FTA RESEARCH

FEDERAL TRANSIT ADMINISTRATION

Flooded Bus Barns and Buckled Rails:

Public Transportation and Climate Change Adaptation

AUGUST 2011

FTA Report No. 0001
Federal Transit Administration

PREPARED BY

FTA Office of Budget and Policy

U.S. Department of Transportation

Federal Transit Administration

COVER PHOTO

Courtesy of Nashville MTA

DISCLAIMER

Flooded Bus Barns and Buckled Rails:

Public Transportation and Climate Change Adaptation

AUGUST 2011

FTA Report No. 0001

PREPARED BY

Tina Hodges, Program Analyst
Office Budget and Policy
Federal Transit Administration
U.S. Department of Transportation
1200 New Jersey Avenue, SE
Washington, DC 20590

SPONSORED BY

Federal Transit Administration
Office of Research, Demonstration and Innovation
U.S. Department of Transportation
1200 New Jersey Avenue, SE
Washington, DC 20590

AVAILABLE ONLINE

http://www.fta.dot.gov/research

Metric Conversion Table

SYMBOL	WHEN YOU KNOW	MULTIPLY BY	TO FIND	SYMBOL
LENGTH				
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
VOLUME				
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
^{3}	cubic yards	0.765	cubic meters	m^3
NOTE: volumes greater than 1000 L shall be shown in m^3				
MASS				
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
TEMPERATURE (exact degrees)				
^{o}F	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	^{o}C

REPORT DOCUMENTATION PAGE		*Form Approved* *OMB No. 0704-0188*
1. AGENCY USE ONLY	2. REPORT DATE August 2011	3. REPORT TYPE AND DATES COVERED Final
4. TITLE AND SUBTITLE Flooded Bus Barns and Buckled Rails: Public Transportation and Climate Change Adaptation		5. FUNDING/GRANT NUMBER n/a
6. AUTHOR Tina Hodges, Program Analyst, FTA Tina.Hodges@dot.gov		
7. PERFORMING ORGANIZATION NAME AND ADDRESS Federal Transit Administration Office of Budget and Policy U.S. Department of Transportation 1200 New Jersey Ave, SE Washington DC 20590		8. PERFORMING ORGANIZATION REPORT NUMBER FTA Report No. 0001
9. SPONSORING/MONITORING AGENCY NAME AND ADDRESS Federal Transit Administration Office of Research, Demonstration and Innovation U.S. Department of Transportation 1200 New Jersey Avenue, SE Washington, DC 20590 Website [http://www.fta.dot.gov/research]		10. SPONSORING/MONITORING AGENCY REPORT NUMBER
11. SUPPLEMENTARY NOTES		
12A. DISTRIBUTION/AVAILABILITY STATEMENT National Technical Information Service (NTIS), Springfield, VA 22161. Phone 703.605.6000, Fax 703.605.6900, Email [orders@ntis.gov]		12B. DISTRIBUTION CODE TRI-20

13. ABSTRACT

The objective of this project is to provide transit professionals with information and analysis relevant to adapting U.S. public transportation assets and services to climate change impacts. Climate impacts such as heat waves and flooding will hinder agencies' ability to achieve goals such as attaining a state of good repair and providing reliability and safety. The report examines anticipated climate impacts on U.S. transit and current climate change adaptation efforts by domestic and foreign transit agencies. It further examines the availability of vulnerability assessment, risk management, and adaptation planning tools as well as their applicability to public transportation agencies. The report provides examples of adaptation strategies and discusses how transit agencies might incorporate climate change adaptation into their organizational structures and existing activities such as asset management systems, planning, and emergency response. By focusing specifically on public transportation, and the unique assets, circumstances, and operations of that mode, the report supplements transportation sector wide studies whose scopes did not allow for more in-depth treatment of transit.

14. SUBJECT TERMS			15. NUMBER OF PAGES
Climate change, adaptation, public transportation, transit, asset management, safety, state of good repair, risk management, weather, flooding, heat, sea level rise, and precipitation			124
			16. PRICE CODE
17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
Unclassified	Unclassified	Unclassified	

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

ACKNOWLEDGEMENTS

Tina Hodges served as the primary author for this report. Dan Drais served as the primary editor. Katie Grasty, Kyle Nicholson, and Brian Smart were contributing authors. Peter Chipman, Eric Eidlin, Ryan Frigo, Carlos Garay, Keith Gates, Charles Goodman, Aaron James, Matthew Lesh, Pam Peckham, Jeff Price, Katherine Mattice, Maya Ray, Trina Reese, John Sprowls, Jarrett Stoltzfus, Robert J. Tuccillo, and Joanne Weinstock also contributed to the report.

The authors would like to thank the individuals who provided interviews and consultations: Thomas Abdallah, Heather Allen, Leith Al-Nazer, Peter Brown, Virginia Burkett, Dan Blair, Dana Coyle, Richard Devylder, Brenda Dix, Projjal Dutta, Tom Fisher, Richard Gerhart, David Gillespie, Shellie Gin, Eric Hesse, Rick Kindig, Cris Liban, Mark Mauer, Kurtis McCoy, Michael Meyer, Robert Paaswell, Joe Recker, Carol Roalkvam, Matthias Ruth, Sandy Salisbury, Randolph Sykes, Missy Stults, and Helen Woolston. Any errors are those of the authors alone. We would also like to thank our colleagues at the Federal Highway Administration who provided helpful input to the report: Robert Hyman, Robert Kafalenos, and Rebecca Lupes.

A special thank you to the team from HDR and Jack Faucett Associates that conducted the GIS mapping: Francisco Brilhante, Daphne Federing, Kate Ko, Mark Korpus, Michael Lawrence, Lewison Lem and Mike McMahon. Finally, much appreciation to those who provided the climate science data for the GIS mapping: Virginia Burkett, Ken Kunkel, Jerry Meehl, Mike Squires, Michael Wehner, and Jeremy Weiss. A special thank you to Wendy Teague of the Center for Urban Transportation Research, University of South Florida, for graphic design and layout of the report.

ABSTRACT

The objective of this project is to provide transit professionals with information and analysis relevant to adapting U.S. public transportation assets and services to climate change impacts. Climate impacts such as heat waves and flooding will hinder agencies' ability to achieve goals such as attaining a state of good repair and providing reliability and safety. The report examines anticipated climate impacts on U.S. transit and current climate change adaptation efforts by domestic and foreign transit agencies. It further examines the availability of vulnerability assessment, risk management, and adaptation planning tools as well as their applicability to public transportation agencies. The report provides examples of adaptation strategies and discusses how transit agencies might incorporate climate change adaptation into their organizational structures and existing activities such as asset management systems, planning, and emergency response. By focusing specifically on public transportation, and the unique assets, circumstances, and operations of that mode, the report supplements transportation sector wide studies whose scopes did not allow for more in-depth treatment of transit.

EXECUTIVE SUMMARY

Climate change impacts are occurring now and will increase in the future [1]. Concentrations of heat-trapping gases in the atmosphere have surged above levels seen for the past 800,000 years and are on track to increase threefold [2]. Aggressive action to reduce greenhouse gas emissions will lower the severity of climate change impacts. Yet the amount of long-lived emissions already in the atmosphere means that a significant level of climate change is inevitable. As such, an effective response requires both reducing emissions and adapting to changes already in the pipeline [3].

Impacts will vary, but all regions and public transportation systems, large and small, will be affected. The most disruptive near-term impact is likely to be intense rainfall that floods subway tunnels and low-lying facilities, bus lots, and rights-of-way. Heat waves will stress materials, buckle rails, and jeopardize customer and worker safety and comfort. In the longer term, rising sea-levels, compounded by worsening storm surges, will threaten assets in many coastal areas. Landslides, heavy snowfall, wildfires, droughts, and power blackouts also pose threats. The increased frequency of extreme events (such as heat waves and severe storms) will be more challenging to manage than gradual effects such as a steady rise in average temperatures. In addition, of low probability but high risk, there is a potential for abrupt climate change impacts, such as rapid ice sheet collapse and abrupt sea-level rise.

Climate impacts on transit assets will hinder agencies' ability to achieve goals such as attaining a state of good repair and providing reliability and safety, which may then impact ridership. Persons with disabilities, older adults, and low-income individuals—groups who disproportionately depend on public transportation—will suffer disproportionately from disruptions and degradation in service. Transit agencies will also be called upon to provide evacuation services in response to more frequent extreme events.

While it is not possible to link individual weather events to climate change, multiple recent incidents are consistent with observed climate trends. Since scientists project the same types of events to become more frequent and severe, the transit impacts associated with this extreme weather offers illustrations. In Vicksburg, Mississippi, river flooding from heavy rains in spring 2011 forced transit providers to shutter routes and relocate paratransit operations [4]. In New York, record snowfall stranded city buses in 2010 while heavy rainfall in 2007 shut down 19 major segments of the subway system, flooding the third rail and affecting two million customers [5]. Flooding of the Cumberland River swamped Nashville MTA's bus lot, maintenance facility, and administrative offices [6]. Heat waves in New Jersey and Los Angeles stretched overhead catenary, disrupting power supply to rail vehicles. During an East Coast heat wave, the Washington Metro and the Boston "T" experienced rail kinks that caused them to slow trains and to remove and replace enlarged sections of rail [7]. Electronic train control equipment and farebox machines in Portland overheated during high-heat days in the historically mild

Pacific Northwest [8]. Hurricane Katrina's storm surge devastated transit agencies along the Gulf Coast, flooding buses and depositing debris [9].

Risk assessment tools developed by governments and non-profits offer transit agencies guidance on how to prioritize climate risks by assessing the likelihood of occurrence and the magnitude of consequence. Key aspects include assessing criticality of transit assets to regional economy, accessibility and emergency evacuation, and identifying thresholds above which impacts are severe (e.g., inches of rain per hour before drainage systems are overwhelmed). Steps generally include 1) identify current and future climate hazards; 2) characterize the risk of climate change on agency infrastructure and operations; 3) link strategies to agency organizational structures and activities; 4) implement adaptation plans; and 5) monitor and reassess. Taking a risk management approach mitigates risk without expensively over-engineering assets. A flexible strategy takes action now but reassesses as new information becomes available—responding to multiple layers of uncertainty regarding future levels of greenhouse gas emissions, how climate hazards will impact transit, and the effectiveness of adaptation strategies [10].

While adaptation is a new issue for the transit industry, a handful of agencies have already begun work in the area. New York State Metropolitan Transportation Authority (MTA) partnered with Columbia University as well as state and local efforts to assess vulnerabilities, finding that a 100-year flood with a 4-foot rise in sea-level would flood a large fraction of Manhattan subways, including virtually all of the tunnels crossing into the Bronx beneath the Harlem River and the tunnels under the East River [11]. Responding to heavy downpours already being experienced, MTA built raised ventilation grates to prevent stormwater incursion. Wave Transit in Mobile, Alabama, participated in a criticality analysis of its assets as a first step in assessing climate vulnerability. Los Angeles Metro and New Jersey Transit each began climate change risk assessments in 2011. Portland's TriMet participated in a cross-sectoral adaptation initiative with stakeholders from across the Willamette Valley region it serves. The metropolitan planning organization for the San Francisco Bay Area is participating in a study of sea-level rise impacts on transportation infrastructure. Maps from the study show transit stations impacted as today's 100-year flood becomes tomorrow's high tide [12].

Internationally, London's transit agency mapped climate risks and integrated climate adaptation into its asset management system. Their major new rail construction project, Crossrail, includes flood protection measures anticipating higher risks from climate change. London's iconic red buses now have white roofs to reflect heat [13]. A new commuter rail link in Istanbul, Turkey, was built to withstand a one-in-ten-thousand-year flood with three feet of sea-level rise. Asian transit systems built to handle monsoon rains far heavier than even the most pessimistic climate change scenarios for the United States provide an upper-bound example of flood engineering standards [14].

There are four broad categories of overall adaptation strategies: maintain and manage, strengthen and protect, enhance redundancy, and abandon infrastructure in extremely vulnerable areas. Strategies for responding to flooding in particular include moving vehicles and other mobile assets out of harm's way, preventing water incursion, improving drain maintenance and debris clearance, increasing pumping capacity, and strengthening or raising bridges. Capturing stormwater with natural ecosystem approaches also reduces flooding: Kansas City's new bus rapid transit system includes rain gardens to collect stormwater, while San Francisco MTA's headquarters boasts a green roof. Strategies for responding to high heat include the use of shade shelters, efficient air conditioning, heat-resistant or heat-reflective materials, and heat management plans for worker and customer safety. During extreme weather events, effective communications with transit customers manages expectations, provides critical safety information, and allows travelers to adjust their schedules. Some adaptation strategies will pay for themselves even without projected climate impacts and have multiple benefits.

Implementing adaptation strategies requires linking them to transit agency organizational structures and activities. Asset management systems offer a streamlined framework for identifying climate risks, tracking climate impacts on asset condition, and incorporating adaptation strategies into capital plans and budgets. Emergency preparedness and response plans become all the more important as extreme weather events increase. Including climate change considerations in the federally mandated state and metropolitan transportation planning process means better data about flood and other risks, and improved decisions about infrastructure location and capital investment prioritization. The Council on Environmental Quality has issued draft guidance that would require consideration of climate adaptation in National Environmental Policy Act (NEPA) documents. State governments such as California and Washington recently began requiring inclusion of adaptation in state environmental documents. Strategies such as wetlands mitigation typically included in transportation projects will need to be designed for future sea-level rise and flooding conditions. Performance measures of asset conditions and quality of service can reveal whether adaptation strategies are improving the resilience of transit assets to climate change impacts.

Factors for success in transit adaptation efforts so far include: a high-level push from outside the agency, the embedding of climate change into existing work streams instead of a special system, a champion or central point person for coordination, interdisciplinary seminars with engaging narratives, coordination with other infrastructure providers and government entities, and reliance on existing climate data from reputable sources.

Climate change adaptation is essentially responsible risk management. It involves planning for system preservation and safe operation under current and projected conditions, recognizing that hazard mitigation costs less than the damage from inaction. Adapting to climate change impacts will require interdisciplinary efforts among engineers, planners, frontline maintenance and operation staff, strategic planners, emergency response experts, and others. It is a long-term effort that will require not so much doing entirely different things, but doing some of the same things in a different way. We hope this report provides a useful departure point to help place the transit industry on the track to climate resilience.

SECTION 1

Introduction

Public transportation provides vital services throughout the United States, increasing mobility and enhancing the quality of life for millions of Americans. Public transit operators provide 10 billion trips each year in the United States, helping commuters to get to work, customers to reach businesses, rural residents to access services, and persons with disabilities and older adults to get around in their communities. Transit also brings long-term economic benefits, promotes efficient land use, and provides an environmentally friendly alternative to driving.

Yet public transportation faces a new stressor, climate change, that to date has not been widely discussed in the industry. Climate change impacts such as heavier downpours, rising sea levels, heat waves, droughts, and wildfires pose threats to public transportation assets and services. Climate-related extreme weather is already being felt in the United States and will increase in the future [15].

Subway tunnels, busways, rail tracks, and maintenance facilities are vulnerable to increased flooding from more frequent and intense rain storms, rising sea level, and powerful storm surges. Extreme heat can deform rail tracks, stress materials, reduce asset life, and jeopardize customer and worker health and safety. Transit dependent populations are particularly vulnerable.

Already challenged by maintenance backlogs on tight budgets, climate change brings additional environmental stressors that deteriorate assets, requiring more maintenance and expense. However, the existing challenges also present an opportunity: when undertaking rehabilitation projects to bring transit assets up to a state of good repair, incorporating climate change adaptive strategies into the design saves money long term in avoided damages and costs less than retrofitting later.

Reducing greenhouse gas emissions will lower the severity of climate change impacts over the long-term. However, even with aggressive action immediately to reduce emissions going forward, past emissions will continue to cause climate change impacts for many years. An effective response to climate change must therefore include both mitigation (reducing greenhouse gas levels) and adaptation (reducing the vulnerability of human and natural systems to climate impacts).

Public transportation must play a key role in both. Transit already provides critical mitigation benefits by offering a low-emissions alternative to driving and by facilitating compact land use patterns that enable less driving [16]. Several transit agencies have already taken additional greenhouse gas mitigation actions, as described in Transit Cooperative Research Program (TCRP) Synthesis Report 84: *Current Practices in Greenhouse Gas Emissions Savings from Transit*. Yet public transportation must also adapt to the impacts of climate change, an area that has received less attention.

Two major studies significantly advanced the transportation adaptation field. The U.S. Department of Transportation (U.S. DOT) *Gulf Coast Study* examined the consequences of climate change impacts on transportation infrastructure in the Gulf Coast region. Transportation Research Board (TRB) Special Report 290: *Potential Impacts of Climate Change on U.S. Transportation* found that climate change would impact all transportation modes and geographic regions and recommended strategic, risk-based approaches to managing, redesigning and retrofitting transportation infrastructure to adapt to impacts.

While these reports laid an important foundation, their broad scope prevented them from focusing in-depth on transit-specific issues. To date, there has been no nationwide assessment of climate change impacts on U.S. public transportation and consequent adaptation. This report seeks to start to fill that gap. It builds upon previous transportation sector-wide adaptation studies by looking specifically at the unique assets, services, and organizational structures of public transportation agencies:

- Transit agencies use a vast array of *assets* to operate a variety of systems (buses, subways, light rail, commuter rail, ferries) and supporting infrastructure including track, platforms, stations, catenary lines and poles, power distribution facilities, signal control systems, park-and-ride structures and lots, bridges, switches, vehicles (buses, vans, trains and ferries), yards, maintenance facilities, fueling stations, HOV lanes, and so on. Many of these assets are unique to public transportation.
- Transit *service* is unique in its importance to low-income families, persons with disabilities, youth, and older adults without other transportation options.
- Also unusual, if not unique, is the variety of transit *systems and infrastructure* across the country. Unlike much of the Interstate Highway System, which was built to largely uniform standards over a relatively short time span, American transit systems developed over a century and a half with varying design, engineering and operating standards. For transit, network effects are even more important as transit networks tend to be much smaller and less redundant than highway and road networks—in other words, a barrier on just one link can shut down major segments of the whole network. Finally, transit agencies may or may not even own the right-of-way they use: bus right-of-way is typically owned and maintained by others, while rail agencies typically own and maintain their own tracks (except for some commuter rail track).

The Federal Transit Administration (FTA) recognizes the importance of climate change adaptation. FTA is responsible for the stewardship of billions of dollars in taxpayer investment in public transportation assets serving millions of Americans. Knowledge of the impacts of climate change on transit and information on how best to respond to the challenge is critical to protecting these assets, the mobility they provide, and the safety of travelers during extreme weather events and evacuations. In addition, FTA grant programs help many communities build new transit infrastructure and rehabilitate older systems. Better awareness of the future environmental stressors these assets will encounter is instrumental to sound planning and design as well as to the nation's ability to bring transit assets up to and maintain a state of good repair over the long-term.

Furthermore, the White House, through its Council on Environmental Quality (CEQ), has directed Federal agencies to conduct climate adaptation planning. It has directed Federal agencies to assess the impact of climate change on agency missions and programs, commit to adaptation actions, submit adaptation plans, and monitor progress. CEQ recommends that government agencies "adopt integrated approaches" and explains that "adaptation should be incorporated into core policies, planning, practices, and programs whenever possible" [17]. CEQ has also established a number of guiding principles for adaptation planning (see page 11).

As with other challenges facing the transit industry, FTA seeks to be a Federal partner with the transit industry—providing technical assistance and structuring FTA programs to provide local flexibility in funding assistance to best meet adaptation goals. Public transportation agency grantees may already take advantage of the broad eligibility of FTA's major capital programs to fund rehabilitation, acquisition, and construction that increase the resilience of transit assets and services to the impacts of climate change. Planning activities such as climate change vulnerability and risk assessments are also eligible under FTA's current statewide and metropolitan transportation planning programs. Even so, this is a relatively new area for most transit agencies. For that reason—compounded by the complexity of climate science data and the competition of other priority issues for attention—most transit agencies have not addressed climate adaptation.

That inattention reflects a critical misunderstanding because climate change adaptation should not be outside the regular purview of transit management. Climate change adaptation is, essentially, responsible risk management. Given that adaptation strategies offer the opportunity to avoid catastrophic losses through cost-effective preventive measures, the issue falls squarely within the mainstream duties of transit agency management. Indeed, some transit agencies have already begun adaptation work and can provide valuable examples. FTA and the transit industry can learn from early leaders.

For this report, the research team first reviewed literature related to climate change, adaptation, and transportation with an eye towards interpreting this information for maximum relevance to the transit industry. The team also learned about on-the-ground experiences by consulting domestic and foreign transit agencies and gleaned more information through interviews with transit agency representatives, academics, and other experts from a variety of fields.

The report is organized into four substantive chapters with four supporting case studies. Section 2 examines anticipated climate change impacts on U.S. transit. It relies on the published, peer-reviewed, consensus-based scientific literature for climate science, primarily from the U.S. Global Change Research Program (USGCRP) 2009 National Assessment, which includes downscaling of global models to the eight major U.S. geographical regions. In forecasting impacts on transit assets and services, the report relies on expert interviews, the transportation literature, and transit agency experiences with the type of extreme events projected to become more common as the climate changes.

Section 3 synthesizes existing vulnerability assessment, risk management, and adaptation planning tools and explains their application to public transportation agencies. It then summarizes the state of the practice in adaptation assessment and planning and describes transit industry efforts so far.

Section 4 describes strategies for adapting transit assets and operations to climate change impacts. This chapter relies primarily on actual agency experiences responding to the same kinds of extreme weather events that will become more common as the climate changes. It also highlights a few examples of domestic and international strategies implemented specifically for climate adaptation purposes.

Section 5 links adaptation strategies to transit agency organizational structures and activities. It discusses implementation considerations and how transit agency operations can incorporate climate change adaptation considerations.

Case studies illustrate the report's key points and describe specific transit agency experiences. The first shows how the New York State Metropolitan Transportation Authority partnered with state and local efforts, leveraged partnerships with climate scientists, and assessed impacts to its infrastructure. From Mobile, Alabama, we get an example of how a criticality assessment can be part of adaptation planning. The Los Angeles case study shows how the region's main transit provider included a vulnerability assessment as part of its broader sustainability efforts. Finally, Transport for London's incorporation of climate change adaptation considerations into its asset management system illustrates a crucial adaptation strategy. Examples from other transit agencies are also included throughout the report.

This report does not attempt to provide a comprehensive treatment of public transportation and adaptation. The topic is too broad and the available information is incomplete. Rather, this report intends to start a discussion in the transit industry on this vital subject, and to provide transit-specific information to help advance that conversation.

Background on Climate Change

Excerpts from U.S. Global Change Research Program, *Global Climate Change Impacts in the United States*, 2009:

> *Observations show that warming of the climate is unequivocal. The global warming observed over the past 50 years is due primarily to human-induced emissions of heat-trapping gases. These emissions come mainly from the burning of fossil fuels (coal, oil, and gas), with important contributions from the clearing of forests, agricultural practices, and other activities.*
>
> *In projecting future conditions, there is always some level of uncertainty. For example, there is high degree of confidence in projections that future temperature increases will be greatest in the Arctic and in the middle of continents. For precipitation, there is high confidence in projections of continued increases in the Arctic and sub-Arctic (including Alaska) and decreases in the regions just outside the tropics, but the precise location of the transition between these is less certain. At local to regional scales and on time frames up to a few years, natural climate variations can be relatively large and can temporarily mask the progressive nature of global climate change. However, the science of making skillful projections at these scales has progressed considerably, allowing useful information to be drawn from regional climate studies.*

Mitigation + Adaptation = A Comprehensive Climate Strategy

Reducing greenhouse gas emissions will lower the severity of climate change impacts over the long-term. However, even with aggressive action immediately to reduce emissions going forward, past emissions will continue to cause climate change impacts for many years. Thus, adaptation and mitigation must work hand in hand. While **mitigation** works to lessen future impacts by taking steps to reduce greenhouse gas emissions today, **adaptation** focuses on making the built and natural environment more resilient against current and predicted future impacts from past emissions. As shown in Figure 1-1, some strategies serve both ends.

Definition of Key Terms:

Mitigation: An intervention to reduce the causes of climate change by reducing greenhouse gas emissions or enhancing sinks for capturing greenhouse gas emissions.

Adaptation: Adjustments to reduce the vulnerability of natural systems and human communities to existing or predicted climate change impacts.

Vulnerability: The degree to which a system is susceptible to, or unable to cope with, adverse effects of climate change, including climate variability and extremes.

Resilience: A capability to anticipate, prepare for, respond to, and recover from significant multi-hazard threats with minimum damage to social well-being, the economy, and the environment.

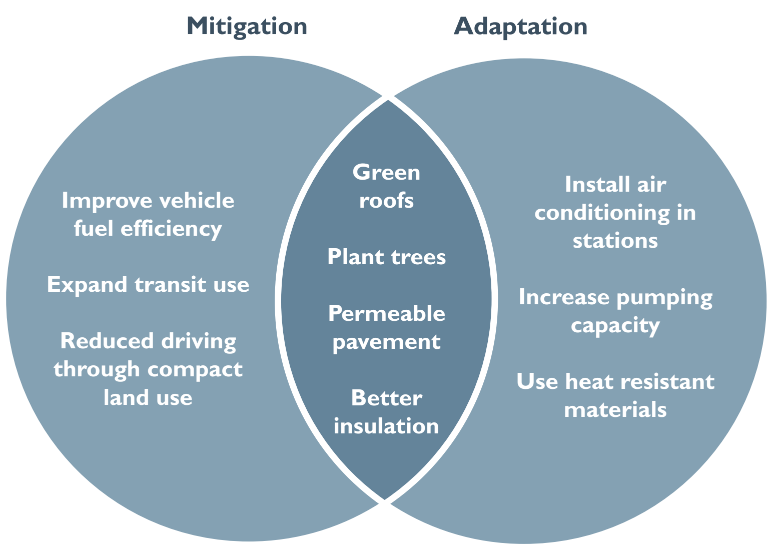


Figure 1-1

Some Adaptation Strategies Also Serve Mitigation Ends

Text adapted from National Oceanic and Atmospheric Administration (NOAA), "Adapting to Rising Tides: Mitigation + Adaptation = A Comprehensive Climate Strategy," *www.risingtides.csc.noaa.gov.*

Definitions of vulnerability and resilience from: National Research Council, *Adapting to the Impacts of Climate Change*, America's Climate Choices: Panel on Adapting to the Impacts of Climate Change, 2010.

Guiding Principles for Adaptation

Excerpted from: The White House Council on Environmental Quality, *Progress Report of the Interagency Climate Change Adaptation Task Force: Recommended Actions in Support of a National Climate Adaptation Strategy*, October 2010.

Adopt integrated approaches. Climate change adaptation strategies should be integrated into core policies, planning, practices, and programs.

Prioritize the most vulnerable. Adaptation plans should prioritize helping people, places, and infrastructure that are most vulnerable to climate impacts. They should also be designed and implemented with meaningful involvement from all parts of society. Issues of inequality and environmental justice associated with climate change impacts and adaptation should be addressed.

Use best-available science. Adaptation should be grounded in best-available scientific understanding of climate change risks, impacts, and vulnerabilities. Adaptive actions should not be delayed to wait for a complete understanding of climate change impacts, as there will always be some uncertainty. Plans and actions should be adjusted as our understanding of climate impacts increases.

Build strong partnerships. Adaptation requires coordination across multiple sectors, geographical scales, and levels of government and should build on the existing efforts and knowledge of a wide range of stakeholders. Because impacts, vulnerability, and needs vary by region and locale, adaptation will be most effective when driven by local or regional risks and needs.

Apply risk-management methods and tools. A risk management approach can be an effective way to assess and respond to climate change because the timing, likelihood, and nature of specific climate risks are difficult to predict. Risk management approaches are already used in many critical decisions today (e.g., for fire, flood, disease outbreaks), and can aid in understanding the potential consequences of inaction as well as options for risk reduction.

Apply ecosystem-based approaches. Ecosystems provide valuable services that help to build resilience and reduce the vulnerability of people and their livelihoods to climate change impacts. Integrating the protection of biodiversity and ecosystem services into adaptation strategies will increase resilience of human and natural systems to climate and non-climate risks, providing benefits to society and the environment.

