidence that the frequency and magnitude of extreme-heat temperature events, both individual days and multiday heat waves, are increasing. In general, the risk of extreme cold is decreasing. The frequency of extreme precipitation, including both rain and snow, is increasing worldwide.

In the United States, the risk of floods in some areas is increasing, and the severity of drought is increasing in some areas as warmer temperatures increase evaporation rates. Hurricanes are becoming more intense. He noted that these observed trends are consistent with basic physics, historical simulations, and future projections.

In terms of other types of extreme events, Wuebbles noted that there is moderate confidence that midlatitude storms will become more intense, storm surges will get stronger, and wildfires in the western United States will become a greater concern, with larger areas burned. He also noted that individual extreme events are being affected by human-induced climate change. He cited the current California drought and the 2003 European heat wave as examples. He noted that formal detection and attribution studies, supported by basic physics and/or future projections, show evidence of human interference with these events.

Wuebbles described a few areas in which there is not enough information to fully assess the long-term impacts of climate change. Examples of these areas include the increased risk of severe winters due a slowdown in the jet stream, changes in hurricane frequency, and the impacts on small-scale extreme events including supercell thunderstorms, tornadoes, ice storms, hail, and straight-line wind events. He noted that the latest science suggests that tornadoes will increase in number and in intensity.

Wuebbles discussed past and projected changes in global sea level, citing information from the 2014 U.S. NCA, which projected an increase of 1 to 4 feet by the end of the century. Risk analyses should consider as high as 2 meters (over 6 feet 6 inches). He noted that the latest analyses, based on new understanding of potential ice losses in Antarctica, suggest that the high end may not be high enough. He also noted that the next NCA is just beginning and that he is coleading the climate science report.

Wuebbles reviewed some of the impacts of climate change on transportation reliability and capacity. He noted that the 2014 NCA included a chapter on transportation and summarized topics presented in that chapter. The report notes that sea level rise and storm surge, extreme weather events, higher temperatures and heat waves, precipitation changes, Arctic warming, and other climatic conditions are already affecting the reliability and capacity of transportation systems in many ways. He highlighted an example of roads buckling from extreme high temperatures in Norfolk, Virginia, and described a study from Chicago, Illinois, that identified concerns with the impact of high temperatures on roadways and rails. He also noted that flash flooding resulting from extreme rainfall causes problems for freeways and roadways and cited recent examples in Texas.

Another key finding in the chapter described by Wuebbles was that sea level rise, coupled with storm surge, will continue to increase the risk of major coastal impacts on transportation infrastructure, including both temporary and permanent flooding of airports, ports and harbors, roads, rail lines, tunnels, and bridges. An example included in the chapter is the vulnerability of the Gulf Coast transportation hubs in Houston, Texas; New Orleans, Louisiana; and Mobile, Alabama. Within this century, 2,400 miles of major roadways are projected to be inundated by sea level rise in the Gulf Coast region. Roadways at risk in the event of a sea level rise of about 4 feet, which is within the range of projections for this region in this century, include 24% of the Interstate highway miles and 28% of secondary road miles.

Wuebbles reported that another finding in the chapter was that extreme weather events currently disrupt transportation networks throughout the world and that projections indicate that such disruptions will increase. He illustrated this point with the destruction of roads in Vermont due to heavy rains and flooding from Superstorm Sandy.

Wuebbles cited information from the Federal Aviation Administration on the vulnerability of airports in the United States to storm surge. According to this agency, 13 of the nation's 47 largest airports have at least one runway with an elevation within the reach of a moderate to high storm surge.

Wuebbles discussed some of the severe weather effects on aviation. He noted that it is already known that severe weather has major effects on aircraft operations, especially flight patterns. He suggested that as climate change leads to an increased incidence and changes in the intensity of severe weather events there will be many other impacts on aviation. As a result, he noted that improved severe-weather forecasting will become even more important than it already is. Examples of these impacts include increases in turbulence and climate variability, convection, fog, and visibility and ceiling, which affect aviation route decisions. Higher temperatures and more heat waves will affect runway pavement, and sea level rise and storm surge will affect airport facilities and operations.

Wuebbles discussed possible costs to the transportation system from climate change and adaptation options. He suggested that climate change impacts will increase the total costs to the transportation systems and their users, but these impacts can be reduced through rerouting, mode change, and a wide range of adaptive actions. He discussed Figure 2 from the last NCA.

He noted that many of the projected climate change impacts and resulting consequences on transportation systems can be reduced through a combination of infrastructure modifications, improved information systems, and policy changes. He commented that Gerry Schwartz added the boxes highlighting the

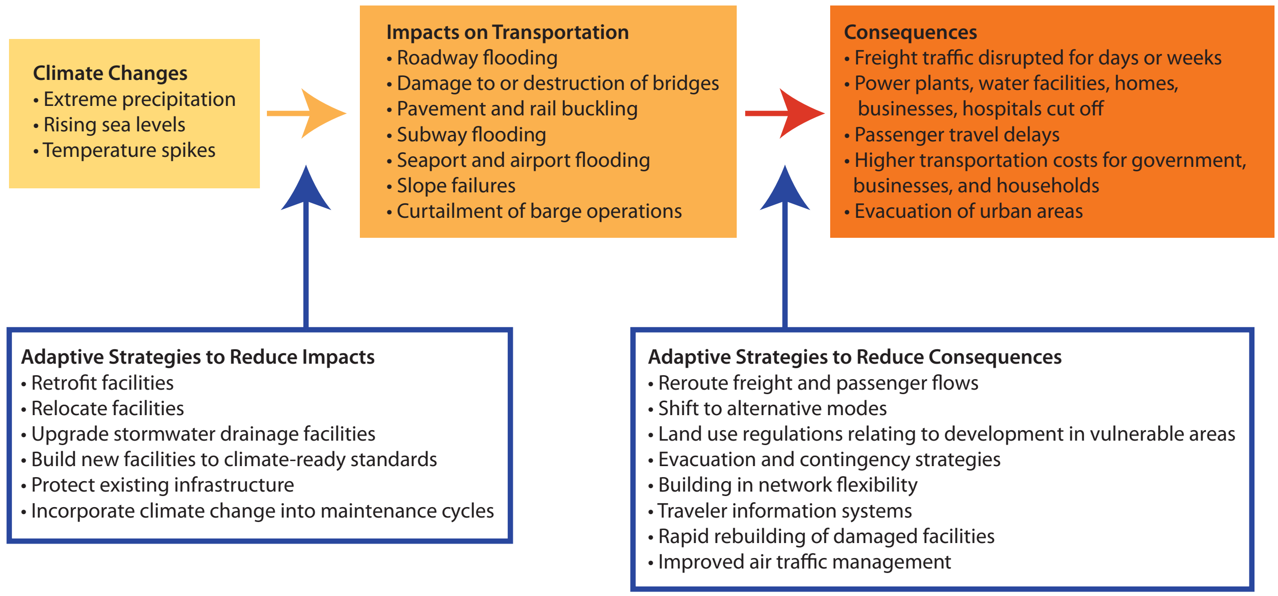

FIGURE 2 Role of adaptive strategies and tactics in reducing impacts and consequences (*1*).

adaptive strategies that can be used to reduce impacts in the first place and the adaptive strategies that can be employed to reduce the consequences of impacts.

Wuebbles concluded by providing a sense of hope, noting that the future depends on how people act to limit climate change. He noted that adaptation is not a choice—the choice is whether to adapt proactively or respond to the consequences. Adaptation requires a paradigm shift, focusing on managing risks. It is possible to draw on the long history of responding to changing conditions in facing the challenges of climate change. He suggested that planning for the future ensures we will all get there safely, together.

White Paper Presentation

Transportation Resilience: Adaptation to Climate Change and Extreme Weather Events

Lori Tavasszy

Lori Tavasszy summarized his and Gerry Schwartz's white paper, "Transportation Resilience: Adaptation to Climate Change and Extreme Weather Events," prepared for the symposium. He reviewed the white paper objective and discussed climate change and its impact on the transport system, the current state of adaptation in the EU and the United States, and critical issues for further discussion. He recognized Schwartz, his coauthor, who was not able to attend the symposium. [The white paper is provided in Appendix A.]

Tavasszy noted that the white paper objective was to set the stage for the discussion of research and development needs at the symposium. The white paper, along with the three case scenarios, provides background information for the discussion in the breakout groups and the identification of challenges, management strategies, and areas for further research.

He reviewed potential climate-related changes, including changes in temperature, sea level, precipitation, storms, hurricanes, and mist. He noted that there is uncertainty associated with the extent of these changes and their impact on the transportation system.

Tavasszy described some of the uncertainty factors associated with climate change and more extreme weather events. He noted that the severity of climate change depends on GHG emissions, which are influenced by the use of personal vehicles and other human behavior. The use of electric and automated vehicles, shared mobility services, and new technologies may result in changes in GHG emissions. He noted that assessing the impacts on society, including the physical impacts and the impacts on well-being and sustainability, is also uncertain. He suggested that the potential impacts will be influenced by many factors and often have a cascading effect.

Tavasszy described some of the system effects related to different types of extreme weather events. For example, high winds may cause trees to fall on the roadway and overturn trucks, which may cause road closures and increased congestion. He noted that systemic effects may also occur with other infrastructure elements, which may result in unexpected effects on and relationships between transport and other systems. He commented that the transport system cannot be viewed in isolation.

The white paper includes a review of literature on the state of adaptation in the United States and the EU. He noted that the literature includes adaptation research focusing on practical results. He reported that current research tends to focus on developing frameworks, analysis tools, and analyzing data. There is less research on developing and assessing actual implementation activities. He suggested there is interest on the part of practitioners in identifying the best models to use, data availability, adaptation approaches, and other practical topics.

Tavasszy discussed some of the research and development needs identified in the literature. Integrative research, addressing specific substantive gaps, and conducting methodological work at the global and regional levels represent a few of the identified needs. Examples include developing costing and analysis methods for specific cases, assessing the impacts of the new high-end climate change scenarios, assessing the impacts on rural development and the resilience of cultural landscapes, and examining the need to manage agricultural and forestry systems.

Tavasszy reviewed the six issues included in the white paper that address achieving resilience. The first issue focuses on defining an acceptable level of resilience and identifying methods to realize this level. He noted that acceptable levels of resilience may vary by country and by area depending on risks, local conditions, and other factors. He suggested that developing objectives and standards for acceptable levels of resilience would be beneficial to help guide investments, approaches, and responses.

The second issue discussed in the white paper is improving sense-and-respond capabilities. Tavasszy suggested that this issue focuses on moving from a predict-and-prepare capability on the part of agencies to a more proactive sense-and-respond capability. He noted that making this transition is not easy given the uncertainties associated with climate change and extreme weather events. Further, accomplishing the transition requires the involvement of all departments within transport agencies, whose members need to address adaptive policies, adaptive planning, adaptive asset management, and adaptive use.

Tavasszy noted that the third issue in the white paper addresses system resilience. He commented that transport systems are more than just the sum of their individual parts. Some elements may be more important because of their vital economic role, the absence of alternatives, heavy use, or critical function. He suggested that identifying critical functions between subsystems was important to prevent unwanted cascading or accumulation of failure effects.

Developing and implementing new planning and engineering approaches represented the fourth issue discussed by Tavasszy. He suggested that new planning and governance models may be needed to better position agencies to be prepared for extreme weather events and to respond when they occur. Designing transport networks for resilience, developing new construction standards, and using new self-healing materials represent some of the engineering practices that may be needed to better respond to climate change and extreme weather events.

The fifth issue described by Tavasszy was the use of risk-based transportation asset management. He noted that this approach is being used in the United States to build resilience into transportation assets to better manage external threats, including climate change and extreme weather events. He further noted that attention in Europe to these approaches has been mostly research, and integration into asset management practice would need to be the next step.

A final issue highlighted by Tavasszy was the societal impacts of climate change and extreme weather events. He suggested that it was important to identify vulnerable user groups and methods to reduce their exposure to extreme weather events.

In conclusion, Tavasszy summarized some ideas in the white paper for achieving greater resiliency. He noted that continuing to develop a better understanding of climate change science and extreme weather events, including vulnerable areas, frequency of events, and possible impacts, was important. He also noted the difficulties of dealing with all the uncertainties associated with climate change. Connected to this, he raised the question of whether it is possible to define adequate resiliency. Applying sound risk assessment and management approaches represents a way to deal with this uncertainty. Finally, he stressed the importance of considering the interdependencies between the networks of different modes and sectors.

Reference

1. U.S. Global Change Research Program. *Climate Change Impacts in the United States*. U.S. National Climate Assessment, 2014. http://nca2014.globalchange.gov.

SESSION 1

Managing the Risk

Gordana Petkovic, *Norwegian Public Roads Administration, Oslo, Norway*
Rebecca Lupes, *U.S. Department of Transportation, Washington, D.C., USA*
André van Lammeren, *Rijkswaterstaat, Ministry of Infrastructure and the Environment, Netherlands*
Alan McKinnon, *Kühne Logistics University, Hamburg, Germany*
Jennifer Jacobs, *University of New Hampshire, Durham, USA*
Richard Wright, *University of Maryland, College Park, USA*

Presentation of First Case Scenario: Rising Sea Level

Gordana Petkovic and Rebecca Lupes

Gordana Petkovic and Rebecca Lupes presented the first scenario, which focuses on sea level rise and managing risks to the transport system. They noted that in this phase, agencies are working to prepare for future risks and threats. Although this scenario considers responses to sea level rise, the same approach to managing risks would be appropriate for flooding, landslides, and heat waves. Appendix B contains more information on this scenario.

Petkovic discussed the observed annual sea level rise, up from 1.7 millimeters/year between 1901 and 2010 to 3.2 millimeters/year between 1993 and 2016, and noted the increasing rate of change. She described the global mean sea level rise from 2006 to 2100 as determined by multimodal simulations showing changes relative to the period from 1986 to 2005. She noted that differences in sea level rise exist along the coasts of the world, and that these differences are related to local ocean temperature variations, salinity, currents, and subsidence or uplift of land. Subsidence is cause by the pumping of groundwater, oil and gas extraction, compression under heavy construction, and land use. She reported that subsidence adds to the relative sea level rise. She noted that postglacial rebound, which occurs in areas that were covered by ice during the last ice age, counteracts sea level rise. She commented that storm surges present a threat today that may increase in the future due to the expected increase in storm activity. She noted that sea level rise is affecting coastal areas in Europe and the United States.

Petkovic introduced the two vulnerability studies that form the basis of this scenario. The first study focused on the U.S. Gulf Coast area, and the second study examined the Languedoc–Roussillon region in France, which is located along the Mediterranean Sea.

Lupes described the Gulf Coast case study, which covered the area between Houston and Galveston in Texas and Mobile, Alabama, and New Orleans in Louisiana. Lupes pointed out that the low-lying Gulf Coast area is extremely vulnerable to sea level rise. She noted that petroleum extraction and sedimentation loss due to the channeling of the Mississippi River have exacerbated subsidence in some areas. Further, much of the coast is vulnerable to erosion and wetland loss from coastal storms.

Lupes noted that the region is nationally significant, handling 60% of the nation's petroleum imports and housing the largest concentration of marine freight facilities in the United States. It has several major urban centers, including Houston, New Orleans, and Mobile. The area has an extensive intermodal transportation network that includes 17,000 miles of highway with 83.5 billion vehicle miles traveled and six Class I railroads. Fifty-six million passengers traveled through the three largest airports in the region in 2005.

Lupes described a two-phased study of the impacts of climate change on the region's transportation network conducted by the U.S. DOT. Phase I of the study, which was completed in 2008, examined the impacts of climate change at a broad regional scale from Houston to Mobile. Phase II was a more in-depth assessment of impacts and risks in Mobile. More information about the two phases of the study can be found at https://www.fhwa.dot.gov/environment/climate_change/adaptation/ongoing_and_current_research/gulf_coast_study/gcs.cfm.

Lupes reported that the Phase I study used the Intergovernmental Panel on Climate Change, or IPCC, terminology for climate assumptions, estimating that a sea level rise of 1 to 6 feet was likely for the area, with an increase of 2 to 4 feet likely by 2100. The Phase 1 study found that a sea level rise of 4 feet could permanently flood almost a quarter of the Interstate miles in the region, 28% of arterial road miles, numerous New Orleans transit routes, over 70% of the port facilities, 9% of the freight rail facilities, and three airports in the area. She noted some caveats with the high-level sketch analysis of impacts, which was based on land elevation rather than the height of facilities. The analysis did not recognize if a facility was on piers above a floodplain, for example. It also did not consider protective structures such as sea walls. In addition, a small flooded segment may render a larger portion of the infrastructure inoperable.

Lupes reported that the Phase II study focusing on Mobile was conducted from 2009 to 2015. The study identified the key infrastructure in the region for each mode, developed projections of climate change for sea level rise and storm impacts, and examined the sensitivity of roads, bridges, port facilities, and other infrastructure to weather and climate impacts. It also developed a method of identifying critical assets that used a high, medium, or low scale. Criticality was evaluated by applying mode-specific criteria related to socioeconomic importance, use and operational characteristics, and the health and safety role in the community. This information was used to assess the vulnerability of crucial assets in the region by using an indicator-based approach to vulnerability. She noted that several hundred assets were considered to be highly critical. Because detailed vulnerability assessments could not be conducted on each asset, the study identified appropriate indicators for the three components of vulnerability: exposure, sensitivity, and adaptive capacity. The indicators suggest how exposed, sensitive, and adaptive each asset is to the projected changes in climate.

Lupes described the process of mapping different sea level–rise scenarios to determine the possible exposure of different assets. Based on the results from the indicator screening, the study identified a smaller set of key vulnerable facilities for each mode. She noted that more detailed engineering assessments were conducted on some of the assets as part of follow-up studies.

Lupes discussed some of the potential implications for transportation planning identified in the study. She noted that climate change is not routinely considered today, but that the longevity of infrastructure argues for its integration. She suggested that the current practice focusing on a 20-year time frame is not well-suited to the assessment of climate impacts.

Petkovic described the second case study, which focused on the Languedoc–Roussillon region in France. She noted that the preliminary study began in 2009, and the French National Adaptation Plan was approved in 2011 (www.development-durable.gouv.fr/The-national-climate-change.html). A discussion of the recently published *National Climate Change Adaptation Plan: Transportation, Infrastructure, and Systems* is available at http://www.sciencedirect.com/science/article/pii/S2352146516300448. The Languedoc–Roussillon region includes 215 kilometers (134 miles) of the Mediterranean coastline between the border of Spain and the Rhône delta. With a population of approximately 3 million people, Languedoc–Roussillon is primarily an agricultural area. Numerous resorts and historical monuments also make tourism an important part of the economy. The port of Leucate includes petrochemical facilities. She noted that if current trends continue, the population could increase by 30% by 2070.

Petkovic reported that Languedoc–Roussillon was selected as a study site due to the exposure of many low-lying coastal areas to ongoing erosion and persistent inundation during storm events. The projected sea level rise adds to concerns in the region. She reviewed the assumptions used in the study. She noted that the conservative estimate of 1 meter (3 feet) of sea level rise by 2100 was used in 2009 due to all the uncertainties surrounding climate change. She suggested these estimates would not seem as conservative today given the advances in climate science. Other estimates used in the study included the extreme water level for a 100-year storm at 2 meters (6 feet), resulting in temporary inundation, and an erosion zone of 500 meters (546.8 yards) inland. Similar to the Gulf Coast study, existing protection measures were not taken into account, nor were natural protection barriers. In addition, despite the increasing population in the region, the current population was used.

Petkovic summarized some of the main findings from the Languedoc–Roussillon case study. The permanent inundation from sea level rise by 2100 was estimated to result in the displacement of 80,000 people and the destruction of 140,000 residences. The study also used available insurance data and assumptions of the share of insured and uninsured properties to estimate the costs associated with these losses. It was noted that the Languedoc–Roussillon region faces large economic and social consequences if adaptation measures are not undertaken to mitigate coastal erosion and inundation hazards. The costs of potential damage due to erosion and permanent inundation were much larger than those due to temporary inundation, indicating that the cost of current coastal risks is negligible in comparison to the expected costs by 2100.

Petkovic described the estimated impacts of 1 meter in sea level rise on the transportation system along the entire coast of France. The impact was estimated to be approximately 22,380 kilometers (13,906 miles) of the linear transport infrastructure, including 2.9% of motorways, 1.7% of national roads, and 6.3% of the railway network. For the Languedoc–Roussillon region, the estimate was approximately 2,500 kilometers (4,553 miles) of linear transport infrastructure.

Petkovic discussed the difficulties encountered in the study associated with estimating the costs of the impacts on the transport system. Due to limited data, only the costs associated with the major national infrastructure networks in mainland France managed by the state were analyzed. She noted that although this roadway system represents only 1.2% of the total French road network, it carries 25% of the total traffic. The study estimated that a sea level rise of 1 meter would result in costs for national roads in mainland France of up to €2 billion ($2.3 billion), not including the costs associated with the loss of use. Petkovic reported that adaptation measures have been implemented for many years along the French coast. These measures include beach nourishments, the placement of coastal defense structures, and the relocation of coastal roads and other exposed assets. She provided the following link for more information on the study (available in French only): http://www.languedoc-roussillon.developpement-durable.gouv.fr/contenu-du-projet-programme-de-l-operation-a2537.html.

Petkovic noted that the French Ministry has been working on a range of questions related to climate change. She reviewed the following questions, included in a recent report from Paul Vergès, President of ONERC, or Observatoire national sur les effets du réchauffement climatique (National Observatory on the Effects of Global Warming), in the report to the Ministry and Parliament:

- Should we really be extending our infrastructure into maritime areas at a time when sea levels are rising rapidly and coastal flooding is already a fact of life for many coastlines?
- Do we need to build new sea defenses?
- Should we withdraw from coastal areas and scale back our socioeconomic exploitation of these zones?
- Do we need to relocate property?

Petkovic reviewed the following questions for discussion by participants in the breakout groups.

- How do we assess our vulnerability to sea level rise? What do we need to know?
- How can we design assets and systems for better resilience to sea level rise and storm surge?
- How can we identify interdependencies now to avoid disruptions later?
- How can different modal transport agencies collaborate and coordinate their responses?
- How do we perform a long-term gradual transition to a less vulnerable infrastructure?
- What are the main transport challenges?
- How can the management of these challenges be improved?
- What are the implications for research?

Breakout Group A

André van Lammeren

Challenges

- Participants in this breakout group discussed general issues and challenges associated with sea level rise and storm surges. One issue focused on the vulnerability of islands to these conditions. Some participants suggested that examining methods to protect islands from extreme weather events and to access the economic and socioeconomic impacts of sea level rise and storm surges on islands would be beneficial.
- Participants discussed the importance of looking beyond the United States and Europe to assess the potential impacts from sea level rise. Changes at the Port of Rotterdam, for example, will likely affect vessels traveling to and from China and Asia.
- Participants discussed the need to reconsider the master planning and long-range planning approaches. A few participants suggested that a more dynamic planning process would help in responding to rapidly changing situations.
- One challenge is to translate climate science data into information that can be used at the state and local levels. A number of participants suggested that knowledge of the local situation was critical in responding to extreme weather events.
- Participants discussed the challenges of coordinating the activities of multiple stakeholders before, during, and after extreme weather events. One participant described the complex situation in the New York metropolitan area with multiple agencies at the local, metropolitan, regional, state, and national levels. It was noted

that private transport providers add further complexity to the situation.

- Participants suggested that most of the focus currently is on responding to an extreme weather event, rather than planning for resilience. Spending more time on prevention and actions before an event occurs was noted as important by some participants.
- Aligning stakeholders and actions at the local, regional, state, and national levels was identified as a challenge by participants. The role of different groups in the United States and Europe was discussed.
- Another challenge voiced by participants was updating design and other standards to reflect climate change. Using stress tests to identify the vulnerability of different system elements, as well as the hot spots for different types of weather events, was an issue that was brought up.

Research

- One research topic discussed was identifying an overarching agency to collect data and maintain a database with current projects and research related to transport and climate change. Participants noted that a lot of work has been done on the topic, and ensuring that information is available in one location would be beneficial (an example of this approach is available at http://climate-adap.eea.europa.eu/).
- A second related research project participants considered was including projects on all modes and on other supporting elements, such as electricity and gasoline, in the central database. A few participants noted that the focus of the information clearinghouse would be beneficial if it were broader than just transport infrastructure.
- A third research topic discussed was translating available climate science data into usable information for transport planning and operations. Participants discussed the wealth of climate data and suggested that research could channel that data into information that could be used by transport agencies at the local, regional, state, and national levels.
- Developing, applying, and evaluating stress tests and other methodologies to determine the vulnerability of transport infrastructure and services was a fourth research area discussed in this breakout group. Discussion in this area focused on current EU projects that could serve as examples, including Novel Indicators for Identifying Critical Infrastructure at Risk from Natural Disasters (INRARISK); Risk Analysis of Infrastructure Networks in Response to Extreme Events (RAIN); Harmonised Approach to Stress Tests for Critical Infrastructures Against Natural Disasters (STREST); and On the Impact of Extreme Weather on Critical Infrastructures (INTACT).

Breakout Group B

Alan McKinnon

Challenges

- Participants in this breakout group discussed the importance of measuring risk, but it was also suggested that new approaches were needed. Vulnerability mapping and identifying hot spots were two key items participants suggested be included in analyzing and managing risk.
- One participant described the role of the insurance sector, which imposes commercial discipline on risk assessments and the measurement of losses. Participants discussed whether the spreading of property risks obscures climate-related impacts.
- Some participants discussed the challenges associated with assessing the resilience of transport operations and the difficulties of conducting stress tests of operating systems. It was suggested that an EU–U.S. initiative on this topic would be beneficial.
- The potential need to plan for mass redistribution of populations was also identified as a challenge.
- Participants discussed the differences among countries in committing resources for adaptation to and preparations for climate change and extreme weather events. A few participants noted that the Netherlands appears to place a higher priority on committing resources than other countries.
- Many of the breakout group participants suggested that sensitizing stakeholders, especially politicians, to the seriousness of climate change and extreme weather events was a challenge. Some participants noted that motivating politicians was difficult given the short electoral cycle. Communicating the long-term trends of changing climate conditions and changing the mindsets of policy makers from short-term improvements to permanent redesigns were also noted as challenges.
- A related challenge was understanding the interdependencies and interactions among the interests of different stakeholder groups. For example, the current business practices of just-in-time delivery and other approaches concentrate traffic though hubs, which increases exposure to transport disruptions. In addition, a number of participants suggested that climate change may not be a priority for all modes and transport sectors.
- Participants described challenges associated with the current spatial planning process. Some participants

suggested that an improved process would assist with developing costeffective resilience measures.

- Participants discussed the challenges of dealing with the uncertainties associated with both climate change and the transport system. It was noted that the rapid evolution of the transport system, including the emergence of electric, connected, automated, and autonomous vehicles, coupled with the uncertainties associated with extreme weather events, increased the challenge for transport agencies.

Research

- Participants discussed a possible research topic measuring the wider socioeconomic impacts of climate change adaptation. Examining social justice and equity issues would be part of the study on this topic, as participants noted that lower-income groups often live in vulnerable locations.
- One possible research project that participants considered focused on assessing the cost-effectiveness of different adaptation measures. Participants suggested that incorporating social factors into the calculations, exploring the relativity of transport-related initiatives versus other expenditures, and identifying the cobenefits of adaptation measures would be beneficial.
- Research exploring some of the positive impacts of adapting to climate change, such as lower spending on snow plowing, would likely be beneficial.
- Participants discussed both the direct and indirect impacts of new technology on resilience programs. Examples of direct impacts identified included new materials and equipment. Examples of indirect impacts included changes in lifestyles, including more teleworking.
- The changing nature of the critical interdependencies between transport and related infrastructure, such as the power grid, was considered. Additional research examining these changing interdependencies and how agencies should respond was suggested.
- Other participants suggested that new paradigms and methodologies could redefine readiness for climate change. It was noted that old assumptions may need to be amended. Research exploring this new paradigm and methods to measure readiness was suggested as potentially beneficial.
- Participants discussed possible research examining the interaction between mitigation and adaptation strategies. Examining if mitigation and adaptation strategies were in conflict or were mutually reinforcing and assessing how to minimize the carbon footprint of adaptation efforts could be beneficial if included in research projects.
- Participants discussed organizational learning and possible research related to organizations' and institutions' ability to assimilate climate change data. It was suggested that building on the organizational learning research field and applying research results from that field to transport and climate change would be beneficial.
- Participants suggested that research examining the level of redundancy required to address transport system needs resulting from different types and intensity levels of extreme weather events was needed.
- The distinction between genuine unknowns and questions for which data might be available but not easily accessible or actionable is an important consideration. It was suggested that research exploring these topics in more detail would be valuable, as well as some recognized methods that may be beneficial to access and analyze critical hard-to-obtain data.

Breakout Group C

Jennifer Jacobs

Challenges

- One challenge discussed by participants was the need to link the climate science community and the transportation community. Although sharing data is important, developing a robust ongoing dialogue between the groups is even more important. Ensuring that the climate science community understands the transport sector and its information needs at different levels, localities, scales, and sectors was noted as important.
- Participants discussed the challenges associated with coordinating materials, assets, and systems at the local level and at the regional and multisector levels.
- Another challenge considered by participants was improving the cost estimation component of benefit–cost analysis methods. Using assessment life-cycle costing techniques was suggested as one possible improvement. Identifying the costs of disruptions was also noted as a challenge, including who ultimately pays for the cost of disruptions.
- Some possible policy challenges will likely include communicating with decision makers, the public, business interests, and other groups. It was noted that gaining the interest and support of politicians in office for only a short time for long-term projects is challenging.
- Other challenges voiced by participants focused on developing improved forecasting technologies and more dynamic engineering responses.
- One participant suggested that developing and maintaining strong regional, multisector, public–private partnerships would help address some of these challenges. Further, these regional partnerships would be able to respond to cascading failures as they occur. The possibility of linking funding from some recovery programs to resilience projects was considered, as was

including a full spectrum of prevention, recovery, and impact costs in benefit–cost analyses.

Research

- One research topic some participants discussed focused on developing and applying methods to identify critical and vulnerable transport infrastructure and operations, including cascading effects.
- A second research topic focused on developing scenario-based adaptive policies, dynamic asset-management techniques, and pathways to resilience. Examining both top-down and bottom-up approaches could be included in the research.
- A third research topic discussed by participants was developing methods to reduce uncertainty through climate science and engineering partnerships. Translating climate change data into usable information for transport planning, design, and operations was identified as part of this research.
- Another possible research topic focused on identifying black swan scenarios—that is, rare catastrophic events—and responses to these types of events.
- Examining the possible environmental impacts of adaptation was suggested as another possible research project. Exploring the impacts on wetlands, air quality, and water quality were a few of the topics identified by participants for inclusion in research projects.
- Developing methods to quantify the damages to the transport system from extreme weather events, including infrastructure repairs, restarting operations, and economic impacts, was suggested by participants as another potential research topic.
- Participants discussed how research examining stakeholder response, emergency management, and the media would be beneficial. Documenting examples of effective public information messages and interaction with the media was suggested for inclusion in this research.
- Participants suggested that examining the roles that new technologies could play in planning for, responding to, and recovering from extreme weather events would likely be beneficial, including exploring the vulnerabilities of these new technologies.