Maximize mutual benefits. Adaptation should, where possible, use strategies that complement or directly support other related climate or environmental initiatives, such as efforts to improve disaster preparedness, promote sustainable resource management, and reduce greenhouse gas emissions including the development of cost-effective technologies.

Continuously evaluate performance. Adaptation plans should include measurable goals and performance metrics to continuously assess whether adaptive actions are achieving desired outcomes. In some cases, the measurements will be qualitative until more information is gathered to evaluate outcomes quantitatively. Flexibility is critical to building a robust and resilient process that can accommodate uncertainty and change.

SECTION
2

Impacts

"Every mode of transportation and every region in the United States will be affected as climate change poses new and often unfamiliar challenges to infrastructure providers."

- Transportation Research Board Special Report 290

Four climate change impacts affect public transportation assets and services:

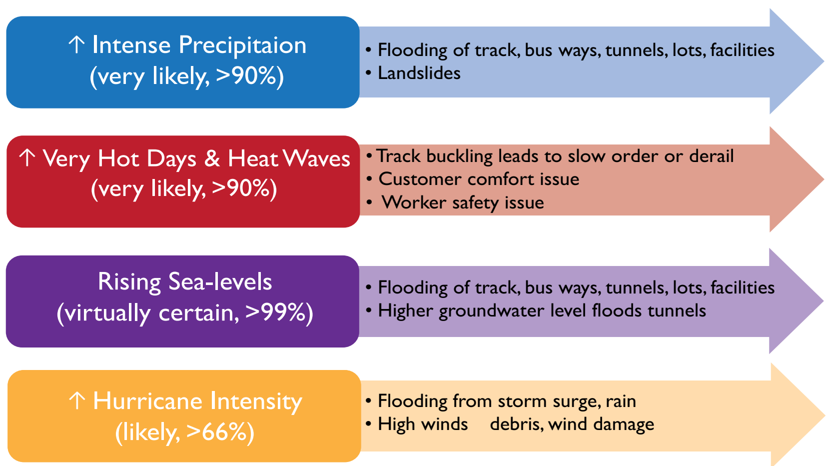
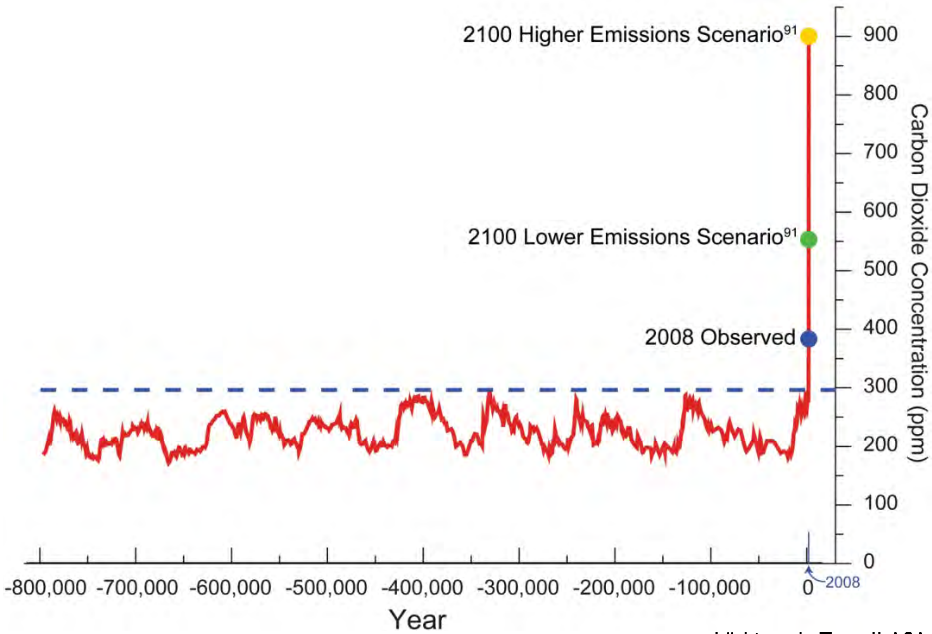


Figure 2-1
Four Main Transit Impacts

The severity of climate-related impacts depends on the level of greenhouse gases in the atmosphere.

Emissions Scenarios

The Intergovernmental Panel on Climate Change (IPCC) developed a set of emissions scenarios based on economic expansion, population growth, and energy mix and intensity. These have been extensively used to explore the potential for future climate change. Most studies, including those cited here, use a "high" and "low" scenario based on the IPCC scenarios. These scenarios do not encompass the full range of possible futures. Recent emissions are actually above the highest emissions scenario developed by the IPCC [18]. There are also possible lower emissions paths since even the "low" scenario does not include implementation of policies to limit climate change or stabilize atmospheric concentrations of heat-trapping gases [19]. Earlier cuts in emissions would have a greater effect in reducing climate change than comparable reductions made later because greenhouse gas emissions warm the planet throughout their long lifetimes.



Lüthi et al.; Tans; ILASA

Figure 2-2

800,000 Year Record of Carbon Dioxide Concentration

Analysis of air bubbles trapped in an Antarctic ice core extending back 800,000 years documents the Earth's changing carbon dioxide concentration. Over this long period, natural factors have caused the atmospheric carbon dioxide concentration to vary within a range of about 170 to 300 parts per million (ppm). Temperature-related data make clear that these variations have played a central role in determining the global climate. As a result of human activities, the present carbon dioxide concentration of about 385 ppm is about 30 percent above its highest level over at least the last 800,000 years. In the absence of strong control measures, emissions projected for this century would result in the carbon dioxide concentration increasing to a level that is roughly 2 to 3 times the highest level occurring over the glacial-interglacial era that spans the last 800,000 or more years.

Source: U.S. Global Change Research Program, *Global Climate Change Impacts in the United States*, June 2009

Public transportation agencies already have experience dealing with weather-related impacts such as heavy rain and heat waves. What is changing is the increased intensity and frequency of extreme events. Sea-level rise will pose new challenges and exacerbate existing threats such as storm surge and degradation of protective features such as wetlands and barrier islands. Environmental conditions may also reach thresholds above which asset and service degradation is significant. The examples below include some of the trigger levels, such as inches of rain above which drainage systems are overwhelmed and ambient temperatures above which rail warping is more likely. These thresholds tend to vary by agency, though, as differing design standards are in place.

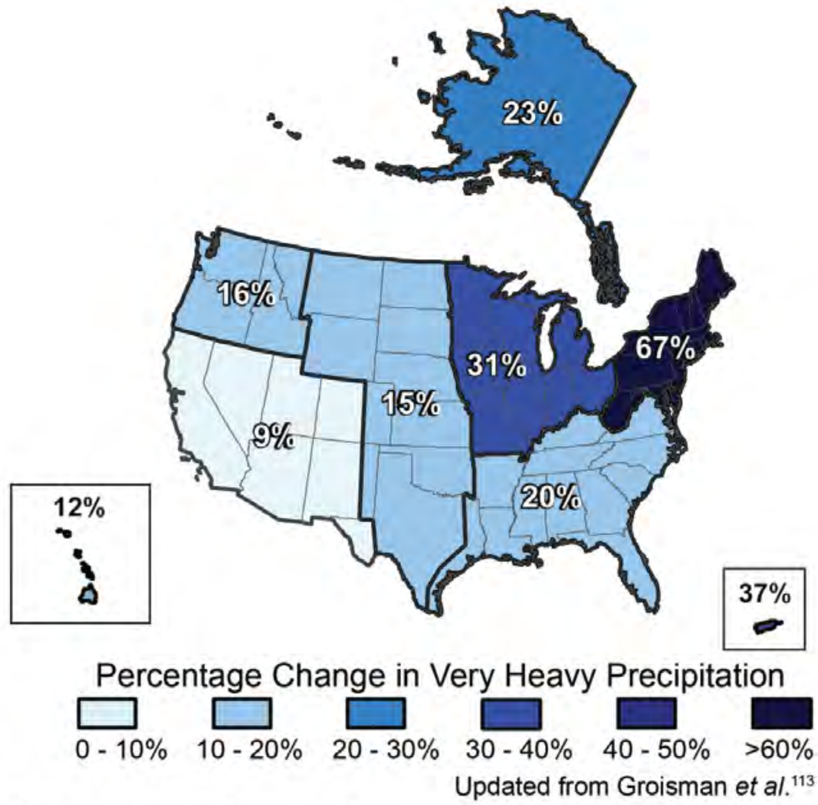
Precipitation

Figure 2-3 shows a climate change impact that is already occurring – increases in the amount of rain falling in the heaviest downpours. Note that the biggest impact over the last 50 years, a 67 percent increase, is in the Northeast, home to some of the country's largest and oldest rail transit systems.

"The biggest increases in very heavy precipitation over the last 50 years have been in the Northeast, home of some of the largest and oldest rail transit systems."

Figure 2-3

Observed Increases in Amounts of Very Heavy Precipitation (1958-2007)



The map shows the percentage increases in very heavy precipitation (defined as the heaviest 1 percent of all events) from 1958 to 2007 for each region. There are clear trends toward more very heavy precipitation for the nation as a whole, and particularly in the Northeast and Midwest.

Source: U.S. Global Change Research Program, *Global Climate Change Impacts in the United States*, June 2009

The trend is very likely to continue as warmer air holds more water vapor evaporating from the world's oceans and land surface. The lightest precipitation is projected to decrease while the heaviest downpours are likely to worsen. Rain events that now occur only once every 20 years are projected to happen every four to 15 years, depending on location, and dump 10 to 25 percent more rain [20]. In addition, in the Northeast, the duration of extreme rain events (defined as more than two inches per day) is projected to increase by one to 1.5 days by 2040-2070 [21].

Widespread increases in heavy precipitation events have occurred even in places where total rain amounts have decreased. Some areas, such as the South and much of the West, will experience more intense precipitation, but will overall become drier as average annual precipitation decreases. Other areas, such as northern areas, will experience more intense precipitation as well as an increase in average annual rainfall [22]. Increases in the occurrences of both droughts and floods are projected.

Flooding

Increased heavy precipitation is already causing impacts on transit systems. In August 2007, three and a half inches of rain fell in New York City in two hours. The heavy rain overwhelmed the regional drainage systems and Metropolitan Transportation Authority (MTA) pumps that are designed to handle no more than 1.75 inches per hour (see Figure 2-4). MTA had to cut off power when water levels reached the electrified third rail. The storm disrupted 19 major segments, forcing the shutdown of much of the subway system and affecting over two million transit users. The event also required MTA to remove 16,000 pounds of debris and to repair or replace induction stop motors, track relays, resistors, track transformers, and electric switch motors. Columbia University's climate change experts project that the threat of flooding in the MTA system will only increase due to sea-level rise, extreme weather events, and a disappearance of permeable land in the region [23]. MTA estimates that about 30 stations in its system are vulnerable to flooding from major storm events [24].

During heavy rain storms, the volume of water can exceed the capacity of street stormwater drains and systems, leaving no capacity to accommodate water pumped out of subway tunnels. In many cities, combined sewer-stormwater systems, and their frequent overflows, compound the problem.

Climate change also affects small transit agencies in the interior of the country.

Smaller and non-coastal transit agencies are not immune to climate change impacts. Heavy rains in Nashville in May 2010 caused the Cumberland River to flood its banks, inundating transit agency offices, maintenance facilities, and bus storage lots (see Figure 2-5). Most rolling stock was moved to other locations, but due to the rapidly rising water, workers were unable to salvage all of the rolling stock and maintenance equipment. Approximately 40 paratransit vans (out of a fleet of 62) and 40 transit buses (out of a fleet of 143) were flooded. Service was suspended for four days while staff made herculean efforts to clean facilities that had been under up to ten feet of water and acquire loaned buses [25]. Nashville is not unique; many transit bus storage lots and facilities are located on low-lying ground, such as Honolulu's major bus facility and some of Portland's park and ride lots [26].

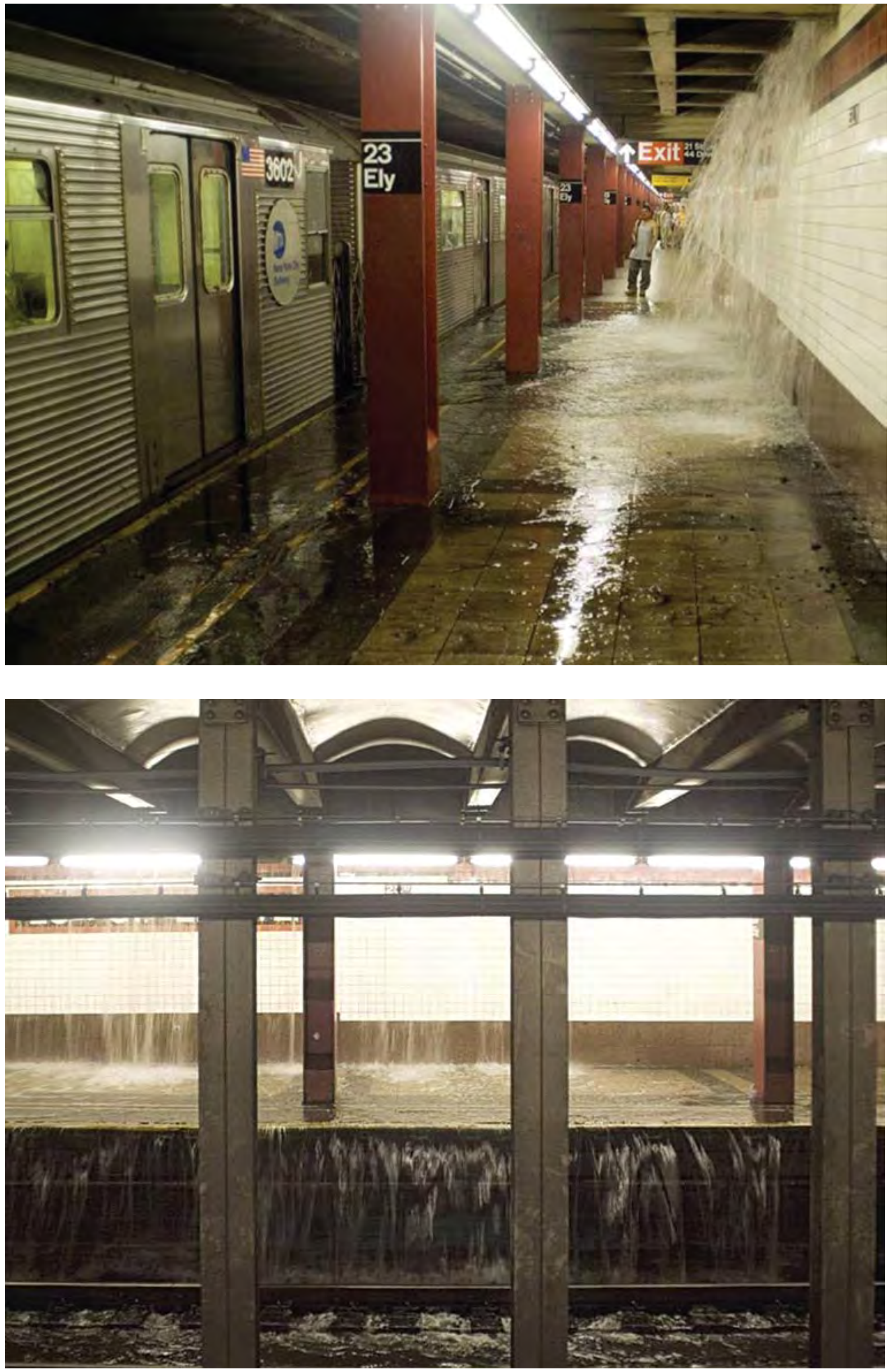


Figure 2-4

New York City Subway Flooding on August 8, 2007

Storm water floods the tracks and the electrified third rail, necessitating power shut-off. The storm disrupted 19 major segments, forcing the shutdown of much of the system and affecting over 2 million transit users.

Photos courtesy of New York City Transit

Figure 2-5

Flooding of Nashville MTA Property, May 2010

Photos courtesy of Nashville MTA

The Mississippi River has experienced two 500-year floods in the last 18 years, in 1993 and 2011 [27]. This flooding from heavy spring rains and snowmelt is projected to become more common as the climate changes. The following gives a snapshot of just some of the transit-related impacts of the 2011 Mississippi River flooding on one particular day [28]:

- NRoute (Vicksburg)—has closed one route in the lower Vicksburg area. The casinos' route will be closed by next week. Only two casinos remain open; however, they are expected to close soon. Casinos that are closed are expected to be closed for 30 days. All vehicles are safe from the flood waters. NRoute is still on standby with their local Emergency Management Agency (EMA).
- Claiborne County Human Resource Agency (Port Gibson) (paratransit provider)—is still on standby with their local EMA. They have not had to relocate. All vehicles are safe from flood waters. If waters reach the agency, they will relocate to the local DHS building along with the vehicles. Routes that normally run the Hwy 61 corridor are being rerouted to Hwy 27. The agency is still on standby with their local EMA.
- Mississippi Christian Family Services (Rolling Fork)—has reserved 11 spaces with NRoute in Vicksburg, MS to relocate their buses if needed. Work is ongoing to prevent the levee from breaking. The agency is still on standby.
- Natchez Transit System (City of Natchez)—is still on standby with the local EMA. Flood waters are having an impact on the power grids. Entergy is working to divert further impact. Power was shut off in parts of Natchez on yesterday. Natchez Transit was without power; however, power has been restored.
- Warren County Association for Retarded Citizens (Vicksburg) (paratransit)—is preparing to relocate. The facility and buses will be ok; however, roads leading to the facility will be covered with water. The program director stated that arrangements have been made with the City of Vicksburg to relocate to the city Pavilion. The agency has been assisting in the community with relocation efforts.

As the snapshot above shows, buses operating on flooded streets may need to reroute or suspend service to hard hit areas. Power outages can also disable transit service. And not only municipal transit providers are impacted—storms and flooding can disable paratransit services, with especially serious consequences for users who have no alternative transportation.

As heavy rains swell rivers and streams, water and debris can scour bridge supports, degrading the asset and potentially shortening its useful life.

Track areas supported by gravel ballast tend to drain better than paved track areas as gravel is a pervious surface. Degradation of material or soil erosion directly adjacent to paved track areas can also be a problem in heavy rains [29].

Flooding may also cause signal track circuit failure, which London Underground reports as a problem [30].

Bus accident rates could be expected to increase as the intensity of precipitation increases. However, only a small portion of bus accidents currently are related to the weather [31].

Costs from flooding can be considerable. As an example, in 1996, heavy rains raised the level of Boston's Muddy River, flooding a tunnel entrance to the city's subway system. The damage closed a busy subway line for several weeks and cost roughly $75 million [32].

Damage from a 1996 flood of a tunnel entrance to Boston's "T" shut down a busy subway line for several weeks and cost roughly $75 million.

Landslides

Landslides are a particular concern in cities with steep hillsides and precipitation patterns that saturate soils. Portland, Oregon, experienced severe landslides during flood events in 1964 and 1996 that were attributed to heavy snow precipitation in upper elevations followed by intense, warmer-temperature rain that quickly melted snowpack and saturated soils. While projected increases in annual precipitation in the Pacific Northwest are relatively small, changes in seasonal variations of precipitation are likely, with more of the annual precipitation falling in the winter, and more falling as rain rather than snow, reducing water storage in the form of winter snowpack. Coupled with earlier snowmelt, these projected conditions may result in the saturated soils and higher stream flows that caused the earlier landslides [33].

In Honolulu, the stability of the island's steep slopes is threatened under heavy rainfall. Landslides that require buses to redirect routes or turn back occur around once a year currently, but will likely become more frequent if the intensity of rainfall increases [34].

New York MTA also projects more frequent embankment failures under increased heavy precipitation conditions projected as the climate changes [35]. The San Francisco Bay Area, Coastal California and Los Angeles have all experienced landslides due to heavy rainfalls over the past decade.

Heavy snowfall

While warming temperatures shorten the season for snowfall and ice, an increase in heavy precipitation can mean that snow storms pile up higher levels of snowfall from a single storm than in the past, disrupting transit services. For instance, in Washington, DC, a snowfall of more than eight inches covers the electrified third rail, ices over the above ground tracks, and renders rail yards impassable. The agency's snow removal equipment for the rails cannot run in these conditions because it is powered by the third rail. For safety reasons, as well as to protect the railcars, Washington Metro suspends above ground rail service in major snow-storms and serves only underground stations [36]. New York MTA reports that it may take up to 12 hours for bus operations to fully recover from a snow storm, even though the NYCT Bus Division deploys its own snow emergency teams and equipment [37]. Paratransit service can be disproportionately impacted by snow storms because the vehicles used are typically smaller than fixed route buses and have more difficulty navigating snow-covered streets. In heavy snow, using chains on bus tires increases traction but also degrades the roadways and can damage buses, increasing maintenance requirements.

Droughts

Too little rainfall can also increase transit agency costs. Droughts increase the dust on vehicles and require increased washing to maintain a quality appear-ance, at the same time that water use restrictions may be put into place [38]. In the Pacific Northwest, hydropower, which supplies roughly half of the region's electricity supply, is predicted to be negatively impacted by changing precipitation patterns. Drought in the summer, lower snowpack, and higher temperatures will mean greater demand and less output, yielding higher electricity prices.

Temperature

Heat waves and regional droughts have already become more frequent and intense during the past 40 to 50 years [39]. By the end of the century, average temperatures in the United States are projected to increase by 7 to 11°F under a high emission scenario and 4 to 6.5°F under a low emissions scenario [40]. A heat wave that now occurs about every 20 years will become almost routine, recurring every two years on average [41].

Urban areas, which form the core of transit services, tend to be hotter than sur-rounding areas. Dark rooftops and asphalt-paved surfaces, which absorb and re-radiate heat, combine with less tree canopy coverage to create the "urban heat island" phenomenon. According to the U.S. Environmental Protection Agency (EPA), core urban areas can be more than 5°F hotter than their suburban and rural surroundings [42]. Heat islands exacerbate the effects from heat waves.

Buckled rail

Buckled rails, also called heat kinks, occur when overheated rails expand and cannot be constrained by the material that supports the track. The most serious problem associated with rail buckling is derailments. To prevent or limit damages due to derailments, transit agencies often issue slow orders in hot weather. For instance, the standard operating procedure for Portland's TriMet when temperatures reach 90°F is to reduce train speeds by 10 mph for all areas with speed limits of 35 mph or more [43]. Slow-orders, however, cause longer transit times, higher operating costs, delays, and reduced track capacity.

During an East Coast heat wave in July 2010, the Washington Metro and the Boston "T" experienced heat kinks that caused them to slow trains and to remove and replace enlarged sections of rail. Maryland's MARC train, Philadelphia's SEPTA system, and the Virginia Railway Express also experienced heat-related delays [44].

Heat kinks more often affect track with rock ballast than concrete slab track with a paved right-of-way, as the concrete slab provides stronger support. Other risk factors include weakened ballast or ties from poor maintenance, above-ground tracks exposed to direct sunlight, and curved areas of track. This problem will likely become more common with the number of days over 90°F projected to increase.

Figure 2-6

Rail Buckle from High Heat

Courtesy of USDOT Volpe Center

A study on the United Kingdom's intercity rail system estimates that costs incurred as a result of the atypically hot summer of 2003 will become typical in the 2050s under a high emissions scenario and in the 2080s under a low emissions scenario. The study estimates that if no operations or maintenance changes are made, the costs of heat-related delays will double to nearly £23 million during such summers. This figure only includes the cost of delays to travelers [45].

Overheated electrical equipment

The extensive and complex electrical train control, monitoring, and communications systems that serve as a vital part of heavy rail and light rail systems are sensitive to overheating. Substations, signal rooms, and electrical boxes are designed with ventilation or air conditioning systems appropriate to the past climate for their regions. For instance, Portland's TriMet designs substations with ventilation systems keyed to the Pacific Northwest's mild climate and provide cooling adequate in weather up to 90°F. These ventilation systems have been inadequate during recent high heat days and the maintenance department has had to increase ventilation to avoid tripping substations. TriMet also reports that stainless steel electronic ticket vending machines, which were designed with a mild climate in mind, have overheated and stopped working on high heat days. Many low-floor rail vehicles house electrical equipment on the vehicle roof and can also be subject to overheating on high heat days [46].

Stretched overhead catenary wires

Overhead catenary wires lengthen in the heat, losing tension and occasionally failing. New Jersey Transit, TriMet, and Los Angeles Metro have all reported this problem. When the catenary wire loses contact with the light rail vehicle's pantograph, the vehicle loses power.

Overheated vehicles and failed air conditioning systems

Temperature stresses on engines and air conditioning systems could affect vehicle availability rates, disrupting overall scheduled service and increasing maintenance requirements. Simply by the nature of the services they provide, transit vehicles must frequently open and close vehicle doors, allowing hot outside air into air-conditioned vehicles on high heat days. On very hot days, air conditioning systems frequently cannot maintain comfortable temperatures in the vehicle and can fail completely. These additional, excessive-temperature-related costs could increase maintenance costs by an amount proportional to the increase in the high-temperature days [47].

Threats to customer and worker health and safety

Heat waves can be extremely dangerous. For instance, more than 1,000 people died during the July 1995 heat wave that hit the Midwest and much of the East Coast. In a normal summer, about 175 Americans die from heat-related causes. The July 1995 heat wave killed more Americans than die in an average year from floods, hurricanes, and tornadoes. Many of those deaths could have been avoided with proper advance planning and heat wave response [48]. Those most vulnerable to heat waves, the elderly and low-income populations without air conditioning in inner city areas, are also disproportionately transit-dependent, increasing the importance of reliable, air-conditioned transit service to move people to cooling centers.

High heat also worsens ground level ozone, the primary component of smog. Repeated exposure to ground-level ozone increases susceptibility to respiratory infections and lung inflammation and aggravates pre-existing diseases such as asthma [49]. For all these reasons, waiting at a bus stop in the heat or riding a bus or train with overwhelmed or failed air conditioning is uncomfortable for all passengers and can be unsafe for many transit customers. "Choice riders" who have other options may choose to drive instead of use transit.

High heat conditions similarly compromise worker productivity and safety. The Occupational Safety and Health Administration (OSHA) recommends extra caution at temperatures above 85°F, and lists 95°F in humid weather as a threshold for possible heat stress and heat stroke [50].

High heat may therefore affect outdoor construction and maintenance schedules. Indoor vehicle maintenance facilities can become uncomfortably warm, compromising workers and slowing down work in these facilities. Operations schedules may also be affected if conditions in vehicles are poor for bus and train operators.

Ventilation and air cooling in subway tunnels vary with age and local historical climate conditions. During heat waves, even relatively new stations can become uncomfortably warm as air flows in through street-level station entrances and as trains entering underground stations from aboveground stations pull in hot air from outside [51]. New York MTA reports that new stations are already being designed with air-tempering systems. Older stations, especially high-traffic ones, would likely require retrofits, as would shops and yards.

Wildfires

Site-specific studies project large increases in the area burned by wildfires in the Pacific Northwest and forested regions of the Rockies and the Sierra. Heat is the primary driver of these changes in most of the regions evaluated, with lesser contributions from changes in precipitation.

Studies are limited in number but suggest that warming of 1.8°F (relative to the 1950-2003 average) would produce 200 to 400 percent increases in median area burned [52]. Bus services on roads closed due to wildfires must be rerouted or suspended; this has affected transit services in the Los Angeles area [53]. Rural public transportation services along roads that do not have alternative routes are particularly disrupted.

Blackouts

Increased electricity demand from air conditioning use during heat waves can cause blackouts. Blackouts disrupting street traffic signals significantly slow bus operations. And even though electric rail transit agencies often build redundancy into their electrical supply,[1] a regional blackout would disrupt supply to train propulsion (major facilities typically have emergency generators to power stations) [54].

[1] For instance, NJ Transit relies on a power system it shares with Amtrak and draws from electricity suppliers Con Edison and PSEG. Thus, a failure by one supplier does not disrupt the rail system.

Sea-Level Rise

Global sea-level rise results from the warming-induced expansion of the oceans, accelerated melting of most of the world's glaciers, and loss of ice on the Greenland and Antarctic ice sheets. Sea level has risen 6.7 inches over the 20th century [55]. The IPCC predicts 8 to 24 inches of sea-level rise by the end of this century. More recent research has attempted to quantify the potential contribution to sea-level rise from the accelerated flow of ice sheets to the sea or to estimate future sea level based on its observed relationship to temperature, factors which were not included in the IPCC estimates. The resulting estimates exceed those of the IPCC, and the average estimates under high emissions scenarios are for sea-level rise between three and four feet by the end of this century [56]. Sea level will continue rising long after the end of the century as ice and oceans respond to higher temperatures from past emissions [57].

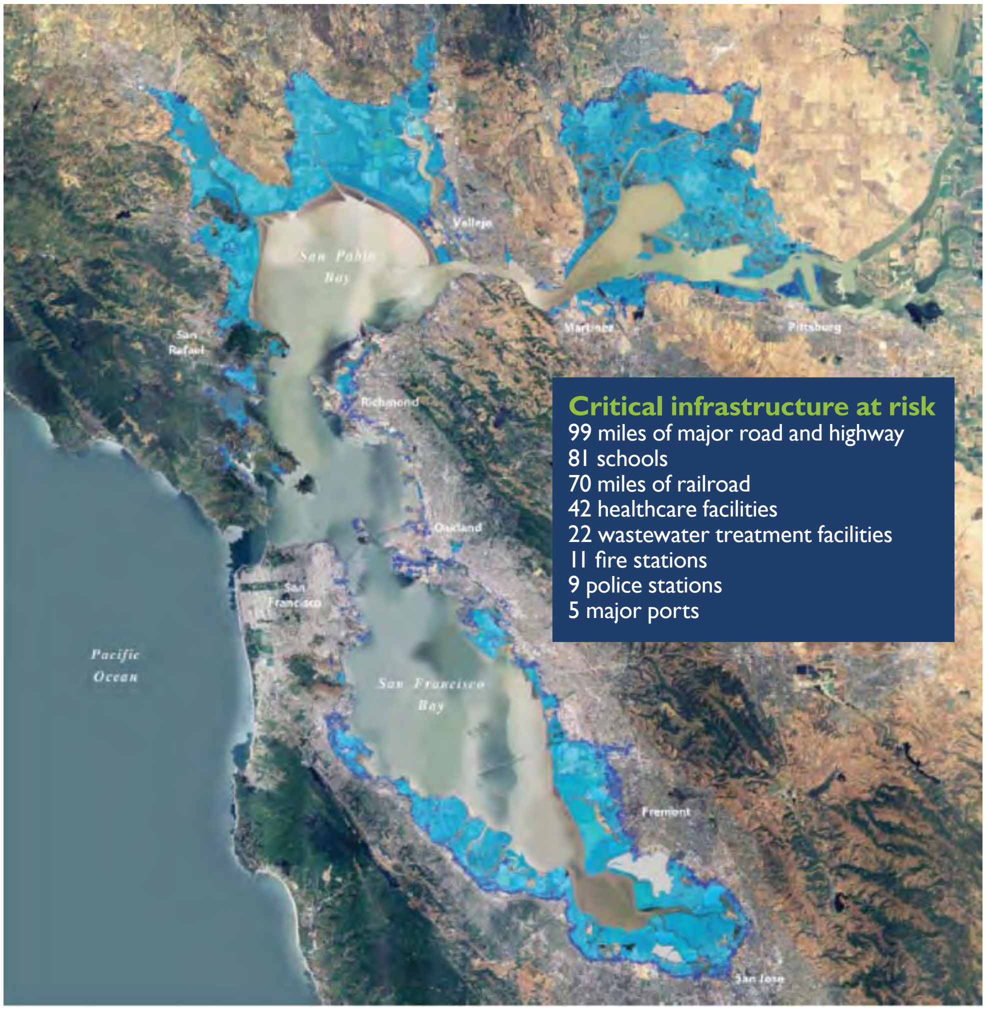
Sea-level rise is not uniform along the coasts. It is greater in areas that are subsiding (sinking), such as the Gulf Coast region, than in areas that are uplifting (rising), such as parts of the west coast. Other variables include atmospheric and oceanic circulation, which will be affected by climate change; the originating locations of the meltwater; and coastal dynamics such as erosion, loss of coastal wetlands, degradation of barrier islands, and decreased sedimentation from human alterations to rivers [58].

On average, almost 10 percent of the land in 180 US coastal municipalities[2] lies at or below one meter (3.3 feet) of elevation above the sea. More than a third of it lies at or below six meters (19.7 feet) in elevation [59].

Although portions of heavily developed coastal areas are guarded by protective structures such as sea walls and levees, rising sea levels significantly increase the challenges to these structures, which were not generally designed with sea level rise in mind, are very expensive, and yield catastrophic damages when they fail. In addition, these structures can cause erosion to adjacent, unprotected areas.

The San Francisco Bay area starkly illuminates the threat. San Francisco Bay is projected to rise 16 inches by midcentury and 55 inches by the end of the century (see Figure 2-7). Today's 100-year floodplain generally corresponds to the area that will be vulnerable to inundation from a 16 inch sea-level rise. In other words, today's 100-year flood is the high tide of the future for the San Francisco Bay Area [60].

[2] The study examined the 180 U.S. municipalities with populations over 50,000, elevations at or below 6 meters, and connectivity to the sea.



Source: San Francisco Bay Conservation and Development Commission, *Living with a Rising Bay: Vulnerability and Adaptation in San Francisco Bay and on its Shoreline*, April 7, 2009.

Figure 2-7

San Francisco Bay Area Sea-Level Rise

The map illustrates shoreline areas of San Fransisco Bay that could be inundated by a 16-inch (blue) and 55-inch (purple) sea-level rise.

Figure 2-8 shows commuter rail and ferry stations vulnerable to sea-level rise in Alameda County, the study area for a Metropolitan Transportation Commission (MTC) vulnerability assessment pilot. Areas of the Bay that were filled for development are particularly at risk of being retaken by the rising water levels. This includes both of the Bay Area's major airports and the transit serving them. Coastal area filling for development and resulting vulnerability to flooding is not unique to the San Francisco Bay Area.

Transit agencies also need to consider the vulnerability of sites slated for joint development or transit-oriented development. For instance, the San Francisco Bay area has identified priority development areas (PDAs) for infill development in areas served by transit. A regional assessment of climate change threats found that 2,000 acres of the total 106,000 acres comprising the 150 PDAs are vulner-

Figure 2-8

Impacts of Sea-Level Rise on Public Transportation in Alameda Study Region of San Francisco Bay Area

Courtesy of Metropolitan Transportation Commission

Source: BCDC, Pacific Institute, AECOM, Georgrafika Consulting able to a 16-inch sea-level rise (the low scenario); 6,000 acres are vulnerable to a 55-inch sea-level rise [61].

Miami is even more vulnerable to sea-level rise. More than 90 percent of Miami lies below six meters of elevation [62]. Miami is ranked first out of 20 cities in the world in total assets exposed to coastal flooding during a 100-year storm surge. Miami's current estimated exposed-asset value exceeds $416 billion, and is likely to top $3.5 trillion by the 2070s [63].

Storms and Hurricanes

The power and frequency of Atlantic hurricanes have increased substantially in recent decades as south Atlantic sea surface temperatures increased by nearly 2°F [64]. Tropical storms and hurricanes develop and gain strength over warm ocean waters. As oceans warm, they provide a source of energy for hurricane growth. The strongest hurricanes (Categories 4 and 5) have, in particular, increased in intensity. Outside the tropics, cold-season storm tracks are shifting northward. In the eastern Pacific, the strongest hurricanes have become stronger since the 1980s, even while the total number of storms has decreased. The United States will see these patterns continue as the climate changes. Climate models project more intense and longer-lasting hurricanes, with related increases in wind, rain, and storm surges, although not necessarily an increase in the number of these storms that make landfall [65]. Increasing hurricane intensity coupled with sea-level rise leads to rising storm surge levels and increasing damage from hurricanes [66].

Storm surge effects

In the Gulf Coast, land subsidence, erosion, and storm surge magnify the impacts of sea-level rise. The U.S. DOT Gulf Coast Study found that 27 percent of the major roads, nine percent of the rail lines, and 72 percent of the ports are at or below four feet in elevation. The study analyzed two to four feet of sea-level rise and 18 to 24 feet of storm surge. (For context, the storm surge from Hurricane Katrina exceeded 24 feet in some areas). The study lists some of the factors that make the Gulf Coast region particularly vulnerable.

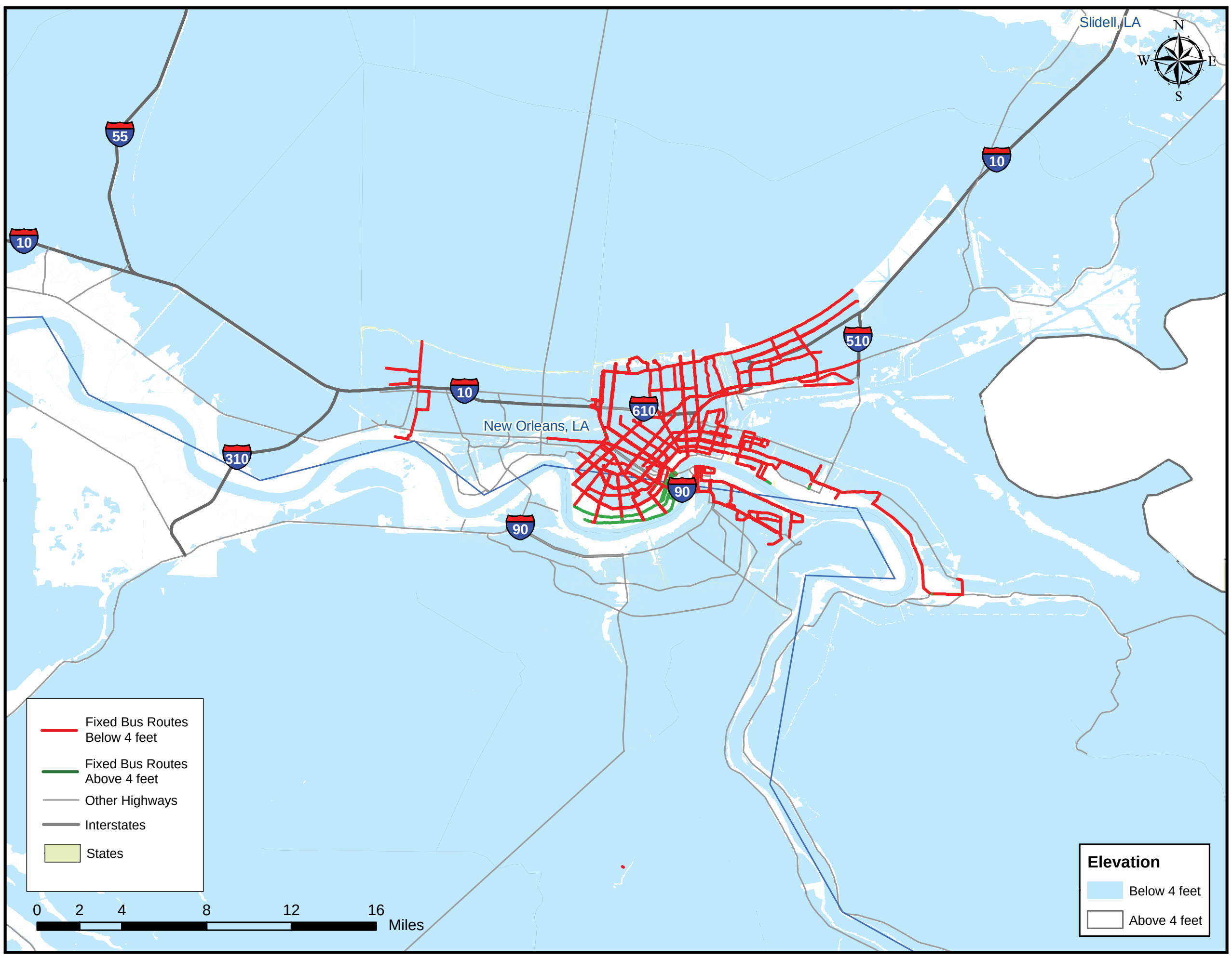
> *Due largely to its sedimentary history, the region is low lying. Due to its low relief, much of the central Gulf Coast region is prone to flooding during heavy rainfall events, hurricanes, and lesser tropical storms. Land subsidence is a major factor in the region, as sediments naturally compact over time. Specific rates of subsidence vary across the region, influenced by both the geomorphology of specific locations as well as by human activities. Most of the coastline also is highly vulnerable to erosion and wetland loss, particularly in association with tropical storms and frontal passages. It is estimated that 217 square miles of land were lost in Louisiana alone during Hurricane Katrina. Further, many Gulf Coast barrier islands are retreating and diminishing in size. The Chandeleur Islands, which serve as a first*

line of defense for the New Orleans region, lost roughly 85 percent of their surface area during Hurricane Katrina. As barrier islands and mainland shorelines erode and submerge, onshore facilities in low-lying coastal areas become more susceptible to inundation and destruction.

The transit systems in New Orleans and Galveston are particularly vulnerable to sea-level rise because of the low elevation of these cities, as seen in Figures 2-9 and 2-10. Houston's higher elevation makes its transit system less vulnerable to even a storm surge of even 18 feet.

Figure 2-9

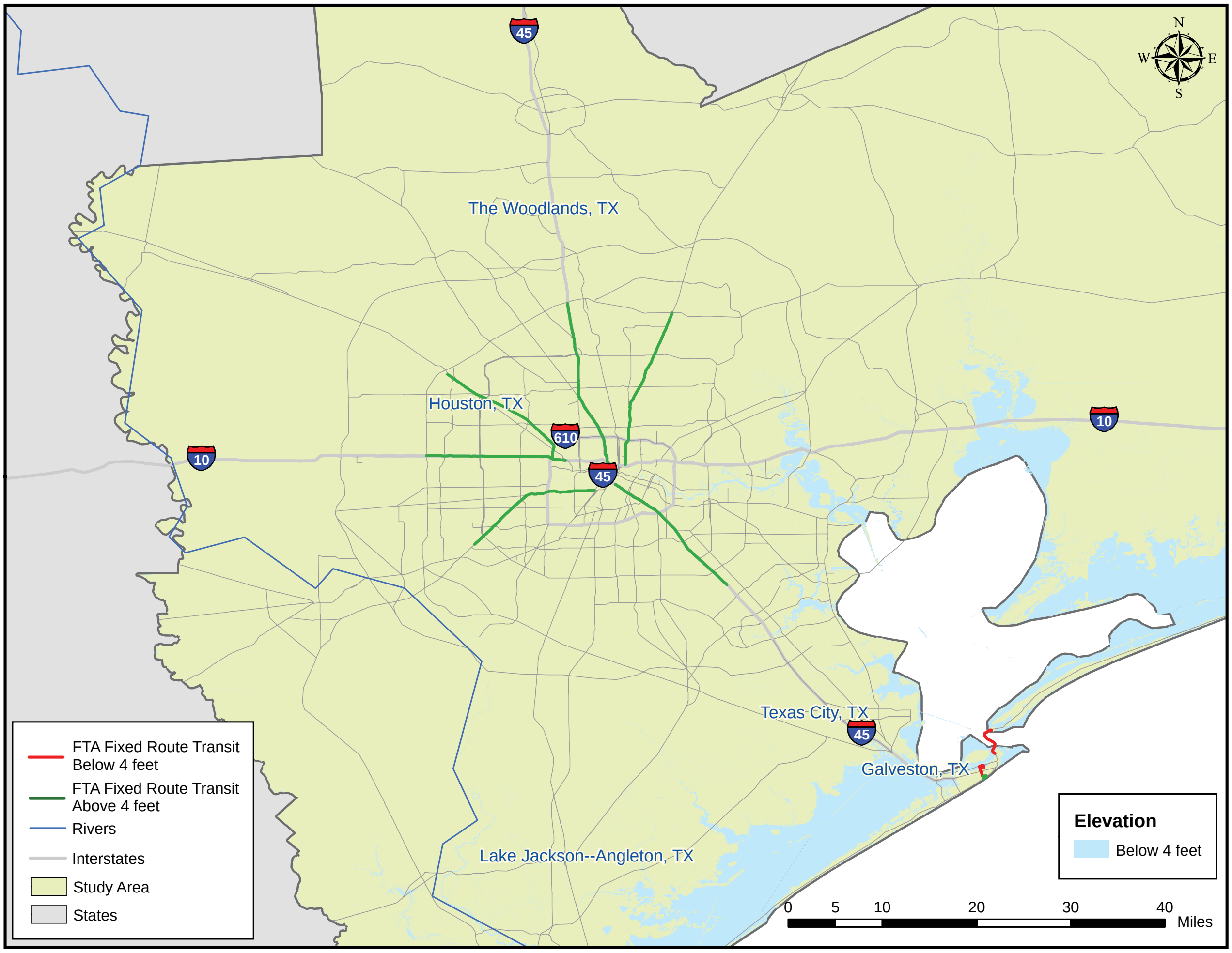
Fixed Bus Routes at Risk from a Relative Sea-Level Rise of 4 feet, New Orleans, LA



Source: U.S. Department of Transportation, Impacts of Climate Change and Variability on Transportation Systems and Infrastructure: Gulf Coast Study, 2008

Figure 2-10

Fixed Transit Guideways at Risk from Storm Surge at Elevations Currently Below 18 feet, Houston and Galveston, TX



Source: U.S. Department of Transportation, Impacts of Climate Change and Variability on Transportation Systems and Infrastructure: Gulf Coast Study, 2008

High wind

Felled trees and other debris from high winds block rail lines, bus routes, and access to stations and bus stops. High winds also mean potential loss of high voltage power lines. Wind damage to radio towers and cell phone towers may temporarily disrupt reliable reception for primary communication systems.

Transit agencies may place slow orders on trains under high wind conditions for safety reasons. For instance, TriMet's standard operating procedure is to issue a slow order when wind speeds exceed 50 mph [67].

Bridge scour and wave action

Bridge scour results when high water flows remove the soil around bridge foundations and weaken the structure. Bridge scour causes the majority of bridge failures in the United States [68]. In the highway sector, FHWA requires bridge owners to evaluate bridges for potential scour associated with a 100-year flood and to check the scour effects for a 500-year flood [69]. Scour can result from high, turbulent water levels in rivers after major rainstorms or spring snowmelt, or as a result of flowing water from hurricanes and storm surge. Like highway bridges, transit bridges and ferry piers are susceptible to damage from bridge scour.

For example, the Sonoma Marin Area Rail Transit (SMART) District is conducting a bridge scour analysis of two bridges over rivers that are under tidal influence. The analysis takes into account projected sea level rise. These older bridges were constructed by railroad companies many years ago and are now under consideration for use in passenger rail service for a 70-mile corridor between Sonoma and Marin counties in California [70].

Wave action during storms impacts bridge structures. The Highway 90 bridge in Bay St. Louis, Mississippi, was destroyed when wave action during Hurricane Katrina lifted the bridge deck from its substructure (see Figure 2-11).

Figure 2-11

Hurricane Damage from Wave Action to Highway 90 in Bay St Louis, MS

Illinoisphoto.com

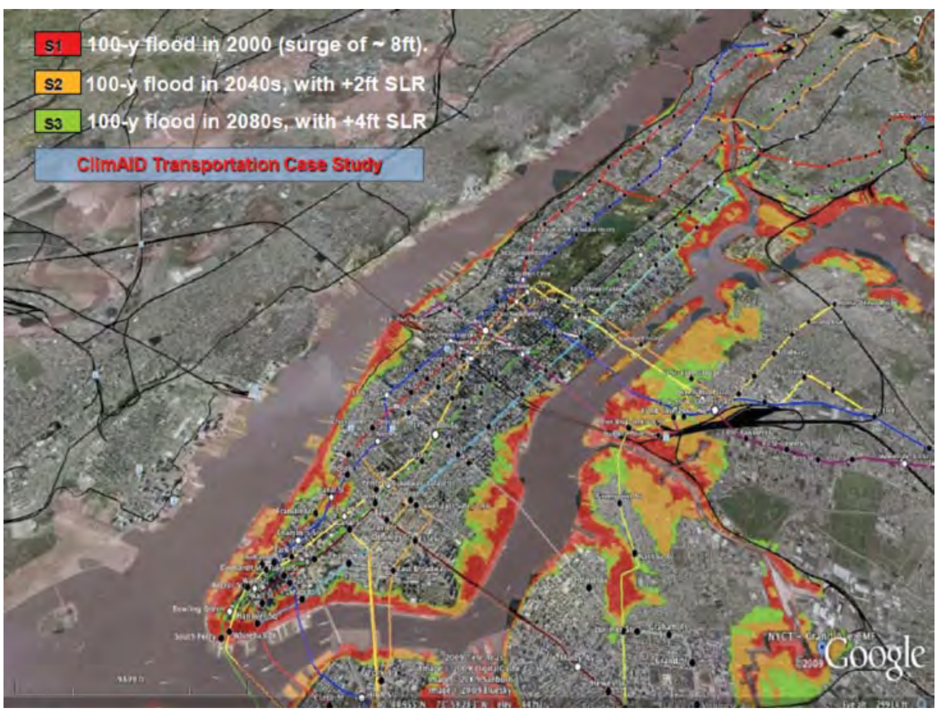
Combined Effects

The discussion above largely examines impacts by individual climate stressors, but transit agencies will face multiple climate stressors with a combined impact on transit assets and services. These climate stressors will interact with existing factors (such as high percentage of impervious surfaces) to amplify effects. The example above of the vulnerability of Galveston's transit system to a combined sea-level rise and storm surge scenario is a case in point. Similarly, researchers are examining the potential impact of four feet of sea-level rise combined with a 100-year flood on the New York City subway in Manhattan (see Figure 2-12).

Boston provides another example. The current 100-year flood from storm surge in downtown Boston would affect only the dock areas directly along the coast. However, when combined with projected sea-level rise and increased storm intensity under the higher emissions scenario, flooding would endanger a considerably larger area. Rail transit stations that would be affected (Haymarket T Station and Aquarium T Station) are shown in Figure 2-13.

Figure 2-12

New York City Vulnerability to 2 to 4 feet of Sea-Level Rise with 100-year Storm Surge

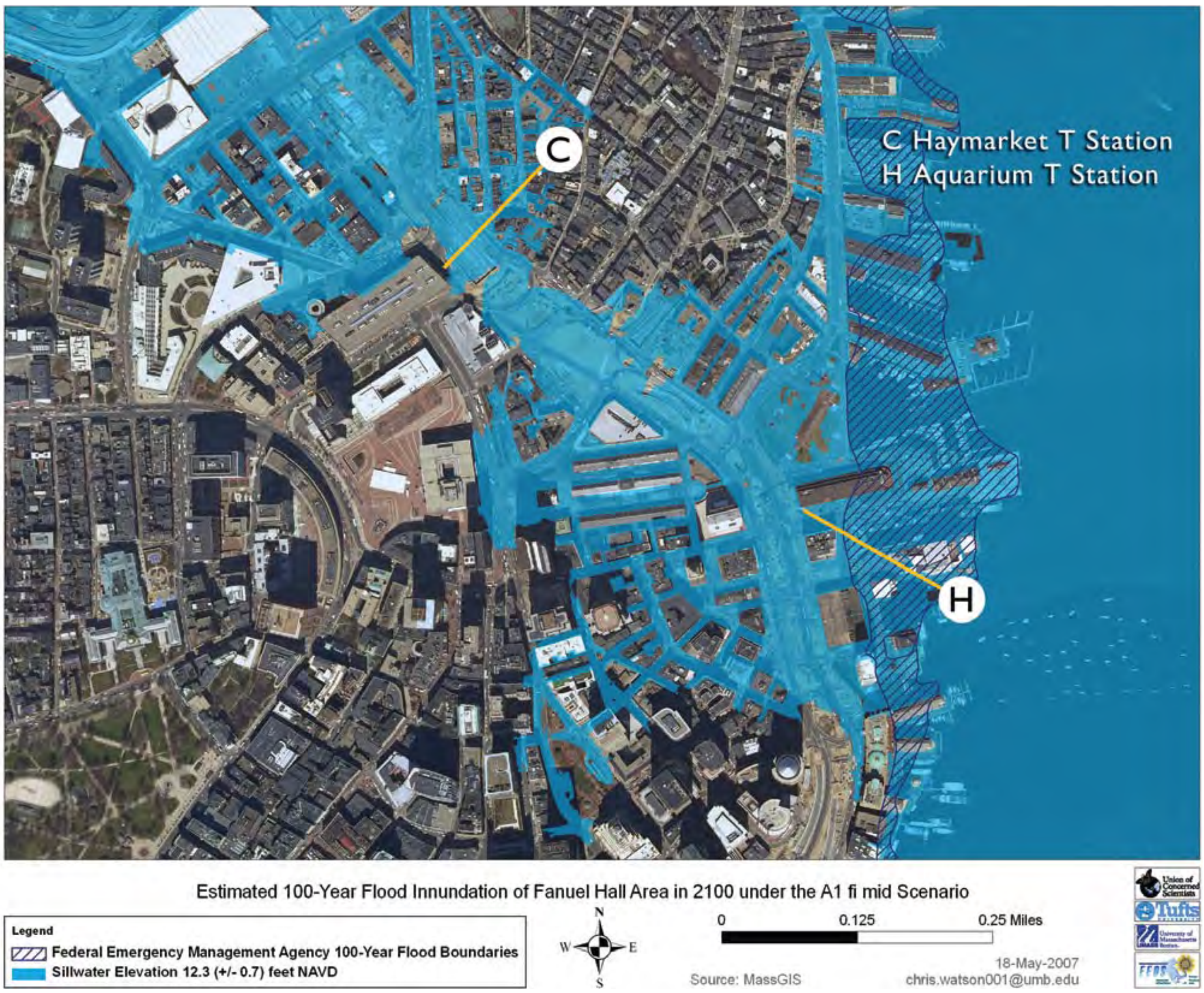


Subway lines are shown in color

Source: Jacob et al, in preparation, 2011

Figure 2-13

Downtown Boston Current 100-year Flood Zone (dark blue hashed) vs. Projected 100-year Flood Zone (light blue)



Source: This map was created using data available from Commonwealth of Massachusetts Executive Office of Environmental Affairs' Office of Geographic and Environmental Information (MassGIS). The blue shading is shown over aerial photographs for reference. The future areas of flooding (shown in light blue) are based on a digital elevation model (DEM) derived from LIDAR (an acronym for Light Detection and Ranging) data obtained by MassGIS in 2002. Graphic adapted from UCS/NECIA 2007.