Breakout Group D

Richard Wright

Challenges

- One of the challenges with managing risks associated with climate change and extreme weather events discussed by participants was developing and sustaining collaborative relationships among the diverse agencies involved at the local, state, and national levels. It was further noted that involving social service agencies and private groups adds to this complexity.
- A second challenge was the uncertainty of the frequency, duration, intensity, and location of extreme weather events.
- A third challenge voiced by a number of participants was the uncertainty associated with the potential demand for transportation based on different extreme weather conditions and scenarios. Participants suggested that a good understanding was lacking for possible changes in travel behavior during different types of extreme weather events.
- Another possible challenge was reversing undesirable land use and development trends, such as the increasing development of vulnerable coastal areas and related population growth.
- The lack of adaptable infrastructure and institutions was also suggested as a challenge by some participants.
- Participants discussed approaches to manage some of these challenges. Developing collaborative relationships among stakeholders was noted as one method to help address many of these challenges. The potential use of financial and other types of incentives to encourage collaboration among agencies, businesses, and other groups was also discussed.
- Developing and using integrated information systems was suggested by participants as another method to address some of the challenges, as was using fail-safe designs or systems that fail safely and not insuring property that is uninsurable in the long run.

Research

- Participants discussed the need for collaborative research focusing on using available climate data for transport planning and operations. It was noted that although a lot of valuable climate data exists, it is not always in forms that are easily used by transport planners, engineers, and decision makers. Involving climate and weather scientists, planners, engineers, operations personnel, social scientists, and other specialists in this analysis was suggested as important by some participants.
- Participants discussed potential research that could examine collaboration and coordination across modes during extreme weather events. It was suggested that providing recent examples of collaboration and cooperation among modes, as well as exploring new and innovative approaches, would be beneficial.
- Another possible research topic was developing design standards and operating methods that address

changing climate conditions. It was suggested that multiple projects focusing on different infrastructure and operation needs for pavements, bridges, tunnels, roadways, and rail could address the broad impacts of climate change on the different elements of the transport system.

- Participants discussed potential research related to vulnerability assessments. It was suggested that examining the incorporation of changing land use patterns, socioeconomic trends, and other factors into vulnerability assessments would be beneficial. Some participants also noted that a multidisciplinary approach for this research would be helpful.
- Participants discussed the need for research focusing on the interdependence of transport mitigation and adaptation strategies. It was suggested that mitigation strategies will influence adaptation strategies and that considering different scenarios for both would be beneficial.
- Possible research related to public transit, resilience, and extreme weather events could involve examining issues associated with the resilience of the transit infrastructure at the local, state, and national levels. It was noted that exploring the impacts on transit services and on transit passengers as part of this research would be beneficial.
- Another research topic could be developing and analyzing a broader range of scenarios and options related to transport and extreme weather events. Elements identified for inclusion in the research were the use of greener infrastructure, advanced technologies, and smart materials. Examining methods to capture cobenefits from different approaches, developing tools for evaluating the flexibility of different combinations, and exploring alternative governance options were also suggested for inclusion in the research.

SESSION 2

Minimizing Disruption During Extreme Events

Jennifer Jacobs, *University of New Hampshire, Durham, USA*
André van Lammeren, *Rijkswaterstaat, Ministry of Infrastructure and the Environment, Netherlands*
Alan O'Connor, *Trinity College Dublin, Ireland*
Alan McKinnon, *Kühne Logistics University, Hamburg, Germany*
Sam Merrill, *GEI Consultants, Washington, D.C., USA*
Gordana Petkovic, *Norwegian Public Roads Administration, Oslo, Norway*

Presentation of Second Case Scenario: River and Storm Flooding

Jennifer Jacobs and André van Lammeren

Jennifer Jacobs discussed the second scenario, which focuses on minimizing the disruption to the transport system during extreme weather events. The scenario addresses abnormal precipitation and flooding. Jacobs described the key elements of the scenario, which highlight the vulnerability of the transport system during a recent series of devastating floods in the United States and Europe. Appendix C contains more information on this scenario.

Jacobs noted that one issue with extreme events is that by definition, extreme events occur rarely, which makes data sets small and sparse. As a result, extreme weather events are hard to measure. In addition, instrumentation may not work during floods, tornadoes, and other extreme weather events. Further, she noted that the processes that generate extreme weather are highly complex and difficult to model.

Jacobs described some recent extreme weather events, including hurricanes, heat waves, snow and ice storms, and floods, and their impacts on the transportation system. Flooded roadways, buckled rails, and overheated runway pavement represent a few of the transportation problems she highlighted. In addition, climate change can lead to changes in the frequency, intensity, spatial extent, duration, and timing of extreme weather events. For example, an increase in intense precipitation events may result in increased flooding of roadways and subterranean tunnels and overloading of drainage systems. It may also cause more road washouts and standing water on the road base, which affect soil moisture levels and the structural integrity of roads, bridges, and tunnels.

Jacobs described the scenario, which was based on U.S. flood experiences in Vermont (2013), Colorado (2014), and South Carolina (2016). All three states experienced heavy rains and resulting flooding. In this hypothetical scenario, 500 miles (805 kilometers) of state highways are closed, over 100 state bridges are closed, 30 railroad bridges are damaged, and 200 miles (322 kilometers) of rail lines are impassable. More than 200 (approximately 90%) of the hypothetical state's towns have to rebuild damaged roads, bridges, and culverts. The storm damages thousands of town culverts and damages or destroys nearly 300 town bridges. She reported that in this scenario the entire state is at a standstill, with dozens of towns entirely cut off, with no way in or out.

Jacobs discussed some of the issues raised in the scenario before, during, and after the event. She noted that the hypothetical state transportation agency (STA) expected impacts across a large part of the state and prepared equipment and resources to respond. Large rainfall events in mountainous regions can confound preparedness efforts, however, because predicting which side of a mountain expected rainfall will flow over is difficult. Even with the preparation, the actual event is at a scale never experienced, expected, or planned for at the STA. She noted that staff resources are too few and too scattered to provide a meaningful foundation for the needed delivery of services.

Recognizing the need for a multitude of resources (including engineering services, materials, contractors, and equipment), the STA has created and maintained a one-stop shopping list. There is initial difficulty in establishing contact with some employees, and some employees experience a 3-month separation from their homes. The STA emergency transportation information system is initially inoperable, but Google reaches out to jointly set up a system for real-time mapping of closed roads, with public updates twice daily. Incident control centers are operated by a unified command that sets priorities, provides overall management, and takes the lead on communication and public information. The state Secretary's Office provides direction to the unified command.

Jacobs noted that the postevent or demobilization phase is sometimes referred to as the "forgotten phase" in emergency management. She suggested it was important to conduct postevent reviews and to make improvements based on those reviews. She commented that if roads and rivers compete for the same space, the river will end up winning eventually. She said that improvements to stream crossings had been made in response to floods in the state. These improvements included increasing hydraulic capacity, sediment transport capacity, and aquatic organism passages.

Jacobs described the 2002 and 2013 floods in Central Europe as other examples supporting the scenario. She reported that flood maps and flood risk management plans were developed in Germany after the 2002 floods, and that the experiences in 2002 helped to prevent and/or reduce costs and damage in 2013. There were still disruptions to road traffic during the 2013 flood, however. The Nationale Hochwasserschutzprogramm (NHWSP; National High Water Protection Program) was launched in the aftermath of the 2013 flood. Measures such as strengthening of levees were taken by the German states.

Jacobs described some of the potential implications for research from this scenario that she thought the breakout groups could discuss. One topic was considering the implications for future adaptation planning and resourcing. A second topic was examining the combined impacts on the transport and river systems. A third topic was assessing the robustness of present climate model estimates for use in justifying major investments. A fourth topic was identifying methods to communicate the message that flooding will become more common in some parts of Europe and the United States to help with improving community preparedness.

Breakout Group A

Alan O'Connor

Challenges

- One challenge discussed by the participants focused on the risks associated with incorrectly pricing some activities, such as locating commercial and residential developments in flood plains. One approach to managing this issue discussed by some participants was requiring benefit–cost analyses prior to any development approvals. The use of green infrastructure was identified as a possible approach for addressing some of these concerns. Enhancing the coordination of the land use and transport decision-making processes was also suggested as a way to address these concerns.
- A few participants discussed transport challenges associated with managing the response to extreme weather events. They suggested that coastal flooding may be considered part of normal operations in some areas. The need to change thinking in these areas was discussed.
- Other challenges focused on coordinating the evacuation process, including evacuation orders, routes, and supporting services. One participant noted that some people may choose to shelter in place rather than evacuate. Another suggested that a better understanding of human behavior during extreme weather events was needed to plan appropriate evacuation strategies.
- The use of real-time data to monitor conditions during extreme events was also an issue. It was suggested that decisions should be based on a combination of expert opinion and real-time data.
- The reliability of communication methods may be a challenge during an extreme weather event. The importance of multiple communication methods was stressed by some participants, including the use of new technologies.
- Participants discussed possible privacy concerns with the use of social media and other related technologies. The potential for third-party groups, such as insurance companies, to assist with communication strategies was suggested by some participants. The potential to provide incentives for people to make desired travel choices was also discussed.
- In some cases the best long-term approach may be to abandon roads that continually flood. It was noted that making these types of decisions is not easy and is politically very sensitive.

Research

- Examining agency interaction and coordination during extreme weather events is one area of research that could be very beneficial. It was suggested that providing case studies that highlighted good examples of multiagency coordination would be beneficial, as well as examples including social service groups and the private sector.

- A related research topic discussed by participants focused on cross-modal substitution. Participants suggested that research examining the ability to substitute different modes for travel during extreme weather events and methods to encourage people to use alternative modes or not make trips would be beneficial.
- Participants discussed possible research that could explore the human aspects of responding to extreme weather events. Topics that could be examined included how people perceive risk, how people make decisions on the basis of risk, how people make travel and mode decisions, and if people trust public-sector information sources.

Breakout Group B

Alan McKinnon

Challenges

- Participants discussed challenges related to recent socioeconomic trends, including increases in teleworking and home shopping. It was suggested that increases in teleworking may result in less travel, but that increases in home shopping may add to the vulnerability of last-mile delivery services.
- Some participants discussed opportunities to use social media and other methods to communicate with the public during extreme weather events. The video developed by the Dutch government on evacuation advice was noted as one example.
- The capacity of the cell phone network was noted as a challenge, with examples cited of problems during recent extreme weather events.
- More real-time information on weather, damage, and operations was cited as an ongoing challenge.
- Participants discussed the challenges associated with international and multistate coordination and cross-border flood management. A related challenge was who assumes control when public safety is involved.
- Participants described possible uses of new technologies to aid in monitoring and responding to extreme weather events and how these technologies respond to changing climate conditions.
- The application of smart materials to minimize impacts was considered, as was sensitizing the materials community to taking this issue seriously.
- Challenges associated with some types of human behavior include people coming to observe or photograph extreme weather events and panic buying of food and supplies.
- Participants discussed the challenges of planning for surprises or black swans (rare extreme events) that may not have been considered.
- Uncertainties about liability issues, including possible constraints on official behavior, were noted as challenges as well. Concerns about budgetary constraints were also highlighted.
- A few participants discussed the fear of being blamed for action or inaction during a disaster. It was suggested that public agencies may be blamed in both cases.
- Participants discussed the challenges of trade-offs between restoring infrastructure quickly to existing design standards and taking longer to alter design standards to meet future climate risks.

Research

- One research topic suggested was conducting comparative studies of plans and practices in Europe and the United States. The project could identify best practices in both continents, examine the differing degrees of openness, and assess the use of performance standards and performance-based planning.
- Research examining communication methods, including identifying applications used in other sectors, could also be important.
- Research on human behavior during extreme weather events, including how advice and response on one occasion influence future actions and changes in travel behavior, could be valuable.
- Exploring methods to use the education system to alert people to the risks associated with extreme weather events and desired responses represented another possible research topic suggested by some participants.
- A few participants discussed the importance of capturing key data during the disruption phase, including changes in the freight flow and diversions from affected modes and routes. It was suggested that a research project identifying data needs, methods to capture and analyze the data, and techniques to present the data to technical staff and policy makers would be beneficial.

Breakout Group C

Sam Merrill

Challenges

- Participants noted that one major challenge in responding to transport disruptions caused by extreme weather events is identifying and following the appropriate chain of command, both within and across agencies. It was noted that distributed decision making may occur when the chain of command is broken.

- A second challenge discussed in this breakout group was that technology systems may fail during extreme weather events and that backup systems may not be adequate or may not support other technologies.
- Another challenge described by some participants was that agencies, and individuals within an agency, may see only one part of the problem and may not have a full understanding of the complete situation. A related challenge was ensuring that managers and supervisors know where both field and office personnel are during an event and have the tools, technologies, and equipment to adequately respond to changing situations.
- Making decisions in real time requires predictions about future conditions and responses. Both historic and real-time data are needed for determining appropriate responses. A few participants suggested that needed data may not always be available or may be disrupted during an extreme weather event.
- Having a good understanding of the entire transport system, including connections between modes, vulnerable areas and facilities, and alternatives, was suggested as a good way to improve management response during an extreme weather event.
- Some participants discussed that funding was not typically available to bring in experts during an extreme weather event. Having adequate funding and the mechanisms in place for on-call services if needed would assist in managing responses to extreme weather events.
- Participants also discussed the importance of relying on knowledgeable personnel who have conducted scenario planning and tabletop exercises in managing responses to extreme weather events. These individuals are trained in response techniques. Participants further noted that having defined and documented decision-making processes and protocols was important.

Research

- One research topic could be examining the availability and use of big data to assist in all aspects of planning for extreme weather events, minimizing disruptions during actual events, and recovering.
- Some participants suggested that research developing simulation tools to capture disaster elements would be beneficial.
- Assessing the total social impacts during and immediately after an extreme weather event, as well as the long-term impacts, could be helpful research.
- Research focusing on monitoring the condition of infrastructure to provide needed data for decision making would be beneficial. A related research topic could be integrating these data into asset management systems.
- A number of participants discussed how ongoing research examining the condition of pavements, rails, and other infrastructure during extreme weather events, including heat, flooding, snow and ice, and other conditions, would be valuable.

Breakout Group D

Gordana Petkovic

Challenges

- Breakout group participants identified coordinating responses among multiple jurisdictions with multiple leaders as a challenge. Developing coordinated management strategies and plans, including identifying the decision-making process, was also suggested as important.
- A related challenge was coordinating involvement in emergency situations across different levels of government, different agencies, and different modes.
- Some participants discussed how unexpected extreme events, called black swans, are a major challenge. These types of events typically require crisis teams.
- A number of participants discussed the communications challenges during an extreme weather event. Developing appropriate and timely thresholds for levels of events, between ordinary and extreme, would be beneficial. Using a population-based criterion focusing on the number of people affected was one suggested measure.
- A few participants noted that institutional barriers are often a challenge in managing the response to extreme weather events. Coordinating the responses of agencies at the local, state, national, and multicountry levels can be complex and challenging.
- Another challenge was that there may be no warning or a very short warning period with some extreme weather events. Managing responses under these conditions can be difficult.
- Challenges discussed in managing an extreme weather event included identifying areas to put debris, developing contracts with other transport modes and vendors, and timely mobilization of emergency services. Coordinating ad hoc emergency measures by volunteers, ensuring that arrangements for emergency services are made in advance, and providing training for decision makers were other challenges considered.
- A number of participants suggested that developing a communication plan would ideally be included as part of the overall response plan. Identifying the indi-

viduals to communicate with the public, the appropriate messages, and the communication methods could also be part of the plan.

- Participants discussed the development and use of jurisdictional agreements in managing responses to extreme weather events. Items suggested for inclusion in these agreements were identifying the jurisdictional boundaries within the emergency areas, the protocols for information sharing, and the decision-making processes. These emergency structures could be used for small as well as large events. They could include processes on prioritizing cascading failures and strategies for managing specific challenges. The link to hazard and mitigation planning was also considered.

Research

- One research project could involve developing improved tools for modeling the cascading impacts of extreme weather events.
- A second research topic discussed by some participants was developing public education and outreach programs on how to respond to weather-related emergencies.
- A related research topic could focus on methods and messages to communicate the agreed-on management strategy. Examining incentives for getting the public to accept an unpopular strategy could also be explored as part of the research project.
- A number of participants discussed a research topic focusing on the use of insurance funds for disasters and using insurance as an instrument for adaptation planning.
- All types of strategies and approaches, not just engineering solutions, are needed to adequately respond to extreme weather events, so useful research could focus on identifying the range of alternatives and options.
- Research examining how nontransportation sectors could be used to respond in emergency situations could be helpful.
- A few participants suggested that research examining fail-safe designs and introducing a system of weak points for graceful failure would be valuable. Several participants suggested that research developing, implementing, and evaluating smart, self-functioning emergency responses would be beneficial.
- Participants discussed how a research project examining the use of unmanned aerial vehicles and satellites to obtain more accurate and timely data could be beneficial. This project could include training on how to interpret and use these data.
- Another possible research topic was exploring new and innovative methods for communicating with the public during extreme weather events, including the use of social media.
- Additional research considered by some participants was developing improved methodologies for contingency planning, including techniques for evaluating contingency plans based on experience and lessons learned.
- Research examining mobility issues, especially mobility for vulnerable population groups, would be valuable.
- Finally, some participants suggested that research focused on better understanding human behavior in emergency situations would be beneficial.

SESSION 3

Recovery

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Susanne DesRoches, *New York City, New York, USA*
Richard Wright, *University of Maryland, College Park, USA*

Presentation of Third Case Scenario: Drought, Heat, and Extreme Temperatures

Michael Meyer and Alan O'Connor

Michael Meyer and Alan O'Connor described the third scenario, which focuses on drought, heat, and extreme temperatures. The hypothetical scenario addresses recovering from an extreme event. Appendix D contains more information on this scenario.

O'Connor used the following quotation from Beatrice Mwangi of World Vision to describe the context for this scenario:

> In the past it was one big drought every 10 years, then it came to one drought every five years, and now the trends are showing that it will be one every three to five years. So we are in a crisis all right, that is true. . . . But it's going to be the new norm. So our responses need to appreciate that . . . there is climate change, and it's going to affect the people that we work with, the communities we serve.

O'Connor described drought as a period of below-average precipitation resulting in prolonged shortages of atmospheric, surface, or ground water. He noted that drought is often caused by extreme temperatures lasting over long periods of time. Possible impacts from drought include water quality degradation and declining water levels. There are also societal and economic consequences, as well as cascading effects. Drought results in design and operational impacts for the transportation system.

O'Connor reported that this scenario is relevant for both the United States and the EU. For example, in the United States, summertime temperatures that ranked among the hottest 5% from 1950 to 1979 are projected to occur at least 70% of the time during 2035 to 2064. Further, by the end of this century, extreme heat days (1-day events) that have occurred once every 20 years are projected to occur every 2 or 3 years over most of the country. He noted similar trends in Europe, with forecasts for increases in the average annual temperature through the end of the century. He suggested that longer drought periods might lead to increasing risks of mortality, particularly in urban centers and agglomeration zones.

O'Connor highlighted some of the possible transportation design and operational issues associated with high temperatures. Examples of these impacts included pavement and rail buckling, subsidence due to lower groundwater levels, lower river levels, and the safety of workers and travelers in all modes.

Meyer reviewed four major themes from the scenario. A first theme is the impact of extreme heat and drought on the transportation system, including the design and operation of all modes. A second theme focuses on the network impacts, such as substitution effects for commodities and redundancy. A third theme focuses on the multimodal nature of the transportation system, including road, transit, rail, port, and air, and their interdependencies with respect to system redundancy. A fourth theme examines system interdependency issues, such as operating a subway system that depends on a working electrical grid.

Meyer described the scenario, which focuses on Metropolis, a major coastal metropolitan area with 8 million inhabitants. Metropolis includes major national transportation links and an extensive urban transportation network. Extreme weather events to date have predominantly related to major storms. Climate change research and planning have focused on sea level rise, storm surge, and flooding. Metropolis University scientists have been warning of the possibility of extreme temperature effects, but to date public policy and attention have not heeded these warnings. Further, the Metropolis metropolitan planning organization transportation plan addresses extreme weather and flooding, with little focus on high temperatures and drought.

Meyer described the various modal agencies involved in this scenario. These include transit, highway, planning, port, and airport agencies. He suggested that one topic for discussion in the breakout groups was the needed multiagency institutional structure for anticipating, responding to, and recovering from extreme weather events.

Meyer reported that in the scenario temperatures reach 100°F (38°C) for 30 consecutive days, with the weather service predicting that these extreme temperatures would likely last for at least another month. This condition results in major increases in heat-related deaths. Shelters are opened for the homeless and for those without air conditioning. Reservoir levels become dangerously low, and water rationing is instituted. Electricity outages occur, and wildfires break out in the nearby Metropolis National Forest.

Meyer noted that transport operations in this scenario are affected due to the duration of the event, as well as the corresponding impacts on supporting infrastructure, such as brownouts. Passenger heat-related impacts and a need to allow access to air conditioning for many of the residents of Metropolis become a concern for the transit agency. Air conditioning malfunctions in transit stations, and 20% of buses are without working air conditioning. Construction projects are delayed, and maintenance issues occur as rail lines and roads buckle. Technology components, including intelligent transportation systems, malfunction due to high temperatures. Barge freight transport is disrupted, resulting in more trucks on the roadways and increases in traffic congestion.

Meyer noted that the scenario includes how the extent of societal impacts, resilience, preparedness, and response are widely questioned and discussed in the mainstream and social media. National, state, and metropolitan officials decide to take action from the drought experience. These actions include establishing a climate change task force with responsibility to identify vulnerable assets and to perform a comprehensive examination of design standards to assess their relevance in a future event. Other responsibilities assigned to the task force are developing a strategy to comprehensively monitor asset performance, to identify when stress levels approach dangerous levels, and to prepare contingency plans to respond to heat-related asset stress emergencies. Stockpiling materials for fast response is another responsibility. The task force is also charged with reexamining operations and maintenance procedures to assess needed changes, examining sensitive equipment with respect to high temperatures, and identifying strategies for protection. Other responsibilities are developing marketing and public information materials to educate system users on how to handle heat-related service disruptions and examining how transport agencies could respond to the human element of system operations. Finally, the task force is directed to consult widely with experts and other authorities with experience of this type of event, perhaps learning from transportation professionals who are already dealing with these types of conditions in other parts of the world.

Meyer described some of the issues raised with the event in Metropolis, including preparedness, interdependence with other critical infrastructures, cascading effects, and severity of the transport impacts. Other issues focus on the user groups affected, management of the event by various stakeholders, observed levels of resilience, and the level of public attention.

Meyer suggested the following questions for discussion in the breakout groups:

- What are the extreme heat–related stresses that are likely to affect normal transport system operations and ultimately affect other sectors?
- What are the steps in an infrastructure vulnerability assessment related to extreme heat?
- How does one identify the interdependencies among different sectors and infrastructure in order to pinpoint potential failures?
- How can different modal transport agencies collaborate and coordinate their responses to extreme heat–related events?
- What advances in materials properties are necessary to develop materials that can withstand long periods of extreme heat? How can “smart” materials be used to monitor asset condition to identify potential failure due to heat?
- What other non-material-related strategies should be considered to protect critical assets from extreme temperatures?

- From a crisis management perspective, how can transport agencies become involved with the total picture in terms of societal response?
- How does the profession learn from an event and incorporate this learning into planning, design, operations, and public outreach?

Breakout Group A

André van Lammeren

Challenges

- A number of participants discussed the difficulty of generating interest among policy makers and the public and generating funding for slow weather events such as heat waves and droughts. Heat is considered to be a stressor on the transport system; it is not treated as a disaster. Further, some suggested that planning for higher temperatures and extreme heat was not being considered by most transport agencies, with few studies, plans, or response exercises.
- Another challenge was the uncertainty associated with increasing temperatures and extreme heat. It was suggested that this uncertainty made it difficult to know when to make investments and when to take action. Some participants further suggested that a better understanding of the potential triggers for extreme temperatures would be beneficial to identify when actions should be taken.
- A few participants noted that although temperature is important, humidity is also important for humans and some elements of the transport system. Furthermore, they thought that more consideration should be given to the impact of humidity during the planning process for extreme heat.
- Examples of experiences that different countries have had with extreme heat include the following. In Greece, heat waves influence mode choice; more intensive use of personal vehicles occurs, as buses are not comfortable at 40°C. The influence of heat waves on vulnerable road users, including school children and the elderly, and on the transport of fresh produce was discussed. It was noted that some countries deal with high temperatures every day. Learning from their experiences was suggested, including examining design standards. One participant described Slovenia, which experiences very high and very low temperatures. These temperature variations place additional requirements on materials, such as asphalt, and also cause problems for workers. In Oregon, road work is conducted at night to avoid hot periods of the day. In New York, the subway is not air conditioned, causing some people to get sick or faint, which affects medical services.
- Some participants noted that the interdependency of the transport system and other systems can be a challenge. For example, the high temperatures after Hurricane Katrina and Superstorm Sandy caused deaths. Although fuel was available in New York, people could not always get it. The importance of cross-agency coordination was noted, and the impact on the power grid and the importance of working with power companies was discussed.
- A couple of participants commented that emergency response plans will be different for Arizona, New York, Greece, Slovenia, and other areas. They discussed ways to improve managing the response to extreme weather events. It was noted that some states are developing adaptation plans with design standards, guidelines, codes, and other elements.
- Involving the engineering and standard-setting organizations in the development of new design standards for higher temperatures was considered as potentially beneficial. It was noted that this process moves slowly and that these organizations typically deal with traditional changes, not with major changes resulting from climate change and extreme weather events. Further, it was suggested that there may also be resistance to changes, as the new standards may increase costs.
- Participants discussed the costs associated with different adaptation measures. Although the costs of some measures can be high, comparisons would have to be made with the costs of weather-related disasters, which cost public agencies and businesses billions of dollars. Obtaining funding for recovery efforts in the United States often requires the President, or the governor of a state, to declare an emergency. Obtaining such funding could be challenging to make needed improvements in advance of possible extreme weather events. Coordinating with public health agencies was suggested as one possible approach by participants.
- Other possible challenges were the stove-piping of funding for different modes and the lack of funding for the local transport system.

Research

- One possible research topic discussed by some participants was making data from climate models and other sources usable for transport planning and operators. Participants suggested that although climate science data appear to be very rich, they are not always presented in ways that are relevant to transport planning and operations. Conducting research on methods to make climate science data more transport-user friendly could be beneficial.
- Another potential research topic was examining the interdependencies of how heat waves will influence

renewable energy sources and power generation, including possible impacts on alternative-fuel vehicles.

- Research on methods to build public awareness of extreme weather events and their impact on transport systems would also be beneficial. Examining the use of new technology to communicate with the general public and working with the media could be part of the projects.
- A few participants discussed developing a synthesis of good practices of transport agencies responding to high heat and humidity.
- Research developing stress test and risk assessment techniques for extreme temperatures was noted as important, including how to identify hot spots.
- Finally, a number of participants said that research focusing on the impact of extreme heat and humidity on transport materials, equipment, and structures would be beneficial. Possible projects could focus on developing pavements, equipment, bridges, rails, and tunnels that are more resilient to extreme temperatures.

Breakout Group B

Alan McKinnon

Challenges

- Participants discussed the challenge of shifting the focus from system design to operational issues in planning for, responding to, and recovering from extreme weather events.
- Another challenge was upgrading information systems during events to monitor failures and to capture data for future analysis.
- Some participants discussed the lack of information on the impacts on transport infrastructure substructures and hardware resulting from climate change and extreme weather events.
- Other participants discussed challenges associated with cross-jurisdictional boundary issues and coordination among agencies. It was suggested that a crisis can create opportunities, however, by raising the visibility of issues. It was further suggested that new programs and additional funding may result from a crisis.
- One participant mentioned the challenge of dealing with the media during extreme weather events. The media may be looking for an agency to blame, which may distort the diagnosis and the learning process.
- Identifying when a weather-related event begins and ends is often a challenge, especially for slow-moving events related to extreme heat. Knowing when to take action in these types of events can be difficult.
- Finally, the challenges associated with moving from vulnerability assessments to adaptation planning were considered. It was suggested that a new framework for adaptation planning was needed that included new data, analysis methods, and institutional relationships to collect and share data.

Research

- Individual participants suggested that research focusing on deploying new technologies to facilitate automated data collection would be beneficial, but they noted that many transport agencies struggle with maintaining existing technologies. Developing methods for conducting an inventory of currently available data, creating more data transparency and data sharing between agencies, and making the data available to researchers could be elements of a research project.
- Developing more robust climate change scenarios and the potential impacts on the transport system could be a possible research topic. Approaches to responding to these scenarios could then be developed.
- Improved information to predict human reactions to transport disruptions, including changes in travel behavior, travel modes, and time of travel, would be useful planning information.
- Some participants suggested that research examining the experience from other sectors on how to manage postevent learning would be beneficial. The defense and insurance sectors were suggested as good examples to learn about these experiences. Others noted that transport agencies are preoccupied with daily, operational challenges, which makes it difficult to diagnose and conduct postevent assessments.
- A few participants thought that research examining the temperature tolerances of transport equipment would be valuable. It was suggested that technical specifications and tolerances may need to be widened.
- A number of participants discussed that research building on organizational learning, which is a well-developed field, would be beneficial. It was suggested that transport adaptation research would be well-served by taking findings from organizational learning research into account.
- There was interest in a holistic analysis of the distribution of risk, responsibility, and cost between the providers and users of transport infrastructure. Research examining sharing the relative cost of different adaptation strategies among stakeholders and mechanisms for more fairly distributing costs and risks was noted as important.
- Participants suggested that research examining methods of raising revenue for adaptation initiatives would be beneficial. Possible funding mechanisms could include road user charges, indexing the gas tax, and development impact fees.
- Developing effective case studies of planning for, responding to, and recovering from extreme temperatures would be beneficial.

- Research to develop and refine methodologies for formulating recovery plans, including learning from other sectors (e.g., earthquake response programs), was also cited.