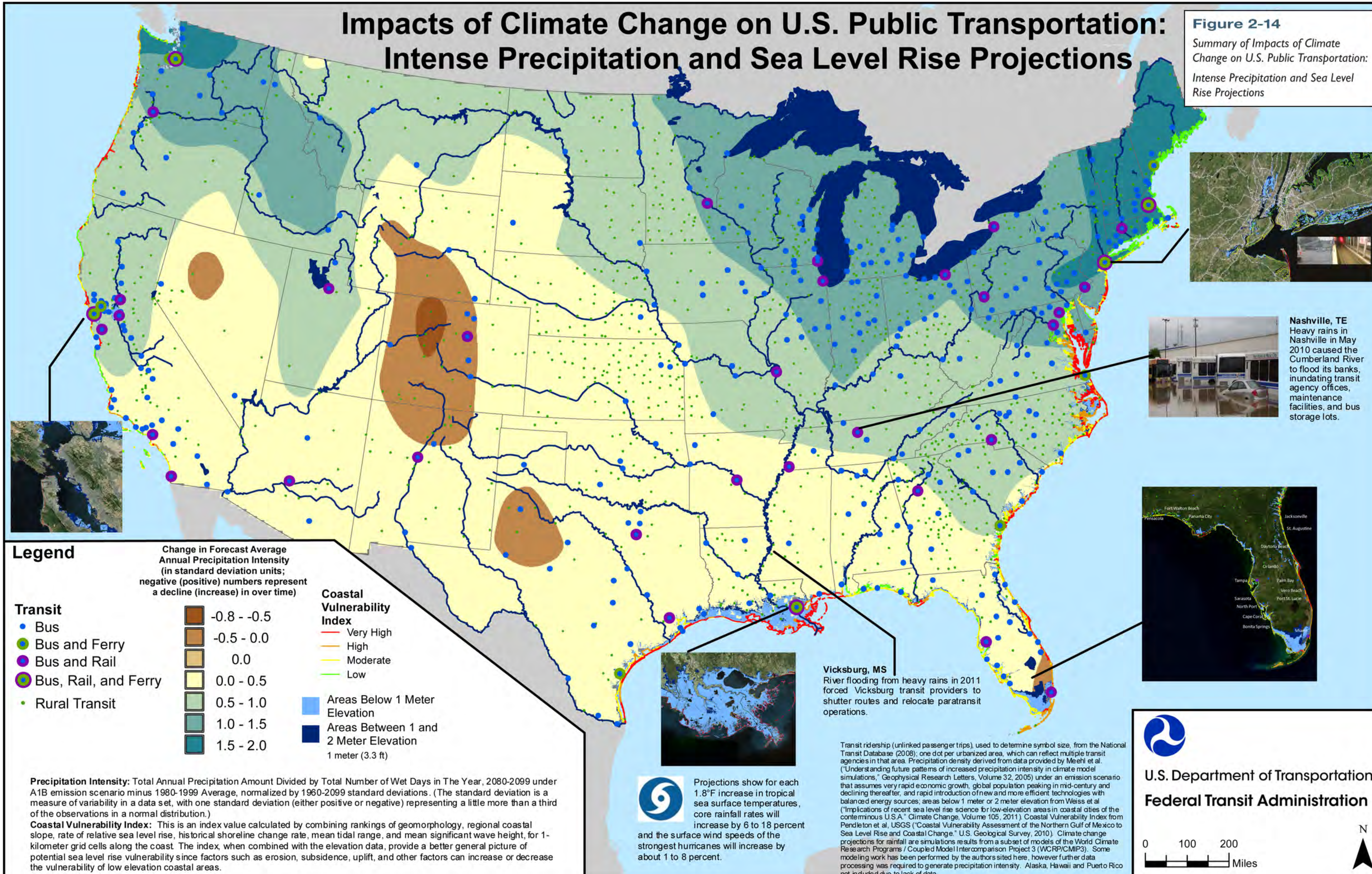
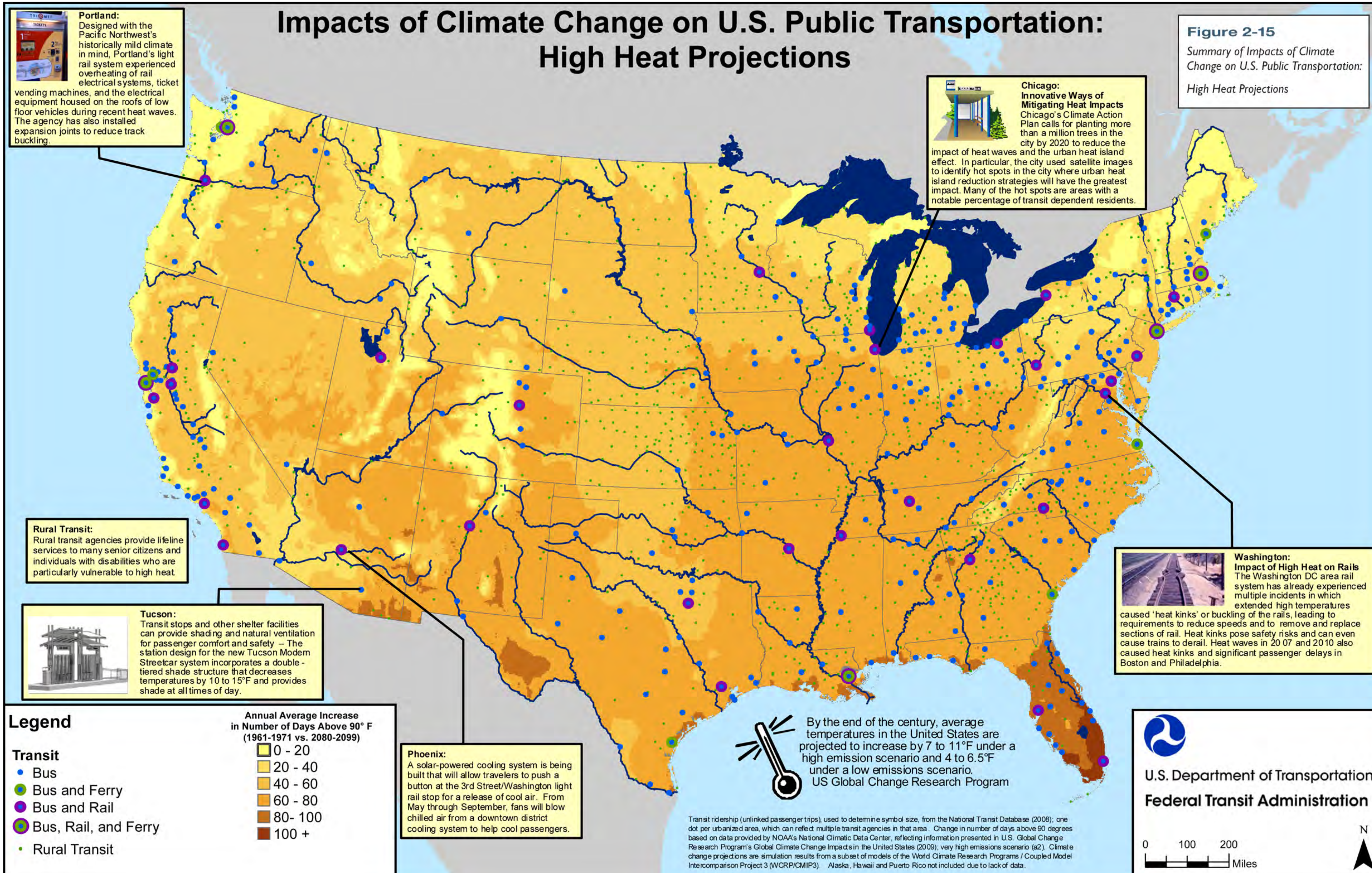


Figure 2-14

Summary of Impacts of Climate Change on U.S. Public Transportation:

Intense Precipitation and Sea Level Rise Projections

(This page intentionally left blank)



Impacts of Climate Change on U.S. Public Transportation: High Heat Projections
Figure 2-15
Summary of Impacts of Climate Change on U.S. Public Transportation:
High Heat Projections
Portland:
Designed with the Pacific Northwest's historically mild climate in mind, Portland's light rail system experienced overheating of rail electrical systems, ticket vending machines, and the electrical equipment housed on the roofs of low floor vehicles during recent heat waves. The agency has also installed expansion joints to reduce track buckling.
Chicago:
Innovative Ways of Mitigating Heat Impacts
Chicago's Climate Action Plan calls for planting more than a million trees in the city by 2020 to reduce the impact of heat waves and the urban heat island effect. In particular, the city used satellite images to identify hot spots in the city where urban heat island reduction strategies will have the greatest impact. Many of the hot spots are areas with a notable percentage of transit dependent residents.
Rural Transit:
Rural transit agencies provide lifeline services to many senior citizens and individuals with disabilities who are particularly vulnerable to high heat.
Washington:
Impact of High Heat on Rails
The Washington DC area rail system has already experienced multiple incidents in which extended high temperatures caused 'heat kinks' or buckling of the rails, leading to requirements to reduce speeds and to remove and replace sections of rail. Heat kinks pose safety risks and can even cause trains to derail. Heat waves in 2007 and 2010 also caused heat kinks and significant passenger delays in Boston and Philadelphia.
Tucson:
Transit stops and other shelter facilities can provide shading and natural ventilation for passenger comfort and safety -- The station design for the new Tucson Modern Streetcar system incorporates a double-tiered shade structure that decreases temperatures by 10 to 15°F and provides shade at all times of day.
Legend
Transit
Bus
Bus and Ferry
Bus and Rail
Bus, Rail, and Ferry
Rural Transit
Annual Average Increase in Number of Days Above 90° F (1961-1971 vs. 2080-2099)
0 - 20
20 - 40
40 - 60
60 - 80
80- 100
100 +
Phoenix:
A solar-powered cooling system is being built that will allow travelers to push a button at the 3rd Street/Washington light rail stop for a release of cool air. From May through September, fans will blow chilled air from a downtown district cooling system to help cool passengers.
By the end of the century, average temperatures in the United States are projected to increase by 7 to 11°F under a high emission scenario and 4 to 6.5°F under a low emissions scenario.
US Global Change Research Program
Transit ridership (unlinked passenger trips), used to determine symbol size, from the National Transit Database (2008); one dot per urbanized area, which can reflect multiple transit agencies in that area. Change in number of days above 90 degrees based on data provided by NOAA's National Climatic Data Center, reflecting information presented in U.S. Global Change Research Program's Global Climate Change Impacts in the United States (2009); very high emissions scenario (a2). Climate change projections are simulation results from a subset of models of the World Climate Research Programs / Coupled Model Intercomparison Project 3 (WCRP/CMIP3). Alaska, Hawaii and Puerto Rico not included due to lack of data.
U.S. Department of Transportation
Federal Transit Administration
0
100
200
Miles
N

(This page intentionally left blank)

Abrupt Climate Change

Abrupt climate changes, although they have a low probability of occurrence, could vastly accelerate and worsen the effects described previously. As explained by the USGCRP:

> *There is also the possibility of even larger changes in climate than current scenarios and models project. Not all changes in the climate are gradual. ... The occurrence of abrupt changes in climate becomes increasingly likely as the human disturbance of the climate system grows. Such changes can occur so rapidly that they would challenge the ability of human and natural systems to adapt. Examples of such changes are abrupt shifts in drought frequency and duration. … Rapid ice sheet collapse with related sea-level rise is another type of abrupt change that is not well understood or modeled and that poses a risk for the future. … There are also concerns regarding the potential for abrupt release of methane from thawing of frozen soils, from the sea floor, and from wetlands in the tropics and the Arctic. While analyses suggest that an abrupt release of methane is very unlikely to occur within 100 years, it is very likely that warming will accelerate the pace of chronic methane emissions from these sources, potentially increasing the rate of global temperature rise. A third major area of concern regarding possible abrupt change involves the operation of the ocean currents that transport vast quantities of heat around the globe. … Changes in this circulation have profound impacts on the global climate system, from changes in African and Indian monsoon rainfall, to atmospheric circulation relevant to hurricanes, to changes in climate over North America and Western Europe.*

Impacts on Transit Agency Goals

Safety: Heat waves jeopardize worker and customer health and safety. Severe rail buckling from heat can derail trains. Flooding and storms as well as debris blown by high winds endanger welfare. Deteriorated asset conditions can also jeopardize safety.

State of Good Repair: Most of the impacts above accelerate the deterioration of assets, challenging transit agency efforts to achieve and maintain a state of good repair. For instance, high heat stresses materials while flooded rivers scour transit bridge support structures. And in a vicious cycle, transit facilities that are not in a state of good repair become still more vulnerable to catastrophic failure during extreme conditions. In addition, impacts on one service can spill-over to others. For instance, when light rail service in a particular area is suspended due to a weather impact, the buses brought in to transport customers around the disrupted area are in use rather than in the shop undergoing scheduled maintenance, leading to a maintenance backlog.

Cost Containment: Transit agencies will suffer direct economic impacts from increased maintenance and the need to replace deteriorated assets before the end of their intended useful lives. In addition, operating costs increase under severe weather due to the need for an "all hands on deck" response, with its associated labor hours and overtime. Service interruptions from extreme weather or from weather-related maintenance issues decrease farebox revenue and harm the agency's reputation, complicating state and local funding requests.

Regional Mobility: Interruptions in transit service prevent employees from going to work and shoppers from getting to stores. One study in the Boston area estimates that traffic delay and lost trips due solely to flood events could increase by 80 percent over the course of the 21st century, compared to what would be expected in the absence of climate change [71]. While this study examined the street and highway network, it provides a useful analogy for transit disruptions, especially bus service. Climate impacts also can have ripple-effects on other transportation modes by shifting demand from one mode to another. For instance, the shutdown of a transit segment might cause or significantly worsen congestion on the roads in the corridor.

Service to Transit Dependent Populations: Persons with disabilities, seniors, and low income individuals are disproportionately dependent on public transportation services. They are therefore disproportionately affected by service disruptions and asset degradation. These individuals are also more dependent on the evacuation services public transit provides in response to life-threatening weather events.

Case Study

New York MTA: Partnering and Assessing Impacts

Background on MTA

New York State Metropolitan Transportation Agency (MTA) is the largest transit operator in the nation. Spanning 5,000 square miles and serving a residential population of 14.5 million, MTA provides 8.5 million passenger trips per day in the New York City metropolitan area at twice the energy efficiency of advanced hybrid cars [72]. Four of every five rush-hour commuters to New York City's central business district take transit, most of it operated by MTA [73]. MTA encompasses New York City Transit (bus, subway, and Staten Island Railway), Metro North Railroad, Long Island Rail Road, Bridges and Tunnels, Long Island Bus, and MTA Bus Company.

MTA's adaptation report

MTA partnered with Columbia University to include climate change adaptation under the umbrella of its Blue Ribbon Commission on Sustainability. The resulting 50-page report, MTA Adaptations to Climate Change: A Categorical Imperative, presents climate science data most relevant to transit in New York, analyzes climate impacts on MTA assets, offers a preliminary assessment of the most vulnerable assets, and includes initial ideas for short and long term adaptation [74]. While the report provides an initial assessment, it recommends that MTA conduct a complete, detailed risk assessment and establish structures to develop, implement, and monitor adaptation strategies. MTA Adaptations to Climate Change is the first publicly available report on the impact of climate change on a U.S. public transportation agency. It was also the only one at the time of this writing, although the Los Angeles County MTA and New Jersey Transit are both currently conducting climate change vulnerability assessments and will likely issue reports soon.

Collaboration with State and local efforts

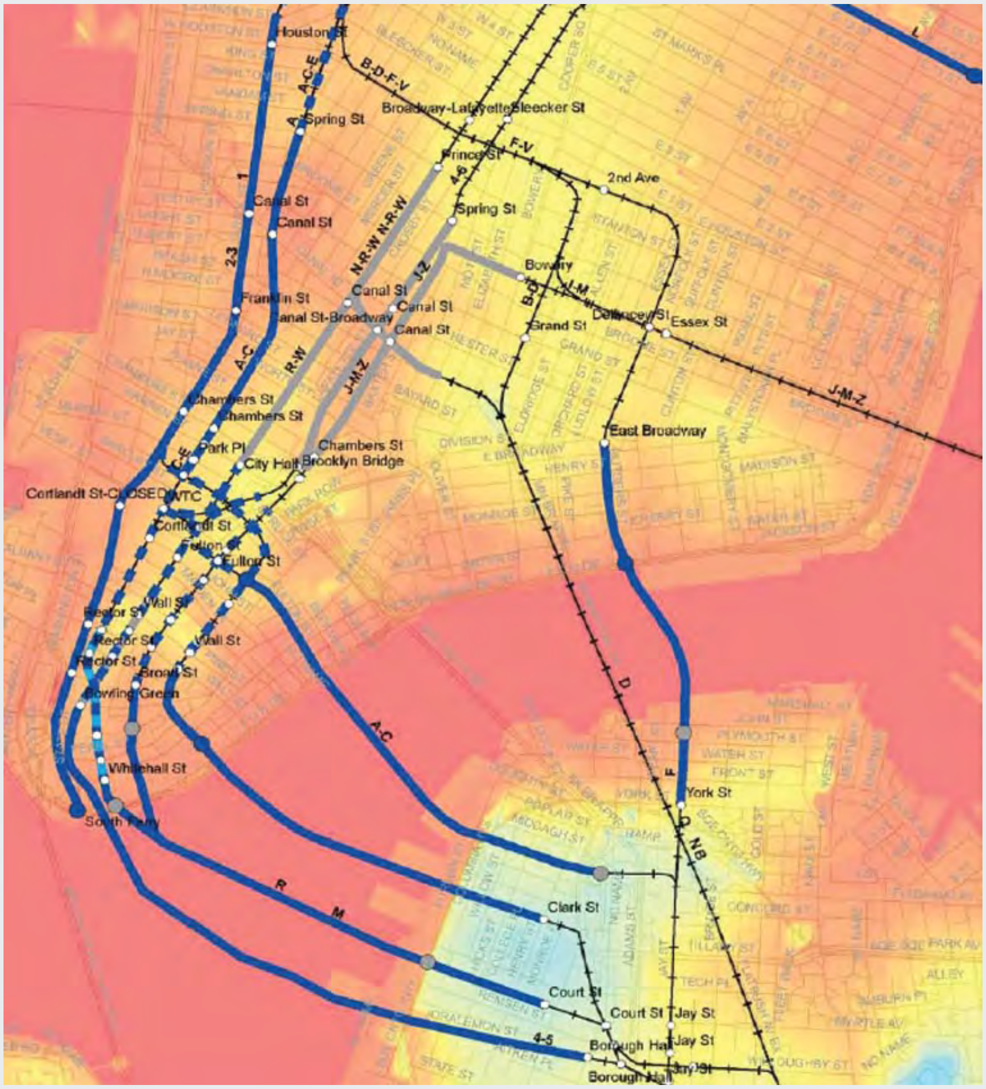
MTA has actively partnered in multiple state and local adaptation efforts (see box). This has resulted in a comprehensive and accurate transit analysis in these state-wide and region-wide adaptation assessments. Because the state and local efforts cut across sectors such as energy, transportation, ecosystems, public health, agriculture, telecommunications, water resources, and coastal zones, MTA's involvement caused transit system impacts to be analyzed in the broader context of an integrated systems perspective, taking into account that the solution to a problem in one sector may lie in another sector. This approach also enabled MTA to work with expert climate scientists and use climate scenarios consistent with those of other regional and state agencies.

Vulnerability to sea-level rise and storm surge

The adaptation assessment efforts described above found that while the effect of sea-level rise alone on MTA assets is relatively minor, when combined with storm surge, the impact is severe. Columbia University researchers studied the impacts of two to four feet of sea-level rise when combined with a 100-year storm surge, which corresponds to a category 1 to 3 hurricane, depending on track and speed. They found that with three feet of sea-level rise, the flooding produced by a 100-year storm at current sea levels will require only a 10-year storm, in other words, a tenfold increase in the frequency of flooding [75]. Even without sea-level rise, a 100-year flood would inundate substantial portions of the subway system. With sea-level rise though, the flooding occurs more rapidly and is more severe. A 100-year flood with a four foot rise in sea level would flood a large fraction of Manhattan subways, including virtually all of the tunnels crossing into the Bronx beneath the Harlem River and the tunnels under the East River (see Figure 2-16) [76].

FIGURE 2-16

New York City Subway Vulnerability to 100-Year Flood with 4-foot Sea-Level Rise



Blue lines: flooded subway tunnels

Orange: < 30 ft elevation

(subway tracks are typically 20 feet below the street level)

100 yr storm surge ~8 ft

Source: New York State Energy Research and Development Authority (NYSERDA), ClimAID: Responding to Climate Change in New York State, Draft Version, 2010

In order to create the map shown in Figure 2-16, MTA staff provided century-old station drawings so that researchers could accurately render the system in three dimensions. Flood waters enter the subway tunnels mostly vertically via ventilation grates and entrances as the streets flood, but also via inclined rail and road tunnels. Hydraulic computations show flooding complete under these conditions in only 40 minutes [77].

A critical yet difficult question is how long it takes the subway system to recover and restore service after flooding. Recovery would require obtaining huge quantities of pumps and hoses, awaiting restoration of power to the electrical grid, pumping out the flood waters, cleaning out miles of muddy and debris-filled platforms, stairs, tunnels and trackway, assessing the damage, and repairing problems. Much of the signal equipment and controls in the tunnels would be damaged by salt or brackish water and would need to be disassembled, cleaned, and repaired or replaced to avoid corrosion and irreparable long-term damage. This specialized equipment, some of it 100 years old, is difficult to obtain and in many cases no longer manufactured. Researchers estimate a minimum recovery time of three to four weeks to reach 90 percent capacity, although when engineers were presented with the question, they believed that it could take one to two years to recover fully. This also assumes trains were moved to portions of the system with elevations above flood levels, in anticipation of the storm and were thus not damaged [78]. Additional problems could result if the floodwaters were contaminated with toxins.

Combined economic and physical damage losses from subway tunnel flooding under a 100-year storm surge were estimated at $58 billion at current sea levels and $84 billion with four feet of sea-level rise, assuming a linear recovery and an estimated subway outage time of three to four weeks. Direct physical damage alone was estimated at $10 billion for the former and $16 billion for the latter [79].

Installing flood gates, raising entrances, and closing ventilation grates (requiring new fan-driven ventilation) are potential adaptation strategies for protecting the subway system from flooding. Detailed engineering and cost studies are not available. As a rough order of magnitude estimate, however, a FEMA-commissioned study found that on average, regardless of hazard (such as flood, earthquake, etc.), for every dollar spent on protecting an asset, the owner saves four dollars in avoided losses [80]. Although it would be a good investment, flood protection would still have an upfront cost in the range of billions of dollars.

Intense rain events are another type of flood threat facing MTA. The Strategies section of this report describes some of the actions MTA has taken to guard against this danger, including raising ventilation grates, more frequent drain cleaning, and onsite stormwater management.

MTA Collaborations on Adaptation

- **ClimAID**: Sponsored by the New York State Energy Research and Development Authority (NYSERDA), ClimAID brought together university researchers with public and private sector practitioners. They created an integrated assessment of New York State's vulnerability to climate change, which is facilitating the development of adaptation strategies. Public transportation is central to the transportation chapter, which analyzes in detail the impact on the subway system of sea-level rise and storm surge [81].
- **New York City Climate Change Adaptation Task Force/NYC Panel on Climate Change**: Mayor Bloomberg launched the Task Force in 2008 to adapt critical infrastructure to the environmental effects of climate change. Its members represent city and state agencies, authorities, and private companies that operate, maintain or control critical infrastructure in the city, including MTA [82]. To advise the Task Force, the mayor formed the Panel, made up of climate scientists, engineers, and legal and insurance experts. The Panel's report included recommendations for adaptation and three workbooks to guide task force members: 1) Climate Risk Information—presenting climate science projections and impacts for the City, 2) Adaptation Assessment Guidebook—outlining a process for developing and implementing plans; and 3) Climate Protection Levels—evaluating policies, rules, and regulations that govern infrastructure to determine how they could be affected by climate change. Examples from MTA and information relevant to public transportation are included throughout [83]. Adaptation initiatives and progress towards these initiatives are reported in "PlaNYC: A Greener Greater New York," updated in April 2011 [84].
- **New York State Climate Action Council**. Formed by executive order, this body is charged with developing New York State's climate action plan, which includes both mitigation and adaptation. The group issued an interim report in November 2010. MTA has participated actively on the Adaptation Technical Working Group [85].

SECTION 3

Climate Risk Assessments

"Adaptation to climate change calls for a new paradigm that takes into account a range of possible future climate conditions and associated changes in human and natural systems, instead of managing our resources based on previous experience and the historical range and variability of climate."

- National Academy of Sciences, Panel on Adapting to the Impacts of Climate Change, 2010

Tools

In recent years, multiple governmental entities have begun to assess climate change impacts on infrastructure and to develop potential responses. Many are using closely related vulnerability, risk, and adaptation assessment frameworks and tools. This section draws out the elements of these frameworks that are most relevant to public transportation agencies.

The frameworks share a general approach: develop or gather climate projections, establish how those climate changes will impact assets, determine the severity of the impacts, and develop measures to address the high-risk impacts [86].

Adaptation Assessment Guidebooks

Transit agencies can benefit from several risk assessment tools developed for state and local governments. The sources below may be particularly relevant.

New York Climate Adaptation Assessment Guidebook
http://onlinelibrary.wiley.com/doi/10.1111/j.1749-6632.2010.05324.x/pdf

Federal Highway Administration Conceptual Model Assessing Vulnerability and Risk of Climate Change Effects on Transportation Infrastructure
http://www.fhwa.dot.gov/hep/climate/conceptual_model62410.htm

University of Washington Center for Science in the Earth System (Climate Impacts Group) and King County, Washington, Planning for Climate Change: A Guidebook for Local, Regional, and State Governments
http://cses.washington.edu/cig/fpt/guidebook.shtml

ICLEI Adaptation Database and Planning Tool (ADAPT)
http://www.icleiusa.org/programs/climate/Climate_Adaptation/climate-resilient-communities-program

UK Climate Impacts Program, Risk, Uncertainty and Decision-Making Framework
http://www.ukcip.org.uk/index.php?option=com_content&task=view&id=63&Itemid=9

The general steps for adaptation assessment frameworks and how they can be applied to public transportation agencies are described in more detail below. This summary draws on the sources listed on the previous page.

Identify current and future climate hazards

Using the best available climate change data, identify climate hazards relevant to public transit agency assets and operations. For several metropolitan areas, localized or regional climate impacts data have been developed by climate scientists by downscaling data from global circulation models (GCM) to a finer resolution. For areas where local or state governments are already using data sets, adopting uniform projections is important so that shared and interdependent infrastructure (such as city streets and bus routes) is evaluated for the same hazards. Transit agencies can leverage partnerships with climate experts to determine the best data to use and receive guidance on how to interpret and apply it to implications for their assets and operations. As an example, the Washington State Department of Transportation has been able to rely on published reports from the Climate Impacts Group (CIG) at the University of Washington for climate data for the state's eight different physiographic regions [87].

Some transit agencies are in areas that have not yet done detailed climate data downscaling. These agencies can rely on multi-state regional level data such as that provided by the USGCRP or the FHWA Regional Climate Effects Report. Agencies can get the most from limited resources by understanding the general climate impacts and focusing on sensitivity and resilience of the transit system to the types of stressors projected and the thresholds above which impacts are felt.

Assessing current (not just future) climate hazards is also important in this step. For instance, areas currently subject to flooding are likely to be even more vulnerable in the future if increases in heavy rainfall or sea-level rise are projected. In addition, since climate impacts such as increased intensity of rainfall are already occurring, transit agencies may have data on increased maintenance costs due to storm or severe weather damage in recent years. This information, especially if there are specific instances where asset life cycles or performance have been reduced due to severe weather conditions, can be useful in adaptation planning.

Resources for Climate Data

U.S. Global Change Research Program *Global Climate Change Impacts in the United States*
http://www.globalchange.gov/

The U.S. Global Change Research Program (USGCRP)'s 2009 report describes current and future impacts of climate change on the nation as a whole and on the major U.S. regions (Northeast, Southeast, Midwest, Great Plains, Southwest, Northwest, Alaska, and Islands). An updated report is due in 2013. USGCRP is the Federal government's interagency climate science coordinating body.

FHWA Regional Climate Effects Report
http://www.fhwa.dot.gov/hep/climate/climate_effects/

This document provides basic information on projected future climate change effects (changes in temperature, precipitation, storm activity and sea-level rise) over the near term, by mid-century and by 2100. The report includes two appendices: maps for some of the climate change effects, and a compilation of projected climate change information gleaned from recent reports.

Regional Integrated Sciences and Assessments
http://www.noaanews.noaa.gov/stories2010/20100922_regionalclimate.html

The National Oceanic and Atmospheric Administration (NOAA) funds climate science collaborations with universities. These Regional Integrated Sciences and Assessments (RISAs) work closely with the public, private, and non-profit sectors to advance new research on how climate variability and change will impact the environment, economy, and society, and develop innovative ways to integrate climate information into decision-making. The awards are made on five-year cycles. The currently funded RISAs are:

- Consortium on Climate Risk in the Urban Northeast—Columbia University: Focus on climate issues in the urban corridor between Boston, New York and Philadelphia
- Pacific Northwest Climate Decision Support Consortium—Oregon State University: Focus on climate, water, energy and land issues in Oregon, Washington, and Idaho
- Great Lakes Regional Integrated Sciences and Assessments Center—University of Michigan and Michigan State University: Focus on watersheds of Lakes Erie and Huron
- Pacific RISA: Climate Adaptation Partnership for the Pacific—East-West Center in Hawaii: Focus on various climate and water issues in Hawaii and the U.S. Pacific Islands
- Southeast Climate Consortium—University of Florida: Focus on various climate, water, coastal and agricultural issues in Alabama, Florida, and Georgia
- Western Water Assessment—University of Colorado: Focus on climate, water, energy and ecosystems in Colorado, Utah, and Wyoming
- Alaska Center for Climate Assessments and Policy—University of Alaska
- Carolinas Integrated Sciences and Assessments—University of South Carolina
- Climate Assessment for the Southwest—University of Arizona and New Mexico State University
- California-Nevada Applications Project—Scripps Institution of Oceanography
- Southern Climate Impacts Planning Program—University of Oklahoma and Louisiana State University

NOAA Regional Climate Centers

http://www.ncdc.noaa.gov/oa/climate/regionalclimatecenters.html

These centers provide user-centric climate services with a regional focus for decision-makers, interdisciplinary climate research, applications, and education.

U.S. Department of the Interior Climate Science Centers

http://www.doi.gov/whatwedo/climate/strategy/CSC-Map.cfm

The Department of Interior and its U.S. Geological Survey (USGS) established eight regional climate science centers to provide scientific information tools, and techniques to resource managers and other interested parties, to help them anticipate, monitor, and adapt to climate change at regional and local scales.

NOAA National Climatic Data Center (NCDC)

http://www.ncdc.noaa.gov/climate-monitoring/index.php#us-icon

This center develops and provides comprehensive historical weather and climate data. U.S. climate maps are available at: http://cdo.ncdc.noaa.gov/cgi-bin/climaps/climaps.pl

State Climatologists

http://www.stateclimate.org/

State climatologists can provide historical climate data and weather forecasting information and can interpret NCDC and weather station data, though they may not necessarily have experience with climate change projections. A state climatologist is chosen by each state and recognized by NOAA. State climatologists currently exist in 47 states and Puerto Rico. They are typically either employees of state agencies or are staff members of state-supported universities.

Coupled Model Intercomparison Project phase 3 (CMIP3)

http://gdo-dcp.ucllnl.org/downscaled_cmip3_projections/dcpInterface.html

This site provides statistically downscaled data from the World Climate Research Programme's Coupled Model Intercomparison Project phase 3 (CMIP3) data set.

North American Regional Climate Change Assessment Program (NARCCAP)

http://www.narccap.ucar.edu/

The international North American Regional Climate Change Assessment Program (NARCCAP) produces high resolution climate change simulations. These simulations assist in investigations of uncertainties in regional scale projections of future climate, and generate climate change scenarios for use in impacts research. NARCCAP models cover the conterminous United States and most of Canada.

Other Sources

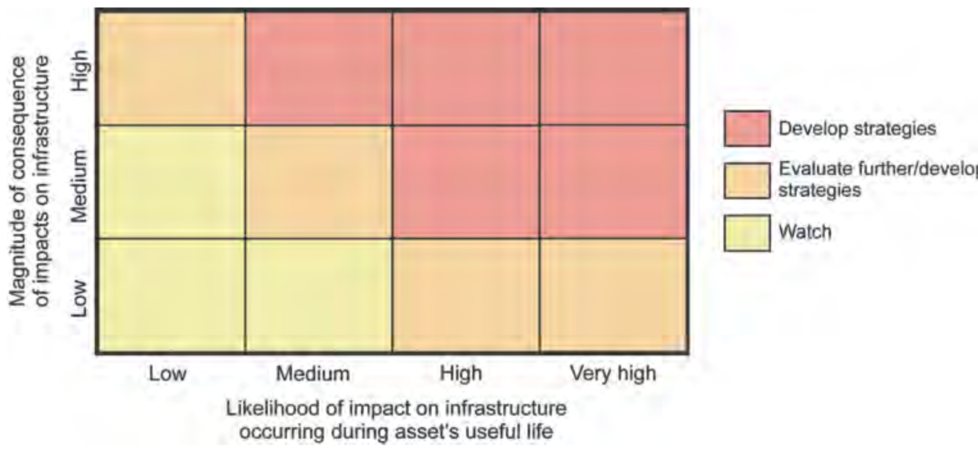
The above list is not comprehensive. Various universities, state environmental protection agencies, nonprofits, and other entities also provide data and interpretation.

Characterize the risk of climate change on agency infrastructure and operations

Probability multiplied by magnitude equals risk. That is, risk is the product of the likelihood of the impact occurring and the size of the consequence should the impact occur. A risk assessment can help prioritize those impacts of most concern. A two-dimensional matrix shows how probability and magnitude interact to create high risk (see Figure 3-1).

Figure 3-1

Risk Matrix



Source: New York City Panel on Climate Change, Adaptation Assessment Guidebook, 2010

The *likelihood* of impact is the probability that a given climate hazard (such as more intense rainstorms) will occur, and that it will result in a transit impact (such as flooding of a maintenance facility) over the lifetime of the transit asset. The *vulnerability* of transit assets and operations to climate impacts is a function of their exposure to climate hazards, their sensitivity to those hazards, and their adaptive capacity. It is thus important to assess thresholds above which transit assets begin to suffer from climate impacts (for example, the amount of rain per hour above which drainage systems and pumps are overwhelmed). It is also important to examine sensitivity indicators—that is, aspects of transit assets that indicate that they are more prone to damage than other similarly exposed assets (for instance, poorly maintained track with weak ballast is more susceptible to rail buckling).

Magnitude of consequence can be measured by damage costs, length of service disruption, safety impacts, and degradation in customer service. The magnitude of the consequence depends in part on the criticality of the transit asset or service to the transportation network. For instance, major transfer stations between high traffic transit lines are typically more critical than lesser utilized stations. In addition, lifeline services to transit dependent populations often provide critical services. The Mobile, Alabama, case study provides an example of a criticality assessment.

Develop initial adaptation strategies

At this stage, the agency and any partners in the assessment must develop and assess strategies to reduce the vulnerability of transit assets and operations to climate impacts. Strategies might include engineering new assets to withstand environmental conditions anticipated in the future (e.g., construction materials better suited to higher heat days), retrofitting existing assets (e.g., adding barriers to prevent water incursion into tunnels), more intensive maintenance schedules (e.g., more frequent cleaning of drains), systems planning (e.g., siting new facilities outside of expanded flood plains), and improved operations plans for weather emergencies (e.g., ensuring evacuation services to transit-dependent populations, and moving rolling stock to higher ground). Adaptation strategies should be evaluated based on cost savings from avoided impacts as well as implementation costs. Strategies should also be evaluated based on their feasibility, efficacy, and ability to withstand a range of climate hazards. Strategy evaluations should also reflect negative or positive impacts on other areas (co-benefits). For instance, capturing rain water to use for washing buses reduces flooding, reduces greenhouse gas emissions from water purification and pumping, and reduces water utility costs.

A key challenge for transit agencies will be walking the line between responsible risk management and expensively over-engineering assets. For instance, a transit agency can simply incorporate a higher incidence of extreme events into its designs (for example, designing for a 500-year flood rather than a 100-year flood as the 100-year flood becomes a much more common occurrence). However, this approach yields much more expensive designs due to the greater strength and resiliency incorporated. Another option is to simply design assets for a shorter useful life. This may end up costing either more or less than the business-as-usual scenario depending on whether the extreme event occurs and how much it costs to rebuild. A third approach, recommended by some experts, determines engineering level based on risk [88]:

1. Assign a likely occurrence probability that the stressor (storm, flood, etc.) will occur over the useful life of the facility.
2. Develop different designs for the facility with varying degrees of design standards applied to account (or not) for the stressor.
3. Estimate the costs of each design, including both replacement cost and cost due to facility disruption.
4. Apply the hazard occurrence probability to the different cost components of the design that will be affected by the changing environmental conditions. Estimate the likely costs in present dollars for each design. The design with the lower net present value cost would be the desired alternative.

A detailed process such as this would only be performed for significant infrastructure with a long life (over 40 years) in particularly sensitive areas where adaptation measures would be a significant expense.

Link strategies to agency organizational structures and activities

Climate change will affect the full range of transit agency departments and activities, including operations, maintenance, planning, environmental review, design, construction, and emergency preparedness. Climate change adaptation will be most effective when mainstreamed throughout the agency's processes, increasing institutional awareness and ensuring that adaptation is addressed in all relevant areas in an efficient and non-duplicative manner. Integrating climate adaptation assessment into an agency's asset management system is a convenient and targeted approach because both efforts involve developing inventories of assets and taking a risk-based approach to factors that affect asset conditions. Asset management systems also offer a streamlined framework for incorporating climate adaptation into capital plans, rehabilitation cycles, and budgets. Adaptation can also be integrated into transportation planning processes, environmental review, project development, and performance measurement. For more information on linking adaptation strategies to existing agency activities, see Section 5.

Develop and implement adaptation plans

At this stage, transit agency staff assemble an adaptation plan with timeframes for implementation and linkages to agency organizational structures and activities. The plan should include the specifics necessary to implement the strategies and committed resources. A plan's level of detail will vary depending on resources available, access to climate experts, and the presence or absence of broader local and state efforts. In addition, the variability in transit agencies' size and complexity will produce differently scaled adaptation assessments.

The agency then carries out the strategies in the plan.

Monitor, reassess and update the plans and their assumptions

The agency should regularly monitor, reassess and update the plan to assure that it is meeting its intended objectives and to re-examine key factors affecting it, including:

- Availability of improved **climate data** such as enhanced modeling and downscaling
- New information on **infrastructure impacts** from observed events in the region or analogues elsewhere
- New information on **changing asset conditions**—perhaps improving due to investments in good repair or new facilities coming on line, or degrading due to cash shortages, unexpected events, or operational issues

- New **adaptation measures** resulting from advancements in technology, materials science, engineering, and regulatory changes, and/or from actions by other units of government
- **Demographic factors** that influence transportation planning, such as population, income, and land use patterns.

State of the Practice

A few transit agencies have begun to conduct climate change risk assessments. The Los Angeles County Metropolitan Transportation Authority has nearly completed a vulnerability assessment of its assets. New Jersey Transit is conducting its own risk assessment of assets as well as an initial cost/benefit screening of potential adaptation strategies, which it expects to complete by the end of 2011. New York MTA partnered with Columbia University to conduct a preliminary assessment of its most vulnerable assets and develop initial ideas for short- and long-term adaptation. The report recommends a full risk assessment, though funding constraints have limited implementation of that recommendation.

Little information is available on transit-specific climate change adaptation strategies. However, much more information is available on transit designs for existing weather conditions. This may provide good analogues for future conditions expected in particular U.S. cities. For instance, cities that now face reasonably mild winters may be able to learn from the experience of transit agencies in places that have dealt with blizzards for years, like Chicago.

On the other hand, some newer systems internationally are being designed to much higher standards than is typical in the United States in order to incorporate rising sea levels and intense rain events. Flood engineering used for subway systems in tropical Asian countries with monsoons could provide high end analogues for U.S. systems expecting more extreme rainstorms (see flooding in Strategies section).

More work on multi-modal transportation adaptation has been done than on transit-specific adaptation. The U.S. DOT *Gulf Coast Study*, now in its second phase, is building a comprehensive, multi-modal transportation vulnerability assessment for Mobile, Alabama, and developing risk assessment tools capable of being applied elsewhere. The study includes Mobile's public transportation system and considers the city's two major bus facilities as critical assets.

The Federal Highway Administration (FHWA) is piloting a conceptual model for vulnerability assessment with three state DOTs (New Jersey, Washington, and Virginia) and two metropolitan planning organizations (Oahu and San Francisco). Of the five, the San Francisco and New Jersey pilots have the most extensive transit components.

Transit agencies can leverage the work being conducted at other levels of government by taking part in efforts in their own state or locality, and by following best practices learned from other jurisdictions. Some of the more extensive adaptation assessments domestically and internationally include those by New York City; King County, Washington; Alaska; California; Maryland; Massachusetts; the United Kingdom Highways Agency; Victoria, Australia; Canada; and Norway [89]. Twelve state governments in the United States have completed or are in the process of completing climate adaptation plans, including Washington, Oregon, Florida, Virginia, New York, New Hampshire, Maine, and Connecticut, in addition to those mentioned previously.

For statewide or local adaptation efforts, the environmental agency often takes the lead, with transportation departments and transit agencies sometimes participating as stakeholders. However, even if adaptation planning is occurring at a state or local level, transit agencies will still need to do significant work internally in order for their community to benefit from a public transportation network that is more prepared for the impacts of climate change. Other agencies cannot effectively inventory vulnerabilities, conduct risk assessments, and develop viable adaptation strategies for systems that only the transit agency understands and controls.

Table 3-1

State of the Practice: Transit and Adaptation

Transit Agency	Adaptation Actions
Domestic	
New York MTA	1st report on climate change hazards at a U.S. transit agency. Partnered with state and local adaptation efforts. Raised ventilation grates.
Los Angeles MTA	Conducting climate change risk assessment of assets
New Jersey Transit	Conducting climate change risk assessment of assets. Participating in FHWA adaptation pilot.
Waves Transit (Mobile, AL)	Part of multi-modal U.S. DOT Gulf Coast Study, Phase II
TriMet (Portland, OR)	Participating in regional adaptation efforts
Cape Cod Transit	Part of interagency climate change pilot, including assessment of sea level rise impacts
Honolulu Transit	Participating in FHWA adaptation pilot
King County Metro (Seattle, WA)	Stakeholder in county adaptation efforts, which are at forefront of field
Foreign	
Transport for London	Adaptation included in risk and asset management systems. Adding air conditioning, addressing flooding to existing system. Climate impacts incorporated into design of major project – "Crossrail"
Istanbul	New rail link built for 3 ft sea level rise + 1 in 10,000 yr flood
Taipei	After typhoon dumped 50 inches of rain in two days, set new standards for entrances: 2-4' above ground + 6" above 100 yr flood, + tunnel floodgates

Key Elements of Successful Adaptation Efforts

Flexibility: Assessing how to adapt transit assets and operations to the impacts of climate change brings with it multiple layers of uncertainty [90]:

- *Climate-related uncertainties*: uncertainties in future levels of greenhouse gas emissions and the sensitivity of the climate to greenhouse gas concentrations
- *Climate impact uncertainties*: whether and how the climate hazard will impact infrastructure and operations
- *Uncertainties surrounding developing and implementing adaptation strategies*: uncertainties regarding the effectiveness of specific measures or strategies, the availability of future funding, and future demands on transit systems from factors such as population growth and economic conditions.

Given these uncertainties, a flexible approach that takes action now but reassesses as new information becomes available makes sense. Flexible adaptation pathways are ones in which "adaptations are defined in terms of acceptable risk levels, and re-evaluated over time, rather than using an approach that sets inflexible standards for adaptation early in the process. More permanent, inflexible approaches are likely to be costlier and less effective ways of implementing adaptations for the dynamic and on-going climate change conditions projected than are flexible adaptation pathways" [91].

Dealing with uncertainty calls for flexibility, not inaction or paralysis. As one report pointed out, "[U]ncertainty is not the same thing as ignorance or lack of information—it simply means that there is more than one possible outcome as a result of climate change" [92]. Waiting for "certain" information may well increase costs more than taking prudent steps based on incomplete or evolving information.

Broad, cross-disciplinary involvement and buy-in: All steps of the adaptation assessment benefit from involving staff from across the transit agency, including planning, operations, maintenance, engineering, etc. Including frontline staff brings key information, engagement, and buy-in. For instance, maintenance staff are often most knowledgeable about things like which sections of track are prone to buckling and which bus facilities are likely to flood; they may have important insights regarding better maintenance processes that could prevent or reduce climate impacts. The assessment process also benefits from leveraging partnerships, bringing in experts from a range of relevant backgrounds such as climate science, civil engineering, and urban planning.

Embed climate change into work streams rather than developing a special system: Transit agencies have long-standing experience with planning for and managing weather-related impacts. Many also have existing asset management systems, state of good repair efforts, standard operating procedures, and other core competencies that can be capitalized on to adapt to climate change. Mainstreaming adaptation efforts throughout the agency's processes increases institutional awareness, builds expertise throughout the agency, capitalizes on existing agency knowledge and resources, and ultimately improves effectiveness.

Prioritize "no regrets" strategies and meet multiple goals: While some adaptation strategies will increase costs, some "no regrets" adaptation strategies will have multiple benefits or actually pay for themselves even without climate impacts. In fact, one study found that flood damages under a "green strategy" with climate change are actually substantially lower than damages without climate change—but also without adaptation strategies [93]. The "green strategy" involved lowering flood risks by enhancing natural vegetative buffers. Some adaptation strategies also serve as mitigation strategies by reducing greenhouse gas emissions. Others have multiple benefits such as reduced pollution and improved transit customer experience.

Transit agencies also need to consider that solving one problem may produce another problem. Agencies must seek solutions that accommodate the multiple demands on the systems for accessibility, sustainability, climate adaptation, and other goals. For example, Transport for London designed newer stations with flat surfaces from the outdoors into the station in order to improve accessibility; unfortunately, this allowed flood waters to easily enter the facility and in some cases, the agency had to close ticket halls while mopping up flood waters [94].

Plan for communication with customers: Effective communication with customers manages expectations, provides critical safety information, and allows travelers to alter routes and make adjustments that minimize the negative impacts on their own schedules as well as those of the system as a whole. With modern communications, transit agencies now have at their disposal the ability to reach customers through smart phones, websites, digital displays, announcements, and the mass media. After the August 2007 storm described in Section 2, New York MTA upgraded its communications technology. While previously it took hours to push out mass emails (1.5 hours to email 24,000 Long Island Railroad customers, for instance), MTA acquired the capacity to send out one million simultaneous email alerts. The agency also improved its website, server capacity, information feeds, public address systems, and information screens that can operate under emergency conditions [95]. How a transit agency communicates with customers and local businesses during extreme weather events determines in large part how successful their response is deemed to be.

Top level external push: In New York, the Mayor's Office has a strong commitment to climate adaptation, spurring efforts in that city. Similarly, the London Mayor's Office's robust adaptation efforts and the United Kingdom's Climate Change Act of 2008 catalyzed Transport for London adaptation work.

Central point of coordination: A central champion to coordinate efforts ensures information sharing and accountability while allowing the detailed work to be done by individual business units with the depth of knowledge of their assets and vulnerabilities.

Interdisciplinary seminars with engaging narratives: Both Washington State DOT and Transport for London implemented a series of seminars that brought together asset engineers, communications specialists, business leaders, emergency planners, and others from the wide range of disciplines affected. They found that when engaging the various parts of their agencies, providing raw climate data projections was an inaccessible and ineffective exercise. Instead, providing visual information, narratives, and discussing previous extremes and how climate change may bring more extremes was much more effective.

Coordination with other infrastructure and service providers: Adaptation requires actions from other infrastructure and service providers on whom transit agencies depend, such as telecommunications companies, cellular systems, state highway administrations, stormwater management agencies, and local environmental departments that manage wetlands as natural buffer areas for flooding.

Case Study

Mobile, Alabama: Developing a Criticality Assessment

The U.S. Department of Transportation is in the second phase of a major study of climate change impacts in the Gulf Coast region. While Phase 1 took a broad look at the entire Central Gulf Coast region and provided a "big picture" view of the climate-related challenges facing infrastructure, Phase 2 is focusing on the single Metropolitan Planning Organization (MPO) region of Mobile, Alabama. The purpose of this focused study is to evaluate which transportation infrastructure components are most critical to economic and societal function, and assess the vulnerability of these components to weather events and long-term changes in climate. Phase 2 will also develop tools and approaches that the MPO and other public and private system operators can use to determine which systems most need to be protected, and how best to adapt infrastructure to the potential impacts of climate change. Through this study, U.S. DOT intends to create a template for an assessment process that can be replicated in other regions of the country. The study is multimodal, including highway, port, rail, and public transportation assets. While the study is ongoing as of the time of this writing, the criticality assessment part of the study has been completed and provides an example of an important step in a climate change risk assessment for a transit agency.

The primary transit system for Mobile, Wave Transit, administers fixed-route and demand-response service. The fixed-route service consists of 11 local bus routes, the Moda! downtown circulator, and the Baylinc regional connection between Mobile and Baldwin Counties. The demand-response service includes neighborhood, Access-a-Ride, and paratransit services. With a fleet of 38 buses and 31 demand-response vehicles, Wave Transit System provided an average of 4,100 weekday, 2,500 Saturday, and 18 Sunday trips in 2008 (Sunday is limited to demand-response service). Additionally, there are four maintenance vehicles to service disabled buses or demand-response vans. Two additional demand-response vehicles and 10 replacement buses were purchased through American Recovery and Reinvestment Act of 2009 funding.

The study team assessed the criticality of Wave Transit System assets qualitatively using three assessment categories: operational, socioeconomic, and health and safety. The assessment was based on review of the metropolitan planning organization's 2035 Long Range Transportation Plan, the area's Coordinated Human Services Transportation Plan, Wave Transit System's 2010 Hurricane Manual, Wave Transit System's web site, and interviews with Wave Transit staff.

Socioeconomic Factors

The assessment of socioeconomic factors considered service to transit-dependent and environmental justice (EJ) populations, as well as the system's ability to provide access to employment and major attractors. These factors were assessed based on

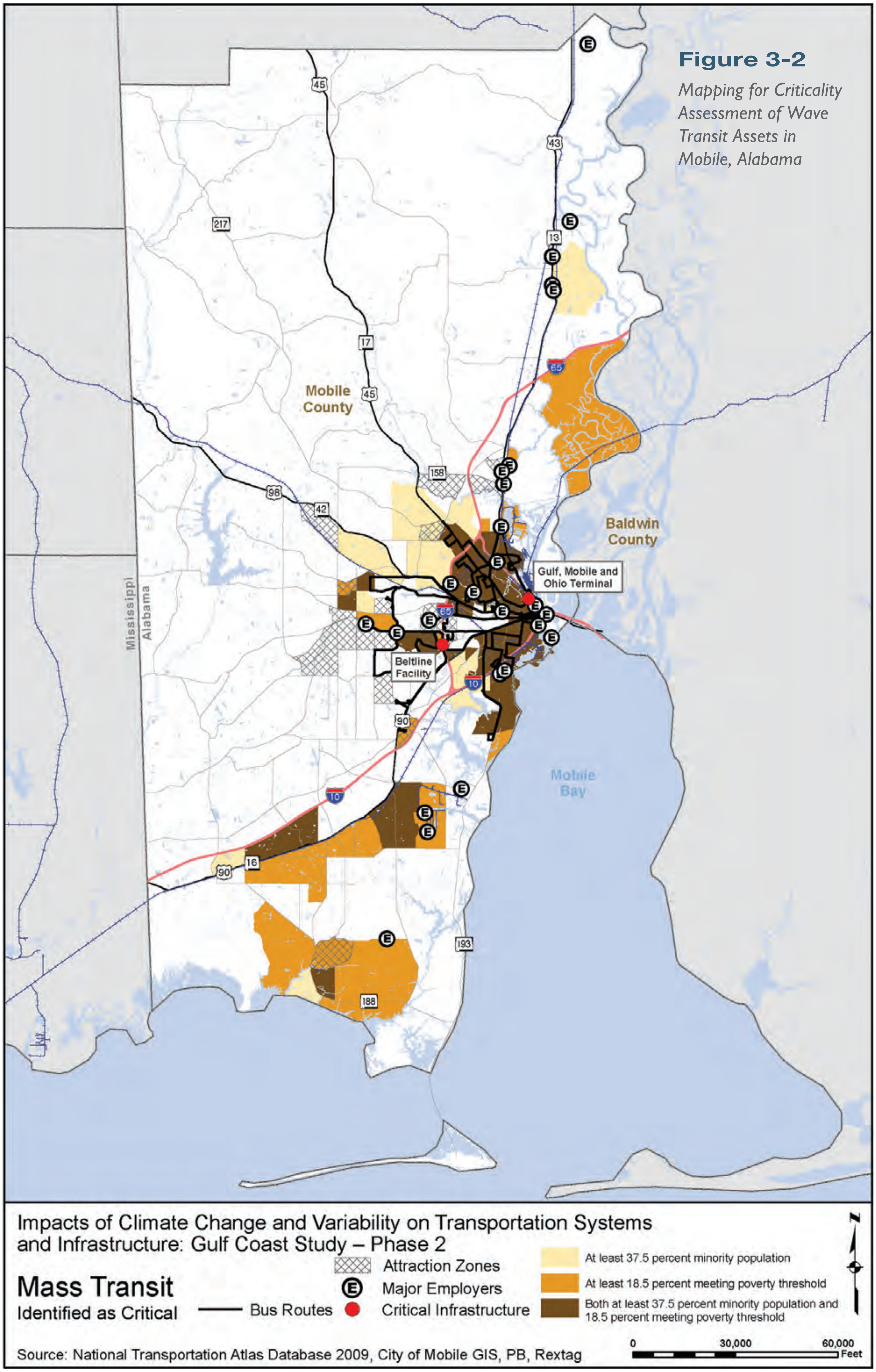


Figure 3-2

Mapping for Criticality Assessment of Wave Transit Assets in Mobile, Alabama a mapping overlay of fixed-route bus service and attraction zones, major employers, and EJ zones (see Figure 3-2). Fixed-route service is provided to many of the area's EJ zones (or transportation analysis zones in which at least 37.5 percent and/or 18.5 percent of the population is minority and below the poverty line, respectively). The service connects EJ populations to many of the area's attraction zones—medical, post-secondary educational, and retail facilities—as well as the central business district. Wave Transit System also provides neighborhood circulator and door-to-door services to transit-dependent customers who live in areas not served by fixed-route service or meet certain requirements for more flexible service.

Operational Factors

The operational factors address the types and variety of services offered by Wave Transit System, its fleet size, and facilities. Although transit in the Mobile area relies heavily on roadway infrastructure, the project team's assessment of criticality of the transit system was based on physical infrastructure and assets under the purview of Wave Transit System.

Wave Transit System operates from two locations. One of these locations is the Gulf, Mobile and Ohio (GM&O) Terminal, which houses some of the agency's administrative functions and serves as the main and central transfer hub for most of Wave Transit System's radial fixed-route service. Nine of the 11 routes terminate at the GM&O Terminal and the facility has 12 total bus bays for use. The second location is the Beltline facility, which houses the agency's main administrative functions, demand-response scheduling service, and operations and maintenance facility. It also is the depot for Wave Transit System's operations fleet and four maintenance vehicles. As an example of the Beltline facility's importance, during Hurricane Katrina, Wave Transit System stored its fleet in the garages at the Beltline facility. While the administrative building itself sustained damage due to the storm, the fleet did not.

Health and Safety Factors

The assessment of health and safety factors considered transit's ability to provide access to major medical, health and safety facilities and its role during weather emergencies and evacuations. These criteria were assessed using the same mapping overlay for the socioeconomic factors and Wave Transit System's hurricane manual. Transit plays an important role during weather emergencies and evacuations. With one of the key threats to the Mobile area being hurricanes, Wave Transit System, under direction from the Mobile County Emergency Management Agency, provides evacuation services. The agency focuses primarily on transporting people who are "relatively healthy and ambulatory" (*2010 Hurricane Manual*, p. 43), as well as those with physical, emotional, or sensory impairments who are unable to respond independently to an emergency situation. Wave Transit System provides transportation from pre-designated pick-up locations to drop-off locations at American Red Cross shelters. The agency also continues to provide demand-response service, limiting it to transport clients only to essential medical treatment. During the recovery phase, Wave Transit System returns evacuees from drop-off locations to their pick-up points and gradually resumes fixed-route and demand-response services at normal levels.

Conclusion

The study team concluded that the critical infrastructure and assets for transit in the Mobile area are the GM&O Terminal, the Beltline facility, and the fixed-route and demand-response fleet.

Source for Case Study: U.S. Department of Transportation. *Impacts of Climate Change and Variability on Transportation Systems and Infrastructure: The Gulf Coast Study, Phase 2. Task 1: Assessing Infrastructure for Criticality in Mobile, AL*. 2011.