Breakout Group C

Susanne DesRoches

Challenges

- Challenges discussed by participants in this breakout group included learning from the event and learning from the experiences in other regions. For example, areas experiencing temperature increases can learn from areas that already experience high temperatures on a regular basis.
- Some participants thought that resource conflicts, such as conflicts over water and power allocations, may emerge during extreme conditions. Identifying principles for resource allocation in advance was cited as potentially beneficial. Addressing water management was part of this discussion.
- Participants discussed the demands placed on emergency workers, safety for workers, heat stress on passengers, and other related issues.
- Some participants considered how extreme heat might change the demand for different transport services and travel behavior and thought that more research on this topic would be beneficial.
- A number of participants discussed the challenges and the importance of communication and coordination among stakeholders, with other groups, and with the public before, during, and after an event. Determining the lead agency or group was noted as important, as was identifying the triggers for activating different outreach levels and messages.
- Developing thresholds and plans for implementing different responses and for managing available resources could be valuable.
- The capacity of communities, human resource agencies, and other groups was also discussed. It was noted that these groups may not have available funding or staff time to deal with issues related to transportation and extreme weather events.
- New design standards based on higher temperatures and the stress on equipment were discussed.

Research

- Some participants suggested exploring the potential to generate energy for the transport sector from the increased heat and higher temperatures as a research topic.
- A second research topic focused on assessing the optimal allocation of energy, water, and other resources to different purposes during extreme heat events.
- A third research topic was assessing the impacts of heat and humidity on our different transportation system equipment, technology, and component parts. Examining the impact on users of the transport system was also noted as important.
- Research examining different combinations of extreme weather events could be beneficial. For example, a drought followed by heavy rains would probably be more catastrophic that just the heavy rains, and exploring the impact of these compounding events was noted as an important topic to consider.
- Some participants also noted that although sharing experiences and lessons learned was important, there was also a need for region-specific research on the impacts of drought and heat waves.
- Research on how to include the potential for higher temperatures in design and construction projects today was suggested as important. Identifying methods to conduct life-cycle cost analyses and benefit–cost analyses on improvements in current investments in equipment and structures to address extreme temperatures in the future could be part of this research.

Breakout Group D

Richard Wright

Challenges

- One challenge discussed in the breakout group was the requirements by the Federal Emergency Management Agency and other agencies on replacing and repairing infrastructure as part of disaster relief programs. Many programs allow only replacement of an existing facility, with no upgrades or improvements.
- A second challenge voiced by a number of participants was inadequate and untimely funding for recovery and gaps between available relief funding and the recovery needs of different transport agencies.
- A third challenge was the adequacy of current codes and standards. One approach to addressing climate change was the use of phased design codes for future adaptation and alternatives. These codes could provide flexibility for design changes in the future based on changing conditions.
- Private-sector collaboration during recovery was noted as a challenge. Collaboration between private-sector groups as well as between public- and private-sector groups was also suggested.
- Some participants suggested that another challenge was possible: institutional and legal barriers to address-

ing uncertainty, which might include limitations on an agency's role, authority, and funding.

- Other participants discussed that optimal systems tend to be brittle and that operational information systems need to be robust. Further, private-sector just-in-time delivery systems tend to be brittle.
- Other individuals suggested that improved disaster relief legislation and policies would be beneficial, along with codes and standards supporting adaptable infrastructure. Some noted that a crisis situation may help focus the need for change. Formalizing intergovernmental collaboration was also noted by participants as needed to manage recovery. Public and private funding during a recovery was also discussed, with participants suggesting that public–private partnerships were important for crisis response.
- Prioritizing recovery actions and investments was noted as an important management strategy by participants, as well as following preestablished networks for emergency recovery. Participants suggested that these elements could also build social capital.

Research

- One research topic considered by participants was developing approaches to maintain flexibility during the recovery stage of an extreme weather event to respond to changing conditions and priorities.
- Another possible research topic was updating infrastructure design standards to address climate change issues.
- A related research topic was developing evaluation procedures for performance-based standards.
- Identifying future demands on the transportation system, including modal preferences of different groups and the impact of these demands on recovery, was considered a possible research topic. It was noted that travel behavior and mode choice may change during extreme weather events.
- Research on organizational collaboration models and methods to evaluate different models would be valuable.
- Some participants suggested that assessing alternative sources for disaster relief funding and evaluating methods to allocate available resources would be beneficial.
- Research on how to address inertia for existing projects that may not fit with future climate changes could be important.
- Research on the use of social media during the recovery phase was considered. Sharing current practices in the use of social media, possible issues, and potential innovative approaches was also suggested.
- Research examining the impact of future urbanization on recovery needs was mentioned as was developing and sustaining methods to share experiences and lessons learned with various approaches in different areas for an effective trans-Atlantic research project.

Closing Session and Final Remarks

Keir Fitch, *European Commission, Brussels, Belgium*
Alasdair Cain, *U.S. Department of Transportation, Washington, D.C., USA*
Neil Pedersen, *Transportation Research Board, Washington, D.C., USA*
Vicki Arroyo, *Georgetown University Climate Center, Washington, D.C., USA*
Thomas Wakeman, *Stevens Institute of Technology, Hoboken, New Jersey*
Rachel Burbidge, *Eurocontrol, Brussels, Belgium*
Thomas Bles, *Deltares, Delft, Netherlands, and Conference of European Directors of Roads, Brussels, Belgium*
Robert Lempert, *RAND Corporation, Arlington, Virginia, USA*
Evangelos Mitsakis, *ITS/Hellas Hellenic Institute of Transport, Thessaloniki, Greece*
Magdalena Kopczynska, *European Commission, Brussels, Belgium*
Kevin Womack, *U.S. Department of Transportation, Washington, D.C., USA*

Sponsor Comments

In this session, representatives from the symposium's three sponsors discussed symposium follow-up activities.

Comments from the European Commission

Keir Fitch

Keir Fitch discussed possible follow-up activities to the symposium. He noted that the symposiums have been successful in bringing together researchers and other professionals from both sides of the Atlantic to discuss specific topics and to generate collaborative research opportunities. He described the scope and scale of the European Commission transport research program, which has a budget of approximately €6 billion over a 7-year period. The program includes a wide range of research topics from aviation to green vehicles to railways to infrastructure.

Fitch described the emphasis on climate change, resilience, and sustainability throughout the research programs. He commented that approximately 60% of the research budget was targeted toward projects that will affect sustainability. As a result, he noted that the topics discussed at the symposium were very relevant to the European Commission transport research program. He suggested that identifying key research areas, especially those with scopes appropriate for collaboration between the EU and the United States, was beneficial.

Fitch described the twinning research process, which has been used to facilitate trans-Atlantic projects. Under this approach, similar projects are undertaken in the United States and Europe in response to a joint call for projects by the appropriate agencies. Funding for researchers on the selected projects is provided by each funding organization, with an amount earmarked to facilitate trans-Atlantic contacts. He suggested that the results from this symposium could be used to identify common trans-Atlantic transport infrastructure resilience research projects that would be appropriate for twinning.

Fitch noted that the EU Horizon 2020 has a topic in the work program for 2017 on resilience to extreme events. Researchers in the EU will be proposing on the topic. He suggested that related projects could be developed in the United States and that the twinning process could be used to bring together the selected researchers from the EU and the United States.

Fitch reported that the work plan for 2018 through 2020 was being developed and that consideration of the program beyond 2020 was beginning. He noted there was an extensive effort under way within the research community to examine the longer-term issues and trends in transport research, including climate change, transport automation, and big data. A series of strategic papers will be developed to assist in developing the work program for future years (the EU's Strategic Transport Research and Innovation Agenda). He suggested that it was important to look beyond incremental changes and to focus research on activities that can be done and must be done to provide a secure and sustainable transport system for the decades ahead. He noted that the results from this symposium will be beneficial in developing the 2018 through 2020 work plan and in framing issues for the longer-term program.

Comments from the U.S. Department of Transportation

Alasdair Cain

Alasdair Cain described the research approach at the U.S. DOT and new opportunities for international research collaboration made possible through the Fixing America's Surface Transportation (FAST) Act, passed in December 2015. He noted that the U.S. DOT has nine agencies that fund research activities, all with their own Congressional mandates, missions, budgets, and research programs. The Office of the Assistant Secretary for Research and Technology (OST-R), U.S. Department of Transportation (U.S. DOT), is responsible for coordinating these research portfolios, disseminating information on international research opportunities, and coordinating U.S. DOT agency responses to these opportunities.

Cain reported that OST-R will distribute the symposium proceedings and conduct briefings with the agency research project directors. He noted that research topics will be reviewed and opportunities for twinning projects and other activities will be discussed. He reported that briefings will also be conducted with the U.S. DOT's Center for Climate Change and Environmental Forecasting (CCCEF), which is a U.S. DOT interagency group. CCCEF conducts multiagency-funded projects on topics related to climate change adaptation and mitigation.

Cain reviewed key elements of the FAST Act, which establishes funding levels and program guidance for the next 5 years. He noted that this 5-year period aligns well with the remainder of Horizon 2020, which means this period offers an unprecedented opportunity for sustained EU–U.S. research collaboration. He further noted that the U.S. DOT is developing a strategic plan, as required by the FAST Act, which is due to Congress by the end of 2016. The strategic plan will be used to set U.S. DOT's research agenda and priorities over the next 5 years. He commented that one of the overarching themes in the strategic plan is transportation impacts on the social and natural environment, which relates to the climate change mitigation strategies discussed during the symposium. Another key priority for the U.S. government, one that is specified in the FAST Act, is preserving critical infrastructure. This topic aligns directly with the discussion of climate change adaptation strategies. He noted that the U.S. DOT has an adaptation policy, but not a mitigation policy. As noted in the symposium, the transportation sector is a major contributor to GHG emissions. In recognition of this, the CCCEF is working to develop a U.S. DOT climate change mitigation policy.

Cain commented that the timing of the symposium was advantageous for providing input to the U.S. DOT strategic plan, which will provide guidance to the modal agencies. He also discussed possible twinning opportunities, noting that the 2016–2017 European Commission program identifies 11 topic areas for potential twinning projects. He reported that the U.S. DOT was examining these topics for possible matching projects in the United States. Priority twinning topics include resilience to extreme (natural and human-made) events as well as intelligent transportation systems, automation, and safety. He suggested that there may be opportunities for twinning with some of the recent topics identified in the breakout groups and to contact him if any of the attendees were interested in pursuing such opportunities.

Comments from the Transportation Research Board

Neil Pedersen

Neil Pedersen discussed anticipated Transportation Research Board (TRB) follow-up activities. He noted that TRB and the U.S. DOT coordinate and cooperate on research, but that the TRB research program is independent of the U.S. DOT program. The TRB research program is oriented toward the needs of the transportation system operators, including state departments of transportation, transit agencies, airport authorities, ports, and other agencies.

Pedersen reviewed some of the activities TRB will undertake to build on the symposium, which will lead directly and indirectly to research. He reported that resilience was one of three major issues identified by the TRB Executive Committee. A task force of the Executive Committee is examining the role TRB can play in addressing the topic of resilience, possible research, and technology transfer activities. He noted that the symposium results will provide an excellent basis for the work of the task force. Pedersen commented that Vicki Arroyo and Katie Turnbull, who are members of the Executive Committee, would provide a summary of the symposium at the Executive Committee mid-year meeting next week.

Pedersen also noted that the symposium proceedings, authored by Katie Turnbull under contract to the EU, will be published by TRB. The proceedings must follow the strict guidelines of the National Academies of Sciences, Engineering, and Medicine. Because the symposium was not set up under the Academies Federal Advisory Committee Act, he reported that the proceedings cannot include formal recommendations. Observations on research gaps and suggestions on research topics are appropriate, however.

Pedersen announced that a special session on the symposium will be scheduled for the TRB Annual Meeting, January 8–12, 2017, in Washington, D.C. Speakers and participants from the symposium will be included in the session. In addition, he suggested that many of the topics discussed at the symposium will be featured in other sessions. He invited all the symposium participants to attend the 2017 Annual Meeting. He noted that Katie Turnbull has volunteered to write an article on the symposium for *TR News*, the monthly publication that is distributed to approximately 10,000 transportation professionals.

Pedersen discussed the new TRB section on resilience chaired by Thomas Wakeman of the Stevens Institute of Technology. The section was established to enhance coordination among committees focusing on resilience and to increase the visibility of the topic within TRB. He suggested that the symposium results will be used by the section and committees across TRB. Some of the topics may be appropriate for follow-up workshops and conferences.

Pedersen suggested that one of the most important follow-up activities will be developing problem statements from the research topics identified in the breakout groups. The problem statements can be submitted to the National Cooperative Highway Research Program (NCHRP), the Transit Cooperative Research Program, and the Aviation Cooperative Research Program, which are all managed by TRB. Given limited resources, he said that identifying the most important research topics would be beneficial. He noted that John Halikowski, director of the Arizona Department of Transportation, serves as the chair of the NCHRP Oversight Committee. Halikowski is interested in TRB and the NCHRP program participating in twinning projects.

Participant Comments

Vicki Arroyo, Thomas Wakeman, Rachel Burbidge, Thomas Bles, Robert Lempert, and Evangelos Mitsakis

In this session, three symposium participants from Europe and three from the United States shared their views on the topics discussed in the breakout sessions and potential trans-Atlantic research topics.

Vicki Arroyo described the role and activities of the Georgetown University Climate Center. She noted that the center convenes activities and serves as resource to states on climate and energy issues. The center brings together academics and policy makers to improve climate policy. Further, it informs the development of legislation, regulation, transportation policy, and adaptation policy.

Arroyo noted that the center has helped identify legal and policy barriers to climate change adaptation strategies. She commented that the center made 100 recommendations to the President's Task Force on Preparedness and Resilience that informed their report. The center maintains an adaptation clearinghouse website that hosts more than 1,000 resources on adaptation. The clearinghouse helps decision makers and others to quickly identify relevant resources. She suggested that it can also serve as a resource for symposium participants.

Arroyo highlighted the state tracking tool available on the website, which presents information on activities at the state level. For example, information is available on 15 state-led adaptation plans, draft plans in other states, and regional and municipal plans. She reviewed other resources available on the center's website. These resources include 175 case studies developed by center personnel highlighting changes in transportation systems made with climate impacts in mind. The Federal Highway Administration (FHWA) Climate Change Adaptation and Resilience Case Study Series, which highlights a range of state and local examples, is also available through a link on the website.

Arroyo described the experience in New Orleans with Hurricane Katrina, noting that her family lost homes in the flooding. She noted that Katrina pointed out the importance of improving communication with people who need support in evacuating. One improvement has been the placement of 14-foot "evacuteer" sculptures to identify places where people can get rides out of town before a storm event. She described the experience of her father during the evacuation from Hurricane Ivan the year before Katrina. She noted that he was turned away from seeking treatment just prior to the storm as hospitals were going into lockdown mode and not keeping scheduled appointments. The evacuation was very stressful, as the contraflow allowing traffic to use highway lanes differently did not go well. After long delays, her father went from a hotel to the hospital where he died that evening.

Arroyo commented that what many people took away from stories like her father's and the difficulties with Hurricane Ivan was that it was safer to stay home when Katrina hit the next year, when, of course, that was not the case, as 80% of the city flooded. She also noted that some people did not evacuate because they did not want to leave their pets, which may be their only companion. In response to this situation, Congress passed the Pets Evacuation and Transportation Standards Act, or PETS Act, which allows pets to accompany individuals in evacuations. She noted that it is important to learn from previous experiences and share case studies, as noted by many participants at the symposium.

Arroyo provided the following links to websites for symposium participants to obtain further information:

- One hundred transportation adaptation case studies are available at http://www.georgetownclimate.org/adaptation/clearinghouse (select "Transportation").
- Case studies on FHWA's website are available at http://www.fhwa.dot.gov/environment/climate_change/adaptation/case_studies/series.cfm.

Thomas Wakeman described his background and experience in examining the impact of extreme weather events on the transportation system, primarily seaports and freight facilities. He highlighted his national and international work in port and intermodal facility development and operation. He also discussed his current role at Stevens Institute of Technology and his involvement in TRB committees focusing on resiliency.

Wakeman discussed working in Iraq to reopen the country's seaports and intermodal facilities after Operation Iraqi Freedom, which enhanced his understanding and appreciation of the global intermodal transportation system and the international economy. His studies of lessons learned following Superstorm Sandy provided a better understanding of the impact of extreme weather events on the regional freight transportation system and the local economy. He noted that the water-side response to Superstorm Sandy was well organized by the U.S. Coast Guard. He suggested that the land-side response was more difficult due to the lack of adequate coordination among private-sector operators and multiple agencies at the federal, state, regional, and local levels. In some cases, these parties had not worked together before and had not developed a high level of collaboration. He noted the importance of including social scientists with civil engineers in developing transportation resiliency plans and actions to enhance activities before, during, and after extreme weather events. He suggested that although concrete and rebar may fail, people are resilient, and supportive communities are an important part of the recovery process from disruptive events.

In discussing his current university role, Wakeman noted the need to include consideration of climate change and extreme weather events in civil engineering curricula. He also outlined the need to develop new tools and methods for analyzing risks, assessing infrastructure vulnerability, and developing adaptation strategies.

Wakeman highlighted his role as the chair of the new resilience section of TRB committees. He noted that the symposium results will be of use to the committees in the resilience section and to other committees within TRB in developing research problem statements and organizing annual meeting sessions, workshops, and other activities.

Rachel Burbidge thanked the symposium organizers for inviting representatives from the aviation sector. She noted that the presentations and discussions were very informative. She described the role of Eurocontrol (the European Organization for the Safety of Air Navigation) and possible impacts of climate change and extreme weather events on aviation.

Burbidge noted that Eurocontrol is an intergovernmental organization with 41 member states. All EU member states are currently members. Established in 1960, Eurocontrol's responsibilities are to achieve safe, efficient, and environmentally friendly air traffic operations throughout the European region. She described the activities of Eurocontrol, which include air traffic flow and capacity management, safety management, controller training, and environmental sustainability.

Burbidge reported that Eurocontrol first identified the impacts of climate change as a potential risk for the aviation sector in 2008 and since then has been working to clarify the impacts and identify adaptation measures. She stressed the interconnectivity of the aviation sector and noted that disruptions in one area due to weather events cause ripple effects throughout the entire system.

Burbidge noted that extreme weather events can significantly disrupt the operation of airports as aircraft operations may be restricted, meaning that flights may be cancelled or delayed. Access to and from an airport may also be affected. She commented that the impact to the aviation network can stretch beyond an individual airport. Delays and cancellations in one part of the network influence flight schedules, aircraft availability, and crew schedules throughout the system.

Burbidge suggested that continuing to share information among transport sector organizations and agencies on adaptation planning, response, and recovery activities would be beneficial. She also noted the importance of ongoing interaction with the scientific community to obtain updated information on climate conditions and possible impacts on the transport system.

Thomas Bles highlighted a few of the topics addressed in the symposium presentations and breakout groups. He noted that some of these topics, including using a risk-based approach and considering the total transportation system, confirmed previous research and experience. He also provided examples from projects conducted for the Port of Rotterdam, Netherlands.

Bles suggested that risk-based assessments provide a good method for identifying the potential for and possible consequences of extreme weather events, as well as the vulnerability of critical assets. The importance of focusing on the total transportation system, including all modes and user groups, as well as the supporting infrastructure, was also reinforced by speakers and discussions in the breakout sessions.

Bles presented an example from the Port of Rotterdam illustrating the cascading effects and interactions among modes, electricity, communication services, data centers, and other infrastructure elements. He suggested that obtaining a better understanding of the relationships between the different modes and components would be beneficial. Bles also presented an example of a risk matrix from a Port of Rotterdam workshop illustrating the likelihood of different extreme weather events and their potential consequences. He stressed the need to examine different scenarios, especially those with a combination of high likelihood of occurring and severe consequences.

Bles discussed a few of the other topics covered in the breakout groups. He noted that the discussion of black swans (extreme, rarely identifiable, events) supported the need to examine a wide range of scenarios. He reviewed the discussions on the types and extent of data needed to analyze the impacts of different scenarios on the transport system. Climate data, asset data, and user data were all identified as important; however, first insight can also be gained by using the experience and expertise of relevant stakeholders without having the appropriate data. In other words, he suggested that lack of data should not be used as an excuse to stop an assessment. Other topics of interest summarized by Bles included communicating with the public and using remote sensing to support monitoring and evaluation efforts. He presented examples of adaptation pathways with different scenarios and techniques to communicate possible risks to the public.

Robert Lempert discussed research focusing on deep uncertainty and its relationship to transportation resilience. He noted Alfred Chandler's book *The Visible Hand: The Managerial Revolution in American Business*, which offers a useful perspective on deep uncertainty and the associated difficulties with addressing transportation resilience.

Lempert noted that a key theme of Chandler's work was that the development of the railroad in the 19th century was linked to the emergence of a new social organization, the managerial corporation. He suggested that this theme was relevant to transportation resilience in the 21st century for several reasons. First, it highlights that technology is not only the physical artifact, but is also the socioeconomic system in which the artifacts are embedded. He suggested that this system view will likely prove important to ensuring resilience, especially to pathways that involve significant transformation of transportation systems. Second, among the attributes of managerial organizations is a preference for long-term stability. Thus, a preference for stationarity and predictability is built into these systems, even though the world is increasingly nonstationary and difficult to predict. Third, these organizations have traditionally been organized as hierarchies that divide the system into silos that are largely managed independently.

Lempert highlighted attributes of the current transportation system, which is more than just technology and engineering and which operates in silos of different agencies, modes, and governmental levels. Research priorities for resilience could thus usefully focus on how to best identify and implement systemic, flexible, and robust plans in the transportation sector. He noted that the analytic means for studying such plans are becoming increasingly available. Important research priorities might include conducting pilots and demonstration projects to identify promising solutions; studying means to align incentives among government agencies and the private sector toward actions and investments that promote resilience; developing methods for valuing resilience to facilitate trade-offs among investments in different components of the system, as well as to help answer the question of how much to pay for flexibility; improving systems models to help evaluate the potential consequences of alternative policies under conditions of uncertainty; and conducting rigorous evaluation of policies to improve the understanding of what is and is not working.

Evangelos Mitsakis described his research interests in transport, including better understanding the impacts of climate change on the transport system and travelers' behavior. He noted that the symposium speakers highlighted the changes that are occurring as a result of climate change. He commented that public agency participants from the United States were well versed in some of these impacts and the responses that had been taken to date. He noted that there was a gap between climate change science and applying that science to practical transport applications. Mitsakis discussed how the following 14 research topics would be useful projects for future research:

- Developing a commonly agreed-on and accepted definition of resilience as well as standardized methods to measure resilience (e.g., key performance indicators);
- Quantifying the impacts of climate change on transport systems and transport networks to ensure reliability and to support transferability of results;
- Assessing cross-modal substitutability of transport systems to efficiently provide transportation services during disruptions;

- Assessing the behavior of travelers under extreme weather events and emergency conditions;
- Accounting for prevailing new technologies and new modes of transport (e.g., cooperative intelligent transportation systems, automated and autonomous vehicles, electromobility) as well as dependencies between transport networks and networks of other facilities (e.g., electricity networks);
- Integrating climate change–related parameters and uncertainty aspects into transport planning;
- Adopting dynamic adaptation planning, as opposed to long-term planning;
- Improving the scale and level of detail of modeling tools to allow better decision support;
- Integrating risk planning and risk management in transport systems planning and adaptation;
- Integrating resilience aspects into sustainable urban mobility planning;
- Modeling the interactions, including cooperation and conflicts, between relevant stakeholders;
- Developing support tools to facilitate cooperation and to assist decision makers and stakeholders;
- Maintaining global perspectives for all aspects of adaptation of transport networks to climate change; and
- Examining a horizontal topic focused on ensuring the availability, reliability, and use of data to support rigorous research and robust scientific results.

Closing Comments from Sponsors

Magdalena Kopczynska, Kevin Womack, and Neil Pedersen

Magdalena Kopczynska provided closing comments from the EU. She noted that the symposium goals presented by Clara de la Torre in the opening session had been accomplished. First, the current state of research on transport adaptation was reviewed and discussed. Second, research gaps and potential research were considered, including topics for trans-Atlantic cooperation. Third, the lively discussions in the breakout groups and the closing session focused on stimulating more research and fostering innovation.

Kopczynska reported that the possible research topics will be helpful in developing future research agendas. She noted that there are differences in approaches to adaptation and mitigation in Europe and the United States and that the mutual exchange of experiences can enrich both communities. The EU Horizon 2020 program already has a focus on climate change adaptation that could allow a quick agreement on collaboration potential. She commented that the discussions in the breakout groups on approaches transport agencies can use to respond to the impacts of extreme weather events, as well as possible policy implications, were beneficial.

Kopczynska suggested that the symposium goals related to fostering trans-Atlantic cooperation, identifying cross-disciplinary research opportunities, and promoting ongoing information sharing had also been met. The TRB follow-up activities would be very beneficial for the dissemination of the symposium outcome. The symposium results will also be communicated at different EU transport research venues. She commented that twinning is the best approach for trans-Atlantic research collaboration. She also suggested that climate change is a cross-disciplinary topic, as is smart transport in the EU Research and Innovation Framework Programme.

According to Kopczynska, the symposium goal of increasing the relevance of research for practitioners had also been met. The symposium included a good mix of individuals from road, transit, aviation, and water transport modes, as well as agencies at the local, state, and national levels. She commented that the social aspects of climate change were important and that transport has a role to play in addressing potential social issues. She also noted the potential for technology to enable innovative adaptation strategies as well as assisting with communicating with diverse groups.

In conclusion, Kopczynska expressed strong interest in continuing the symposiums. She noted that the topics of the three previous symposiums—city logistics, the implementation of research, and automated road transport—were all important. She stressed the importance of ongoing trans-Atlantic research collaboration and the benefits realized from the EU, U.S. DOT, and TRB partnerships.

Kevin Womack provided closing comments from the U.S. DOT. He voiced support for continuing the symposiums for another 4 years. He thanked the EU representatives for hosting this symposium and for their leadership in ongoing trans-Atlantic research collaboration.

Womack recognized and thanked the planning committee for organizing an interesting, informative, and interactive symposium. He acknowledged the leadership of Chair Alan McKinnon and Cochair Dick Wright. He also thanked the participants for their active involvement throughout the symposium.

Womack suggested that one of the common themes from the breakout group discussions and the closing panels was the importance of turning available data into valuable information for use by policy makers, decision makers, and practitioners. He suggested that this theme was the main underlying issue in most of the discussions and represented an essential research area. He noted that this need is present with all types of data, including translating historical climate data into information for use by infrastructure designers and turning real-time data into information for use by personnel needing to make immediate decisions in response to changing conditions.

In conclusion, Womack requested feedback from symposium participants on follow-up activities, involvement in twinning projects, uses of information for policy making, collaboration on research, and ongoing information sharing. He noted the importance of documenting the benefits from the symposiums and illustrating follow-up activities.

Neil Pedersen of TRB concluded by recognizing and individually thanking the members of the planning committee. He stressed the outstanding job Alan McKinnon did in chairing the committee and the energy he brought to the symposium. Pedersen also recognized all other members of the planning committee.

Pedersen acknowledged the outstanding support of Frank Smit from the European Commission, Monica Starnes from TRB, and Alasdair Cain from the U.S. DOT. He further thanked all the representatives from the EU, the keynote speakers, the white paper authors, and all the participants for making the symposium a success.

Potential Portfolio for EU–U.S. Research on Transportation Resilience

Katherine F. Turnbull, *Texas A&M Transportation Institute, College Station, Texas, USA*

Symposium rapporteur Katherine Turnbull summarized the keynote presentations, panels, and breakout group reports. She also attended the breakout groups, gaining a better understanding of the challenges and research topics discussed by participants. A number of common cross-cutting challenges and research topics emerged from the symposium.

The rapporteur developed a potential portfolio for EU–U.S. research on transportation resilience and adaptation to climate change and extreme weather events. The potential research topics are grouped by the following subject areas: climate science data for transport uses; adapting materials and designs; climate change and transport planning; risk assessments, stress tests, and benefit–cost analyses (BCAs); technologies, innovations, and impacts; and communication and outreach strategies and methods for diverse stakeholders. These research topics may be considered by the European Commission, the U.S. Department of Transportation (U.S. DOT), the cooperative research programs managed by the Transportation Research Board (TRB), and other groups. The potential research projects are also appropriate for twinning. Opportunities for ongoing trans-Atlantic information sharing and coordination activities are highlighted after the six research subject areas.

Climate Science Data for Transport Uses

The need for research translating climate science data into useful information for transportation planning, design, and operations was discussed in the breakout groups for all three of the scenarios. Symposium participants cited the following research topics as being potentially useful as a means of facilitating the use of climate science data by the transport sectors:

- Identify climate science data relevant to transport planning, design, and operations and translate those data into usable information. This research would focus on making available climate science data more user friendly for the transport sectors. It would develop guides and examples for the use of climate science data for different transport planning, design, and operation applications.
- Develop a robust ongoing dialogue among climate scientists and transport engineers, planners, operators, and policy makers to facilitate information sharing. Ensuring that climate scientists understand transport issues at the local, regional, state, national, and global levels would be part of this research.

Adapting Materials and Designs

The need to examine the long-term impacts of climate change and extreme weather events on transport infrastructure materials and designs was discussed throughout the symposium. The following research projects were considered by individual participants on this topic:

- Identify the potential impacts of climate change on the transport infrastructure. An initial research project would examine the possible impacts of climate change, including higher temperatures, on a range of transport infrastructure, materials, and equipment. Vulnerable assets would be identified for more detailed examination in additional research.

- Develop pavement and materials for higher temperatures and humidity. Research would develop specifications and standards for pavements and materials to withstand higher temperatures and higher humidity levels. The research would involve working with the appropriate specification- and standard-setting organizations.
- Develop design and operational criteria for modal infrastructure to respond to changing climates. Multiple research projects could examine the needs of different modes and develop new design and operational criteria as needed to respond to climate change, using data that climate change models can reasonably provide.
- Assess the impacts of climate change on infrastructure supporting transport operations, including the power grid, water supplies, and food sourcing.