Case Study

Los Angeles County MTA: Initiating a Vulnerability Assessment as Part of a Broader Sustainability Framework

Los Angeles County Metropolitan Transportation Authority (Metro) used the *Guidelines for Transit Climate Action Planning* [96] as a take-off point for its climate change adaptation efforts. The guide was developed as a recommended practice by the APTA Climate Change Standards Working Group, which is funded by FTA. Metro included both adaptation and mitigation in the climate action planning process.

Metro began its adaptation assessment with an informal scan of the activities of other U.S. transit agencies in fall 2010, finding it was one of the earliest to conduct an adaptation assessment. Metro formed a technical advisory committee of stakeholders to advise it on factors to consider. After hiring a consultant with experience in climate change adaptation, Metro began a vulnerability assessment of its assets, which it expects to complete in the summer of 2011. Generally following the FHWA conceptual model *Assessing Vulnerability and Risk of Climate Change Effects on Transportation Infrastructure*, Metro will screen for the most critical elements of the system and then perform a qualitative risk assessment on these assets.

In Los Angeles, the main climate change impacts relevant to transit are more frequent and intense heat waves, more frequent heavy precipitation, an increase in wildfires, and sea-level rise. For instance, bus services on roads closed due to wildfires must be rerouted or suspended. As another example, extreme rainfall briefly suspended Metro's blue line rail service: rainwater undermined the ballast, and also flooded conduits in some of the electrical boxes. Sea-level rise threatens coastal Los Angeles County, and the largest port on the west coast, Los Angeles/Long Beach Seaport.

Initial adaptation strategies being considered include designing increased flexibility in the transit system, decentralizing asset storage, and identifying flood prone areas early on in the planning process. For projects that are still in the planning stages, such as a planned subway line that will run close to the Pacific Ocean, the agency hopes to incorporate design changes that will make the infrastructure more resilient to climate change impacts.

Metro has sought to incorporate adaptation as well as other aspects of sustainability into the broad range of its day-to-day activities and long-term planning through a consistent environmental framework and guideposts. At the broadest level, Metro adopted an agency-wide environmental policy in 2009. Procurement templates require that contractors bidding for Metro work follow the environmental policy. Additionally, Metro used its revamp of design criteria for busway, light rail, and heavy rail projects as an opportunity to specifically identify the need for climate change adaptation. Metro is also using the structured procedures of its Environmental Management System, sponsored by FTA, as a climate change management tool.

The Environmental Compliance and Services Department, which is spearheading the adaptation effort, found early on that broader awareness of the climate change impacts was a necessary first step. When beginning conversations with staff in other departments, individuals were often confused at first, but they found the more they talked about it, the more they understood the relevance to their daily activities. The Environmental Compliance and Services Department's work cuts across planning, operations, procurement, and other business units, allowing the Department to weigh in from a sustainability standpoint and provide expertise.

Source for Case Study: Author Interview with Cris B. Liban, Environmental Compliance and Services Department Manager, March 17, 2011.

SECTION
4 Strategies

"As transportation agencies work to meet the challenges of congestion, safety, and environmental stewardship—as well as maintaining transportation infrastructure in good repair—addressing the risks posed by a changing climate can help ensure that the substantial investments in the region's infrastructure are protected in the coming decades by appropriate adaptation strategies."

- U.S. Department of Transportation Gulf Coast Study, Phase I

At the broadest level, there are four categories of adaptation strategies:

- **Maintain and manage**: Absorb increased maintenance and repair costs and improve real-time response to severe events. Incorporate "smart" technologies such as sensors that detect changes in pressure and temperatures in materials; these can set off alerts of approaching damage thresholds for bridges and other structures, or of rising water levels and potential flooding [97].
- **Strengthen and protect**: Design new infrastructure and assets to withstand future climate conditions (larger drainage capacity, stronger structures to withstand high winds, materials suited to higher temperatures). Retrofit existing structures and facilities. Build protective features such as retaining walls, levees, and vegetative buffers.
- **Enhance redundancy**: Identify system alternatives such as increased bus service in the event of rail interruption as well as a broader regional mobility perspective, considering all transport modes.
- **Retreat**: Abandon transportation infrastructure located in extremely vulnerable or indefensible areas. Potentially relocate. Site new facilities in less vulnerable locations.

At a finer-grain level, a range of specific near- and long-term strategies apply to transit agencies for reducing vulnerability and enhancing resilience to the impacts of climate change. They are categorized here by climate impact—flooding, heat waves, etc. They should be considered illustrative rather than comprehensive. The examples, however, can prove useful in stimulating discussion and providing experience from which other agencies may benefit. While some examples are drawn from targeted climate adaptation efforts, most are from agencies responding to environmental conditions and were not implemented specifically as climate adaptation strategies (though that does not lessen their applicability).

Fortunately, as a large and geographically diverse country, the United States has transit agencies in different climate zones that can share experiences on running a transit system under different conditions. For instance, based on present-day average heat index values, the state of Massachusetts is projected to resemble New Jersey under the lower emissions scenario by mid-century, and Maryland under the higher emissions scenario (see Figure 4-1) [98]. As such, Maryland MTA or Washington Metro may have information relevant to Boston's MBTA. Internationally, some transit agencies currently experience much more extreme conditions than what U.S. agencies will experience, even on the high end of climate change projections. For instance, Singapore's transit system is designed to handle that country's frequent monsoon rains of up to twelve inches per day.

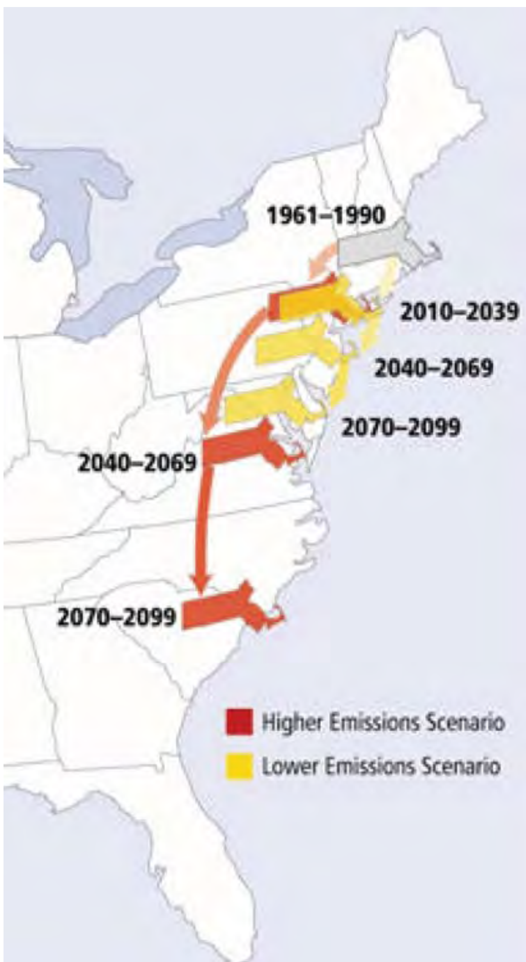


Figure 4-1

Analogues: Massachusetts is Projected to Resemble Maryland under the Higher Emissions Scenario by Mid-Century

Source: Northeast Climate Impacts Assessment (NECIA). *Confronting Climate Change in the U.S. Northeast: Science, Impacts, and Solutions*. Union of Concerned Scientists. July 2007

Flooding from Intense Precipitation, Sea-level Rise, and Storm Surge

Move assets out of harm's way

Bus and rail storage and maintenance facilities frequently occupy low-lying, cheaper land subject to flooding. A standard operating procedure can be implemented to move vehicles and other portable assets out of harm's way to an alternative location when flooding is predicted. For instance, during hurricane evacuations, the buses that Honolulu's transit agency uses to evacuate residents to storm shelters are stored at those shelters rather than at the low-elevation bus storage facility. The agency is also pursuing a memorandum of agreement with a nearby military installation to store additional vehicles at that location when flooding is predicted. While this solution sounds simple, it has not been used in some cases, leading to vehicle damage and significant capital cost. This highlights the importance of ensuring that a clear standard operating procedure is laid out in advance, identifying alternative locations for vehicle storage and addressing responsibility for moving the vehicles, recognizing that employees may need to attend to their own families in preparation for potential flooding.

Pumps

Subway tunnel pumps typically are active even on dry days to remove water seepage into tunnels. Systems have varying design standards for pumps for addressing flooding. A review by the Region II University Transportation Research Center found that there are no general, national public transportation design standards or protocols to address floods. Instead, standards are adopted locally based on local experience and conditions thought to be most likely [99]. Hence, BART provides two pumps at stations, each with 500 gallons-per-minute (gpm) capacity. (Toronto is similar.) In Los Angeles, primary and alternate pumps are rated at 1000 gpm. New York MTA's pumps and drainage systems are designed to handle 1.75 inches of water per hour. San Francisco's Central Subway is being designed to handle 1.5 inches of rain per hour (a 100-yearstorm) plus normal water infiltration through the tunnel lining (0.2 gallons per minute per 200 linear feet) and water needed for fighting a fire incident in the system. WMATA's pumps are scaled to handle 50-year storms. New York MTA deploys portable pumps during intense rain and WMATA stores portable pumps in known problem areas [100]. In Tokyo, underground tunnels susceptible to flooding have triple pumps, so that two can still be used even if one breaks down. Prague Metro and RATO in Paris are installing more powerful pumps to better handle water [101]. New York MTA reports that pumping capacity is not as much of an issue as the susceptibility of the system to water infiltration from sidewalk level ventilation grates; moreover, when city stormwater systems are overwhelmed, there is simply nowhere to pump the water. The schematic of the New York City subway's drainage and pumping systems in Figure 4-2 shows these vulnerabilities.

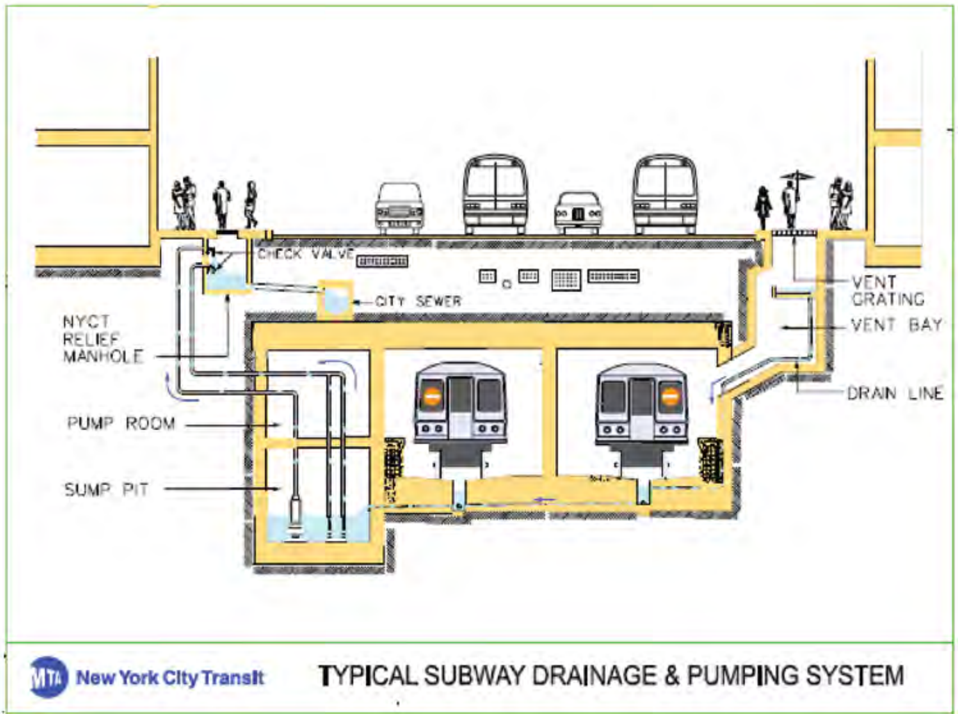


FIGURE 4-2

New York City Subway Drainage and Pumping Systems

Source: Metropolitan Transportation Authority, August 8, 2007 Storm Report, 2007

Modify ventilation grates

Following the August 2007 flood, as well as other less severe floods, New York MTA raised many of its sidewalk level ventilation grates so that water could not enter from flooded sidewalks. New York held a design competition to incorporate the vents into street furniture (see Figure 4-3). MTA can also cover vents temporarily with plywood.

Figure 4-3

Rasied Ventilation Grates

Courtesy of MTA New York City Transit

Tokyo's ventilation shafts are closed when a heavy rain warning is issued (see Figure 4-4). They can be closed manually, or by remote control, or automatically in response to a flood sensor. New York has experimented with ventilation grates that close automatically when water reaches a certain level.

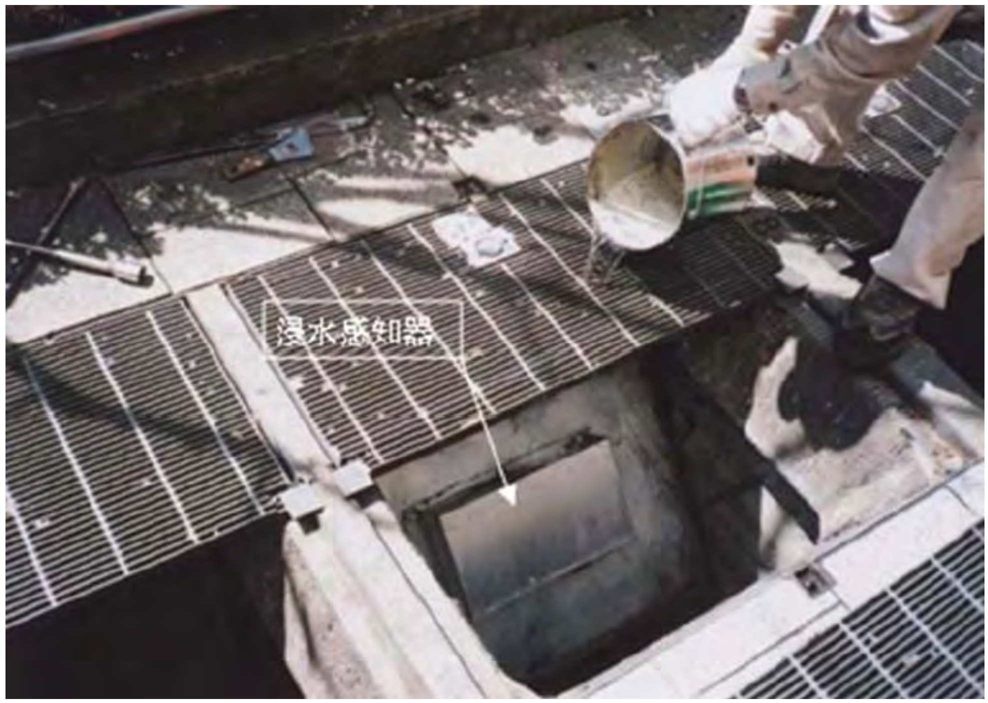


Figure 4-4

Tokyo Metro Ventilation Shaft that can be Closed by Remote Control, Manually Onsite, or Linked to a Flood Sensor

Source: Paaswell, Robert and Pillich, Jose, "MTA Storm Task Force Peer Property Comparisons," September 5, 2007.

Physical barriers and improved drainage

In response to increased flooding, the Port Authority of New York and New Jersey raised the floodgates at the top of stairways leading to station platforms at the PATH Hoboken Station to account for sea level rise and sealed all gates that were below the one hundred year floodplain [102].

In Toronto, stations located in an area with a history of flooding are built at least one foot above the high level flood elevation [103]. Some stations in Tokyo can be closed by gates against water, which prevents water incursion but also shuts down that link in the system (see Figure 4-5) [104].

Figure 4-5

Tokyo Metro Flood Prevention Gate at Tunnel Entrance and Flood Prevention Board at Station Entrance

Source: Paaswell, Robert and Pillich, Jose, "MTA Storm Task Force Peer Property Comparisons," September 5, 2007

The metro system in Vienna, which dates from 1978, had not previously experienced flooding, but experienced a flood during heavy rain that officials believe was linked to climate change and is likely to recur in the future. The agency has thus decided to increase drainage capacity. They also have aluminum and concrete barriers that can be erected to protect two lines that run parallel to the city's rivers.

Southeast Asia receives much more intense rainfall than the United States even under late-century climate change predictions, and as such their experience may prove instructive for the high end of adaptive responses. The Singapore Rapid Transit System, for example, must contend with twice yearly monsoon rains and high groundwater levels on this small island nation. Twelve inches of rainfall in a single day is not uncommon. The relatively new underground rail transit system was designed to meet the demands imposed by this high-precipitation climate. As the first line of defense, all efforts are made to prevent water from entering tunnels. The system channels runoff from the surrounding area into surface drains separate from the underground facilities to avoid overwhelming system drains. Water-tight barriers at least three feet (one meter) above flood and ground levels protect the stations and tunnel entrances. Tunnel pumps can handle a 100-year storm [105].

In another example from Asia, Typhoon Nari struck Taiwan in September 2001, dumping 50 inches of rain in two days, with 32 inches falling on the first day. The flood protection built into the capital city's Taipei Rapid Transit System could not cope with such extreme conditions. After the typhoon, the agency reviewed its flood response measures and set enhanced design standards for all stations. As before, station entrances would be at least six inches above the 100-year flood level and two to four feet above ground level. In addition, however, flood barriers at station entrances would now be 43 inches above the 200-year flood level [106], which was 24 inches over the previous standard. The agency also assessed all portal areas, tunnel interchanges, river crossings, and earthquake fault crossings for the possibility of fitting tunnel floodgates [107].

The engineering standards for a new commuter rail in Istanbul, Turkey, are also instructive. The barrier heights for the Marmaray project, a new underground commuter rail link in Istanbul, are designed based on a one-in-ten-thousand year flood with three feet of sea-level rise anticipated during the design life of the transit system. It has hydraulic flood barriers designed to rise in event of flood [108].

In addition, transit tunnel linings vary in degrees of engineering to prevent groundwater infiltration. New transit tunnels can be engineered to stricter standards if needed and older tunnels retrofitted.

Finally, clearance of debris from drainage systems before and during storms is critical to prevent flooding, as is proper maintenance of pumps. For instance, track inspection personnel at Atlanta's MARTA system walk the entire track system weekly and clear any obstructed drains to ensure full capability to remove stormwater [109].

Bridge design

Engineers may consider design to reduce bridge scour by strengthening protections around piers. The FHWA *Bridge Scour and Stream Instability Countermeasures; Experience, Selection, and Design Guidance, Third Edition* offers information also applicable to transit bridges.

When considering expensive engineering design consequences such as bridge heights, detailed risk and cost analysis makes sense. Portland's TriMet considered the impact of higher river levels in the area of a bridge crossing for the seven-mile Portland-Milwaukie Light Rail line that is scheduled to be completed in 2015. In that case, TriMet found that the worst case scenario from projected climate change impacts was a one-quarter inch rise in water levels, which did not warrant design changes [110].

Green infrastructure stormwater management best practices

Transit agencies have significant opportunities to prevent localized flooding by reducing runoff from park and ride lots, administrative buildings, maintenance facilities, storage lots, and joint development projects. Best practices include rain gardens, stormwater ponds, trees, native plants, pervious pavements, and native vegetation buffers along waterways. These strategies allow stormwater to be absorbed through natural processes, reducing or even preventing flooding of facilities, and bringing multiple co-benefits [111].

For example, Kansas City's new Bus Rapid Transit (BRT) System has 30 stations with rain gardens in bump-outs designed to collect and filter stormwater runoff from roads and sidewalks (see Figure 4-6). This reduces flooding, erosion, and the entrance of pollutants in rivers and streams. The BRT system also features a pervious concrete parking lot so that stormwater can seep into the ground, and shade trees that capture rain water (see Figure 4-7).

Source: Kansas City Board of Parks Commissioners, Presentation: Troost BRT Streetscape, January 2009

Figure 4-6

Kansas City Bus Rapid Transit Station Rain Gardens

Figure 4-7

Construction of Pervious Concrete Parking Lot that Allows Stormwater to Seep into Ground, Kansas City

Courtesy of Kansas City Area Transportation Authority

Transit agencies can also capture rain water using vegetated "green roofs" and rain barrels or cisterns for maintenance facilities and buildings. For instance, New York MTA's LEED-certified Corona maintenance facility captures rain water for washing vehicles. In addition to reducing flooding, capturing rain water to use for washing vehicles reduces greenhouse gas emissions from water purification and pumping, and reduces water utility bills. As another example, MTA plans to install a green roof on its new Mother Clara Depot. The new roof will also capture rain water for bus washing. The incremental cost of the green roof is approximately $15 per square foot. The added insulation from a green roof offsets this by reducing heat gain and loss, lowering energy costs. The green roof also protects the roof membrane from ultraviolet radiation, extreme temperature fluctuations, punctures, and other physical damage, potentially doubling the roof's life expectancy. MTA has not yet completed a detailed cost/benefit analysis for the project but calculates roughly that the investment will pay itself back based on energy bill savings alone within 20 years [112]. The U.S. DOT headquarters building also boasts a green roof. The facilities management office estimates a five-year payback period for the green roof from energy savings for heating and cooling. San Francisco MTA also has installed a green roof at its headquarters office building. These types of adaptation strategies that pay for themselves and provide multiple benefits are "no regrets" strategies for implementation.

Figure 4-8

New York City Transit Green Roof

Courtesy of MTA New York City Transit on the E180th Street Signal Crew Quarters in the Bronx

As further evidence of the benefits of these strategies, Philadelphia's city-wide policies and demonstration projects since 2006 to promote green infrastructure in planning and development drastically reduced combined sewer overflows and saved

$170 million. New York City's 2010 Green Infrastructure Plan finds that using green stormwater reduction practices can reduce combined sewer overflow by 2 billion gallons by 2030 and cost $1.5 billion less than traditional methods [113].

Connecting to broader community adaptation strategies

While some strategies fall firmly under the control of transit agencies, others require action by other entities or would be strengthened by community-wide approaches. Transit systems depend on local agencies that manage roads, stormwater and sewers, and zoning and permitting. To prevent incursion of storm water into bus routes or transit tunnels, street drainage capacity and storm sewer capacity needs to be improved, but this is typically under the jurisdiction of the local water and sewer agency, highlighting the need for collaboration. Transit agencies can also collaborate with municipal authorities on broader implementation of stormwater best management practices to prevent flooding. Area-wide protections against storm surge and river flooding such as hard protections (levees, sea walls, revetments, etc.) and soft protections (wetlands, vegetation buffers) are also elements that transit agencies do not control but affect the vulnerability of their assets. As an example, Transport for London coordinated adaptation efforts with the Greater London Authority's "Drain London Programme" regarding surface water management.

Transit-oriented development

Transit-oriented development (TOD) is compact, mixed-use development within walking distance of public transportation. Transit agencies foster TOD through collaboration with local planning agencies and undertaking joint development projects. (In joint development, the transit agency partners with developers to create compact, mixed-use development on, above or adjacent to property that was purchased for construction or staging of transit infrastructure.) While TOD has often been touted as a greenhouse gas mitigation strategy [114], it also serves as an adaptation strategy. Natural systems preserved by compact development, such as wetlands, forests, and barrier islands, provide protections against the type of flooding projected to become a greater threat as the climate changes. The natural services would be prohibitively expensive to replicate with human-built systems [115]. TOD co-benefits include convenience and quality of life benefits for residents.

Houston-Galveston recognized the advantages of compact and transit-oriented development. The metropolitan planning organization convened an expert panel to analyze regional adaptation for the largely low-elevation region. The panel recommended more "compact communities, meaning less area for local government to maintain, manage, and protect and less dependence on large transportation facilities, especially before and after extreme weather events." Its report notes that "Compact communities also use less land than traditional developments, reducing the amount of impervious surface in the region's watersheds and lessening flooding impacts" [116]. Interconnected street grids typically used for compact development also provide more route redundancy.

The City and County of San Francisco are looking to several new developments at Treasure Island, Hunter's Point Shipyard, and Candlestick Point to achieve several objectives: connect new developments with enhanced transit service (BRT, Ferries, Light Rail) and bicycling infrastructure, require that developers pay for and provide transit passes to new residents and employees, plan for rising tides and storm surges, and restore portions of the developable land to natural conditions such as wetlands and salt marshes along the bay to provide natural habitat as well as climate adaptation and mitigation [117].

Landslides

Stormwater management

Heavy stormwater saturates soils, increasing landslide vulnerability. A study of the 1976 landslides in Portland (Oregon) resulting from a heavy rain-on-snow event found that 76 percent of the landslides studied resulted in part from human activities such as fill failures and the formation of cut slopes. The study estimated that nine percent of the landslides could have been prevented by better stormwater control measures, such as conveying standing water off the property to avoid soil saturation and better siting of buildings on properties [118].

Hardening

Additional hardening (e.g., retaining walls) may be called for in some instances to prevent landslides. For instance, the Hawaii State DOT hardened an area along a bus transit route near Waimea Bay on Oahu that is particularly vulnerable to landslides [119].

Heat

Preventing rail buckling

Setting and maintaining high "rail-neutral temperatures" is a key strategy for preventing buckling from rail expansion at high temperatures. During the installation process, the rail is either heated to a high temperature or is mechanically stressed by pulling on the ends of the rail and installing it at tension. A rail-neutral temperature of 90°F is typically used in the northern United States and 100°F in the southern part of the country. This allows the rail to expand up to that temperature before it reaches a state of compression and a potential buckling situation. Setting a rail-neutral temperature too high, however, means that the rail may be prone to breaking during cold weather. It is important to design and install tracks suited to the conditions they will face in order to reduce the future level of maintenance that will be needed. This is especially true as most transit agencies hire contractors for construction and conduct maintenance in-house.

As a complicating factor, rail-neutral temperatures change due to operational and environmental parameters. The actual rail neutral temperature may thus be lower than the installed temperature. Rails can be re-stressed, but without doing so, there is no convenient way to assess the actual neutral temperature [120]. When replacing buckled sections, it is also important to install the replacement at an appropriate rail-neutral temperature. A Federal Railroad Administration (FRA) funded study provides equations for optimizing rail-neutral temperature during rail re-stressing operations [121].

Yet another complication is that ambient air temperatures are not an accurate predictor of actual rail temperatures (which vary based on sun exposure and the passage of trains). Yet one cannot determine the actual rail temperature without direct monitoring (i.e., with a thermocouple). Rail agencies typically issue slow orders when ambient temperatures reach a certain level, such as 90°F. However, the true determinant for the risk of buckling is the differential between the temperature of the rail itself and the rail-neutral temperature, not simply the temperature of the ambient air. Amtrak has approximately 20 wayside weather stations that directly monitor and record rail temperatures. Amtrak now uses these direct measurements as one of their means for issuing slow orders. Since it is not practical to have weather stations on all sections of rail, for those sections where they do not have direct measurements, Amtrak partnered with FRA to create a model that predicts rail temperature based on sun exposure and ambient temperature [122, 123].

Expansion joints can provide space for rail expansion, thereby preventing buckling. Some older rail systems have such joints (e.g., the historic Galveston and New Orleans trolley systems) [124]. In the 1950's most rail construction shifted from jointed rail to continuously welded rail, which made for a smoother ride and reduced maintenance. But it also eliminated the joints that created extra room for rail expansion under high heat conditions.

Areas of track with concrete slab rather than stone ballast are not generally prone to buckling incidents as concrete slab provides more stability than rock ballast. Also, concrete crossties with improved fasteners can withstand greater track stress than wooden ties with spikes [125].

Ballast maintenance to improve stability and support of rail reduces vulnerability to rail buckling. A United Kingdom study of the impact of climate change on that country's rail system recommends changing operations and maintenance due to the higher risk of rail buckling [126].

Temperature increases expected under climate change would not generally necessitate replacing existing track (other than the short segments that buckle from extreme heat). Replacement is most likely to occur as part of normal maintenance, in upgrades to handle increased traffic volumes, or following storm surge or other catastrophic events. Depending upon the type of upgrade, the slope and curvature, and the number of bridges and tunnels, track replacement costs range from $500,000 to $3 million/mile [127].

Network Rail, which manages the intercity rail infrastructure in the United Kingdom, is working with the meteorological agency to develop a tool that will enable the rail industry to evaluate policy options for adaptation. The tool will marry climate data with engineering and cost data. It will help rail managers determine at what point it is more cost effective to replace rails with more heat resistant rail material rather than continue to maintain the existing rail [128].

Portland's TriMet noted a significant increase in slow orders due to high heat over a period of three years. Recognizing the inconvenience to customers, TriMet implemented a concerted set of strategies with an ultimate goal of no slow orders. TriMet identified areas with frequent rail buckling, many of which were adjacent to curves or in direct sunlight. The Maintenance of Way division developed expansion joints and installed them by breaking the continuously welded rail in eight to nine key areas and applying the joints. The joints allow for one and a half to two inches of relief, permitting the rail to expand. TriMet estimates that this work cost about $100,000 to $150,000, but reduced heat-related slow-orders from ten in 2008 to three in 2011. A ten-mile stretch of TriMet's red line, for instance, which was previously often subject to slow orders, has now been able to function at regular speed, eliminating what had been a ten-minute delay on hot days. TriMet is also looking at rail attachment systems that allow movement of the rails and are resilient enough to accommodate expansion. For new rail construction, track and systems engineers are looking at designing resistance to buckling by focusing on areas such as curves. This saves the cost of having to install joints or other solutions in the future [129].

Preventing electrical equipment failure

In response to recent heat waves, TriMet is installing more ventilation for its electrical equipment. In New York, MTA is building a relay room that will keep electrical equipment cool using energy efficient natural and mechanical ventilation systems.

Protecting customer and worker comfort and safety

A key strategy for protecting customer and worker comfort and safety is the development and implementation of heat policies and action plans to be initiated when a heat wave is forecast. Heat policies and plans will vary considerably from region to region, but key components include reduced work hours for transit employees and contractors, especially for construction- and maintenance-related activities; rescheduling of construction and maintenance activities; mobilization of emergency responders to victims of heat-related illnesses; and coordination plans in the event of service cancellations.

Other strategies for keeping workers and customers cool depend on capital investment and long-range system planning: upgrading to energy-efficient air conditioning on rolling stock; the use of heat-resistant construction materials and reflective paint for vehicle roofs; and providing shade shelters and landscaping around transit stops and along pedestrian corridors leading to transit stops. Each of these strategies is briefly discussed below.

Energy-efficient air conditioning can be considered for new vehicle procurements as well as for rehabilitation and retrofits. For example, TriMet in Portland, Oregon, is increasing the cooling capacity of its electrified cooling systems on buses. All TriMet buses run on a biodiesel fuel blend and the newly purchased buses use a NASCAR-inspired engine cooling system with computer monitoring to boost fuel economy [130]. Turning bus engines off while at transit centers, rather than idling reduces waste heat energy output. Many European transit agency members are purchasing buses with air conditioning for the first time [131].

Reflective roofs are frequently quite cost-effective. They consist of light-colored or white paint, or a white membrane, covering the surface of a given structure, vehicle or paved area. Both techniques have been mainly applied on roofs and pavements. Cool roofs are especially important in buildings, where significant energy demand for cooling can be saved by reducing heat gain to the building. For instance, New York MTA's Corona maintenance facility has a white roof and a strategically designed natural ventilation system. The surface temperature of a typical black roof on a hot summer day in New York is around 130°F, pushing up interior temperatures in maintenance facilities to around 95°F. In contrast, the Corona facility's white roof typically only reaches 110°F, which combined with

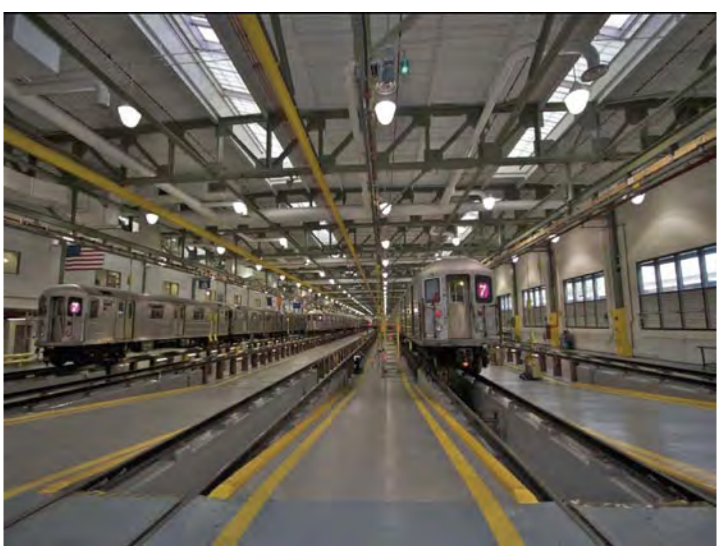


Figure 4-9

New York City Transit's Corona Subway Car Maintenance Shop has a White Roof and a Strategically Designed Natural Ventilation System

Courtesy of MTA New York City Transit

the natural ventilation system, keeps temperatures comfortable. NYCT reports that workers in the Corona facility have higher work satisfaction and productivity; in fact, the mean distance between vehicle failures has improved [132].

Similarly, transit vehicle rooftops can be painted white to prevent heat energy absorption. This strategy not only maintains customer comfort, but reduces the fleet's overall cooling and energy costs.

Pavements that absorb less heat can be achieved through increased albedo (greater reflectivity) and other material and structure choices.

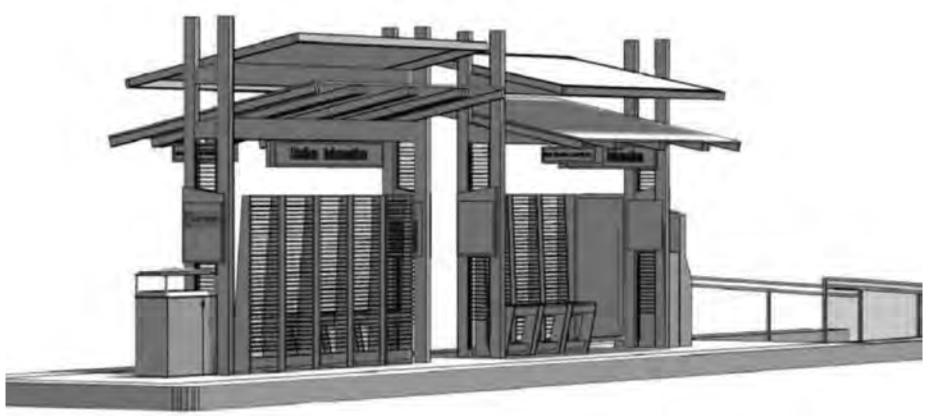
Transit stops and other shelter facilities should be designed to provide shading and natural ventilation for passenger comfort and safety. Tucson's transit system provides several examples.

The station design for the new Tucson Modern Streetcar system incorporates a double-tiered shade structure that decreases temperatures by 10 to 15°F and provides shade at all times of day (see Figure 4-10).

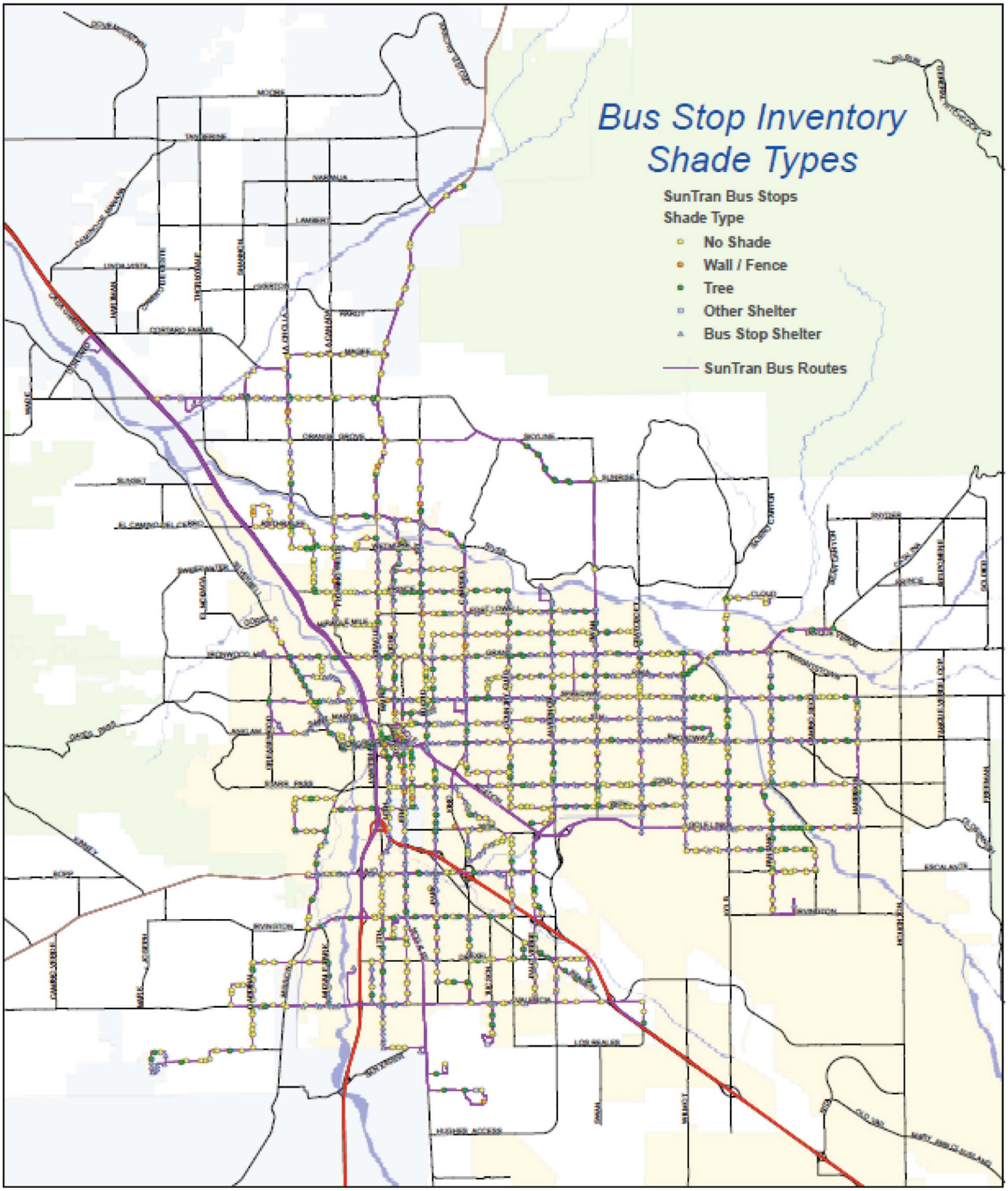
Figure 4-10

Double-tiered Shade Structure Design for Tucson Streetcar Stops

City of Tucson and Regional Transportation Authority



The Transit Services Division of the Tucson Department of Transportation conducted a bus stop inventory and gathered data on how many of their bus stops have shade. This was part of a larger effort to inventory the accessibility of the city's bus stops for individuals with disabilities. They found that of their 2,271 bus stops, 59 percent have some type of shade (e.g. shelter, trees, buildings, etc.); 40 percent have shelters [133]. While bus stops are generally placed every quarter mile along routes, high volume bus stops are prioritized for installing shelters. From an informal consultation with other transit agencies, Tucson found that its percentage of bus stops with shelters is higher than that of most cities. Because of the challenge of providing comfortable waiting areas in a hot, sunny climate, Tucson's Transit Services Division is always trying to improve, such as by tracking customer complaints in a heat database. It will even relocate bus stops up to 100 feet if it can move the stop near to a mature tree. The agency planted 50 trees adjacent to bus stops and these trees had an 80 percent survival rate. Like many



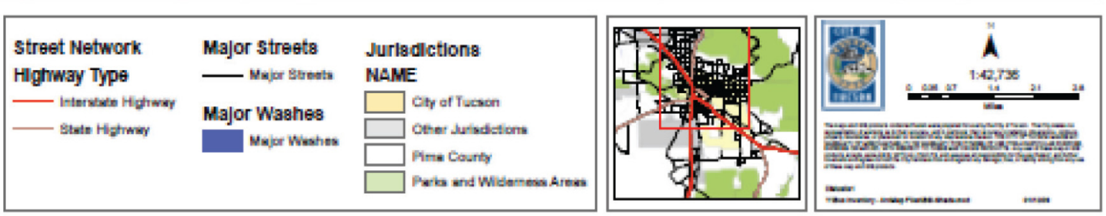


Figure 4-11

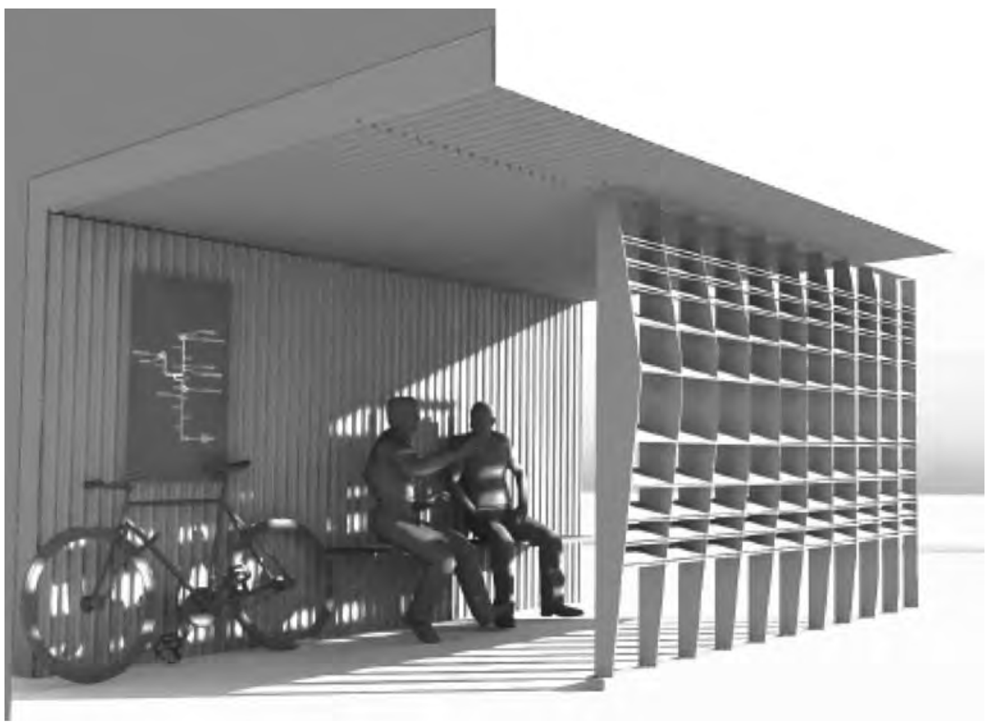
Tucson Bus Stop Shade Inventory

Courtesy of Tucson Dept. of Transporation transit agencies, Tucson has a contract with an advertising company to maintain bus stops in exchange for the company being able to use the space for advertising. That income stream has diminished as advertising revenues declined during the economic downturn and much advertising is shifting to online [134].

The Tucson DOT, as part of a collaborative effort with the Drachman Institute of the College of Architecture and Landscape Architecture at the University of Arizona, designed and built four prototype bus shelters in Pima County, Arizona. The shelters were designed to employ common regional strategies for mediating sunlight. The eastern and western light is regulated by vertical surfaces while the southern light is regulated by horizontal surfaces. A structural louvered screen has been developed and integrated into each of four orientations, enabling visual contact between the customer and driver, while also offering shade from the eastern and western sunlight. The pre-design phase of the collaboration included the analysis of existing bus shelters and surveys and interviews with SunTran customers [135].

Figure 4-12

Tucson Bus Shelter Prototype



Source: University of Arizona, College of Architecture and Landscape Architecture, Drachman Design Build Coalition, Bus Shelter Prototypes, 2011

Landscaping at shelters and along pedestrian corridors leading to transit shelters can create microclimates with temperatures that are cooler than surrounding areas, which can significantly increase customer comfort level and increase the overall appeal for using the transit system. Furthermore, planners have long understood that a continuous and integrated sidewalk network flanked by street trees and other amenities directly stimulates public transportation ridership by providing a safe and visually attractive setting between residences and public transportation nodes [136]. Using native trees and vegetation reduces costs associated with maintenance and watering.

SECTION
5

Implementation

"State and local governments and private infrastructure providers should incorporate climate change into their long-term capital improvement plans, facility designs, maintenance practices, operations, and emergency response plans."

- Transportation Research Board Special Report 290

Implementing adaptation strategies requires linking them to transit agency organizational structures and activities. Climate change will affect the full range of transit agency operations, maintenance, construction, and planning departments, activities, and staff. Climate change adaptation will be most effective when mainstreamed throughout the agency's processes, increasing institutional awareness and ensuring that adaptation is addressed in all relevant areas in an efficient and non-duplicative manner. Using existing mechanisms cuts costs and effort. Keeping in mind the particular institutional and funding issues that the industry must navigate, this section links adaptation actions to highly relevant transit agency processes, specifically:

- Organizational Culture and Budget Priorities
- Asset Management Systems
- Metropolitan and Statewide Transportation Planning
- Environmental Management Systems
- Environmental Review and Project Development
- Floodplain Assessment
- Real Estate Acquisition and Relinquishment of Assets
- Design and Construction
- Retrofit
- Maintenance
- Emergency Preparedness, Response, and Recovery
- Performance Measures

Organizational Culture and Budget Priorities

Transit agencies face multiple priorities competing for attention and limited budget resources. While focusing on short-term indicators such as on-time performance is important, broader trends such as climate change can sometimes get pushed to the side. Furthermore, the current economic downturn has left transit agencies with lower funding levels. Agencies across the country are cutting service and raising fares. A frequently asked question is: "In this environment, how can climate change adaptation be added as one more item requiring attention and funds?"

Unfortunately, it is not a matter of "if" the agency will pay, but "when" it will pay. Responding to extreme weather is always an issue for agencies, and with climate change impacts already being experienced, responsible risk management requires planning for system preservation and safe operation under reasonably foreseeable conditions. Hazard mitigation costs less than the damage from inaction. In fact, a FEMA-commission study estimates that each dollar invested in hazard mitigation saves four dollars in avoided damage costs [137]. While spending now to avoid costs in the future is never politically enticing, it is cost-effective.

"Hazard mitigation costs less than the damage from inaction. In fact, FEMA estimates that each dollar invested in hazard mitigation saves four dollars in avoided damage costs."

In addition, rather than requiring an entirely new set of activities, adapting to climate change means mainstreaming climate change consideration into existing management systems and activities. Capitalizing on existing competencies and incorporating climate change into core agency processes and procedures offers a streamlined and cost-effective approach. A top level push, a central champion, and vertical integration throughout the organization are factors for success.

Washington State Department of Transportation (WSDOT) provides an example from a transportation agency that has been in the lead for adapting to climate change. In response to a question about funding its adaptation planning, staff said that WSDOT characterizes its adaptation work as falling within the agency's existing emergency response planning program and its existing asset stewardship program. It analogized the adaptation work as taking into account new seismic data in updating engineering standards. Indeed, the agency is strengthening its disaster preparedness even if climate change projections prove inaccurate. In a time of dwindling resources, it is critical to locate vulnerabilities in costly and important assets and address them in advance [138].

Transit agencies can also rely on existing knowledge bases for adaptation rather than needing to invest in entirely new capabilities. For instance, maintenance staff are very knowledgeable regarding areas vulnerable to flooding or heat impacts. Transit agencies can also rely on already published climate change data and relationships with universities, state climatologists, and NOAA and USGS outreach rather than conducting or sponsoring their own analyses and downscaling of climate data.

Asset Management Systems

Both adaptation assessment and asset management systems require agencies to inventory assets, evaluate risks to those assets, and prioritize capital improvements. As such, incorporating climate change adaptation considerations into an existing asset management system offers a streamlined decision-making platform for monitoring and responding to climate changes.

The American Association of State Highway Transportation officials (AASHTO) defines Transportation Asset Management (TAM) as follows:

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

Based on this definition, asset management is:

- Strategic and not tactical: it has a long-term perspective
- Broadly focused: it seeks to balance the competing needs of operations, maintenance, reinvestment and system expansion; it is not aimed solely at maintenance or reinvestment
- Organization-wide: it seeks to integrate planning, engineering, funding and IT perspectives;
- Thoughtful: it seeks to make informed and prioritized decisions regarding the use of scarce resources based on reliable data in support of clear organizational objectives [139].

Federal Transit Administration (FTA) asset management initiative

FTA has assumed a leadership role in encouraging transit agencies to utilize more efficient asset management practices. The goal is to assist agencies in optimizing long-term capital planning, reinvestment and forecasting decisions. FTA has adopted the following goals in the agency's own Annual Performance Plan:

- Enhance Transit Asset Management (TAM) techniques, data collection and analysis.
- Increase the number of transit agencies that invest in transit asset management systems.
- Assist transit agencies in developing asset management programs, strategies and solutions.
- Enhance communication and technical assistance.

FTA is funding several pilot projects of transit agency asset management systems. FTA is also exploring opportunities to collect data on the condition of fixed assets in the National Transit Database. This data is useful to both tracking state of good repair progress and climate adaptation.

The development of an asset inventory is a critical step in the asset management process. The following list is an example of data elements that may be used when developing an asset inventory:

- Asset age
- Asset condition
- Quantity
- Expected useful life
- Replacement cost
- Rehabilitation schedule and associated costs
- Location
- Asset type or category

Many transit agencies are already using some form of asset management software. The tools range from widely available industry accepted off-the-shelf applications to customized and configured solutions. There are some very sophisticated and innovative solutions currently being used or under development. Some of these applications include functions such as:

- Mobile GPS
- Virtually segmented linear assets
- Sensor devices (Radio Frequency Identification)
- Business intelligence analytics
- Predictive failures
- Decision support tools/optimization

These extremely robust solutions offer agencies the capability to address climate adaptation through their existing applications and processes. With scarce resources, adaptation assessments utilizing an asset management system would provide agencies a strategic tool for optimizing resource allocation while minimizing risk. Additionally, asset management systems offer the opportunity for integration of adaptation into the culture of the organization. Climate adaptation can be seamlessly integrated into the asset management process by including it in risk assessment.

Based on climate change models, asset conditions may deteriorate at accelerated rates. Asset management systems offer a tool to measure the cost of deferring maintenance or not replacing an asset. This may take the form of increased downtime of mission critical assets, higher maintenance expenditures or safety issues.

Linking climate change to asset management systems

The following information comes from a report by Michael D. Meyer, Adjo Amekudzi, and John Patrick O'Har entitled, "Transportation Asset Management Systems and Climate Change Adaptive Systems Management Approach" [140]. It discusses many of the key components of asset management systems and how climate change adaptation may be integrated into the process:

Table 5-1

Opportunities to Integrate Climate Change Adaptation into Asset Management Systems

Asset Management System Component	Opportunity to Include Climate Change Adaptation
Goals and Policies	Incorporate climate change considerations into asset management goals and policies; these could be general statements concerning adequate attention of potential issues, or targeted statements at specific types of vulnerabilities (e.g., sea-level rise).
Asset Inventory	Map infrastructure assets in vulnerable areas, using GIS where possible; inventory critical assets that are susceptible to climate change impacts.
Condition Assessment and Performance Monitoring	Monitor asset condition in conjunction with environmental conditions (e.g., temperature, precipitation, winds) to determine if climate change affects performance; incorporating risk appraisal into performance modeling and assessment; identification of high risk areas and highly vulnerable assets. Use of "smart" technologies to monitor the health of infrastructure assets.
Alternatives Evaluation and Program Optimization	Include alternatives that use probabilistic design procedures to account for the uncertainties of climate change; possible application of climate change–related evaluation criteria, smart materials, mitigation strategies, and hazard avoidance approaches.
Short and Long Range Plans	Incorporate climate change considerations into activities outlined in short- and long-range plans; incorporate climate change into design guidelines; establish appropriate mitigation strategies and agency responsibilities.
Program Implementation	Include appropriate climate change strategies into program implementation; determine if agency is actually achieving its climate change adaptation and monitoring goals.
Performance Monitoring	Monitor asset management system to ensure that it is effectively responding to climate change; possible use of climate change–related performance measures; "triggering" measures used to identify when an asset or asset category has reached some critical level.

A review of domestic transportation adaptation plans (primarily highway focused) found that none of these plans specifically mentioned an asset management system. However, several adaptation plans did mention components of an asset management system [141]. While transportation agencies are not currently widely taking advantage of asset management systems to manage climate change impacts, there is much potential.

The Maryland State Highway Administration is an exception and has used its asset management system as a climate adaptation tool. The agency collects climate change data in its Transportation Asset Management Program (TAMP) to better analyze priority assets. Climate-related asset data include age, elevation, materials used, design lifetime and stage of life, FEMA flood maps, current and historical performance and conditions, vegetation, soil type, average daily traffic, bridge scour criticality, and length and width of bridges [142]. Transport for London offers a similar public transportation example (see case study below).

Case Study

Transport for London: Incorporating Adaptation into Asset Management Systems

Transport for London manages London's buses, underground rail, road network, traffic operations and signals, taxis, and river taxis. The agency serves as an international example of implementation of climate adaptation into the asset management process and organizational culture.

Risk and asset management systems

The United Kingdom's Climate Change Act of 2008 requires government agencies to report to the Department of Environment, Food, and Rural Affairs on their climate change adaptation efforts. The UK government provided climate change projections for the country in 2009 that include a range of scenarios and confidence levels [143]. During 2010, all of Transport for London's operational business areas (bus, underground, road, etc.) assessed the updated climate change risks to their assets and services using these projections. The key results from the review were incorporated into the agency's robust risk and asset management systems [144]. The risk management system is an overarching system for evaluating and mitigating risks from a broad range of factors influencing the agency. The asset management system incorporates and responds to these risks.

The impact of external events, including weather, is one of Transport for London's strategic risks in the top level risk register for the organization. The other risks in the top five are project delivery, quality and quantity of people, effective contract management, and use and availability of funding. The risks are fully evaluated and documented mitigation strategies and action plans are put in place. Transport for London uses a risk management software package across the agency's business units to ensure consistency of content and quality of data and to enable efficient and comprehensive reporting [145].

The agency measures risk based on probability and consequence of potential impacts to the organization and stakeholders. There is a central measurement scheme, but each unit within the agency adapts it somewhat for their own needs. A brief overview of the strategy is as follows:

- Each climate-related risk is detailed by climate risk type (heat, heavy rain, etc.), asset type (stations, vehicles, etc.), brief description of impact, and explanation of consequence.

- Probability of occurrence is measured on a scale from 5 very high (>75%) to 1 very low (<5%).
- Cost, time, customer, and reputation impacts are similarly measured on a scale of 5 very high to 1 very low.
- Cost impact is measured in terms of revenue reduction or additional expense.
- Time is measured by delay to achievement of key milestone.
- Customer impact is measured by reduction in customer service, from very low short-term, minor trip delays to very high, catastrophic asset loss for several weeks or months.
- Impact to organizational reputation is measured, including damage to relationship with stakeholders and negative media coverage.
- A risk score is then assigned by multiplying the probability (from 5 very high to 1 very low) by the highest scoring impact (from 5 very high to 1 very low). As such, the highest possible score and highest priority is 25.
- Risks are then laid out on a two dimensional risk map with likelihood as the y-axis and impact as the x-axis (see Figure 5-1).
- Risks with the highest likelihood and impact are prioritized for action.

For example, assume there is a very high probability for heavy rain events causing flooding to station systems. The potential cost of the maintenance, impact to the customer and potential impact to the reputation of the organization are all valued and weighed. Current and long-term risk mitigation strategies are developed based on likelihood of occurrence and organizational impact.

The risk management framework involves a quarterly review of strategic risks, with more frequent reviews as necessary, regular team meetings, and an annual review of risk tolerance levels and strategic risk matters. Reports are audited by an internal audit.