Climate Change and Transport Planning

The following possible research topics were discussed during the symposium as possible ways to better integrate climate change and extreme weather events into transport planning, including near-term and long-range plans and addressing the needs of different population groups:

- Document and share current practices on incorporating climate change into transportation planning.
- Develop methods to integrate climate change and weather uncertainty into near-term and long-range transport plans.
- Develop dynamic adaptation planning methods and undertake pilot applications.
- Develop and apply more robust climate change scenarios, including examining the potential impacts on the transport system and identifying possible responses.
- Examine possible black swan climate change scenarios (rare catastrophic events), the possible impacts on the transport system, and responses to these types of events.
- Examine the impacts of changing land use patterns on the transport system during extreme weather events, as well as methods to better coordinate more resilient development patterns.
- Enhance the scale and level of detail of travel demand modeling tools and simulation models to account for extreme weather events.
- Assess changes in human behavior during extreme weather events, including travel choices, modes, and trip-chaining. Assess the impacts of these changes on the transport system.
- Examine cross-modal substitutability during extreme weather events.
- Examine the needs of vulnerable population groups during extreme weather events and identify approaches to address their transport, mobility, and other needs.
- Assess the broader socioeconomic impacts of climate change and transport, including environmental justice and equity issues.
- Review and document organizational learning research for applications that can be used with transport agencies and climate change adaptation.
- Examine the use of big data to assist in all aspects of planning for extreme weather events, minimizing disruptions during actual events, and recovering.

Risk Assessments, Stress Tests, and Benefit–Cost Analyses

The following possible research topics were suggested by participants to enhance methodologies for conducting risk assessments, stress tests, and BCAs:

- Document and share current practices on assessing the risks to different modes from extreme weather events.
- Develop standard measures of resilience and risk assessment tools.
- Examine approaches to link risk assessment, vulnerability, and asset management, including the use of risk-based asset management.
- Develop, test, and apply scenario-based adaptive policies, dynamic asset-management techniques, and pathways to resilience.
- Develop, apply, and evaluate stress tests to determine the vulnerability of transport infrastructure and services.
- Examine the level of readiness needed for different adaptation strategies and extreme weather events.
- Examine the interaction between mitigation and adaptation strategies and assess if some strategies are mutually reinforcing or are in conflict.
- Develop BCA methodologies that account for lifecycle costs and the costs of disruption to the transport system.
- Assess the cost-effectiveness of different transport adaptation measures.

Technologies, Innovations, and Impacts

The following possible research topics were considered by some participants to be related to new technologies and innovative approaches to monitor and respond to extreme weather events, as well as evolving transport technologies:

- Assess new technologies to assist in planning for, managing, and recovering from extreme weather events. Possible technologies include unmanned aerial vehicles, sensors, cameras, and smart phones.
- Assess the potential impacts of extreme weather events on connected, automated, autonomous, and low-carbon (e.g., electric) vehicles and related technologies.
- Assess the impacts of extreme weather events on these new technologies and identify methods to mitigate negative impacts.
- Develop innovative transport adaptation strategies and conduct pilot tests.

Communication Strategies and Methods for Outreach to Diverse Stakeholders

Several participants believed the following research topics could enhance communication and outreach to diverse stakeholders before, during, and after extreme weather events:

- Assess current messages and methods for communicating with policy makers, other stakeholders, and the public.
- Develop messages to better communicate the potential risks associated with climate change and different types of extreme weather events and the need for investments in the transport sector.
- Examine the use of social media, smartphones, and other related methods to communicate with the public, especially during extreme weather events.
- Develop educational and outreach materials and methods for communicating the impact of climate change and extreme weather events on the transport system.
- Develop case studies of public–private partnerships and multiagency coordination in planning for, responding to, and recovering from extreme weather events.
- Develop support tools to facilitate multiagency and multilevel coordination and cooperation.

Information Sharing and Ongoing Coordination

Several opportunities for ongoing trans-Atlantic information sharing, coordination, and collaboration were suggested by individual participants during the symposium:

- Distribute the symposium proceedings to diverse stakeholders at the global, national, state, regional, and local levels.
- Provide summaries of the symposium to participants and agency staff at conferences and other appropriate venues, including those sponsored by the European Commission, U.S. DOT, and TRB. A PowerPoint presentation highlighting the symposium is available for use by all interested parties.
- Produce a *TR News* article on the symposium and follow-up articles on related research and activities as appropriate.
- Convene symposium participants at the 2017 TRB annual meeting for an information-sharing meeting.
- Develop a general session on the key topics addressed at the symposium for the 2017 TRB annual meeting and promote sessions at future annual meetings and specialty conferences and workshops.
- Pursue possible conferences, workshops, and meetings sponsored or cosponsored by the U.S. DOT, the European Commission, TRB, and other organizations and groups.
- Continue the involvement of the TRB Executive Committee task force, sections, and committees in developing research needs statements; coordinating research and outreach activities; and organizing annual meeting sessions, conferences, and workshops.
- Pursue twinning research projects and facilitate trans-Atlantic research and sharing of results. Encourage ongoing EU–U.S. dialogue and information sharing through a variety of mechanisms.
- Develop best practice case studies of adaptation efforts from throughout the world and share at conferences and meetings.

APPENDIX A: WHITE PAPER

Transportation Resilience

Adaptation to Climate Change and Extreme Weather Events

H. G. Schwartz, Jr., *Consultant, USA*
Lori Tavasszy, *Delft University of Technology and TNO, Delft, Netherlands*

1 Introduction

This white paper is intended to set the stage for the June 16–17, 2016, European Union–United States (EU–U.S.) symposium Transportation Resilience: Adaptation to Climate Change and Extreme Weather Events. Climate change is a matter of increasing concern worldwide, and nowhere will its impacts be felt more strongly than with the built infrastructure—the transportation, energy, water and wastewater, health care, and communications systems that underpin our economy and society. The focus of this symposium is on the research needs to design, build, operate, and maintain transportation systems that are better adapted to the predicted changes in Earth's climate. In other words, it is on how to develop more resilient transportation systems.

Resilience has been defined as "the ability to prepare and plan for, absorb, recover from, and more successfully adapt to adverse events" (*1*). It is a complex problem, especially for the vast transportation networks of the world, encompassing not only the physical infrastructure, but people, environment, operation, maintenance, and emergency response. Moreover, the interactions between transportation systems and other sectors, such as power generation and distribution, agriculture, manufacturing, retailing, waste management, health care, and communications, must be understood and addressed.

There are so many aspects to the term *transportation resilience* that it will be a challenge to the symposium participants to identify the critical research needs of the transportation community to create a more resilient future. A few of the overarching questions that might be addressed include the following:

- What do we know or need to know about climate change and extreme weather events?
- How can broad geographic climate projections be downscaled to local and regional levels?
- Do we understand how to make decisions when faced with inherently uncertain conditions?
- What makes a transportation system, or its parts, resilient enough?
- What technologies might be developed or refined to reduce or even prevent damage from extreme weather events?

To set the stage, the next section (Section 2) addresses the science of climate change: what scientists are predicting and why. Section 3 discusses decision making under conditions of uncertainty. As climate change is itself complex and our understanding of it is continually improving, how do transportation professionals make decisions today for systems that have lifetimes of 50 or more years? The fourth section of the paper deals with risk assessment and suggests the need to incorporate risk management techniques into decision making. Finally, in Section 5 we attempt to draw on the preceding sections to address the fundamental subject of the symposium, transportation resiliency.

2 Climate Change Impacts on Transportation

The preponderance of scientific research indicates that Earth is warming at an accelerating rate and that this change is due in large measure to the use of fossil fuels. Earth is surrounded by an envelope, the troposphere, filled in part with what we call greenhouse gases (GHGs) such as carbon dioxide (CO_2), methane, and water vapor. These GHGs are essential in maintaining a temperate climate, but increases in their concentrations are causing changes to the climate, namely global warming. Fifty million years ago CO_2 levels in the atmosphere are believed to have averaged 1,400 parts per million (ppm), and temperatures were 10°C (18°F) higher than in the preindustrial period—there was no ice on Antarctica *(2)*. Data from ice cores have been used to reconstruct Antarctic temperatures and atmospheric CO_2 concentrations over the past 800,000 years. Over the past 800,000 years, CO_2 concentrations in the atmosphere have increased from a range of 170 to 300 ppm to just over 400 ppm, mostly in the past 40 years. As the record shows, the recent increase in atmospheric CO_2 concentration is unprecedented in the past 800,000 years (Figure 1) *(3, 4)*. During that period Earth's temperature has also risen significantly.

The data clearly demonstrate a steady increase in global temperatures (Figure 2) (*5*). Indeed, although the first decade of the 21st century was the warmest on record, 2013 through 2015 were even warmer, with 2015 being the warmest on record (*5*). Temperatures on land, in the oceans, and in the troposphere have all increased over this time period, with the greatest increase in the Arctic.

These climate changes coincide with the great increase in the use of fossil fuels, beginning with the Industrial Revolution, but accelerating greatly since the 1970s. Natural variability due to sun spots, Earth's wobble on its axis, and events like El Niño and La Niña cannot explain the climate changes over the past 30 years. Only when one factors in the use of fossil fuels can the recent changes be explained. The clear conclusion is that Earth's climate is warming and that the changes are due in large measure to anthropogenic activities.

Much of the discussion about climate change has revolved around actions to decrease GHG emissions to reduce or mitigate the extent of climate change. The COP [Conference of Parties] 21 meetings in Paris this past fall [2015] established new targets for reducing CO_2 emissions for both the industrialized world and developing countries. The new agreement accommodates international differences in political attitudes and approaches to climate change, especially the perspectives of developing countries.

Regardless of the policies and indeed actions implemented today and in the near term, the impact of increasing worldwide GHG emissions will continue for decades.

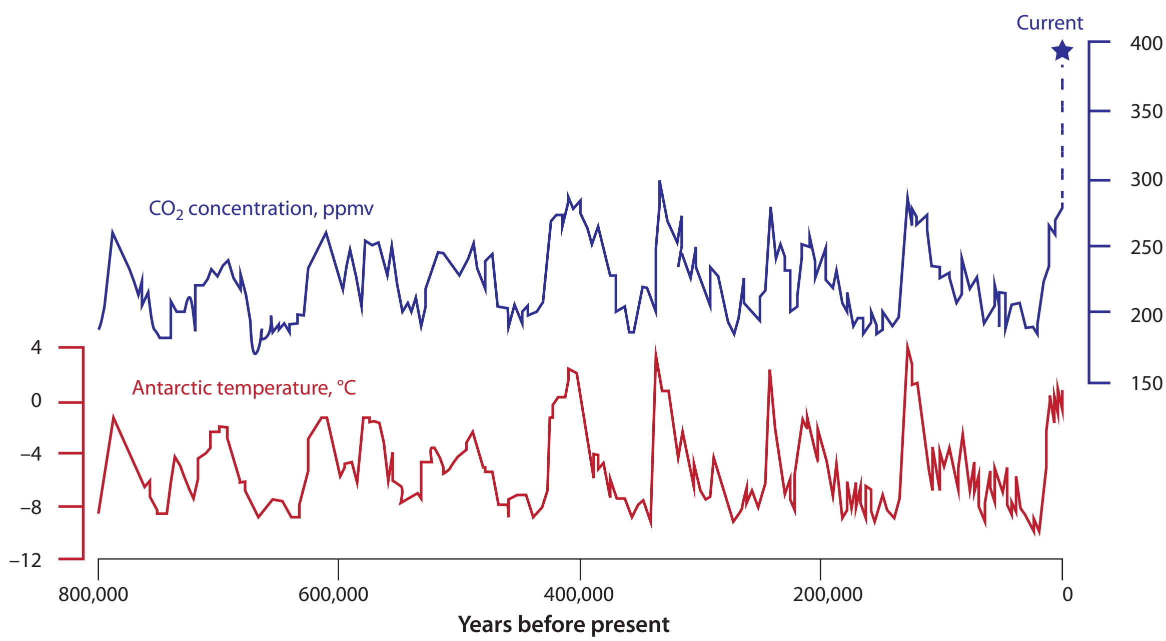


FIGURE 1 Temperature and CO_2 from Antarctic ice cores over the past 800,000 years. The cyclical pattern of temperature variations constitutes the ice age and interglacial cycles, during which changes in CO_2 concentrations (blue line) track closely with changes in temperature (red line) (ppmv = parts per million by volume) (*4*, Figure 3, p. 10, and https://www2.bc.edu/jeremy-shakun/FAQ.html). Accessed May 10, 2016.

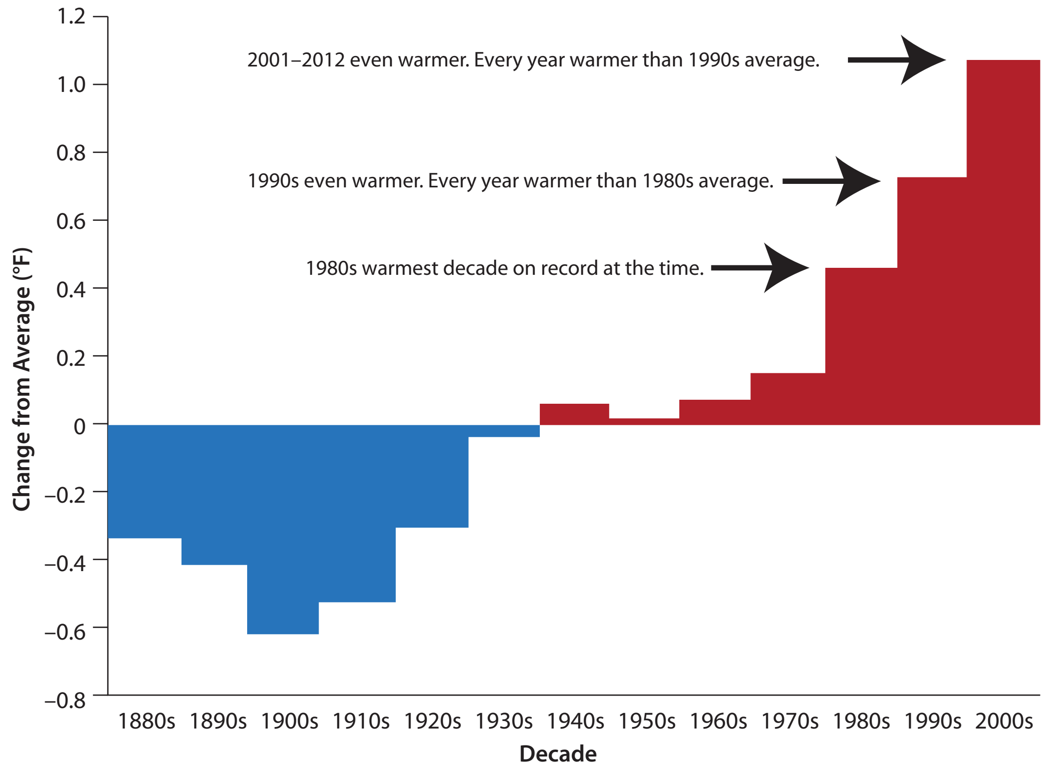


FIGURE 2 The past five decades have seen a progressive rise in Earth's average surface temperature. Bars show difference between each decade's average temperature and the overall average for 1901–2000 (*5*).

Mitigation is a long-term solution, perhaps, but the world must take proactive steps now to adapt to climate changes.

2.1 Major Impacts on Transportation

In transportation, as with much of the built infrastructure, five specific impacts will need to be addressed (*6*):

- Sea level rise,
- Higher temperatures and longer heat waves,
- Changes in precipitation patterns,
- Rising Arctic temperatures, and
- Increased intensity of storms and hurricanes.

These impacts may occur simultaneously, which will aggravate the final effects.

Sea Level Rise

Globally, sea levels are projected to rise by as much as 1.5 to 3 feet (0.5 to 1.0 meters) or more (Figure 3*c*) by the end of this century as a result of melting glaciers, most notably the Greenland ice sheet, and expanding oceans as the sea warms (*3*). But the increases are not uniform around the world; instead, they reflect local or regional factors such as subsidence, land rebound as glaciers melt, and prevalent wind conditions and ocean currents. For example, in many regions such as the Gulf Coast of the United States, relative sea level rise will be greatly exacerbated by land subsidence. Relative sea level rise could be as much as 4 feet in this region by 2100, inundating as much as 2,400 miles of roadway as well as rail lines and ports (*6*).

Couple storm surge with higher sea levels, and the impacts and damage will extend much farther inland. Hurricane Katrina in New Orleans in 2005 brought storm surges of 25 feet, literally lifting major bridge structures off their piers and flooding the New Orleans airport. Similarly, storm surges from Hurricane Sandy on the East Coast of the United States flooded miles of the New York subway system as well as two of the three New York airports. Impacts on other elements of the transportation system as well as most other segments of the built infrastructure, the economy, and social systems are too numerous to discuss in detail in this paper.

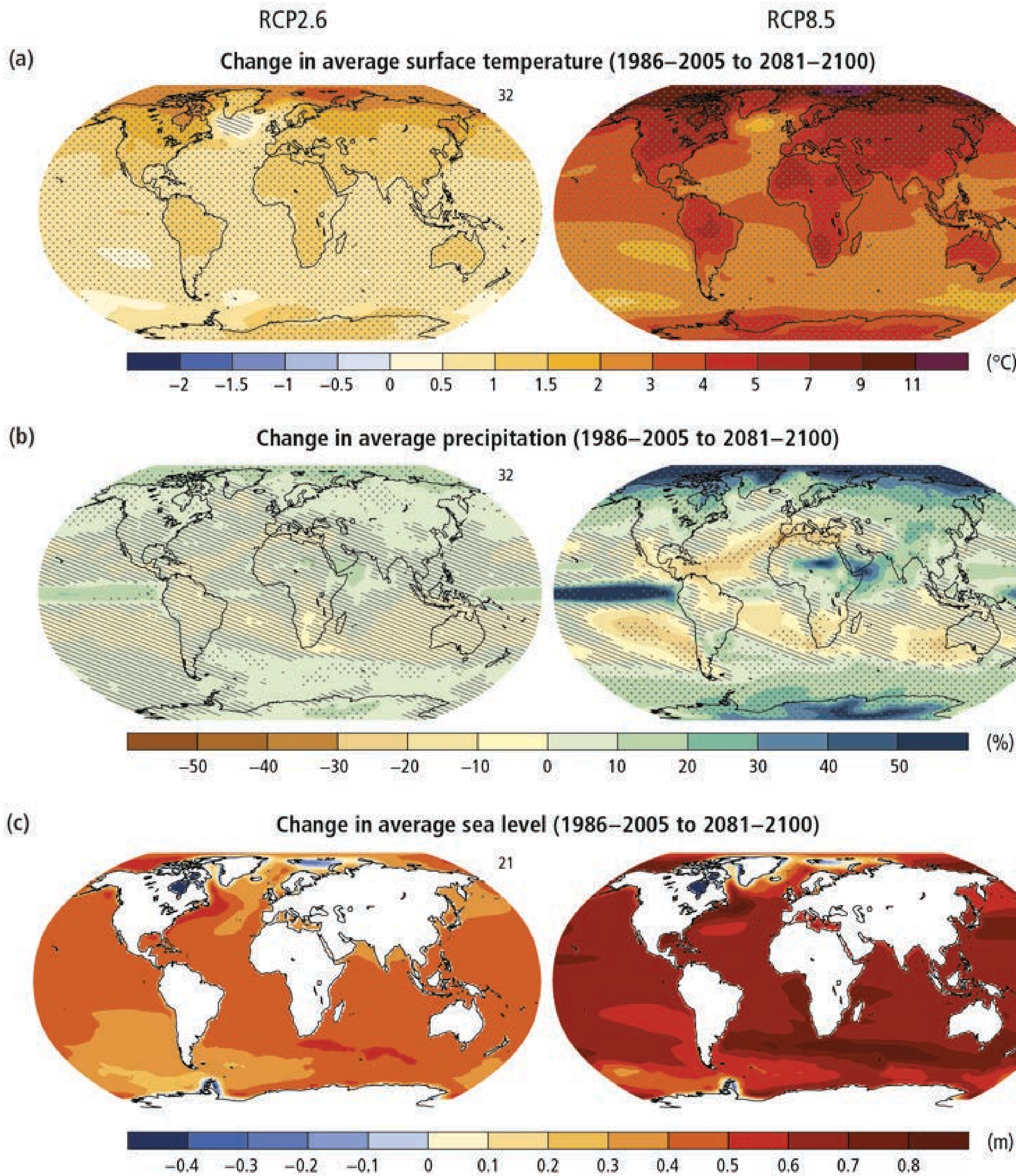


FIGURE 3 Worldwide (*a*) temperature, (*b*) precipitation, and (*c*) sea level increases predicted by the end of this century under two models: (*left*) RCP 2.6, with aggressive emission reductions, and (*right*) RCP 8.5, with emissions continuing on their present trajectory (*7*).

Higher Temperatures and Longer Heat Waves

Scientists are confident that Earth will continue to warm, perhaps by as much as 2.6°C to 4.8°C (4.7°F to 8.6°F) by 2100 in the absence of significant mitigation measures. Figure 3*a* shows projected temperature changes across the globe under two modeling scenarios. Recognizing the political realities of implementing carbon mitigation measures rapidly, it is very likely that the Earth will continue to warm for decades to come.

High temperatures and heat waves will become more intense, longer lasting, and more frequent. The impacts on the built infrastructure will be severe. In transportation, the heat will affect expansion joints, rail stresses, and pavement deterioration. Construction work in many regions will have to shift to night hours to protect workers from extreme temperatures. More severe drought in many areas will affect not only agriculture, but transportation systems, most notably by creating the kindling for potentially huge wildfires that can disrupt many modes of transportation.

Changes in Precipitation Patterns

Warmer atmospheric temperatures will lead to important changes in precipitation patterns: more drought in some regions and heavier storms in others (Figure 3*b*). To simplify, warm air causes more evaporation, but it also can carry more moisture so that rain- and snowstorms may well become more intense. For example, in the United States, the Southwest is currently suffering from extreme droughts, a condition that is likely to continue, while the Midwest and Northeast receive more intense rainfall events and flooding.

Not all changes in precipitation patterns can be attributed to anthropogenic-driven climate changes. In fact, natural variability, especially the El Niño and La Niña Southern Oscillation in the Pacific Ocean, has an enormous impact on precipitation patterns worldwide. The extreme weather events arising from these phenomena are equally disruptive and should be a part of any adaptation strategy. It would certainly appear that the traditional return frequency calculations based on historical data no longer will accurately guide designers and operators of transportation systems. What was once a 1:100 year storm may become a 1:20 year event.

These shifts in precipitation have profound effects on the transportation industry. Strong storms and flooding will affect and are affecting many communities in the EU and the United States. Heavy rains and changing waterway levels will affect operations of the transportation services sector. Engineering design standards and operating practices must change to accommodate more frequent heavy storm events. By contrast, as mentioned previously, severe drought can create a different set of challenges for transportation professionals.

Rising Arctic Temperatures

Climate change, particularly warming, is manifest most strongly over land and in the far northern latitudes. Arctic Alaska, for instance, has already witnessed temperature rises of 3°F to 5°F, double those of the continental United States. Thawing of permafrost will create major disruptions to highways, railroads, pipelines, and even buildings.

Sea ice is retreating rapidly, particularly during the summer months, but the maximum extent of Arctic sea ice in March 2016 was a record 431,000 square miles below the long-term average (*8*). The fabled Northwest Passage through Canada and Russia is now open for shipping in the summer months.

Increased Intensity of Storms and Hurricanes

There is some uncertainty about how or if climate change affects hurricane frequency, but there are basic scientific reasons to believe that the intensity of hurricanes may be increasing. As the oceans warm and the atmosphere becomes more moist, especially in the North Atlantic and the Caribbean, more energy will build up in these storms. With stronger hurricanes and higher sea levels, resulting storm surges will reach much farther inland. Changing wind directions may disrupt airport operations, and strong or gusty winds may cause delays in traffic and accidents due to truck rollover crashes.

Although hurricanes are not a problem in Europe, very strong storms with sustained high winds are a major concern. Storm surge accompanying high winds and high tides can cause extensive flooding of both urban and rural communities. London's Thames Barrier and the Dutch Delta Works system of dams and surge barriers are examples of the extensive engineering structures built to protect coastal cities. Moreover, high winds can reduce vehicular speeds, especially the speed of large trucks, affecting overall traffic flow.

Superposition of Changes

The above impacts will occur simultaneously and together determine the final effects on the transportation user. Figure 4 illustrates this for road transport.

The superposition of effects can have several consequences. It may cause a culmination of problems in critical places. Impacts may be softened or exacerbated. Knowledge about the propagation of effects and their interplay is vital to be able to design cost-effective policy packages.

2.2 Attribution of Extreme Weather Events

Not surprisingly, many of these climate changes are reflected in extreme weather events, but at present few singular events can be directly attributable to climate change. A new area of climate and weather research is emerging, however, called *event attribution*. Using either observational records or modeling or, more likely, a combination of both, the science of event attribution is advancing rapidly according to a recently released report by NAS (*10*). Confidence in making a connection between

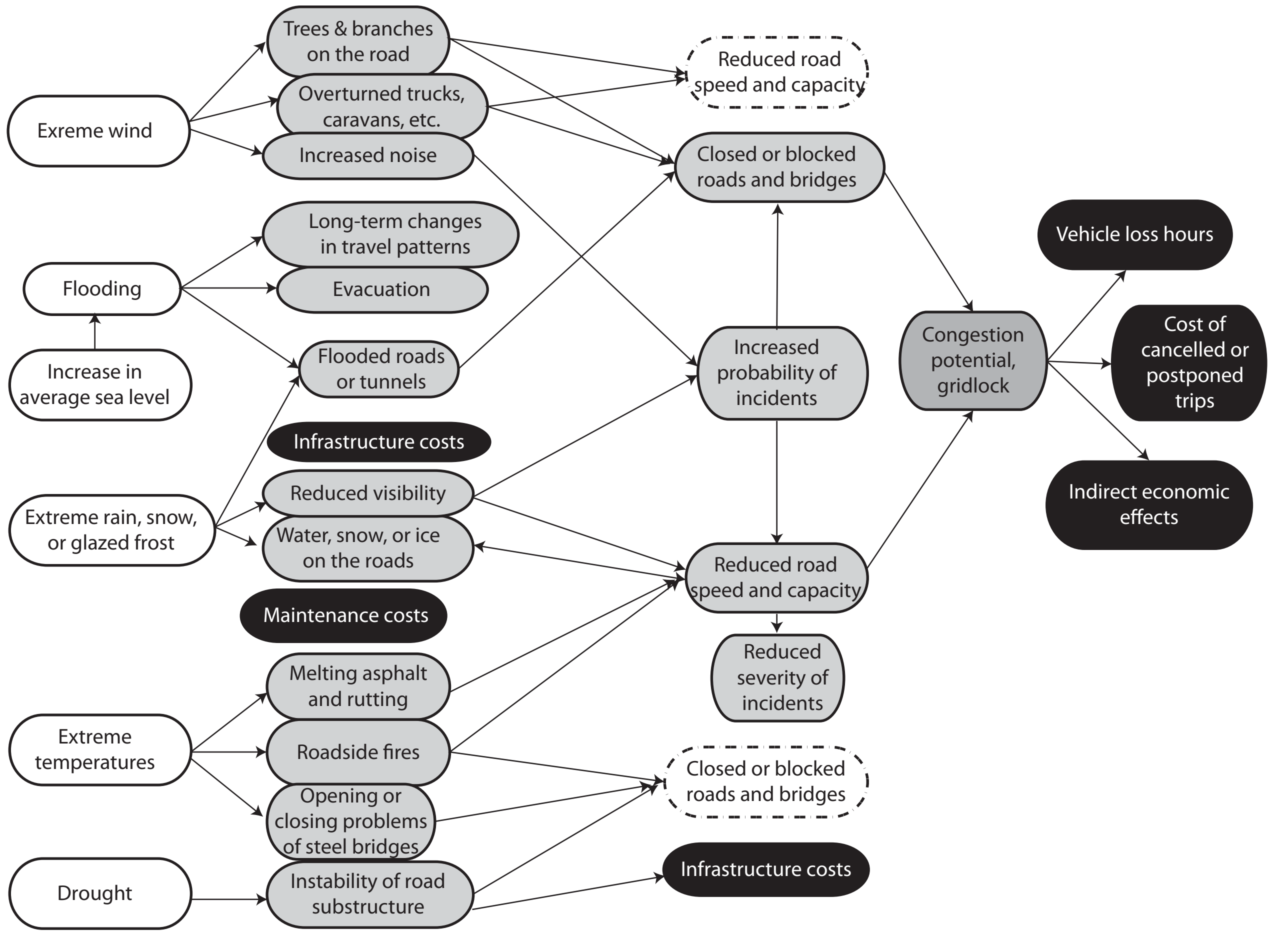


FIGURE 4 Aggregation of impacts on road infrastructure (*9*).

a specific weather event and climate change is greatest when the type of event has a long-term historical record, such as events related to temperature. Such information would be of great value to transportation professionals, but there is much more research needed before meaningful information will be available to the practitioner.

2.3 Climate Models

Forecasting future climate changes is a very complex matter, but one of immense importance if we are to adapt successfully to these changes. Climate scientists have expended great effort developing a panoply of models. Consider some of the variables: atmospheric–ocean circulation, population and economic growth, energy sources and utilization, new clean technology development, continued deforestation, and the CO_2 absorption capacity of the ocean.

In 2000, IPCC9 (Intergovernmental Panel on Climate Change 9) developed a series of socioeconomic scenarios that were used to calculate global GHG emissions. These scenarios, known as Special Report on Emission Scenarios, have been widely used to estimate future conditions. The National Climate Assessment in the United States published in 2014 used two scenarios, B1 and A2, to create an envelope of possible futures as shown in Figure 5*a* (*11*, *12*). They also included more recent models, adopted by the IPCC in 2013 (*13*), with the representative concentration pathways shown in Figure 5*b*. Both sets of models show fair agreement in temperature and CO_2 projections through about 2050 but, not surprisingly, the models clearly diverge after the mid-century mark. The lower values reflect faster and greater control of fossil fuel emissions, and the upper curves anticipate greater population growth and higher levels of emissions.

A related issue concerns scale. Most of these models are at a global or at least continental scale. What transportation and other infrastructure designers and operators need are projections at the local or regional scale. So-called downscaling techniques can be used to

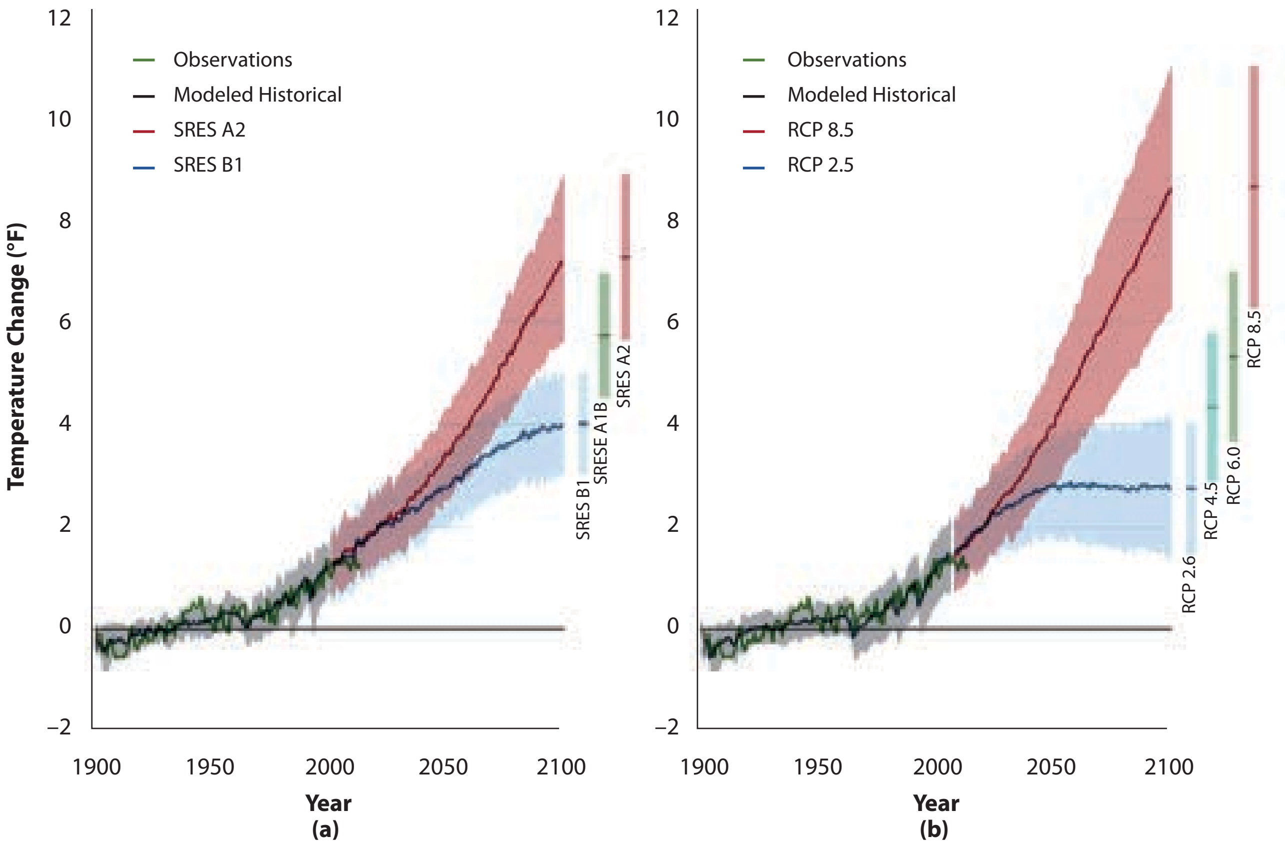


FIGURE 5 Temperature forecasts from (*a*) Special Report on Emission Scenarios (SRES) and (*b*) representative concentration pathway (RCP) scenarios (*11, 12*).

provide more localized information, but the accuracy may be limited. Certainly one important need is for accurate climate projections at the regional and local levels.

2.4 Intermodal and Cross-Sector Issues

Transportation in its entirety can be thought of as a system of systems, many interconnected and dependent on each other both in normal operations and in emergencies. Just this past winter, floods in South Carolina closed Interstate 95, one of the busiest highways in the United States, for weeks, necessitating a 150-mile detour partially on surface roads for passenger and freight traffic. In the United Kingdom, a series of severe storms in December 2015 destroyed a railway viaduct on the main line linking Scotland and England, interrupting train services for 2 months—a major disruption with serious economic consequences. Critical nodes and routes must be identified and plans made to operate in times of stress.

Although it may be obvious, transportation cannot be considered in isolation, but as an essential, integral part of the world's social, economic, and environmental fabric. Like the warp and weft of a fabric, transportation interacts with many, if not most, sectors of today's society. Extreme weather events and climate change will affect the whole cloth and will also affect energy, water and wastewater, information technology (IT) and communications, health care, agriculture, the economy, the environment, and more. Consider a few examples of the cross-sector impacts:

- Power system failures can disrupt many transportation modes and transportation-related infrastructure, such as airports, pipelines, traffic signalization, and communications.
- Conversely, transportation disruption may prevent fuel from reaching power plants and chemicals from being delivered to water and wastewater treatment facilities.
- Hurricanes and floods can totally disrupt commerce and freight movement, with major impacts on a nation's economy. Logistics and supply chains can be affected.
- IT and communications breakdowns will bring parts of the transportation networks to a halt, notably

passenger and freight rail service, air service, transit systems, and pipeline fuel distribution.

- In emergency conditions, transportation is critical to provide safe evacuation and maintain health care operations.
- Major flooding can make movement of agricultural products difficult or impossible.
- With rising sea levels comes increased risk to coastal communities, their homes, businesses, and virtually all aspects of their infrastructure.

Detailed maps can be built of cascading impacts across infrastructures. Little research has been done on these effects from a systems perspective (*14*).

2.5 Key Challenges for Adaptation Practice

There is general acceptance that the climate is indeed changing and that our planning, design, operation, and maintenance practices must proactively address these changes. No longer can we rely on historical data to plan, develop, and operate the transportation systems of the 21st century. Rather, we must recognize the importance of climate science, acknowledge that our scientific understanding of the climate is improving, and apply new techniques of decision making using more sophisticated risk management and uncertainty methodologies. In essence, the development of future transportation systems has become more complex, but ever more important to the overall welfare of society and the environment.

The past decade has witnessed a great change in the approach to climate change within the transportation community. The management of most public and private transportation agencies and companies now insists that climate change be addressed not only in new facilities, but in the operation of existing systems and the development of response mechanisms for extreme weather events. From individual passenger drivers, to freight haulers, to shipping lines, to the businesses they serve, all want more resilient transportation systems.

Policies directed at increasing system resilience have to operate simultaneously at different geographical scales (local, national, global), at several temporal scales (short, medium, and long term), and in different stakeholder dimensions (public and private) and are therefore inherently complex. Depending on this scoping, different strategies will prevail, from short-term approaches based on early warning and coping to long-term-oriented adaptive or transformative policies (Figure 6).

Adaptation policy efforts have accelerated in the past decades. For a detailed overview of achievements we refer the reader to the IPCC's climate adaptation reports (*11–13*). In the next subsection, we provide a brief impression of the state of research and practice within the EU and the United States and the key areas for research and development (R&D) that have been identified by the IPCC.

2.6 Achievements in the European Union and the United States

The IPCC's *Fifth Assessment Report* on adaptation recognizes the globally increasing attention to adaptation policies, both in terms of policies and of actual adaptation measures (*7*). The IPCC also points out differences in how adaptation has developed in the EU and the United States. Adaptation efforts appear to have been more equally spread across different levels of government in Europe as compared to the United States. The EU has seen large international R&D programs directed at climate adaptation of infrastructures. The priorities and implementation approaches of the two regions dif-

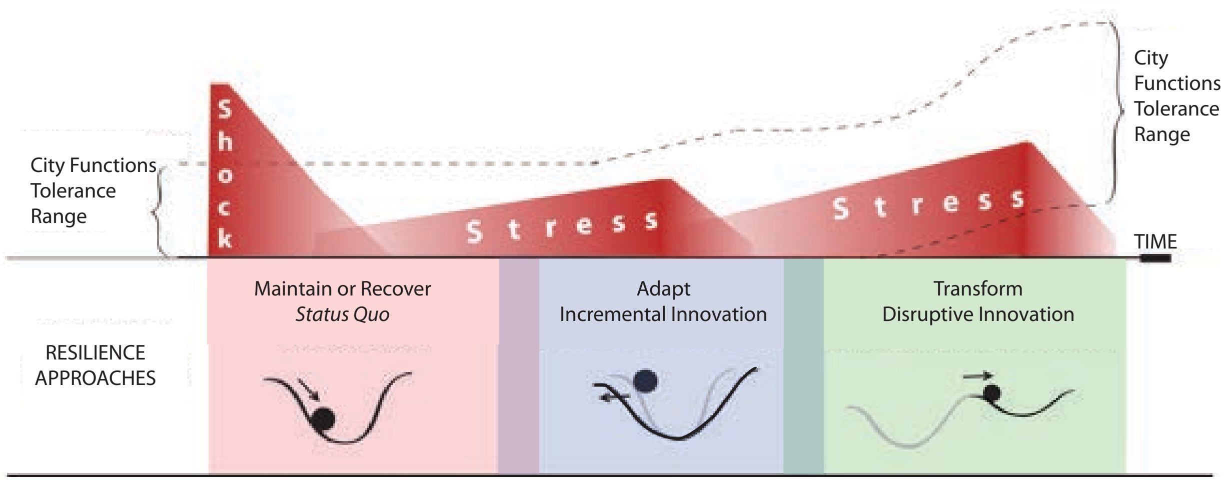


FIGURE 6 Illustration of impact of temporal scale on preferred strategy (*15*).

fer due to differences in adaptation priorities, availability of funding, and degree of top-down regulation of infrastructure policies. Nevertheless, the EU and U.S. regional reports are broadly in agreement about three key gaps in climate adaptation research.

First, there is agreement on the need for integrative research that allows understanding of phenomena across different sectors and types of impact, toward accumulation at the local level. Overall, R&D efforts have primarily focused on incremental adaptation measures to be mainstreamed into existing asset policies, rather than on comprehensive adaptation policies. Particular attention would need to go to cobenefits or counterproductive effects of combined measures and into approaches that explain place-based resilience from a complex of factors.

Second, these regional reports mark similar substantive gaps in the current body of knowledge. Both call for more research on critical infrastructures, including transport, water and energy supplies, and health services, including related urban and rural planning and governance challenges. Other caveats include the following:

- Costing methods and statistics are lacking for specific cases, including biodiversity, business and industry, and population health costs.
- The impacts of the new high-end scenarios of climate change (>4°C global average change, with higher temperature change in Europe) need to be developed.
- Rural development, including resilience of cultural landscapes (e.g., old cities, heritage sites) and communities and managing adaptation in low-technology (productively marginal) landscapes, needs consideration.
- Information is needed to manage agricultural and forestry systems.

Third, they identify a need for additional methodological work, in particular through increased alignment of regional monitoring and evaluation approaches, for adaptation policies and climate change knowledge.

As we discuss further in Section 5, R&D efforts have so far focused on creating framework conditions for adaptation policy (in terms of data, instruments, and assessment methods) and incremental adaptation measures that have been mainstreamed into existing asset policies rather than on comprehensive adaptation policies. One could derive from these efforts that climate adaptation is still at an early stage of the policy cycle.

To our understanding, an important stumbling block for transformative policy actions is the phenomenon of deep uncertainty that is associated with climate change. We discuss this issue in the next section.

3 Decision Making Under Conditions of Uncertainty

3.1 Uncertainty in Climate Change: What Is It About?

The notions of probability and uncertainty are deeply embedded in the recent global agreements about climate change. The United Nations Framework Convention on Climate Change of 1992 uses danger as a central concept in its aims, in which *safe* levels of climate change allow "ecosystems to adapt naturally, food production not to be threatened and economic growth to proceed in a sustainable manner." As danger can be associated with risk and risk with probability, the notion of uncertainty becomes more than just a numerical fact that we need to deal with in our calculations. It becomes instrumental in measuring the magnitude of the real problem and our progress in managing the outcome. The IPCC's *Fifth Assessment Report* on adaptation mentions the word "uncertain" and its variants around 1,100 times, at an average frequency of slightly less than once per page (*11*, *12*).

TABLE 1 Breakdown of Uncertain Factors Behind Impacts of Climate Change on Society

	Natural Variability of the Climate System		
Severity of climate change	Human influence on GHG stock	Autonomous development	Demography, economy, social, technology, politics
		Effect of mitigation measures	International agreements and their implementation
		Climatic response	Response mechanisms
Impact on society	Socioeconomic impacts	Vulnerability	Future welfare levels
		Exposure	Detailing climate predictions
		Responsive capacity	Resilience, robustness
	Impact on well-being and sustainability	Economy	Interest rates
		Environmental	Absorptive capacity, valuation
		Social equity	Intergenerational and social redistribution

NOTE: Shaded cells indicate the current focus of climate adaptation measures.

There is substantial uncertainty in the expected impact of climate change on the functioning of society (see Table 1). Measuring the effects of climate change in economic terms, the 2006 *Stern Review* predicted a permanent impact of a reduction of between 5% and 20% of the gross domestic product (*16*). There has been a lot of debate about the assumptions behind these figures, and the resulting uncertainty, despite the already broad bandwidth. To predict a decrease in quality of the transportation system, as experienced by its users, several factors need to be taken into account.

It is possible to reduce uncertainty in projected impacts but impossible to eradicate it completely. Epistemic uncertainty (due to limited knowledge) can be reduced to a certain extent by research and improved measurement, aleatory uncertainty (due to inherent variability of the system) by using scenario-based or stochastic projections, and ambiguity (due to multiple definitions of phenomena) by improved communication (*17*). It is therefore important to understand the different factors that cause uncertainty in impact projections (Figure 7).

The natural variability of the climate system and, primarily, our lack of understanding of these variations create significant uncertainty in predictions of atmospheric concentrations of GHGs, global warming, and phenomena such as sea level rise and weather changes. Emissions due to human activity are strongly dependent on economic and population growth as well as technology and geopolitics. The physical impact of climate change on society is the primary concern of adaptation policies. The severity of these impacts depends on vulnerability (i.e., the natural sensitivity of areas to changes such as drought), the expected exposure to changes in climate, and the capacity to respond to this exposure, either through coping (resilience) or by adaptive mechanisms. As adaptation measures only affect part of the causes of climate change impacts, they will be limited in their ability to reduce the uncertainty of these impacts. The propagation of the physical impacts into wider and final socioeconomic and environmental damage is a separate question. Especially surrounding cost–benefit analysis and sustainability impact analysis, important topics are second- and third-order effects, discounting for capital loss, and avoiding double counting of impacts. As an illustration, the numbers from the *Stern Review* mentioned above would be an order of magnitude lower (i.e., gross domestic product impact below 2%) if the assumed discount rate were a couple of percentage points higher.

Uncertainty occurs in each of these factors and cascades through the different steps by which we predict climate change. In order to reduce uncertainties, besides understanding the main phenomena, their formal description and modeling need to be improved. Transportation system models generally have a much higher spatial granularity than climate models, which makes it necessary to detail forecasts to a level at which one can distinguish individual roads, for example. But even if accurate and detailed predictions of extreme weather situations were available, often the transportation system models are incapable of calculating the consequences, due to a lack of empirical knowledge of these relations.

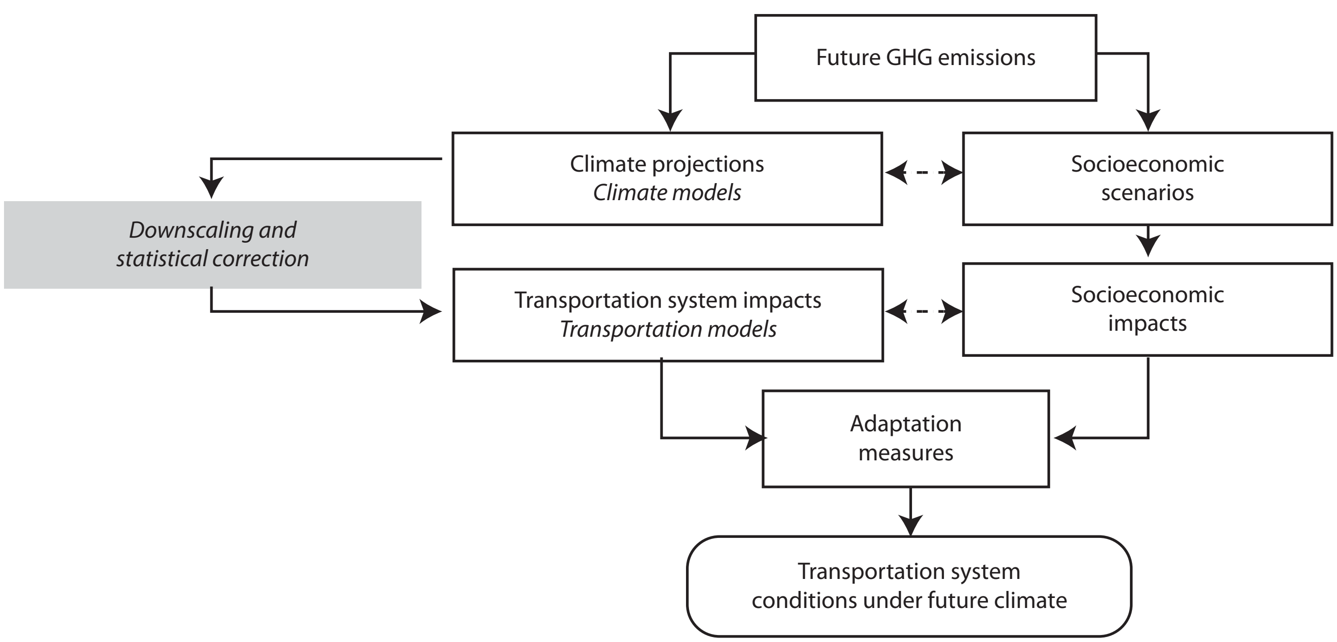


FIGURE 7 Climate impact projection pathway (*17*).

3.2 The Science of Decision Making Under Great Uncertainty

Uncertainty in projections will remain and, therefore, it is important for decision makers to develop approaches that use this information and embrace uncertainty rather than deny it. Climate change has been termed by some as "post-normal science" (*18*). Normal science uses expert knowledge–based decision making and conventional tools for policy analysis such as utility theory, contingent valuation, cost–benefit analysis, and statistical decision theory. Post-normal science functions in a world of intractability of facts, deep uncertainty, disputed values, high stakes and, sometimes, urgent decisions. Under these circumstances, the decision-making process becomes as important as the facts that support decisions.

Decision makers have fundamental problems dealing with uncertain factors. First, there are different types of uncertainty (e.g., on the one hand caused by knowledge that is incomplete but potentially attainable, such as the effects of extreme weather, and on the other hand caused by unknowable factors, such as the future). Not only are uncertainties difficult to understand, they also require responses that sometimes lie far away from decision makers' capabilities or mandates. Second, the different ways in which calculation and presentation of uncertainties can be accomplished make their processing by decision makers a complicated task and, more importantly, introduce the subjectivity of the researcher into the process. Policy makers, often unknowingly, act with information that appears much more certain than it actually is (*19*). Once uncertainty is of a different nature or a higher level than what the decision maker is accustomed to, decision-making processes become more difficult (*20*).

The concept of deep uncertainty is central to understanding climate change impacts. Figure 8 shows different levels of uncertainty, from a certain world to a fully unknown world. Level 4 and Level 5 uncertainties depict the so-called deep uncertainties. These are the ones that cannot be treated probabilistically and include uncertainties of model structure or those that experts cannot agree upon (*21*). Climate change uncertainties in general can be classified as such, although there will be variations in predictability between factors (e.g., temperature anomalies are easier to predict than rainfall, and global phenomena generally easier than local ones).

The approach toward policy analysis will be heavily dependent on the level of uncertainty recognized. Prediction-based, linear policy measures are usually based on a perception of the world at Level 1. This approach is equivalent to ignoring uncertainty. Already more sophisticated policies are based on projections that take into account historical

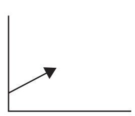
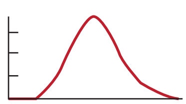
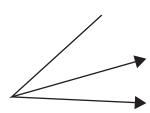
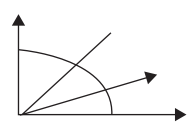
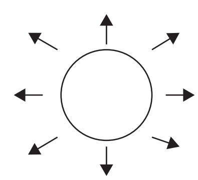
			LEVEL					
		Complete Certainty	Level 1	Level 2	Level 3	Level 4	Level 5	Total Ignorance
LOCATION	Context		A clear-enough future 	Alternate futures (with probabilities) 	Alternate futures with ranking 	A multiplicity of plausible futures 	An unknown future 	
	System model		A single (deterministic) system model	A single (stochastic) system model	Several system models, one of which is most likely	Several system models with different structures	Unknown system model; know we don't know	
	System outcomes		A point estimate for each outcome	A confidence interval for each outcome	Several sets of point estimates, ranked according to their perceived likelihood	A known range of outcomes	Unknown outcomes; know we don't know	
	Weights on outcomes		A single set of weights	Several sets of weights, with a probability attached to each set	Several sets of weights, ranked according to their perceived likelihood	A known range of weights	Unknown weights; know we don't know	

FIGURE 8 Increasing levels of uncertainty and underlying assumptions (*21*).

uncertainty (Level 2). Level 3 policies are usually based on a choice of a most likely future scenario. The typical answers to Level 4 and Level 5 uncertainties include planning for the worst conceivable situation (resistance), planning for quick system recovery (resilience), or for adjustment for different scenarios (robustness) (*22*). We elaborate on these strategies in Section 4.

3.3 Implications for Adaptation Policy

Deep uncertainty requires a different approach to policy design than shallow uncertainty. The most fundamental change from current practices will be that we can no longer base our policies on simple predictions. We have to learn to become adaptive to hedge our investments against severe uncertainty.

A relatively new approach, adaptive policy making, which is gaining interest among decision makers, replaces the forecasting-based planning paradigm with a dynamically responsive approach (*23*, *24*). As prediction becomes harder, proactive planning loses its value, and preparation for response in multiple scenarios is preferable. By setting predefined thresholds (e.g., sea level rise at a certain point in time), including an appropriate response policy, the necessary policy will only be activated once these thresholds are passed. Depending on the circumstances, different policies will be needed. Several policies are kept in stock to cater to all realistically conceivable cases. To select the best alternative policies, the expected value of different policies is determined under different circumstances. To this end, option-valuation approaches are used instead of conventional benefit–cost analysis.

Currently, however, most infrastructure planning and management systems still build on notions of mild uncertainty, using means and probabilities. Essential for asset management practice is the recent inclusion of risk as a new concept on which to base decisions. Including risk is a precondition to address events that have a low-frequency, high-impact nature. In a world of deep uncertainty, risk can be used as a dynamic concept in which thresholds for risks are used to trigger the implementation of adaptation actions. The next section introduces risk management, in particular the U.S. risk-based system for building resilience into transportation assets, along with recent R&D efforts in the same direction within the EU.

4 Risk Management

4.1 Risk

Risk can be defined as "the positive or negative effect of uncertainty or variability upon agency (or personal) objectives" (*6*). Statistically, risk is the probability of an event occurring times some measure, often cost, of the consequences of that event.

In terms of climate change and its impact on transportation, risk analysis is the identification of the hazards of concern (e.g., sea level rise, extreme weather events, storm surge); the vulnerable infrastructure assets (e.g., bridges, highways, airports); the potential direct and indirect consequences, including cost to the economy and social and environmental costs; and the probability that the hazardous event will occur. The challenge is to balance the risks with the benefits and costs in a rational manner.

Situations will vary from high-probability, low-consequence events such as flooding of low-traffic roads located in the floodplain to low-probability, high-consequence events such as Hurricane Sandy in New York and New Jersey or the extensive flooding in Central Europe in 2013. Some climate changes will develop gradually over years or decades (e.g., sea level rise), but other changes relate to extreme weather events, whether a direct result of climate change or other more transient climate impacts such as El Niño.

So-called "black swan" thinking emphasizes the importance of unpredictable, extreme events in contrast to the traditional normative analysis. This school of thought has much to recommend it with regard to climate change and extreme weather events. Transportation systems are developed with a long-time horizon, 50 or more years, and traditionally have used historical weather data for planning and design purposes. Yet so often damage to these systems arises from unexpected or, at least, unplanned-for events. It might be argued that the planning process underestimates the impact of unpredictable events, extreme weather, or otherwise disrupting events.

There has been much discussion about climate change tipping points or thresholds beyond which changes may be irreversible. Determining specific tipping points is, at best, an inexact science, but we must recognize that climate change is likely to be a nonlinear phenomenon.

4.2 Risk Analysis

Risk analysis as it relates to climate change is anything but simple. Many complexities have to be considered, including the following:

- Uncertainty. As discussed in the preceding section, various uncertainties must be considered, including uncertainty in the level of future GHG emissions, socioeconomic impacts, natural perturbations, the Earth's response to GHG increases, and the capacity to respond.
- Gradual versus sudden change. Gradual change must be contrasted with extreme weather events.

- The issue of scale. Climate scientists are much more confident about projecting climate changes, especially temperature increase and sea level rise, at the global scale. Accurately downscaling this global information to the regional and local levels is difficult, but transportation professionals need data at the local and regional scale.
- Multiple stresses. Climate change cannot be considered in isolation, but rather in the context of many other stresses (environmental, economic, and social) that affect the human experience. Climate change then becomes an additional stress on the system, one that may become the tipping point that causes the system to be permanently altered. Continued sea level rise coupled with higher storm surge, for example, will place coastal communities—homes, businesses, and the infrastructure that supports them—at greater risk.
- System and modal interconnectivity. The interconnectivity of different modes of transportation and different infrastructures (e.g., power, water and wastewater, health care, communications) must be considered in risk analysis.
- Probability of an event occurring. Predicting probability is not as simple as using the return frequency alone as a surrogate for probability. For example, over the 50-year life of a specific transportation project, a 1:500 year event has a probability of happening during the project's design life of 9.5%.

4.3 Risk-Based Asset Management

In recent years, the Federal Highway Administration of the U.S. Department of Transportation has promoted risk-based transportation asset management (RBTAM), which calls for building resilience into transportation assets. Their 2013 report focuses on the "three R's": redundancy, robustness, and resilience (*25*), defined as

- Redundancy: "duplicative or excess capacity that can be used in times of emergency."
- Robustness: "the capacity to cope with stress or uncertainty. . . . Well-maintained assets generally are better able to withstand stresses of storm events and other disasters."
- Resiliency: "the ability to prepare and plan for, absorb, recover from, and more successfully adapt to adverse events, . . . better anticipation of disasters, better planning to reduce disaster losses, and faster recovery after an event."

Although much of this U.S. Department of Transportation report deals with climate change, it importantly notes that good RBTAM practices will better prepare an agency, a community, or a business to absorb other unexpected disasters (an "all hazards" approach) (*25*). The actions needed to develop a risk-based approach to asset management include the following:

- Maintenance of accurate inventories of transportation assets, their vulnerabilities, and criticalities;
- A prioritization of vulnerable assets that will undergird capital improvement plans, maintenance programs, and recovery actions;
- Better maintenance practices to strengthen assets (e.g., bridges with well-maintained retaining walls and scour protection will be more robust during floods);
- Asset inventories coupled with good repair cost data to speed recovery efforts; and
- Thorough geographic information service mapping and preplanning, which are essential for rapid evacuation of affected areas.

One interesting comparison and possible guideline is the earthquake preparedness program for bridges in California. Following two major earthquakes in the late 1980s, the California Department of Transportation (Caltrans) developed a risk-based approach to prioritizing the seismic upgrading of every bridge in the state, some 24,000 bridges. The primary objective was to prevent loss of life at every location, but not to prevent all damage. Caltrans based the prioritization on three factors: site hazard, structure vulnerability, and system impact. For the seven major toll bridges, the criteria were a little different. Several, including the Golden Gate and Oakland Bay bridges, had to remain serviceable immediately after the design earthquake (8.5 on the Richter scale); others might suffer damage but had to be restorable to service within 6 months. All have been retrofitted to meet the appropriate criteria.

A somewhat different or less regimented approach to risk analysis, the observational method, is suggested by the American Society of Civil Engineers and has been applied in the European engineering community. The key elements of the observational method are as follows (*26*):

- Project design is based on the most probable climate condition(s) rather than the most unfavorable.
- The most unfavorable conceivable deviations are identified.
- A course of action is devised (in advance) for every foreseeable unfavorable climate deviation from the most probable condition(s).
- The performance of the project is observed over time and the response of the project to observed changes is assessed.
- Design and construction modifications can be implemented in response to observed changes.

The technique has been used for decades in geotechnical engineering and in its simplest form is an iterative cycle of analyze, plan, design–construct–operate, monitor, and revise. It seems most appropriate for gradual climate changes such as temperature and sea level rise and least applicable when extreme weather events are considered.

Recent overview studies on climate adaptation recommend climate risk management as a tool but also indicate that this practice is not at all commonplace (*27–30*). In Europe, less than a handful of countries (Austria, France, Spain, and Switzerland) have adopted such explicit risk management plans (*28*). A notable R&D effort in Europe, funded by 11 countries, was directed at developing a risk management approach that can be adopted by the diverse set of road agencies in Europe. The RIMAROCC framework operationalizes the ISO 31000 risk-management process standard and provides a systematic yet qualitative approach to identify and respond to climate-related risks for road infrastructure (*31*). It primarily stresses the process dimension of risk management and positions the qualitative method next to analytic approaches. It distinguishes structure, (road) section, and network levels of analysis, which may be a useful feature in aligning the levels of analysis. A detailing of quantitative approaches was provided recently for tunnels (*32*).

5 Achieving Climate Resilience

The IPCC defines adaptation as "an adjustment in natural or human systems in response to actual or expected climatic stimuli or their effects, which moderates harm or exploits beneficial opportunities" (*33*). Interestingly, there appear to be two distinct streams of thinking about climate adaptation policy. When research and policy are discussed, care must be taken about the existence of this difference in perspectives. The first approach is identified as bottom-up as it deals with the social, or citizen's perspective, in the form of a preexisting condition of vulnerability. The second approach can be seen as top-down, taking the perspective of larger social-technical or biophysical systems, focusing on physical exposure (Figure 9). Resilience is the positive result of low vulnerability from both perspectives. Ultimately, the two directions need to meet in sensible policies in which biophysical stressors and social stressors are reduced so that resilience is increased (*33*).

The results of our adaptation efforts so far have been a mixed bag in terms of types of effort and outputs. A 2011 report of the worldwide state of adaptation practice (*34*) concluded that a majority of actions involve *intentions* to adapt, without implementation. Adaptation appears to be motivated by short-term climate variabil-

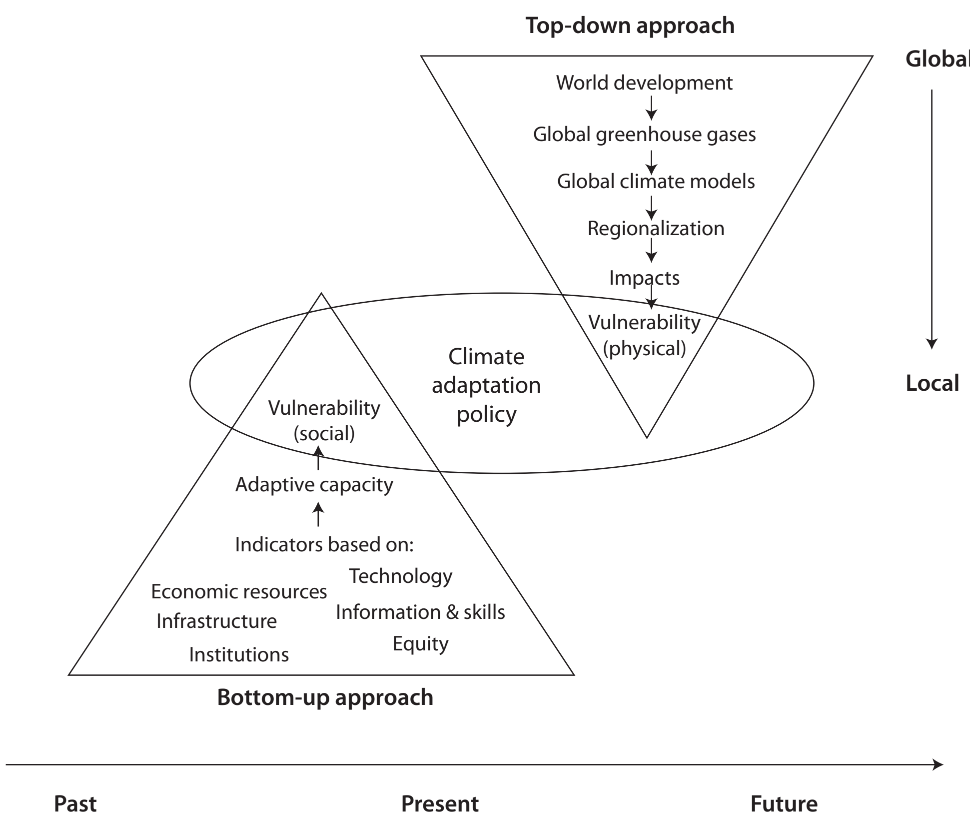


FIGURE 9 Dominant perspectives on climate vulnerability (*18*).

ity, especially extreme events; is typically mainstreamed into existing policies; is mainly national government driven; and is directed at final economic impacts. A more recent and larger study (*35*) analyzed over 4,104 adaptation projects from 117 countries worldwide from 2008 through 2012. Although it ranked the United States and five EU countries among the top 10 leading countries in adaptation practice, actions mostly consisted of so-called groundwork activities (assessments and development of assessment tools); only around 15% of efforts related to infrastructural, technological, or innovation projects. This characterization of current adaptation practice indicates that we are only at the beginning of a longer and deeper adaptation process that aims to improve overall system resilience.

To be able to determine appropriate levels of effort for adaptation, it is important to ask what level of resilience should be achieved, for which activities or assets, and by when. Especially when considering how to address research opportunities in the area of climate impacts on transportation, it helps to establish what a reasonable balance of investment for resiliency of transportation assets and services is, and what set of goals should provide the context for achieving a resilient system. A baseline can be established in part by first asking the question "When is something resilient enough?" Investing too much in making transportation assets resilient can lead to shortfalls for other societal needs, but underinvesting in transportation assets can lead to premature repair costs and increased system disruptions due to service interruptions. Additionally, resiliency must be compared with our current thresholds of acceptance for levels of transportation infrastructure, operational state of repair, and available mobility services. In the face of climate change impacts, do we want to maintain levels similar to today, which may not be desirable to begin with? Or do we want instead to maintain infrastructure in a state of good repair, and is this feasible in the face of climate change? How do we ensure compatibility of adaptation measures with longer-term mitigation plans? With these questions in mind, it is also helpful to identify goals for research that can help set the larger context for resiliency at both the modal and intermodal levels.

In this section, we look at the baseline and goals for transportation resiliency and also explore a set of topical areas in which research collaboration is needed to effectively address the increasingly complex scenarios being created by climate change impacts on transportation.

5.1 Define Acceptable Levels of Transportation Resilience

Having the capacity to understand whether a transportation asset is resilient enough to withstand projected impacts of climate change and extreme events without overinvesting scarce resources is a critical need. If a transportation project is overbuilt, it may preclude other, more useful investments in the transportation sector and elsewhere in society. If it is underbuilt, it may be subject to risks of premature damage or destruction that require premature repair or replacement and impose an additional cost of being out of service to the public and to the industry. What do we need to know to have this capacity? Is it a particular level of skill in climate projections and downscaled models necessary to design corresponding transportation asset attributes? Is it a better understanding of how those assets' attributes can be designed "just well enough" to withstand increasing environmental stresses through time? If we can determine what makes a transportation system "resilient enough," how do we then develop a process for achieving overall transportation resiliency? Our existing transportation infrastructure, the transportation infrastructure we are building and will build, and the overall performance and dynamics of the system of transportation need to have goals for resiliency in order for us to know what research is needed to help identify pathways for achieving desired outcomes.

Critical Issues and Research Needs

- Cost-effective materials that are robust enough to withstand climate impacts are needed, as well as alternative structural solutions or concepts in addition to materials (e.g., floating elements, extra capacity activated in an emergency situation, deliberate weak points, alternative ways of foundation).
- Improved climate and weather models are needed to provide more precise projections of regional impacts for better understanding the level of resiliency needed before building.
- Better weather forecast systems will allow the application of early warning systems.
- Better communication is needed between climate scientists and transportation researchers on other Earth observation tools that are more closely aligned or better "fit for purpose" with transportation needs.
- An investigation of opportunities for cost saving and increased speed (without dilution of quality) would improve construction and rebuilding mechanisms.
- Remote sensing applications are needed that provide for more frequent, cost-effective, and detailed monitoring of transportation assets to address problems sooner for longer life of assets.
- An understanding of current capacity to map vulnerability (e.g., identification of critical infrastructure, geographical locations, crucial nodes, specific constructions) is required, as well as an understanding of the gap between this capacity and what is needed. In addition,

acceptable risk levels to define intervention needs must be identified. Also needed are models and assessment approaches that are accurate enough and practicable to allow thorough vulnerability assessment, which ideally will include the full effects of climate change, including direct and all indirect economic effects, such as supply chain impacts and economic growth.

- Available technologies and operations that can prevent and/or mitigate disruptions caused by weather and other extreme natural events should be assessed, as well as the gap between these technologies and operations and what is needed.

5.2 Implement Risk-Based Asset Management

Once organizations responsible for transportation assets achieve a better understanding of what an acceptable level of resiliency means for a transportation asset and the assets and services connected to it in a system, those organizations must have the capacity to integrate this knowledge into their asset management and performance management programs. Risk-based approaches to managing transportation assets can help make this transition. Broader in scope than traditional transportation asset management and performance management systems, RBTAM is the application of risk management to these systems. If we define risk as "the positive or negative effects of uncertainty or variability upon agency objectives," then risk management is the "cultures, processes, and structures that are directed towards the effective management of potential opportunities and threats." Within the context of this paper, climate impacts are risks that can constrain, or in some cases enhance, a transportation organization's ability to meet its objectives. Risk management is the effective organizational response to those climate risks that results in resiliency. Transportation organizations that implement some form of risk-based approach to asset management will be able to better communicate climate risks to their stakeholders and provide a clear understanding of the suite of responses needed to ensure resiliency against those risks.

Critical Issues and Research Needs

- What transportation organizations have used RBTAM or other risk-based approaches to develop and institutionalize resiliency, and what are some of the common best practices among them?
- How can risk-based asset management be instituted in organizations throughout the transportation sector to help achieve consistency and effectiveness in overall transportation resiliency?
- In some countries, the implementation of good risk analysis processes will require new skills at many transportation agencies. What resources will these agencies need to acquire these skills?
- The variability of robustness in different transportation agencies' climate-based risk assessments and vulnerability assessments may well determine the effectiveness of risk-based decisions in developing resiliency for transportation assets and services. Can a necessary baseline for the effectiveness of an agency's risk assessment and vulnerability assessment for climate impacts be established in order to have greater confidence in the effectiveness of a subsequent implementation of a risk-based approach to asset management at that agency?
- Involving all stakeholders, from users to suppliers of the system as well as cross-modal and cross-sector partners, is essential to the ultimate success of the planning and implementation of resiliency measures. It is to be expected that different stakeholder groups will have different views of what constitutes adequate resilience in the transportation system, and these differences need to be resolved. In addition, cooperative efforts to adapt are expected to be more effective.

5.3 Improve Sense-and-Respond Capabilities

Existing transportation infrastructure is owned and operated by various public agencies and private firms and covers an enormous range of ages, service life, and levels of sophistication. Existing infrastructure has been built to many different design standards, and its current and future environmental risks are similarly varied. As environmental risks change, the probability of unexpected failures may increase. Further, as existing infrastructure approaches the end of its service life, decisions about replacement or abandonment should, but may not currently, take into account changing future risks. Research is needed to better understand how disparate levels of resiliency in existing transportation assets that were not necessarily built with the foresight of climate change impacts can be managed to adapt as well as possible in the decades to come.

Critical Issues and Research Needs

- What is the state of technologies such as laser imaging detection and ranging, or lidar, and remote sensing in terms of their application for monitoring and determining asset integrity?
- What is the gap between the state of the art of these technologies and what is needed to more accurately and economically gauge the level of robustness of existing

transportation assets relative to their ability to withstand increasing climate change impacts?

- What innovative technologies can enhance adaptation capacity (e.g., the protection of tunnels, the maintenance of bridges, soil stabilization, and drainage)?
- How can we improve our measurements and predictions of weather phenomena, especially at the local level?

5.4 Adopt Planning and Engineering for Climate Resilience

Newly constructed infrastructure should be designed and built in recognition of the best current understanding of future environmental risks. For this to happen, understanding of projected climate changes would need to be incorporated into infrastructure planning and design processes across the many public and private builders and operators of transportation infrastructure. A comprehensive long-term vision should encompass this integration of climate projections with a strategy laid out for revision of existing construction standards and guidelines and definitions of new targeted ones in order to ensure adequate redundancy, accessibility measures, and spatial planning. Additionally, the confluence of new technologies taking place in the sector brings new considerations of how climate change impacts may negatively affect or be mitigated by vehicle connectivity, automated vehicles, electrification of transportation fleets, advanced materials, and renewable energy, and energy storage deployment in support of transportation assets. Consideration should also be given to the effects that extreme weather conditions can have on the functionalities and reliability of these new technologies. Finally, challenges for long-term planning and governance include group design processes under uncertainty, cross-jurisdictional collaboration, mainstreaming of climate policies, and budgeting of climate change measures.

Critical Issues and Research Needs

- What fundamental research in nanomaterials inspired by transportation-specific concerns could lead to dramatic improvements in the "toughness" of materials—or even self-healing attributes—used in new construction? How do new technologies improve or make more challenging conventional plans to adapt to climate change in the transportation sector?
- How can spatial planning and governance approaches be adopted to address climate adaptation in a responsive rather than prediction-based manner? Should we factor in competition between mitigation and adaptation funds in climate change policy?
- With the increasing ties to the power sector through electrification of the fleet and to the communications sector with the advent of autonomous vehicles, what are the crossover impacts for these three sectors? What research is needed to better understand how more interconnected economic sectors either endure larger impacts or have the ability to combine for greater resistance to impacts?
- What innovative multimodal governance methods can support new options in land use and planning, accessibility plans, and other variables that can improve the capacity for functional redundancy in the face of climate change? For example, if switching to alternative transportation modes is part of the contingency plan, the vulnerability of the intermodal hubs becomes even more important.

5.5 Address System Resilience

Transportation systems are more than just the sum of their individual parts. Some elements are of particular importance because of their vital economic role, absence of alternatives, heavy use, or critical function. Transportation systems are potentially vulnerable to the loss of key elements. Therefore, selectively adding redundant infrastructure may be a more efficient strategy than hardening many individual facilities on the existing system. In addition, smart solutions on the user's side, such as buffer inventories or excess vehicle capacity, may obviate the need for expensive infrastructural measures. System resilience is best viewed across transportation modes and multiple system owners, building on component resilience to prevent system failure (Figure 10) (*9*). Lately, new holistic engineering approaches have been developed for climate adaptation adoption of sociotechnical systems (*14*) or systems-of-systems perspectives (*36*).

Cooperation among stakeholders is indispensable to allow integrated, complementary, and mutually supportive actions in the sector and outside it. Although some key elements are obvious, other dependencies may be less well recognized. For example, some airports rely on petroleum pipelines, which may depend, in turn, on electric power for pumping. Transportation systems are also interdependent when passengers or freight carriers rely on multiple transportation modes to reach their destinations. For these reasons, research is needed to better understand the collective potential set of ripple effects that may be induced by climate change impacts on system dynamics within the transportation sector.

Critical Issues and Research Needs

- Disruptions in waterborne shipping due to sea level rise, major flooding, or extended drought may force goods delivery to less efficient rail services, and even less

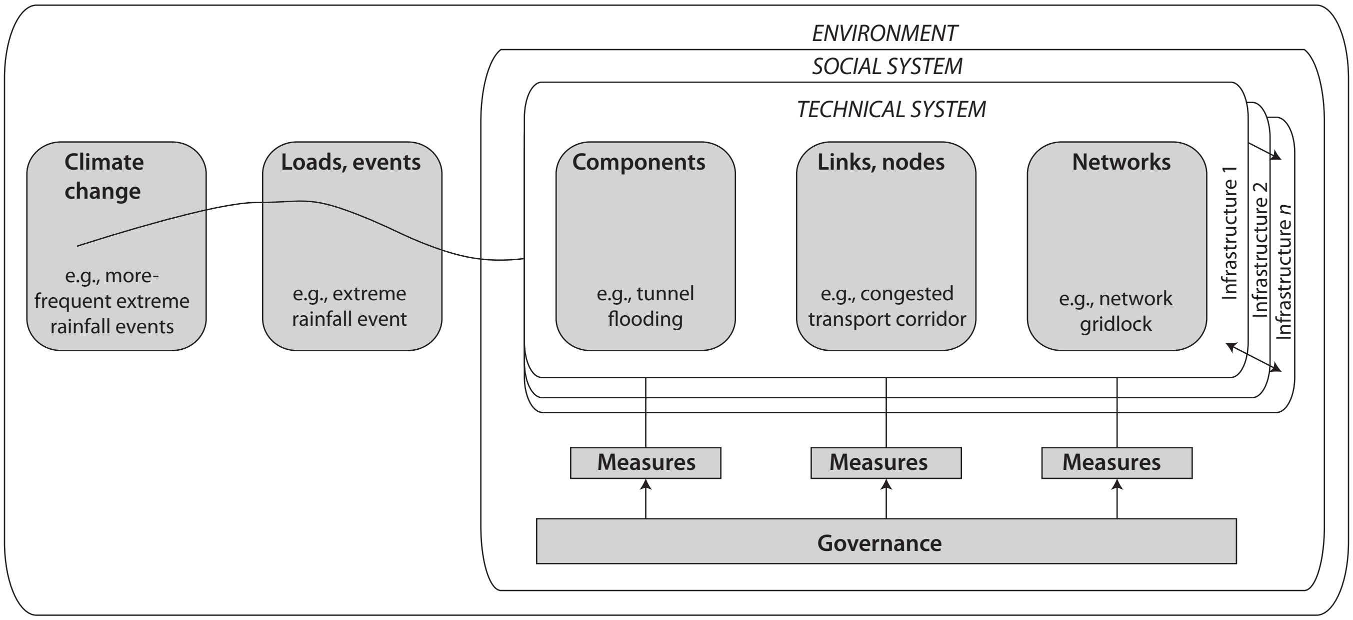


FIGURE 10 Conceptual framework of impact propagation (*9*).

efficient than that, truck service. Both rail and truck service might struggle to absorb additional volumes given up by water-borne shipping. A similar scenario could occur with rail goods shifting to truck–freight service due to climate change–related problems like rail buckling and cracking.

- What areas of research can address lock- and port-related technologies to better prepare waterborne shipping for climate change impacts?
- Although research is ongoing for predictive capabilities in rail buckling and cracking, what materials research might find solutions to prevent the frequency of these occurrences in the first place?
- What algorithm and modeling applications can better understand ripple effects that spread through the transportation system when a critical transportation node (or nodes) is increasingly impaired by a changing environment?
- How can we assess the overall systems impact of increasing environmental stressors (direct and indirect) on critical transportation nodes at the aggregate level?
- What research can help identify critical nodes in transportation that are not obvious to us today?
- What indicators assess the efficiency of adaptation measures (e.g., prevention of disruption in vulnerable zones, reduction of downtime, efficiency of rerouting)?

5.6 Assess Societal Impacts

Several areas in society may be affected by climate change, adaptation to climate change, and resilience efforts. Older populations and those with disabilities are particularly sensitive to the availability of mobility services. Communication and information, emergency response, and evacuation management are important to ensure efficient use of transport in case of major disruptions of service. The broader impacts of disturbances in road transport can escalate quickly. The disruption of a country's road freight system can paralyze its economy and social welfare system in as little as 4 to 5 days (*37*).

Critical Issues and Research Needs

- Is there a potential for impacts on transit, demand-response services, pedestrians and sidewalk quality, protection from the elements, or simply accessibility to transportation assets?
- Can automation and improved logistics serve in mitigating potential negative consequences in this area? More responsive supply chain organization, early warning systems, and adaptive planning systems could, individually and cooperatively, create built-in automated resilience.
- What will be the general impact on logistics in terms of production sourcing, inventory levels, storage location, and delivery routing and scheduling?
- How will the relocation of tourist destinations affect the transport system? What will be the socioeconomic impact of relocation of settlements for adaptation purposes?
- Lastly, is there a social equity issue in climate change, adaptation, and resilience efforts? How do we define the

issues and the collective set of objectives to address social equity in the face of climate change impacts?

6 Synthesis and Concluding Remarks

This paper attempts to lay out the broad issues confronting the transportation community as it addresses the need to build greater resilience into the transportation infrastructure and its users to meet the increasing demands and threats of a changing climate and more extreme weather. Developing sound resilience measures begins with an understanding of the basic science of climate change. Simply put, there are five major changes of import to transportation and much of the built infrastructure:

- Sea level rise, sometimes exacerbated by land subsidence;
- Higher temperatures and longer heat waves;
- Changes in precipitation patterns leading to both droughts and stronger rain- and snowstorms;
- Rising Arctic temperatures resulting in melting permafrost and reduced ice sheets; and
- Increased intensity of hurricanes: not more frequent but stronger storms.

But the devil is in the details. When? Where? How often? These are the questions that designers, builders, and operators of transportation systems need to have answered. Today, much of the information on climate change is at the global or continental scale, but transportation professionals need information at the regional or, ideally, the local scale.

The science of climate change, as with other areas of science, is one lacking stationarity. Historical records are of limited value in predicting the future. One can model changes in the climate, but even the input to the models is uncertain. How aggressively will the nations of the world address fossil fuel consumption? What new technologies will evolve to reduce the need for fossil fuels or to capture and sequester CO_2? What is the impact of naturally occurring events such as El Niño and volcanic eruptions? How will the ecosystem itself react to increased levels of GHGs? And how resilient are the socioeconomic systems that depend on transportation?

There are techniques for dealing with problems of deep uncertainty, but by and large they have not been used in the engineering profession. These techniques, such as robust decision making or adaptive planning, must become ingrained in the decision process for climate change impacts. Equally important and essential is the development of sound risk management methodologies. RBTAM is but one of several approaches that incorporate probability analysis with decision matrices to reach optimum decisions on the development and operation of transportation and other infrastructure systems. References to several of these approaches are provided in the text.

This paper also examines the essential question raised by the conference organizers: How do we achieve better resilience to climate change in the transportation industry? We attempt to identify the critical issues that must be addressed through needed research. What is an acceptable level of transportation resilience? Can we develop more precise climate and extreme weather models and forecasts? Are there new structures or materials, including nanoproducts, that can better withstand heat, drought, or flooding?

The issue of developing sound risk management approaches to managing the entirety of transportation assets is discussed. Monitoring systems, including lidar, must be improved to measure the robustness of assets and the responsiveness of those assets to extreme events.

The transportation system itself is undergoing significant change with new technologies such as automated vehicles, electrification of transportation fleets, and new materials. How will climate change enhance or hinder the implementation of these new developments? One cannot consider climate change just in relationship to today's systems, but how it will affect the systems of the future.

Transportation is not simply a set of individual parts, but rather an amalgamation of many components linked together by nodes and forming a giant network. It operates with a multiplicity of interdependencies with other critical infrastructure elements (e.g., energy, water and wastewater, IT and communications, buildings, and health care). Furthermore, transportation is essential to agriculture, forestry, and, most importantly, to our social and economic systems.

The task for this symposium is to begin to prioritize the major research needs of the transportation industry in relation to creating stronger resilience in transportation systems. Perhaps no more important research need exists than to better understand the interdependencies that exist between transportation modes and between transportation and all the sectors with which it interfaces. This paper suggests other critical issues that must be addressed, most of which require more research. The main areas of interest for researchers and practitioners appear to be the following:

1. Defining acceptable levels of transportation resilience and acquiring practice in the design of measures at an appropriate scale;
2. Implementation of risk-based transportation asset management, including improved information provision as well as design methodological and institutional aspects;
3. Improvement of sense-and-respond capabilities to allow adaptive policies to be formulated and implemented;

4. Adoption of planning approaches for climate resilience, recognizing that spatial planning and governance practices need to be reviewed in the light of climate change;

5. Addressing system resilience by developing cross-modal, cross-sectoral, and cross-infrastructure asset-management approaches; and

6. Assessment of societal impacts, with the aim of ensuring that top-down adaptation initiatives and bottom-up absorptive capacities and resources are in balance.

Acknowledgments

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APPENDIX B

Scenario 1: Sea Level Rise

1 Introduction

The subject of this case study scenario is long-term sea level rise. The main reasons for sea level rise are thermal expansion of the earth's water masses and melting of glaciers. Natural changes are aggravated by human activity. Sea level rise can have a great impact on coastal areas. Although it is a slowly approaching climatic threat, the anticipated impacts of sea level rise on existing infrastructure and societies can be so severe that adaptation has to start now.

According to the *Fifth Assessment Report* of the Intergovernmental Panel on Climate Change (IPCC), the global mean sea level rose by 0.19 meter (7.5 inches) between 1901 and 2010 (*1*). There is high confidence that the global mean sea level rose at an average rate of 1.7 millimeters (0.07 inch) per year over the period 1901 to 2010, 2.0 millimeters (0.08 inch)/year over 1971 to 2010, and at a rate of 3.2 millimeters (0.13 inch)/year from 1993 to 2010. Tide gauge and satellite altimeter data, available since the early 1990s, are consistent regarding the higher rate of the latter period.

A source of uncertainty is the effect of the melting of glaciers. Quoting Bamber and Aspinall, one source notes, "Combined with melting glaciers and ice caps and thermal expansion of the ocean, Bamber and Aspinall gave a range of 33–132 centimeters (13–52 inches), with 62 centimeters (24.4 inches) the average estimate, for sea level rise by 2100. It's still uncertain, but it's the best estimate we have for now" (*2*). There is evidence that the contribution to sea level due to mass loss from Greenland and Antarctica is accelerating to 5.4 mm (0.21 inch)/year by 2100 (*2*).

Sea level rise varies from year to year due to short-term natural climate variability (e.g., El Niño). There are also large differences along the coastlines due to local ocean temperature variations, salinity, currents, or because of uplift or sinking (subsidence) of the coastal land areas.

Uplift due to postglacial rebound in areas that were covered with glaciers during the last Ice Age is favorable for the relative sea level rise. This potential uplift includes land areas in Canada, the West Coast and northern part of the United States, and Scandinavia. Subsidence, on the contrary, increases the relative sea level rise and creates a serious problem in some areas. Subsidence is caused by pumping groundwater, oil and gas extraction, compression under heavy construction, and land use. Damming rivers has reduced sedimentation in some deltas, causing subsidence in areas such as the Mississippi River delta. One of the most dramatic examples of subsidence is in Louisiana, where land is subsiding at a rate of approximately 0.9 meter (3 feet) per century (*3*). Parts of the city of New Orleans, Louisiana, are subsiding by 28 mm per year. This subsidence is due to drainage systems within metro New Orleans and construction of river levees, which starve the wetlands of sediment and fresh water (*4*).

In addition to long-term sea level rise, an expected increase in storm activity will increase the threat from storm surge, when especially high sea levels occur. Storm surge is usually forecast and is managed as a forecast river flood or storm. The consequences of storm surge are, nevertheless, concrete examples of impacts brought by long-term sea level rise. Several large storm surge events in Europe (*5*) and the United States (*6*) have caused loss of life and damage in the past century. The North Sea storm surge in 1953 killed more than 2,000 people and caused massive damage to properties along the southern coastline of the North Sea (*7*). Hurricane Katrina in the United States in 2005 resulted in the deaths of between 1,245 and 1,836 people and caused $108 billion (€84 billion) in damage. As the sea level rises, resulting impacts from hurricanes and sea storms will be intensified. In the United States, the greatest impacts will be in the Gulf Coast and East Coast states, and in Europe, the lowland coastal regions of the North Sea (*8*).

A study of 136 major coastal cities showed that vulnerability to sea level rise is high (*9*). Because flood defences have been designed for past conditions, even a moderate rise in sea level would lead to substantial losses. Inaction is not an option. Even with better protection, the magnitude of losses will increase, often by more than 50%, when a flood does occur.

2 Impacts of Sea Level Rise on Transportation (*10*)

Navigation

- Port facilities are placed on the water's edge and are therefore potentially vulnerable to sea level rise.
- Sea level rise and storm surges can damage essential protective infrastructure.
- Storm surges and flood-related scouring can weaken bridges, quays, and pier foundations.
- Docks, jetties, and other facilities are deliberately set at an optimal elevation relative to historic water levels and therefore a rise in sea level leaves them at a sub-optimal elevation. (However, these facilities tend to be rebuilt relatively frequently compared with the time it takes for a substantial rise in sea level.)
- Sea level rise could result in a reduced need for dredging and easier navigation for deeper-draft vessels in particular channels (small effect compared with the draft of most vessels). Saltwater advancing upstream can alter the point at which flocculation leads to sedimentation and creation of shoals.
- Storm surge and storms could cause difficulties with docking and congestion.
- Sea level rise could cause decreased clearance under bridges, which could limit the ability of boats to pass underneath a bridge (probably a problem for smaller boats and smaller bridges).
- Port services could be affected by high sea level and flooding because storm surges and flooding of port facilities prevent vehicle movements.
- Goods handling and storage can be affected by storm surge and flooding (e.g., damage or restriction of crane operations or loading of bulk, flooding of storage platforms and facilities, damages, material losses of infrastructure, spoiling of goods).
- Ports can become inoperable if critical inland networks fail.

Aviation

- Sea level rise is a problem for coastal cities, where airports are built along tidal waters, sometimes on filled areas. The runways are vulnerable to flooding and splashing from waves. Storms can move rocks and debris onto runways, causing damage to the pavement and costs to clear the debris.
- Protection zones around runways are exposed to erosion, requiring erosion measures and monitoring.

Roads

- Coastal roads and railways on fillings are exposed to increased erosion when sea water levels are high, and drainage systems can become less effective, increasing the risk of flooding.
- Subsea tunnels are exposed to wave splashing or flooding if entrances are low, and they are also exposed to higher water pressure on the tunnel walls.
- Wave splashing of coastal and island roads is a traffic safety problem before the roads are flooded.
- Flooding of roads causes road closure, a serious problem if the road is the only access to coastal communities and/or if the road is used as an evacuation route.
- Increased flooding increases evacuation times, which increases the risk to life or requires emergency officials to begin an evacuation sooner.

Railways

- Railroads often cut across marsh areas in coastal zones. Low-lying tracks are often flooded, and the beds may be vulnerable to sinking from compaction of marsh peat. This situation makes them more vulnerable in the future climate.
- Tunnels may also become more vulnerable because the risk of their entrances and vents flooding will be greater and because the hydraulic pressure on the tunnel walls increases as water tables rise.

Examples of Protection Measures (*11*)

- In-shore protection and strengthening of transportation infrastructure, as well as physically raising existing transportation structures or relocating transportation infrastructure, will help maintain existing infrastructure.

- Constructing seawalls, bulkheads, retaining structures, revetments, dikes, dunes, tide gates, and storm surge barriers will protect beaches and coastal areas.
- Beach nourishment or sand replacement adds material to a beach to make it higher, wider, and less vulnerable to the sea.
- Further protection is afforded by converting eroding beaches to a cobble or pebble beach and placing hard structures offshore.

3 Vulnerability Study: Gulf of Mexico

The U.S. Gulf Coast states (Texas, Louisiana, Mississippi, Alabama, and Florida) have been identified as highly vulnerable to sea level rise. The vulnerability of the transportation infrastructure to projected sea level rise and increases in storm surge is a critical area of uncertainty for communities in the extremely low-lying and flat northern Gulf Coast zone. White, young adult, and nonpoor populations have shifted over time away from zones with higher risk of wind damage, while more vulnerable population groups—the elderly, African Americans, and the poor—have actually increased in the higher-risk areas (*12*). A rapidly growing population along some parts of the northern Gulf of Mexico coastline is further increasing transportation development, thus increasing the impacts of projected sea level rise in the region, where observed relative rise rates range from 0.75 to 9.95 millimeters (¾ to 4 inches) per year on the Gulf Coast of Texas, Louisiana, Mississippi, Alabama, and Florida. By 2100, a worst case scenario could be a 75- to 200-centimeter (2.5- to 6.6-foot) rise.

A detailed study on the potential impacts of climate change on transportation systems in the Gulf Coast region was conducted by the Federal Highway Administration (FHWA) (*13*). The vulnerability of transportation highways, bus transit, ports, rail, aviation, and pipeline components to weather events and long-term changes in climate was assessed. The focus was on those transportation components that are most critical to economic and societal functions.

Phase 1 of the study (completed in 2008) examined the impacts of climate change on the transportation infrastructure at a regional scale. Phase 2 (completed in 2015) focused on Mobile, Alabama. The main features of the study are as follows.

- Climate assumptions. In Phase 1, scenarios of 61 and 122 centimeters (2 and 4 feet) of relative sea level rise were selected as inputs. In Phase 2, scenarios of 30 centimeters (1 foot) of global sea level rise by 2050 and 75 centimeters (2.5 feet) and 200 centimeters (6.6 feet) of global sea level rise by 2100 were used. Global sea level rise values were adjusted based on local data on subsidence and uplift of land. In addition, 11 storm scenarios were applied.
- Criticality assessment. A scoring system was developed that ranked each asset's criticality as high, medium, or low. Criticality was evaluated using mode-specific criteria related to socioeconomic importance, use and operational characteristics, and the health and safety role in the community.
- Vulnerability screening. Several hundred assets were considered to be highly critical. Because detailed vulnerability assessments could not be conducted on each asset, this study identified appropriate indicators of the three components of vulnerability (exposure, sensitivity, and adaptive capacity). These indicators are characteristics of an asset that may suggest how projected changes in climate may affect the exposure, sensitivity, and adaptive capacity of each asset.

According to this study, relative sea level rise of approximately 1.2 meters (4 feet) could permanently inundate more than 2,400 miles of roads, over 70% of the existing port facilities, 9% of the railway lines, and three airports (Figure 1); in the case of a 5.5-meter storm surge (less than that of Katrina), more than 50% of Interstate and arterial roads, 98% of port facilities, 33% of railways, and 22 airports in the U.S. Gulf Coast could be affected (*14*). These results should be viewed in relation to another finding of the study, that is, that the connectivity of intermodal systems, including goods movement to and from ports, can be severely disrupted even if short segments of roadways are flooded. A more recent study on the exposure of the U.S. Gulf Coast critical infrastructure assets has suggested that critical port facilities are the most vulnerable to extreme weather and storm surge, together with critical coastal rail lines; the extent of inundation of critical transportation assets from storm surge will be much greater than that due to long-term sea level rise, which will, however, exacerbate the severity of storm surge; and pipelines have the lowest fractional extent of exposure (3% to 16% of exposed pipeline miles), while exposure varies (16% to 62% of the road length) for the critical roads depending on the scenario (*15*).

Transportation impacts from increased relative sea level rise in the area will make existing infrastructure more prone to permanent and/or frequent inundation from tropical storms and storm surges. A total of 27% of the major roads, 9% of the rail lines, and 72% of the ports are built on land with an elevation of or below 1.2 meters (4 feet). Therefore, increased storm intensity may lead to infrastructure damage and service disruption: more than half of the area's major highways (64% of Interstates, 57% of arterials), almost half of the rail miles, 29 airports, and virtually all seaports are below 7 meters

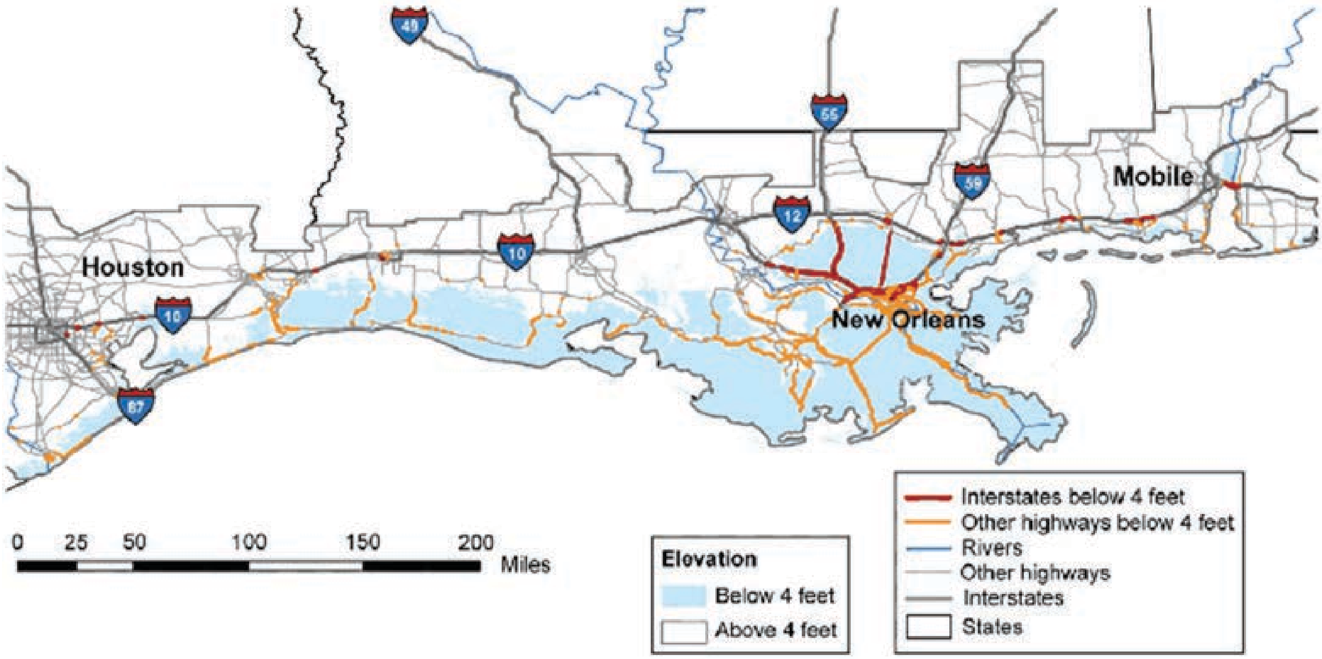

FIGURE 1 Predicted inundation along the Gulf Coast with a 4-foot sea level rise. (SOURCE: **https://www3.epa.gov/climatechange/impacts/transportation.html.**)

(23 feet) in elevation and subject to flooding and possible damage due to hurricane-induced storm surges (*15*).

Key findings from the FHWA study (*16*) include the following:

- Highways appear to be vulnerable to storm surge and sea level rise.
- The port and marine waterway systems are vulnerable to storm surge and sea level rise.
- Airports are considered to have low vulnerability to sea level rise and storm surge due to higher elevations or inland locations.
- Rail lines appear to be most vulnerable to sea level rise and storm surge due to location.
- Critical transit facilities could be exposed to sea level rise and storm surge depending on location.
- On-shore pipelines have relatively low vulnerability to climate change due to the fact that they are often buried underground or are located in areas not expected to be exposed to extreme events. Pumping stations are the most vulnerable part of a pipeline system to sea level rise and storm surge.

4 Vulnerability Study: French Mediterranean Coast

The Mediterranean Coast of France is exposed to inundation during storms and splashing from waves and erosion, which causes problems for coastal communities and for infrastructure. Both physical assets and services are affected (*17–19*; G. Le Cozanett, Marie Colin, and Jerome Duvernoy, personal communication).

A vulnerability study was conducted in the Languedoc–Roussillon region; this study also extended to other coastal areas of mainland France.[1] Languedoc–Roussillon covers 215 kilometers of the Mediterranean shoreline between the border of Spain and the Rhône delta (Figure 2). The area suffered significant damage in storms in 1982, 1997, and 2003. Projections of global sea level rise add to the concerns. Adaptation measures have been implemented for years; they include beach nourishments, the placement of coastal defense structures, and the relocation of a coastal road and other exposed assets (*21*).

Demographic trends and trends in coastal development are contributing to the vulnerability of the region. The coast is increasingly popular; the concentration of housing and enterprises in coastal municipalities is growing. Exposure to the sea is actually the basis for one of the main sources of income, which is tourism.

To conduct the vulnerability analysis, researchers made several assumptions:

[1] This study was one of the preliminary studies (2008) leading to the French National Adaptation Plan. Systematic work has been done in France on adaptation to climate change. See, for example, the newly published *National Climate Change Adaptation Plan: Transportation Infrastructures and Systems* (*20*).

- Due to established uncertainties, especially concerning modeling the development in the Mediterranean, the vulnerability assessment was based on a conservative assumption of a sea level rise of 1 meter (3 feet) by 2100 (Figure 2). This was somewhat higher than IPCC's projections at the time (IPCC *Fourth Assessment Report*), but it was consistent with some more recent models and estimates (*22*, *23*). The projected sea level rise was also in accordance with the "common methodology" developed in 1995 (*24*).
- An additional 1-meter sea level rise was chosen as the level of future temporary inundation for a 100-year storm.
- The zone exposed to severe erosion by 2100 was chosen to be 500 meters (1,640 feet), covering large local differences in various morphologies.
- The effect of the existing coastal protection is not taken into account because it will have no effect in the given scenario unless adjusted or resized.

The area that would be submerged and eroded by 2100 was estimated. Population and residence density models were overlaid with the estimates of eroded and inundated areas to calculate exposure. Demographic assumptions, however, correspond to present-day demographic statistics.

The impacts on the communities in the Languedoc–Roussillon region were significant (although the rough assumptions have to be taken into consideration).

- Irreversible erosion or permanent inundation will lead to the displacement of 80,000 people and the loss of 140,000 residences.
- People and residences will be exposed to a higher hazard of marine inundation, in both extent and frequency. The final estimates of people potentially affected by temporary inundation hazard by 2100 lie between 40,000 and 80,000 (between 60,000 and 140,000 residences). These estimates are with the limitation due to the hypothesis of constant stake.

FIGURE 2 The Languedoc–Roussillon region in southern France. (SOURCE: http://www.languedoc-roussillon.developpement-durable.gouv.fr/local/cache-vignettes/L480xH502/Les_reseaux _de_transports_en_LR_V4_Light_cle745349-2-11334.jpg.)

Costs were assessed for loss of assets, buildings, and transportation infrastructure (direct) and loss of use of the destroyed properties (indirect). The costs of damage from coastal erosion and permanent inundation are estimated to be €60 billion ($69 billion) by 2100 for loss of buildings, but over €140 billion ($161 billion) if land loss is included. Costs of temporary inundation, estimated to be €6 billion ($6.9 billion) by 2100, must be added to that figure.

Data from road and rail databases were used to supply the map with infrastructure. Ecologically valuable areas were taken into consideration by including the low-water areas (ponds and marshes), as they can be crossed by roads or railways, and are often included in ecological zoning.

For the entire mainland of France, the linear transport infrastructure estimated to be inundated by a sea level rise of 1 meter (39 inches) is close to 17,000 kilometers (10,500 miles). This estimate includes 2.9% of motorways, 1.7% of national roads, and 6.3% of the railway network.

For the Languedoc–Roussillon area, approximately 2,500 kilometers (1,553 miles) of roads will, according to this study, be inundated by 2100. Of the submerged roads, 85 kilometers (53 miles) are national roads and highways.

Due to data availability, the assessment of costs was limited to the major national infrastructure networks in mainland France managed by the state, or "national roads." Although this limitation corresponds to only 1.2% of the total length of the French road network, it is responsible for 25% of the total traffic on French roads. For coastal submersion, it seems reasonable to consider that the overall sea level rise of 1 meter would mean costs for national roads in mainland France (excluding highways and "other roads") of up to €2 billion ($2.3 billion), excluding the costs of the loss of use. This cost was assessed by applying an estimate of the mean monetary cost of road asset loss of €10 million/kilometer ($18.5 million/mile) and of reclamation of temporarily submerged roads of €250/kilometer ($463/mile).

The port of Leucate, which has petrochemical facilities, is among the structures exposed to coastal hazards and sea level rise. It experiences flooding. The major Mediterranean port of Marseilles, located approximately 80 kilometers (50 miles) east of Languedoc–Roussillon, is one of the 136 cities covered by the study "Future Flood Losses in Major Coastal Cities" (*9*). Although Marseilles is on a "closed" sea, the impact of sea level rise cannot be neglected (*25*).

Key Findings and Proposed Measures

- The analysis suggests that the cost of current coastal risks is negligible in comparison to the expected costs by 2100. The costs of potential damages due to erosion and permanent inundation are larger than those due to temporary inundation.
- This study highlights the importance of defining long-term management strategies for the coastal zone, taking into account current risks and predictions of additional future risks due to climate change. "At a minimum, it is advisable to reduce short-term coastal risks and to discourage urbanisation and population growth in low-lying, high-risk areas" (*26*).
- The knowledge base is important: regular data acquisition at study sites, maps, and data sets (e.g., natural phenomena, hazard estimation, vulnerability, asset exposure, damages, costs) will better support effective planning.
- It is necessary to reinforce the application of regulations; take into account coastal risks due to climate change in local-, regional-, and national-level strategic plans; and consider future climate change in the management of coastal sediment supplies (e.g., with the acquisition of land by the Conservatoire du Littoral[2]).

5 Issues Raised by the Cases

The areas of the two studies are very different: Languedoc–Roussillon is an agricultural and tourist region on the coast of the "closed" Mediterranean Sea, and the Central Gulf Coast region is a critical location of the entire United States for the import and export of industrial, commercial, and agricultural products and oil and gas. Both regions, however, confirm the trend of increasing pressure on attractive coastal areas.

The Languedoc–Roussillon study illustrates the problems lack of data can cause, such as uncertain sea-level rise projections, taking into account local morphological differences, data on damage costs of previous events, and uncertain demographic projections. Vulnerability and criticality were estimated only on the basis of location and available data. [Criteria for vulnerability and criticality are described in the 2015 *National Climate Change Adaptation Plan: Transportation Infrastructures and Systems* (*20*).]

Both studies show that the connections and interdependency regarding area use (transportation, housing, tourism and nature, industry) require solutions that see the system as a whole. The long-term challenge requires long-term planned solutions that will result in a gradual reduction of the pressure on the coastal areas.

[2] The Conservatoire du Littoral (Coastal Protection Agency) is a French public organization created in 1975 to ensure the protection of outstanding natural areas on the coast, banks of lakes, and stretches of water of 10 square kilometers or more. The Conservatoire is a member of the World Conservation Union.

6 Research Possibilities and Opportunities

Sustainability Questions

Some questions of sustainability as raised by the French ONERC[3] report, *The Coastline in the Context of Climate Change* (27), include the following:

- Should we really be extending our infrastructure into maritime areas at a time when sea levels are rising rapidly and coastal flooding is already a fact of life for many coastlines?
- Do we need to build new sea defenses?
- Should we withdraw from coastal areas and scale back our socioeconomic exploitation of these zones?
- Do we need to relocate property?
- How do we find the right balance between the pressing needs of spatial occupation and resource use?
- The effects of climate change serve as a reminder that our planet is not infinite. How do we respond to the facts that our resources are not unlimited and that inaction is not a viable option?
- How do we mobilize and face the challenges of the present, together, while preparing for the challenges of the future?

Possible Research Topics

- How can vulnerability assessment related to sea level rise be carried out in the best possible way on the asset level and on the system level? What do we need to know?
  - Regional climate scenarios, sea level projections, storm surge projections, wave height;
  - Basis for analyses for vulnerability: geographic information service maps, the effect of protective areas; and
  - Criteria for estimating vulnerability and criticality.
- How can we design assets and systems for better resilience to sea level rise?
  - Design values of high sea level and wave loading and
  - Flexible design for future adjustments.
- How do we identify, and maintain the focus on, the interdependencies among different sectors and infrastructures in order to avoid disruptions due to sea level rise?
- How can different modal transport agencies collaborate and coordinate their responses to sea level rise?
- How can we go about long-term gradual transition to a less vulnerable infrastructure?

[3] ONERC is the Observatoire national sur les effets du réchauffement climatique (National Observatory on the Effects of Global Warming).

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Abbreviations

CCSP	U.S. Climate Change Science Program
IPCC	Intergovernmental Panel on Climate Change
ONERC	Observatoire national sur les effets du réchauffement climatique (National Observatory on the Effects of Global Warming)
UNECE	United Nations Economic Commission for Europe

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Additional Resource

U.S. National Climate Assessment. http://nca2014.globalchange.gov/report/our-changing-climate/extreme-weather.

APPENDIX C

Scenario 2: Minimizing Disruption During Extreme Weather Events

This case scenario considers a set of extreme rainfall events drawn from events in the United States (2011, 2012, 2015, and 2016) and Central Europe (2002 and 2013) and the nature and scale of the effects of these events on transport infrastructure and services. The scenario highlights the vulnerabilities identified during a recent series of devastating floods. The central case is modeled on riverine flooding in mountainous regions in the United States caused by intense late summer storms, with its scope broadened to include considerations of longer-duration flooding.

The U.S. states are each responsible for building and maintaining more than 15,000 miles of roadway, with individual towns or counties maintaining many more local roadways. The states also oversee hundreds of miles of state-owned railways and numerous small airports. The case study describes a large-scale flooding event that affected a region of several hundred miles including several large towns and small, remote villages in mountainous regions and is enriched by a brief description of the central European floods in 2002 and 2013. Box 1 describes the causes and locations of the European floods, and Box 2 examines Germany's response to the floods. The conditions (geographical, climate, extreme weather, and storm surges) in Europe differ considerably from those in the United States, but ways of preparing for, and dealing with, extreme events can be of use for both locations.

1 Introduction

Our built infrastructure is routinely put in harm's way from extreme weather, whether from coastal and inland flooding, wildfires, strong winds from hurricanes and tornados, or extreme snow loads. The current practice in design codes is to examine historical extreme events. With climate change and changing extremes, this approach is similar to driving while looking in the rearview mirror. "Instead of preparing ourselves for past disasters, a common error, we should use existing climate research and risk studies to prepare for future disasters."

In the United States, the frequency of extreme precipitation is increasing across the mid latitudes, and storms in those areas will become more intense. Intensification of precipitation is often associated with an increased flooding risk in places such as the northeast United States. There is also high confidence that the strongest hurricanes are becoming more frequent.

A recent study of the European Joint Research Centre estimates that under high levels of global warming:

> [T]he population affected and direct flood damages indicate that by the end of the century the socio-economic impact of river floods in Europe is projected to increase by an average 220% due to climate change only. A larger range is foreseen in the annual flood damage, currently of 5.3 B€, which is projected to rise at 20–40 B€€in 2050 and 30–100 B€€in 2080, depending on the future economic growth. (*1*)

Changing rainfall and flooding patterns are potentially important factors to consider in transportation infrastructure design, planning and operations, and maintenance. Today's infrastructure was built and new

BOX 1

Central European Floods in 2002 and 2013

Causes and Locations of Flooding

Both floods in Central Europe were caused by heavy rainfall. In 2013, rainfall intensities of up to 250 mm were registered in just a few days. The 2013 flood was caused by a low-pressure system that was locked into place by a disturbance in the global wind patterns.

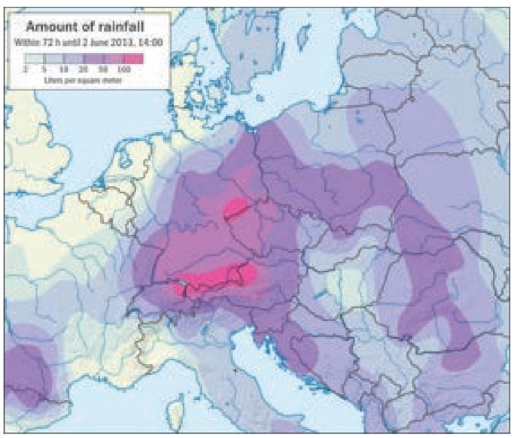

Figure 1. Amount of rainfall.

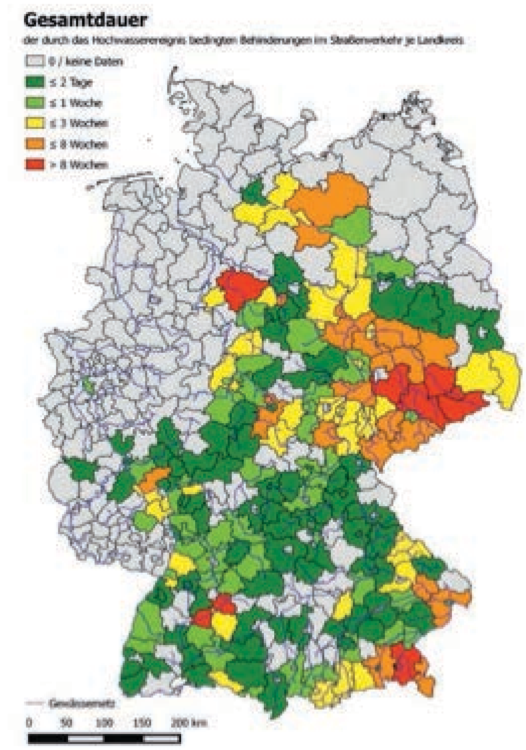

Figure 2. Obstruction of road traffic in 2013 in Germany per county ("Landkreis") in number of weeks ("Wochen").

In June 2013, large-scale flooding occurred in many Central European countries—Switzerland, Austria, the Czech Republic, Slovakia, Poland, Hungary, Croatia, Serbia, and particularly in Germany. By the end of May 2013, rainfall totaled 178% of the average monthly amount, and record-breaking soil moisture was observed in 40% of the German territory. High initial stream-flow levels were reported in the river network.

At several locations, embankments were unable to withstand the floodwater, resulting in dike breaches and inundation of the hinterland.

Costs and Impact of Damage

For the 2002 event, total costs of damage in Germany were €11.6 billion, of which €1.8 billion was covered by insurance (19% of all houses). In the Dresden area alone, the damage was €1 billon (due to a return period 1/200 per year event). The direct damage to railways was €1 billion, but this amount does not account for the damage due to the obstruction of railway traffic and loss of consumer satisfaction. In 2013, the total damage costs were €6.5 billion for the provinces. In 2002, €1.8 billion was covered by insurance (34% of all houses).

The total damage in Germany mounted to €10 billion, with the damage to railways totaling €0.1 billion. For example, the important long-range line between Hannover and Berlin was obstructed, leading to detours, which forced people to use planes, cars, and other means of transportation. This flood and other weather impacts have made authorities responsible for the Deutsche Bahn increase investment in maintenance and preparation for extreme weather.

The damage to other infrastructure in Germany in 2013 was €0.3 billion. In large parts of the country road traffic was obstructed because of actual flooding of the roads and because of other causes such as landslides.

BOX 2

Issues Raised by Central European Floods in 2002 and 2013

What Measures Were Taken after the German 2002 Floods? What Was Their Effect in 2013?

After the 2002 floods in Germany, risks were assessed, flood maps were developed, and flood risk management plans were prepared to prevent damage in the future. The experiences in 2002 in the flood areas helped to prevent and reduce costs and damage in 2013.

In 2013, the Bavaria and eastern Germany water levels significantly exceeded those of 2002 in many places on the Danube and Elbe. In Dresden, by contrast, the old city center was largely spared, unlike in 2002. Thanks to better flood control, fewer dykes on the upper reaches of the Elbe broke than in 2002, but this meant that the flood wave farther downstream was all the higher. In Magdeburg, floods reached a record level.

The Nationale Hochwasserschutzprogramm (National Flood Protection Program) was launched in the aftermath of the 2013 flood and is run in part by the Bundesanstalt für Gewässerkunde (Federal Institute of Hydrology) (http://www.bafg.de/EN/Home/).

Measures Taken with Stakeholders Along the River

Measures such as strengthening levees were taken individually by the states. Some states spent a lot of money in a short time, others spent less money. Examples of good coordination of measures are

- Treaty for flooding of a polder (Havelpolder);
- Coordination of different measures along the rivers and monitoring the collective impacts of measures; and
- International commissions to protect rivers (Mosel, Rhine, Saar, Elbe).

Crisis and Emergency Organization for Flood Events in Germany

Germany's civil protection is based on fire departments (professional and volunteer), technical public aid (volunteer), and other public aid organizations financed by the government. Responsibility for flood prevention and civil protection is conducted by the states and country, which in certain cases can cause a problem for coordination.

In 2013, 1.7 million volunteers from fire departments and technical public aid assisted with the flood event. A total of 5.15 million sandbags were used, and an extra €60 million was spent by civil protection organizations.

In principal the emergency response is organized so that the chain of responsibility begins with the lowest level of government. In Germany, this level is the Kommune, or town council. If an emergency gets worse, the Kommune asks the following level for help, and so on.

infrastructure is still sized using the principle of stationarity, which assumes that rainfall statistics will remain constant across time. However, as mentioned previously, the data suggest otherwise. Current design standards may need to be altered to account for the nonstationary nature of hydrological statistics. In the Netherlands, for example, climate scenarios since 2009 show that increased precipitation and rising sea levels must be considered in the designs for infrastructure to withstand higher water levels.

Because existing infrastructure may be more vulnerable to future extremes than in the past, disruptions are likely to be more frequent and over larger regions, with large impacts on the transport system. Not only are floods disruptive to the transport system during the event, but the recovery after the event requires a major effort. Floods influence all stages of event preparedness, from preparation for the event, managing during the event, and recovery after the event. In this paper we focus on management during the event.

2 Description of the Scenario

This scenario is drawn from the flooding in Vermont (2011), Colorado (2013), South Carolina (2015), and Houston, Texas (2016), as well as Central Europe (2002 and 2013). Just weeks prior to this hypothetical state's biggest tourist event, which brings in an annual $3 billion from visitors, an intense flood closed over 500 miles (800 kilometers) of state highways, destroyed dozens of state bridges, and closed numerous railroad bridges, making 200 miles (300 kilometers) of railroad impassable.

Days prior to the event, the state had tracked a warm humid southerly air mass as it moved toward the region. The region was already on high alert due to high water levels as a result of prior storm events and soils saturated well into the 90th percentile compared with long-term averages. These conditions are ideal for rapid runoff, flooding, and uprooting trees.

Despite forecasts of large, slow-moving systems, the storm track, timing, and pattern as well as rainfall intensities and locations were still quite uncertain. The tall mountains in the region make it difficult to predict the side of a mountain on which any expected rainfall will flow. Before the storm's arrival, the National Weather Service (NWS) worked directly with the Governor's office. A day before the storm hit the Governor proactively declared a state of emergency, and the state government initiated emergency management procedures. The state department of transportation (DOT) carefully monitored the NWS projections and prepared for flash flooding. The DOT expected impacts across a large part of the state and prepared equipment and resources. However, NWS predictions do not readily predict destruction from floodwaters to roadways, culverts, bridges, and railways.

Rainfall Picture and Runoff Response

As the storm approached and pushed up the mountains, it stalled. It began to rain steadily in the afternoon, but late in the evening the wind picked up and torrential rains hit. In the first 12 hours, over 9 inches (23 centimeters) of rain fell. Because the ground was already saturated from previous rains, runoff in streams and rivers led to catastrophic flooding across two-thirds of the state. The first reported mudslides occurred shortly after midnight, and a widespread deluge of flood impacts followed throughout the region, particularly across the central part of the state, where rockslides, landslides, mudslides, and washouts destroyed residences, roadways, and local-access bridges. Flooding was so severe that it fully rerouted creeks and rivers by more than 500 feet in some locations. The state department of environmental services had its entire complex flooded and all computer systems rendered useless when a nearby river breached its banks. The storm also spawned scattered tornados that uprooted countless trees and downed power lines across the access roads to a major state DOT maintenance yard. By the time the storm had passed, more than 18 inches (46 centimeters) of rain had fallen in a little more than 2 days, making it a 1-in-1,000-year event.

Transport Effects

As a result of the storm, 500 miles (805 kilometers) of state highways were closed, more than 100 state bridges were closed, 30 railroad bridges were damaged, and 200 miles (322 kilometers) of railroad lines were impassable. More than 200 (more than 90%) of the state's towns had to rebuild damaged roads, bridges, and culverts. The storm damaged thousands of town culverts and damaged or destroyed nearly 300 town bridges The entire state was at a standstill. Dozens of towns were entirely cut off from the outside with no way in or out.

Figure 1 shows the Vermont transport corridor response before, during, and after Hurricane Irene in 2011.

3 Issues Raised by the Case

The main issues related to levels of preparedness before, during, and after the event raised by the case are discussed below.

Before the Event

The agency studied NWS projections and prepared for flash flooding. The DOT expected impacts across a large part of the state and prepared equipment and resources. Unlike large, slow-moving systems such as hurricanes that allow timely evacuations, large rainfall events in mountainous regions can confound preparedness efforts because no one can predict on which side of a mountain any expected rainfall will flow. Before the storm's arrival, NWS worked directly with the Governor's office. The Governor proactively declared a state of emergency, and the state government initiated emergency management procedures.

The DOT was aware of the storm and established crews who readied equipment and other resources. In hindsight, it is believed that distributing resources even farther would have made the situation worse.

Another level of preparation is the preparation of traffic management strategies and evacuation routes in case of obstructions and extreme events, which is a no-regret, multievent preparation.

Preparation can also consist of the design and building of (multimodal) extreme weather–resilient infrastructure.

During the Event

Simply put, the event was at a scale never experienced, expected, or planned for at the DOT, and the personnel

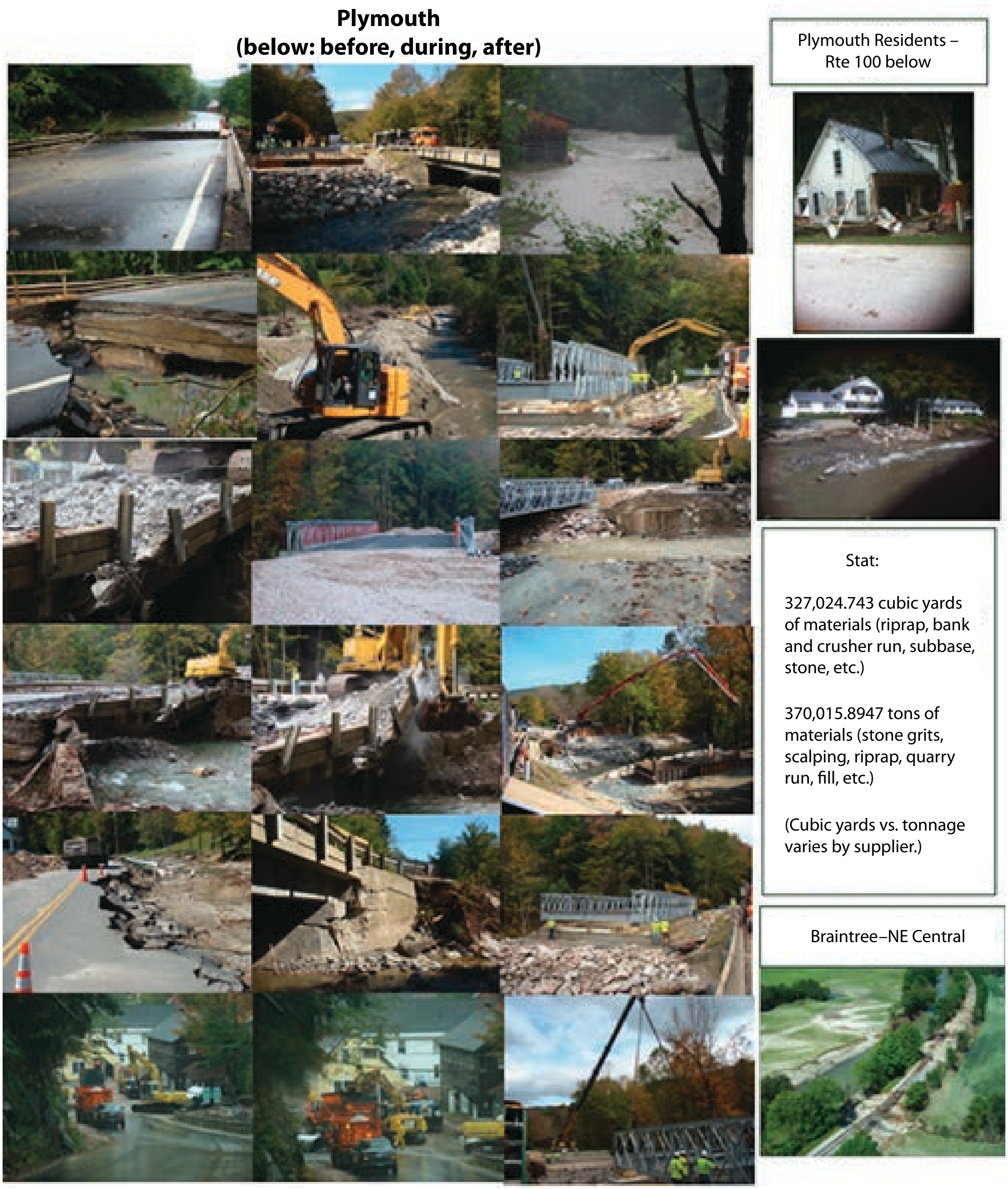

FIGURE 1 The Vermont transport corridor response before, during, and after Hurricane Irene in 2011. The devastation from the hurricane exceeded that of the 1927 flood.

it needed were too many and too scattered to provide a meaningful foundation for delivery of services.

An incident command system (ICS) is defined by the U.S. Federal Highway Administration as "a systematic tool used for the command, control, and coordination of emergency response." The DOT organized two ICSs that worked with the state's unified command. Under a unified command, a single, coordinated incident action plan directs the emergency response effort and supports agencies or divisions with different legal, geographic, and functional authorities and responsibilities to work together effectively without affecting individual agency authority, responsibility, or accountability. The DOT's ICS focused on reopening state and local roads, providing access for emergency relief efforts to stranded communities, and enhancing communication for the recovery effort. The incident command centers were the home base to over 1,000 people including nearly 300 DOT employees, hundreds of National Guard members, and DOT workers from neighboring states.

Recognizing the need for a multitude of resources such as engineering services, materials, contractors, and equipment, the DOT created and maintained a "one-stop" shopping list. This list acted like a clearinghouse in which to collect names of private contractors, consultants, bridge inspectors, trucking companies, surveyors, utilities, quarry owners, and others.

Response Staffing

For half a day, the DOT operations director sought to establish the facts and conditions that the state would address. Although radio contact was available with eight of the nine maintenance districts, there was initial difficulty in establishing contact with some employees. Some crews spent the night in their trucks, and one employee hiked five miles through the woods to get to a location where he could contact his supervisor.

Although the DOT employees had hastened to immediately support storm response and recovery despite road and bridge closures and other physical barriers, they were not prepared for what turned out to be, in some cases, a 3-month separation from their homes.

Communications

The DOT emergency transportation information system had been "brought to its knees." With the system down, Google reached out to set up a system for real-time mapping of closed roads, with public updates twice daily. By this time, the storm had passed and communities were stabilizing and assessing impacts. The mapping tool was widely used to counsel travelers to the state as well as state residents.

The state's emergency management division issued a statement early that morning via social media stating: "Remain. Where. You. Are. Dangerous flooding conditions through the state for most of the day." However, drivers still moved or drove around barricades onto flooded roads (https://www.youtube.com/watch?v=LtlsIwhZHLo).

Social media provided valuable updates throughout the event, and the DOT website began to list daily release times for storm event information. The DOT also used a mobile phone microsite to allow for easy access to information and used social media to communicate conditions. Media outlets followed the DOT Facebook and Twitter accounts; at one point, five DOT administrators worked full-time maintaining the Facebook page.

After the Event

Demobilization

The demobilization phase is sometimes referred to as the "forgotten phase" in emergency management. As they closed out the ICS and people returned to their usual jobs, the ICS Logistics Section made a point to tell employees about the typical feelings experienced after a traumatic event. Subsequently, the DOT held informal lunches and offered a counseling program. The state also developed a commemorative coin recognizing the assistance of major stakeholders, and the coin was presented to everyone, including those who had kept on with day-to-day activities. The DOT also sent thank-you letters to everyone involved, including their families.

River Management

This event clearly showed that although roads and rivers compete for the same space, there are numerous locations where we have failed to build roads in a way to ensure they "get along" with rivers. In all cases, if a balance is not struck in this game, the river will win eventually. It is clear that during an emergency, field staff who have not been properly trained in river dynamics need to make decisions. This storm raised awareness for a need for all field staff to have some basics in river mechanics to lessen impacts to rivers and decrease the potential for future damages.

Recovery Phase

- Within 1 month of the storm, over 75% of the closed bridges had reopened, and more than 96% of the state highway road segments had been reopened.

• In 4 months, all of these state assets were serviceable again. Town bridges, culverts, and highway segments recovered in the 4-month period following the event. To accomplish this, the DOT expedited and streamlined procedures, which resulted in a reduction in the initial estimate of transportation system damages from $700 million (€625 million) to $175–$250 million (€156–€223 million).

• The longer phase included continued efforts a year later to close out certain federal reimbursement issues, plan and design permanent repairs, and watch for sinkholes and riverbank landslides.

4 Implications for Research

The case study presented suggests several leads for further research as listed below. In Annex 1, the current approach in the Netherlands is presented as an example.

• What considerations emerge for future adaptation planning and resourcing?
  – Bridge (and infrastructure in general) design criteria addressing the structure's ability to withstand flooding,
  – Review of riverbank design methodologies and increasing the use of riprap (stone shoreline protection),
  – Route logs as a resource for design engineers in identifying structures and their locations,
  – Design and location of infrastructure and evacuation strategies multimodally and on the system as a whole,
  – Simplification of design plans, including minimization of repetitive information,
  – Methods to reduce potential costs (e.g., with improved land use planning), and
  – Methods to translate uncertainty of developments in the future (e.g., mobility patterns, climate change) into infrastructure planning and investments, with an eye on robustness and fitness for extreme events.

• Rivers are a coupled system. Measures taken in one part of the river system will affect the behavior of the system as a whole. These effects reach out over state and country borders. The same is true for the transport system (including traffic management strategies). How can the coupled effects of these two systems be determined, especially for coordination during an extreme event?

• How robust are the present climate models' outcomes? Are their predictions sufficiently solid to justify major investments?

• Based on the present forecasts, flooding will be "business as usual" for some parts of Europe and the United States. How do we communicate this message and improve the preparedness of the affected communities?

• How can we evaluate and improve the performance of emergency measures and response?

• What are the most effective methods of assessing hydrological system performance (including cascades and retention) and damage?

Acknowledgments

Information about the floods in Vermont (2011), Colorado (2013), South Carolina (2015), and Texas (2016) was reviewed and amalgamated to develop the case study. Thanks to Gina Campoli, Vermont Agency of Transportation. Information about the European floods of 2002 and 2013 (please see the bibliography) was gathered by Kees van Muiswinkel, Rijkswaterstaat, Netherlands, supported by Enno Nilson, Department of Water Balance, Forecasting, and Predictions, Federal Institute of Hydrology, Germany; Heidi Kreibich, University of Potsdam, Germany; and Jens Reuber and Rita Lammersen, Rijkswaterstaat, Netherlands.

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LAWA Bund/Länder Arbeitsgemeinschaft Wasser. Zusammenfassende Analyse der Ergebnisse der vom Hochwasser 2013 betroffenen Flussgebietsgemeinschaften beschlossen auf der 147. LAWA-VV am 27–28 März 2014 in Kiel.

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Annex 1

Strategy for the Use of Main Infrastructure Before, During, and After a Flood (Rijkswaterstaat project group MEGO, 2016, Reference 9)

In the Netherlands, the Minister of Infrastructure and the Environment developed a strategy with respect to improving evacuation in case of major floods, mainly by marking evacuation routes, instructing the safety regions, and influencing the behavior of people by informing them about the strategy.

Measures for Using Highways for Prevention or Evacuation

The most cost-effective measures for using highways for prevention or evacuation are focused on administrators and citizens:

- Make decisions in a more timely manner;
- Improve the time span of forecast models;
- Influence the evacuation behavior and self-reliance of citizens through a well-designed and communicated evacuation network. This beneficial influence will increase the number of people who can leave an endangered area; and
- As needed, add options to the current traffic management plan that can strengthen the function of the main infrastructure for major evacuations.

Major adjustments of infrastructure are not cost-effective, as the probability of a major flood in the Netherlands is low. However, regional measures on specific critical locations may be worth the investment.

Recommendations to Be Discussed with the Ministry of Safety and Justice Responsible for the Crisis Organization

- Develop a default strategy. (In the Netherlands, this strategy is "go upstairs and stay dry; driving away is more dangerous in many cases." Under certain circumstances citizens may be advised to leave an area in time if possible.)
- Model and simulate an evacuation over the main roads to gain insight into the available capacity. This knowledge is necessary to develop possible strategies for preventive evacuation (the current strategy has to be updated).
- Make the "all hazard evacuation scenario highway infrastructure" part of the crisis and safety plans of the safety regions.
- Enforce unity and connection of the crisis and safety plans to ensure that the highway infrastructure is able to accommodate all the evacuation traffic.
- Train the people involved with the new plans.

APPENDIX D

Scenario 3: Drought, Heat, and Extreme Temperatures

> In the past it was one big drought every 10 years, then it came to one drought every five years, and now the trends are showing that it will be one every three to five years. So we are in a crisis alright, that is true. . . . But it's going to be the new norm. So our responses need to appreciate that . . . there is climate change, and it's going to affect the people that we work with, the communities we serve.
>
> —Beatrice Mwangi, *World Vision*

1 Introduction

Weather and Climatic Phenomena

Many areas of the world have experienced massive droughts that have had significant impacts on both the human condition and the stability of the economy and security. A drought is defined as a period of below-average precipitation that results in prolonged shortages of atmospheric, surface, or ground water. Drought is often caused by extreme temperatures often lasting over long periods of time.

The primary impacts of drought are on water quality degradation, declining surface and groundwater levels, and land subsidence. Secondary impacts reflect the effects on the economy (such as declining agricultural productivity), effects on natural resources (such as an increased number of wildfires), and the effects of subsequent weather events on environmental conditions (such as large-scale erosion due to the die-off of protective vegetation and increased flooding when it eventually rains again).

Extreme temperatures contribute to, but do not necessarily lead to, a drought (they must be accompanied by a decrease in precipitation). In the United States, recent heat waves have set records for highest monthly average temperatures, exceeding in some cases records set in the 1930s, including the highest monthly contiguous U.S. temperature on record and the hottest summers on record in several states. As noted in the U.S. National Climate Assessment,

> the number of extremely hot days is projected to continue to increase over much of the U.S., especially by late century. Summer temperatures are projected to continue rising, and a reduction of soil moisture, which exacerbates heat waves, is projected for much of the western and central U.S. in the summer. Climate models project that the same summertime temperatures that ranked among the hottest 5% in 1950–1979 will occur at least 70% of the time by 2035–2064 in the U.S. if global emissions of heat-trapping gases continue to grow. By the end of this century, what have previously been once-in-20-year extreme heat days (1-day events) are projected to occur every two or three years over most of the nation. (*1*)

In Europe, the *Regions 2020* report produced by the European Commission details how

> modelling results show that annual mean temperature in Europe is likely to increase more than the global mean temperature. Until the end of this century the average annual temperature in Europe is projected to increase by 2.5–5.5°C for the A2 scenario, and 1–4°C for the B2 scenario. Southern Europe will be most affected, with consistent temperature increases between 3°C and more than 7°C, with warming even greater in the summer. As a result of this the risk of summer drought is likely to increase in central Europe and in the Mediterranean area. Longer periods of droughts and more restricted drinking water availabilities combined with a lower density of health infrastructure might lead to a situation of an increasing risk of mortality, particularly in urban centers and agglomeration zones. (*2*)

Transport Impact

Extreme temperatures and drought potentially have a wide range of impacts on the design and operations of the transport system. These impacts can be classified as follows.

Design

- Instability of materials exposed to high temperatures over longer periods of time can result in increased failures, such as pavement heave or track buckling. Pavements, in particular, are very sensitive to temperature.
- Ground conditions and less water saturation (due to drought conditions) can alter the design factors for foundations and retaining walls, such as is occurring with the loss of permafrost in Alaska.
- Encased equipment such as traffic control devices and signal control systems for rail service might fail due to higher temperatures inside the enclosure.

Operations

- Increased electricity usage and power outages during heat waves might affect the electrical power supply to rail operations and supporting ancillary assets (such as electronic signing) for highway operations.
- Low water levels could significantly curtail barge operations along major river arteries as well as lock and dam operations.
- Extended periods of high temperatures will affect safety conditions for employees who work long hours outdoors, such as those working on infrastructure reconstruction and maintenance activities.
- Right-of-way landscaping and vegetation will have to be more drought resistant and able to survive longer periods of high temperatures.
- Other water-use activities in a transportation agency might have to be curtailed, at least on a temporary basis (e.g., washing of transit vehicles).
- Extreme temperatures will create dangerous conditions for many users of the transportation system, placing greater emphasis on the use of air conditioning for transit vehicles and stations and on increased use of green design approaches.
- Extreme temperatures could result in increased maintenance activities, such as replacing tracks that have buckled and pavement sections that have experienced heave, as well as removing landslides and erosion that occur with extreme precipitation events after drought or extreme temperatures have dried out the soil.
- Drought-induced wildfires and/or dust storms can create dangerous blackout conditions for road users.
- Airplane operations in high-temperature environments might have to be reconsidered due to less lift available in higher elevations to allow a plane to take off. (In Phoenix, Arizona, flights were cancelled due to extreme temperatures and officials' concern that the runway was not long enough for the planes to take off.)
- Extended periods of high temperatures will likely result in changes in rail operations, at a minimum requiring mandatory reduced speeds in areas where the track has been exposed to high temperatures over many days.
- Similarly, extended periods of high temperatures will negatively affect bicycle use and the desire and propensity of individuals to walk outdoors.

Temporal Focus

Unlike some other extreme weather events, extreme temperatures and drought can be predicted with some certainty and prepared for. Climate models, for example, are fairly consistent in their projections of where higher-than-historical temperatures are likely to occur in the world. Extreme temperature and drought conditions usually become serious when they persist over extended periods, and with the "blocking systems" meteorologists talk about, these periods of extreme conditions are lengthening. The longer an event lasts, the more impact there will be on the economy, the human condition, and system operations. During an extended extreme weather event, transport officials should aggressively disseminate information to transport employees and to the riding public on the strategies they should use to minimize heat-related complications. The transport agency should monitor the conditions of key assets, such as track, road segments, locks and dams, and other key facilities, at a much more frequent schedule than usually occurs during the normal asset management program. For example, rail transit agencies might have to monitor track condition and the potential occurrence of rail buckling or train breakdowns (especially in tunnels) on a weekly or daily basis.

2 Description of the Case: Catastrophic Heat Wave Hits Metropolis

Background

Metropolis is a major metropolitan area and economic center in the nation. It is a major port city with inland waterways (including locks) connecting to the hinterland. Because of the economic significance of the port, three major national railways serve Metropolis along with a major international airport for both passengers and cargo. The most recent population census indicated that just over 8 million people live within the urban area, with a major portion of the population representing mid- to low-income households. The central city is well-served by a metro rail network and has good intercity rail connections to the rest of the nation. There are 1,500 buses in the bus fleet, with 58 metro stations. Metropolis is a growing region, thus experiencing significant demands on government agencies to provide the infrastructure and services needed to serve this growth. As is typical in many urban areas, inadequate investment has occurred in such services due to the limited amount of available funding.

Being on the coast, Metropolis has experienced some significant storms that have inundated the coastal areas. Popular concern in the region for climate change has thus focused on sea level rise, storm surge, and flooding. Very little attention has been given to the implications of other extreme weather events. However, the region has experienced five straight years of below-average rainfalls, so water levels are down everywhere. Metropolis University climate scientists have been warning about the possibility of extreme temperature events, but to date not much policy or public attention has been given to such a possibility. Metropolis Transport (MT) is responsible for the transit system in the region. The Metropolis Highway Administration (MHA) is responsible for the major highway network, and 85 different transport agencies are responsible for local roads, sidewalks, and paths. The Metropolis Airport Authority is responsible for the airport and its operations. MHA has placed intelligent transport systems technology throughout the region to provide the most up-to-date monitoring and user information systems. The Metropolis Planning Agency is responsible for regional planning, but it has no implementation authority over the regional or local governments. The most recent climate change–related topic in the regional transportation plan focused on sea level rise and extreme precipitation events.

The Event

The national weather service issued warnings at the beginning of the year (6 months ago) that the summer could be unusually hot. Two months ago the temperatures started to reach above 95°F (35°C) for the first time. The temperature has reached 100°F (38°C) for the past 30 consecutive days, with the weather service predicting that these extreme temperatures will likely last for possibly another month or month and a half. The impact of these temperatures on Metropolis has been dramatic. There has been a major upswing in heat-related deaths, especially among older people. Shelters have been opened for individuals not having air conditioning in the home or who are homeless. Levels in the Metropolis reservoir have never been so low, and water rationing has been instituted for both business and residential uses. Power surges during the day have caused five brownouts during the last month, and the Metropolis Utility District (MUD) has warned that more will likely occur as long as the heat wave continues. The mayor has suggested that MUD negotiate to purchase power off of the grid, but MUD officials say the local grid network is unable to handle the increased demand. Two months ago, lightning strikes caused the Metropolis National Forest, some 100 miles away, to erupt in wildfires, catalyzed by the extremely dry forests. Massive smoke plumes from these fires reached the city, and large amounts of land were left barren. There is great concern about erosion once heavy precipitation events return.

Transport Impacts

At first, the heat wave had little impact on Metropolis's transport system. After 2 months, however, transport officials started getting indications that the heat wave was affecting operations. Several transit passengers collapsed at bus stops and in transit stations due to heat-related symptoms. The air conditioning in several underground transit stations stopped due to maintenance issues, resulting in very high temperatures in the station area. Twenty percent of the bus fleet began to experience air conditioning problems as well, resulting in an avalanche of customer complaints about the bus conditions. Several transit construction projects were delayed due to the unbearable working conditions for the construction workers. Perhaps most surprising (especially to MT officials) was the buckling of rail track on two of the major metro lines due to excessive heat. Luckily, MT had stockpiles of replacement track, and the track was reopened in one day, minimizing disruption. Electrical systems, which were a peripheral but critical part of the transportation systems, were tied to the region's electricity grid and began to fail as the brownouts continued.

The biggest public relations issue for MT related to the use of its facilities by the homeless and those without air conditioning as a means of coping with the extreme heat. Initially, MT enforced its rules of "no loitering" and "one ticket–one ride," thus removing from its facilities and services those who had nowhere to go. Public outrage over "putting citizens at risk" quickly caused MT to temporarily suspend these rules for the duration of the crisis. MT officials quickly realized they were part of the human impact story and initiated efforts to take care of those seeking shelter from the heat wave, including providing free transport to other shelters that had been established in Metropolis to handle such demands.

MHA had assumed the pavement design used for its major highways could withstand extended periods of high temperatures. In fact, this was true. However, the pavements on several minor highways experienced pavement heave, shutting down the roads for approximately 4 days. Given the nature of the highway network, the drivers on these roads were able to find alternative routes to their destinations. Some businesses in these highway corridors were disrupted due to interrupted freight deliveries, but they were able to find alternative locations for the deliveries to be made. The biggest impact on the highway network (again to the surprise of the agency responsible for it) was the breakdown of the intelligent transport system due to many of the assets being unprotected from extreme heat. Overhead signs, surveillance cameras, and many traffic signals were shut down because of equipment malfunction. The MHA minister was quoted on local television as saying that this level of disruption was unforeseen, but that MHA officials were replacing the equipment as fast as they could. Similar to MT, several MHA construction projects were curtailed during daytime hours due to unbearable heat for construction workers. MHA was also constrained by legal limits on the maximum temperatures at which people can be allowed to work, and the agency instituted contract negotiations to see if construction could occur at night.

Several sectors of the Metropolis economy were beginning to be affected because of the potential disruption to transportation services. Water levels on the major inland waterway were so low that major barge operators were warning that barge operations might be curtailed. This possibility was not a serious issue because some commodities could be transported by truck or rail (although freight rail operators were also concerned about rail buckling and had lowered their speeds on sections of track that were considered most vulnerable). However, for bulk commodities, such as coal and agricultural products, the limitation on barge operation was potentially an economic disaster. The MHA did notice an appreciable increase in large trucks on the major highways in the region due to the shifting of freight modes, causing increased levels of congestion. Metropolis Airport Authority announced that the airport was still operating without delays, but that if the heat wave continued limitations on plane departures might have to be instituted. This possibility was not considered to be a major disruption because flights could be rescheduled (if the airlines agreed) to hours when the heat would not affect operations.

The Press

Not surprisingly, the media and press focused on the human element of the heat wave story. How many heat-related deaths have there been? How are people coping? What is the government doing to help those in need? However, as disruptions to the transport system continued to grow, reporters began to question why the transport agencies were so unprepared for the impacts of the heat wave on the transport system. Why did so many bus air-conditioning units fail? How could transport agencies design pavements and MT design track that could not withstand extended high temperatures? Given that national, metropolitan, and local transport agencies are responsible for similar types of infrastructure and services, why had there not been any coordinated planning and foresight on how transport agencies should prepare for and respond to heat waves? Most importantly, what are these agencies going to do to avoid these disruptions in the future?

The Aftermath

National, state, and Metropolis officials decided to draw important lessons from the drought experience. It was realized that transport officials could take steps to prepare for the likely impacts that higher temperatures and droughts could have on transport infrastructure and system operations. The steps taken included the following:

- Establish a climate change task force that will be responsible for identifying vulnerable assets for all possible climate change–related stressors facing the transportation system in Metropolis, based on the best science available. The task force is also mandated to develop a coordinated and collaborative institutional response strategy when a climate-related emergency is declared.
- Engage the local university to examine carefully the behavior of materials under extreme temperatures to determine vulnerabilities. It is likely that in the short

term (i.e., 10 to 20 years), many of the design and materials specifications for transport infrastructure will result in assets that can withstand higher temperatures over extended periods. However, it is not clear that the much greater exposure to extended higher temperatures expected in the latter part of the century will have a similar experience. In addition to the university studies, all the infrastructure-related agencies will be jointly undertaking a comprehensive examination of their design standards to assess their relevance in a future that could be very different than the past.

- Develop a strategy to comprehensively monitor asset performance to identify when stress levels are approaching dangerous levels (this approach most likely will use sensors and "smart" materials to provide advance warning of stresses caused by unusual environmental conditions). Prepare contingency plans to respond to heat-related asset stress emergencies (e.g., establish detour routes for potentially vulnerable critical network links). Assets and materials that might be most susceptible to heat extremes will be stockpiled to minimize the replacement time to restore service.
- Reexamine operating and maintenance procedures to assess likely changes in light of recent experience with drought and high temperatures. For example, the MHA executive director wanted to know if more drought-resistant vegetation could be used in rights-of-way to avoid replacing any that succumbs to drought (and perhaps save funding by not requiring as much maintenance). In addition, MHA was examining new design standards for drainage and erosion control in anticipation of massive erosion near roads adjacent to the burned-out portions of the Metropolis National Forest.
- Examine sensitive equipment with respect to high temperatures, and identify strategies for protection.
- Examine how transport agencies could respond to the human element of system operations (e.g., increased shade and air conditioning in service areas, and more rests and water breaks for construction workers). This area of interest had been considered by very few officials.
- Develop marketing and public information materials to educate system users on how to handle heat-related service disruptions.
- Seek knowledge and experience from transport officials working in different climatic zones, especially in those areas already experiencing drought and high temperatures—there is no need to reinvent the wheel.

3 Issues Raised by the Case

Level of Preparedness for the Event

Public officials had focused on those climate change stressors that had been experienced via past storms and that had received the most public attention, giving little attention to extreme temperatures. Transport agencies had not anticipated or prepared for the challenges related to higher temperatures. An example of this lack of preparation was the transit system's experience with air-conditioning breakdowns on transit vehicles.

Interdependence with Other Critical Infrastructures

The region's rail transit system was dependent on the electrical grid and was thus affected by the much-higher-than-normal electrical demands. The constraint on barge traffic due to low water levels had a domino effect throughout the economy, as well as on the transport system.

Severity of the Transport Impacts

The severity of impacts on the transport system varied with the extent to which assets and infrastructure were sensitive to prolonged higher temperatures (such as rail track) and the degree to which network redundancies provided system resilience (such as the aviation network). Some impacts (such as nonworking air-conditioning units in transit vehicles) were minor nuisances; others (such as the electrical shutdowns) caused major network breakdowns. Extreme temperatures may also increase absenteeism in the transport workforce.

User Groups Affected

From a transport perspective, the primary groups affected were users of the system, in particular those who were exposed to higher temperatures, such as transit users. Others were affected because services that transport systems provided were curtailed or interrupted (such as the impact on the economic sector due to more constrained barge transport). The big surprise to transport officials was the degree to which they became part of the "bigger story" of how people were surviving the extended heat wave, that is, how their facilities and vehicles became a refuge for those seeking relief from the heat.

Management of the Event by Various Stakeholders

There was little coordinated planning among the many transport agencies relating to extreme heat issues, even when the transport agencies were responsible for similar assets (e.g., both the highway and transit agencies were responsible for pavements and structures). Until the press highlighted the seemingly uncoordinated nature of transport agencies' responses, agency officials had not discussed and certainly had not coordinated common response strategies.

Observed Levels of Resilience

The level of resilience of different transport networks varied by mode. The aviation network was able to respond quickly, and the transit agency (MT), which was equipped with prepositioned rail supplies when track buckling occurred, was also able to respond quickly. Others, such as barge transport, showed very little resilience because of the long-term nature of the disruption (low water levels) and the inability of alternative modes to economically and efficiently carry the types of commodities most often transported by barges. Some of the obvious substitute capacity, such as rail, could experience its own problems, especially as the extreme heat could also reduce this capacity (e.g., through lower speed limits and equipment breakdowns).

Public Attention

Because of the visibility and importance of the transport system to Metropolis citizens, it became the focus of media attention very early in the crisis. This attention caught transport officials by surprise; the agencies' press information offices were unprepared to answer extreme heat–related questions from the press. The public information aspect of the crisis had been completely overlooked by the transport sector.

4 Research Questions

- What are the extreme heat–related stresses that are likely to affect normal transport system operations and ultimately affect other sectors?
- What are the steps in an infrastructure vulnerability assessment related to extreme heat?
- How does one identify the interdependencies among different sectors and infrastructures in order to pinpoint potential failures?
- How can different modal transport agencies collaborate and coordinate their responses to extreme heat–related events?
- What advances in materials properties are necessary to create materials that can withstand long periods of extreme heat?
- How can "smart" materials be used to monitor asset condition to identify potential failure due to heat?
- What non-material-related strategies should be considered to protect critical assets from extreme temperatures?
- From a crisis management perspective, how can transport agencies become involved with the "total picture" in terms of societal response?

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APPENDIX E

Program

TRANSPORTATION RESILIENCE: ADAPTATION TO CLIMATE CHANGE AND EXTREME WEATHER EVENTS

Fourth EU–U.S. Transportation Research Symposium

Organized by the
European Commission
U.S. Department of Transportation
Transportation Research Board

June 16–17, 2016
THON Hotel Brussels City Center
Brussels, Belgium

THURSDAY, JUNE 16, 2016

8:30 a.m. **Welcome and Opening Remarks by the Organizers of the Symposium**
Clara de la Torre, European Commission
Kevin Womack, U.S. Department of Transportation
Neil Pedersen, Transportation Research Board

9:00 a.m. **Opening Plenary Session**
Alan McKinnon, *Chair*
Richard Wright, *Cochair, presiding*

Keynote Presentation 1
Jan Hendrik Dronkers, Rijkswaterstaat

Keynote Presentation 2
Donald Wuebbles, Executive Office of the President of the United States

White Paper Presentation
H. Gerry Schwartz, Consultant
Lori Tavasszy, Delft University of Technology and TNO Delft

10:30 a.m. Networking Break

11:00 a.m.	**Plenary Session 2: Preparing for a Climate Impact—Sea Level Rise**
	Presentation of First Case Scenario: Sea Level Rise Gordana Petkovic, Norwegian Public Roads Administration Rebecca Lupes, U.S. Department of Transportation
11:30 a.m.	**Breakout Session 1: Preparing for a Climate Impact—Sea Level Rise**
1:00 p.m.	Lunch
2:00 p.m.	**Plenary Session 3: Feedback from Breakout Session 1**
2:45 p.m.	**Plenary Session 4: Minimizing Disruption During Extreme Weather Events**
	Presentation of Second Case Scenario: Severe Storm and Flooding Jennifer Jacobs, University of New Hampshire André van Lammeren, Rijkswaterstaat
3:15 p.m.	**Breakout Session 2: Minimizing Disruption During Extreme Weather Events**
5:00 p.m.	**Plenary Session 5: Feedback from Breakout Session 2**
5:45 p.m.	**Wrap-Up Day 1**
6:00 p.m.	Cocktail Reception

Friday, June 17, 2016

8:30 a.m.	Welcome Coffee
9:00 a.m.	**Plenary Session 6: Welcome**
9:15 a.m.	**Plenary Session 7: Recovering from a Weather-Related Transport Disruption**
	Presentation of Third Case Scenario: Drought, Heat, and Extreme Temperatures Michael Meyer, WSP–Parsons Brinckerhoff Alan O'Connor, Trinity College Dublin
9:45 a.m.	**Breakout Session 3: Recovering from a Weather-Related Transport Disruption**
11:15 a.m.	Networking Break
11:45 a.m.	**Plenary Session 8: Feedback from Breakout Session**
12:30 p.m.	Lunch
1:30 p.m.	**Plenary Session 9: Knowledge Gaps and Research Requirements**
3:00 p.m.	**Plenary Session 10: Concluding Remarks** Magdalena Kopczynska, European Commission Kevin Womack, U.S. Department of Transportation Neil Pedersen, Transportation Research Board
3:30 p.m.	**Adjourn**

APPENDIX F

Symposium Attendees

Michele Acciaro
Kühne Logistics University
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Kathy Ahlenius
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Cheyenne, Wyoming, USA

Ángel Aparicio
Technical University of Madrid
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and
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Brussels, Belgium

Rachel Burbidge
Eurocontrol
Brussels, Belgium

Marina Bylinsky
Airports Council International Europe
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Alasdair Cain
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Marie Colin
Center for Studies and Expertise in Risks, Environment, Mobility and Planning (CEREMA)
Bron Cedex, France

Charlotte Coupé
Ministry of Ecology, Sustainable Development, and Energy
France

Clara de la Torre
European Commission, Directorate General for Research and Innovation
Brussels, Belgium

Susanne DesRoches
New York City Mayor's Office of Recovery and Resiliency
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