Each of Transport for London's units incorporates risks into their asset management systems, which are regularly reviewed. As an example, London Underground, the subway system business unit, has a series of Asset Management

Plans that consider a number of issues including weather in the management of track, rolling stock, signals, and stations. London Underground mapped assets

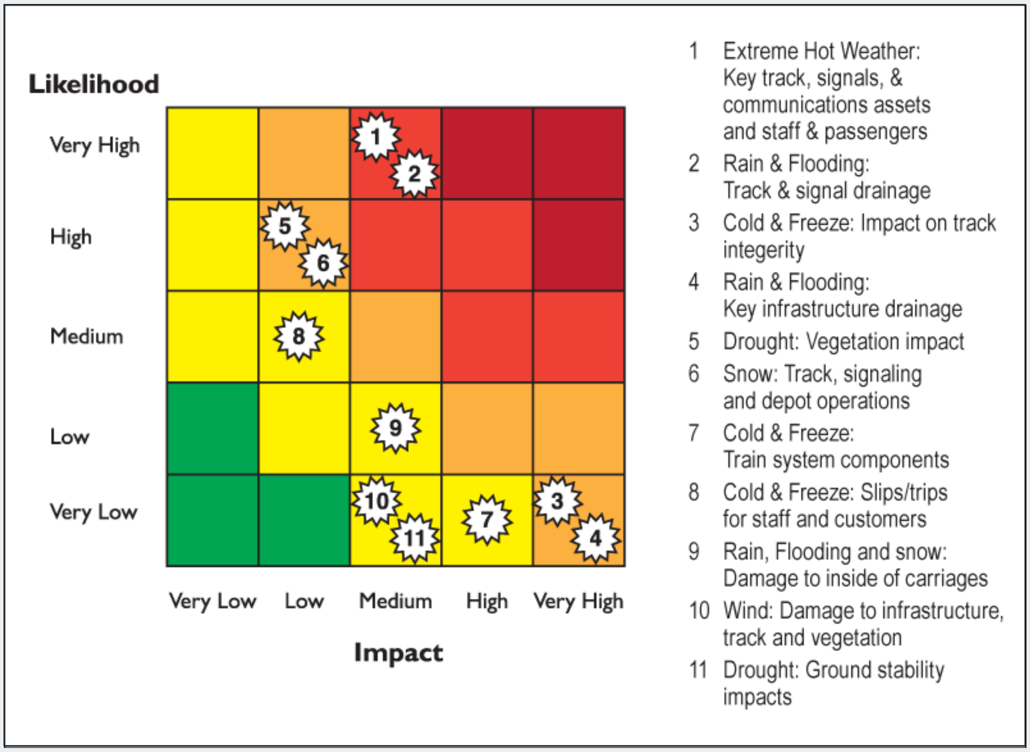


Figure 5-1

London Underground Weather-Related Risks Map

against 200 identified risks and opportunities from climate change, identified critical points and their impacts on operations, and developed correlation graphs between climate change parameters, effects on asset management and predicted costs and savings.

Transport for London reports that they are able to calculate costs of adaptation features and costs of avoided damages. Harder to measure are the economic impacts of disruption in transport service and indirect, cascading effects. Also difficult to quantify are the negative impacts such as the reputational and political impacts that result from disrupted or poor service. In addition, adaptation features are rarely included only for climate adaptation purposes. They also often have wider transport benefits that are not included in the calculations for the risk assessments. They have found that an adaptive feature does not always costs\ less than the avoided damage costs. In those cases it makes financial sense to leave things as they are if there are not other co-benefits or reasons to implement the strategy. As a general principle, risks will be mitigated to as low a level as possible, but only as far as the benefits gained from risk reduction outweigh the costs of mitigating the risk.

Transport for London Adaptation Examples

Passenger comfort on the Underground and buses

High temperatures are frequently experienced during the summer in the world's oldest subway system. Maximum temperatures of 107°F and 97°F were recorded on a train and station respectively [146]. The current ventilation system, relying on fans and draft relief shafts is inadequate. Overcrowding and failed trains exacerbate these conditions. Plans to increase capacity will add additional heat from more trains.

London Underground has been working for several years to address the issue. All new trains on the sub-surface lines now have air conditioning and the agency has improved ventilation in the deep tunnels. Work is also ongoing to reduce heat at the source through plans to introduce more energy efficient trains.

Recognizing that short term options are limited, London Underground also implemented a "Stay Cool" communication campaign, urging passengers to bring water with them on the system and ask for help if they are not feeling well [147].

Transport for London introduced a new specification in 2005 that all buses ordered have white roofs, tinted windows that open, upper deck ventilation systems, and air conditioning in the drivers' cabs. The majority of buses now in service have these features [148].

Figure 5-2

London's Iconic Red Buses now have White Roofs

Courtesy of Transport for London

Flooding of existing stations and track from intense rain

London Underground recorded over 1,200 flooding incidents and 200 station closures between 1992 and 2003, approximately half related to flash flooding. Costs due to passenger delays alone reached £14.5 million between September 1999 and March 2004 [149]. While not all problems were related to weather (some were due to burst pipes or other issues) and the number of closures for flooding is small compared to other reasons such as security, addressing flooding still warranted attention. Climate change projections for the United Kingdom show intense rainfall becoming more frequent and severe. London Underground has mapped areas subject to flooding and has put in place measures to prevent flooding, including physical barriers.

Incorporating adaptation measures into major new capital projects

Transport for London incorporated climate change projections into the design for its major new rail project, Crossrail, with a 120-year design life. Adaptation measures were built into the design and remained through pressure to reduce the budget. The main adaptation is flood prevention in the tunnels, which will traverse a floodplain predicted to be more subject to flooding as the climate changes. The design includes "passive" flood protection such as raising entry and egress levels, raising track levels, and extending portal walls. Where these measures do not suffice (above 0.4m), active flood protection measures have been identified such as flood gates and stop logs. Design standards for all tunnel entrances are set to withstand a 1-in-200-year flood. Anticipating higher temperatures, the trains and platforms will have air conditioning [150].

Another major new project, the Docklands Light Railway extension, also included climate adaptation considerations in the design. Future potential flood levels were analyzed and the elevation of the light rail adjusted accordingly [151].

Metropolitan and Statewide Transportation Planning

The Federally mandated state and metropolitan transportation planning process is intended to promote the safe and efficient management, operation, and development of surface transportation systems [152], a goal clearly impacted by the climate hazards discussed in Section 2 of this report. In addition, it is through the planning process that states and metropolitan regions prioritize capital investments in new transportation infrastructure and rehabilitation of older infrastructure, both of which will be impacted by changing climate conditions over the generally long lifetime of these assets.

Furthermore, the planning process informs the location of infrastructure. Since the location of transportation infrastructure influences land development, locating new transportation infrastructure in geographic areas that will be subject to flooding from climate change in the future risks not only the transportation assets themselves but also the development that follows them, multiplying hazardous conditions to populated areas in the case of an extreme event.

Finally, transportation planning agencies have experience analyzing network interruptions, that is, how interruptions to one segment or mode affect other segments and modes. Interruptions are likely to become more frequent as climate change brings extreme weather events and degrades assets. The planning process offers a venue for incorporating redundancies and developing contingency plans for interrupted operations.

To ensure that the planning process and adaptation considerations are carried out in a coordinated and multimodal way, transit agencies should be "at the table" with planning agencies and actively participating [153].

Incorporating climate change adaptation considerations throughout the transportation planning process can create a transportation system more resilient to the impacts of climate change. The following table (Table 5-2) outlines opportunities at each stage.

A research review of the transportation plans of 100 transportation planning organizations revealed that climate change considerations are not yet incorporated into the transportation planning process in any significant numbers [154]. When plans do address climate change at all, they typically include only mitigation [155].

Nonetheless, there are a few examples of incorporation of adaptation into planning documents, though incorporation is primarily at the vision and issues level rather than incorporated in detailed strategies. For instance, Connecticut DOT's Long Range Transportation Plan, adopted in 2009, mentions in the

Table 5-2

Opportunities to Integrate Climate Change Adaptation into the Transportation Planning Process

Stage in Planning Process	Opportunity to Include Climate Change Adaptation[1]
Establish a vision	Emphasize preservation of the system in the face of shifts in climate.
Set goals, objectives, and performance measures	Establish objectives for asset conditions. Include performance measures related to adaptation.
Stakeholder identification and outreach	Engage environmental and state and local government agencies, additional infrastructure providers, and other organizations relevant to climate action planning. Coordinate to leverage adaptation work of other stakeholders.
Conduct analyses	Assess the vulnerability of the transportation system to climate change during this stage, in which agencies characterize the existing system relative to performance criteria, gather input from stakeholders and the public on priority deficiencies, and forecast future issues.
Develop alternative plan scenarios	Identify alternatives that facilitate adaptation to climate change. Specific strategies and improvement projects can be included in the alternatives developed. In this stage agencies develop various approaches for achieving the stated objectives and distill several diverse, manageable alternatives. Agencies typically identify fiscal constraints and opportunities at this stage as well.
Evaluate alternatives	Examine the impacts of proposed adaptation strategies to ensure that the selected alternative appropriately addresses climate change. It is important to note that decisions often include tradeoffs among community goals.
Programming	Use performance measures related to climate change to prioritize projects for funding. The transportation improvement program (TIP) details what near-term projects are going to be built and when, based on funding cycles.
Project development	Incorporate adaptive design considerations based on a risk assessment process.
System monitoring	Monitor the vulnerability and resilience of the transportation system to climate impacts.

"mandates, issues, and actions" section that "the impacts of climate change on Connecticut may eventually affect our transportation infrastructure; impacts may include sea-level rise, increases in the extent and frequency of coastal flooding, shoreline erosion and retreat, and increased likelihood and severity of damaging rainstorms" [156]. Some metropolitan planning organizations (MPOs) are studying the issue; MPOs in San Francisco, New Jersey, and Oahu are participating in FHWA adaptation assessment pilots. Metro, the MPO for Portland, Oregon, worked with partners from across the region and across sectors (natural, built, economic, human and cultural) in developing stakeholder findings and recommendations for building climate resiliency in its region [157].

[1] Federal Highway Administration, *Integrating Climate Change into the Transportation Planning Process*, July 2008. Schimdt N. and Meyer, M., "Incorporating Climate Change Considerations into Transportation Planning," *Transportation Research Record: Journal of the Transportation Research Board*, No. 2119, 2009, pp.66-73.

New York State has recognized the importance of including climate change adaptation considerations in the long range transportation planning process. A technical working group convened to advise the state on transportation adaptation recommended that the New York State Transportation Master Plan consider and incorporate State-endorsed climate projections. The group observed that in addition to the direct asset deterioration impacts of extreme weather and other climate changes, demographic and economic trends will also be affected by climate change impacts, and will in turn influence travel patterns. The group recommended that decisions relating to siting, design, operation, and maintenance of key transportation infrastructure elements should consider climate change projections for the entire proposed useful life of those elements [158].

At present, there is no Federal regulatory requirement for state DOTs and MPOs to consider climate change in transportation plans. Agencies working on climate change are thus creating their own models for integrating climate change into their transportation plans. Absent any Federal action, the treatment of climate change in transportation planning is likely to continue to vary depending on the interests and concerns of local stakeholders, the size of agencies and their capacity to address climate change, and the vulnerabilities specific to regions and their transportation systems. A number of DOTs and MPOs await direction from State agencies or committees on how they should address climate change. Others see a need for greater involvement from Federal or State government in climate change issues. Many agencies are wary of taking steps to change their planning process before more direction from higher government levels is provided [159].

Small MPOs in particular may benefit from guidance on how and where to incorporate climate change in long range transportation plans. Small MPOs have fewer resources and less power to set policy precedents than do larger MPOs. The potential burden imposed by future climate change regulations at the State or Federal levels is likely greater for small MPOs. The political reality of climate change as a contentious issue may also be impeding the integration of adaptation as a solution at the State and regional levels of transportation planning.

Environmental Management Systems

Environmental Management Systems (EMS) also offer opportunities for incorporating climate change adaptation. Over the past few years, FTA has provided EMS training to 26 transit agencies. An EMS is an organizational plan. It considers an agency's activities, products, and services and provides a structured framework (system) for reducing environmental impacts. An EMS typically helps an agency handle change and respond to emergencies using cross-functional support, measures which could clearly be applied to the agency's adaptation approach. Also, the performance evaluation and continual improvement components of an EMS can help ensure that an agency is considering new information on climate change impacts and adaptation strategies. Los Angeles Metro is an example of an agency that sees its EMS as a climate change management tool [160]. While there is much potential, this is a very new area.

Environmental Review and Project Development

The White House Council on Environmental Quality (CEQ) issued draft guidance in February 2010 regarding consideration of climate change in environmental documents under the National Environmental Policy Act (NEPA). While the guidance has not yet been made final as of this writing, the draft guidance would require consideration of both mitigation and adaptation. On the adaptation side, project sponsors would need to consider the impacts of climate change on the project, as well as the impacts of climate change on the environment surrounding the project. This would include for instance considering whether proposed coastal wetlands mitigation will be effective in light of anticipated sea-level rise.

At the state level, California Environmental Quality Act (CEQA) guidelines now direct public agencies in that state to consider potentially significant impacts to the environment that could result if development is located in areas particularly sensitive to the effects of climate change. This change stemmed from Governor Schwarzenegger's Executive Order S-13-08, issued in November 2008, directing that, "all state agencies within my administration that are planning construction projects in areas vulnerable to future sea-level rise shall, for the purposes of planning, consider a range of sea-level rise scenarios for the years 2050 and 2100 in order to assess project vulnerability and, to the extent feasible, reduce expected risks and increase resiliency to sea-level rise." Since that date, California has issued sea-level rise projections that state agencies are to use in analyses [161].

The Washington State DOT adopted an agency-wide policy in 2010 that requires climate change analyses—both mitigation and adaptation—to be included in all WSDOT environmental impact statements performed under the State Environmental Policy Act [162]. The policy was in response to two Executive Orders in 2007 and 2009 that committed state agencies to preparing for and adapting to climate change. The internal guidance explicitly directs WSDOT staff to employ the best available science in strategic planning as well as facilities design. It also directs agency staff to "examine the future affected environment differently from the past," to design new facilities "to perform under the variable conditions that are expected as a result of climate change," and to make proposed projects "more resilient to future climate impacts and severe storm events." The guidance also directs staff to designate departmental climate change experts for help in locating the most current information on regional climate change projections and guidance on how to assess the potential climate-related risks to any particular project. At a fundamental level, therefore, department leadership has clearly articulated to the entire agency the reality of climate change, the need to consider climate-related risks to new and existing agency infrastructure, and the necessity of taking action to be well informed about and design around those risks to the extent possible.

A proposed ferry terminal replacement provides a recent example of how this policy is playing out. WSDOT staff determined during NEPA review that the existing Mulkilteo ferry terminal is vulnerable to inundation with two to four feet of sea-level rise. WSDOT staff provided inundation maps to project development staff, who incorporated the information into the alternatives analysis and impact assessment. This will lead to a more resilient facility.

Floodplain Assessment

The floodplain assessment process for siting transit facilities becomes all the more important as risks of flooding increase from intense precipitation, sea-level rise, and storm surge.

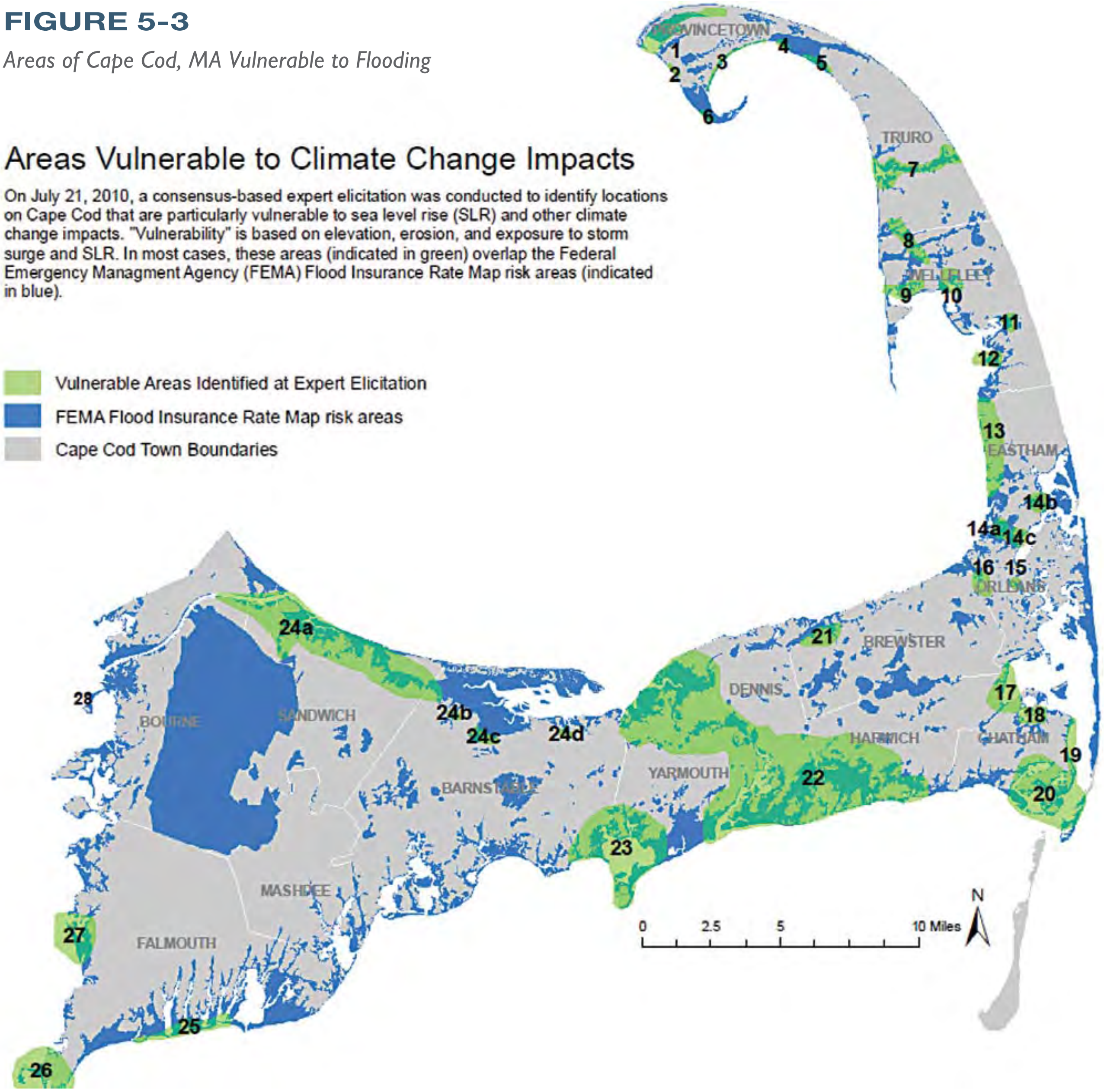
Current practice is that during the environmental review process, the grantee and FTA determine if a proposed project to receive Federal funding is located in a 100-year floodplain based on Federal Emergency Management Agency (FEMA) flood maps. If so, the environmental assessment or environmental impact statement must include a detailed analysis of the risks and flooding impacts. The analysis should discuss flood risk to the transit facility, impacts of the transit facility on the ability of the floodplain to absorb floodwaters, the degree to which the transit facility provides direct or indirect support for development in the floodplain, and actions to minimize harm or to restore or preserve the floodplain benefits affected by the project. If the preferred alternative lies in a floodplain, the environmental document must include FTA's finding that the proposed action is the only practicable alternative and supporting documentation reflecting consideration of alternatives to avoid or reduce adverse impacts on the floodplain [163].

Under current practice, existing structures are not considered to have a new impact, so rehabilitation of a site for transit uses would not be judged to impact the flood zone. Also, if a facility is protected by a flood wall, it is not judged to impact a flood zone or to be impacted by flooding [164]. This leaves the risk in current practice of significant investment in vulnerable existing facilities and the risk of further vulnerability if a flood wall becomes insufficient protection for the transit facility due to climate changes.

The reliance on flood maps described above underscores the importance of accurate, up-to-date maps that indicate not only the current 100-year floodplain, but ideally the floodplain of the future during the asset's useful life. FEMA's flood maps are updated on a regular basis. However, incorporating into the maps

FIGURE 5-3

Areas of Cape Cod, MA Vulnerable to Flooding



Source: Cape Cod Interagency Transportation Land Use, and Climate Change Pilot Project. Sponsored by the U.S. Department of Transportation, National Park Service, and U.S. Fish and Wildlife Service. http://www.volpe.dot.gov/publiclands/projects/capecod5_interag.html.

projected changes in floodplains due to future climate impacts poses a challenge both because of uncertainties in the precise timing and scale of climate impacts and because of the typical mapping process of relying on historic flooding information. Flood frequencies, such as the "100-year flood," are determined by plotting a graph of the size of all known floods for an area and determining how often floods of a particular size occur. While the FEMA flood maps were designed for the National Flood Insurance program, they are used in practice for a wide range of land management, zoning, investment, and other purposes. Determining better methods for assessing floodplains in the era of climate change is a challenge that goes well beyond public transportation.

One method that has been used as a shorthand by practitioners conducting climate risk assessments is to examine the 500-year floodplain rather than the 100-year floodplain, as the 100-year flood of today may be the 50-year flood of tomorrow.

Another method to determine areas subject to flooding is to use what is called an expert elicitation (a consensus-based process that convenes coastal and atmospheric scientists, geologists, and other experts). For instance, Cape Cod Regional Transit Authority is participating in an interagency transportation, land use, and climate change pilot project that used a consensus-based expert elicitation to identify vulnerable locations (see Figure 5-3).

A more detailed approach would involve relative sea-level rise assessment, storm surge modeling, downscaling of climate change precipitation data, and hydrology analysis well beyond the capabilities of typical transit agencies.

Real Estate Acquisition and Relinquishment of Assets

New projects are better able to determine if the location can withstand climate changes and adequately adapt, especially when flooding is a risk, and resolve any additional real estate acquisition that may be necessary. Improvements to existing facilities should be evaluated to determine if the improvement is cost-effective, considering the risk from climate change, or would a new site provide greater sustainability. If the risk of climate change is great and the adaptation potential is limited, it may be more prudent to relocate a facility to a new location that can adapt to climate change in a more effective manner. Real estate acquisition for relocation of a facility should be considered as an adaptation strategy, if feasible.

Design and Construction

Historical weather patterns are typically used in the design of transit systems for withstanding flood, wind, and temperature impacts. However, these historical patterns are no longer a good guide to the future. New transit infrastructure should be designed to withstand the climate these assets will face during the long period of their life span.

It is generally cheaper to incorporate climate considerations into design and construction than to retrofit assets later. The New Zealand transportation department studied the problem of incorporating changing climate conditions into infrastructure design. New Zealand decided not to change design standards for those assets with a lifespan of less than 25 years. For bridges with a life design over 25 years, however, specifications now require probabilistic approaches to account for increased flood flow due to climate change [165].

The literature on highway adaptation, notes that "development of new design standards follows a time-consuming and systematic process that involves professional organizations in an extensive research and testing program over a period decades. Once the standards are in place, engineers are understandably reluctant to change them" [166]. However, since no industry-wide standards appear to exist for preventing subway tunnel flooding, minimizing track buckling, or other transit climate change impacts, the formal design standard problem seems less of an issue for transit.

The key components of infrastructure design that can be significantly affected by changing environmental conditions are [167]:

1. *Subsurface conditions*—The stability of the infrastructure (e.g., track, road, bus bay, building) depends on the soils it upon which it is built. Under saturated conditions, such as heavy rain events expected to be more common with climate change, soil is subject to sinking or a change in shear strength causing mudslides. Certain types of soils are more susceptible than others.
2. *Materials specifications*—Different materials respond differently under varying freeze-thaw cycles, temperatures, loads, and precipitation levels. Much research on cost-effective transportation materials best for different conditions has been conducted by the American Society for Testing and Material, FHWA, and State departments of transportation, much of which is applicable to transit. Particularly important for transit agencies are pavements for stations and lots that are maintained by the transit agency rather than state DOT and handle frequent stop and go heavy duty vehicle loads under high temperatures. Also important for transit agencies are materials for bridges, tunnels (especially regarding permeability to water), tracks, and track beds.
3. *Cross sections and standard dimensions*—The slope of paved surfaces is important for run-off, as is vertical clearance over waterways for transit bridges.
4. *Drainage and erosion*—Flood levels, flood flow patterns and velocities, hydraulic controls, clearance over water, protection of bridge foundations from water flows and scour from debris, storm surge, and wave crests are all important considerations for designing new transit infrastructure to withstand a changing climate.

Retrofit

The same key components of infrastructure design are relevant for retrofits as well, though opportunities are more limited for whole scale changes. Addressing assets deemed particularly vulnerable through risk assessments as well as taking advantage of regular rehabilitation and maintenance cycles makes sense here.

Maintenance

Climate change stressors will likely increase maintenance cycles and expenses. However, avoided damage from increased maintenance is typically significantly less costly than the maintenance itself. Front line maintenance staff can be enlisted to monitor asset condition and environmental stresses.

Emergency Preparedness, Response and Recovery

Standard Operating Procedures (SOPs) for extreme weather events become all the more critical as a changing climate increases the frequency of these events. As an example, London Underground's SOP for dealing with heavy rain and flooding events lays out responsibilities of the chief maintenance operator, operations control center, pumps manager, station asset manager, and others. It lists thresholds above which flooding is likely to occur - 0.6 inches per hour, or 1.4 inches per twenty-four hour period. It identifies track circuits, stations, and track sections most vulnerable to flooding along with maps of pump locations and floodplains [168].

FTA's, 2006 report, *Disaster Response and Recovery Resource for Transit Agencies*, contains a helpful list of recommended practices, including best practices for emergency management plans, policies, and strategies; serving people with disabilities and others with access and functional needs; communications; staffing and training; and facilities equipment and supplies [169]. This report will be updated in the future. FTA's *An Introduction to All-Hazards Preparedness for Transit Agencies* also provides a useful resource [170]. Some of the information in these reports most relevant to responding to severe weather events projected to become more common is summarized here.

Emergency Management Plans, Policies, and Strategies: Emergency Management Plans should detail personnel responsibilities, action timelines, and standard operating procedures.

Bus/Rail Parking and Deployment Strategies: Transit agency Emergency Management Plans should identify specific strategies and procedures for parking and/or deploying bus and/or rail fleets during a storm event or other emergency. Some general guidance and practices employed include:

- Moving buses out of flood prone areas
- Using perimeter fencing to minimize the impacts of flying debris
- Parking buses “nose-to-nose” to minimize debris striking the windshields
- Parking buses inside structurally safe facilities where available
- Avoiding parking buses inside marginally safe facilities
- Parking buses in front of the bus facility garage doors to protect the doors
- Tying down engine compartment doors and front doors to keep them closed during high winds and to avoid damage by wind driven rain
- Splitting a fleet between two or more locations to maximize the survival of vehicles
- Avoiding parking near light poles, trees and similar potential hazards
- Fueling fleet and staff vehicles prior to an emergency event

Facility Protection: Transit agency facilities should be considered as essential facilities that must remain functional and accessible after any storm or emergency event. When designed, transit facilities should be hardened to maximize their storm survival as well as to provide a shelter for agency personnel. Existing facilities should be assessed to determine weak links and proactive retrofits and supplementary actions should be programmed and undertaken on a priority basis. Storm shutters should be installed where appropriate. In addition to protecting transit agency facilities for an emergency event, transit agencies may elect to prepare a Continuity of Operations Plan (COOP) that designates alternate facilities to be used in an emergency event for the continuation of critical agency functions.

Back-up Power: Anticipating loss of electrical power, transit agencies should purchase extra batteries for portable radios and cell phones and/or devices to permit recharging of batteries using vehicle engine power. Back-up electrical generators should be acquired and installed to at a minimum power the fuel system, radio communications, a minimum of lights, electrical outlets, and shop equipment.

Communications: Transit agencies should be prepared for disruptions in communications systems from occurrences such as wind damage to radio and cell phone towers and loss of electricity to communications systems. Hard copy backups of key electronic documents needed during emergencies are recommended. Educating passengers regarding emergency preparedness is also recommended.

Staffing and Training: Job responsibilities during emergencies should be part of job descriptions if mandatory. If voluntary, commitments should be obtained prior to emergencies. Staff training and mock drills ensure employee readiness.

Coordination With State And Local Emergency Planners: In a survey, several states alleged that there appears to be a lack of recognition among state and local emergency managers of public transportation providers' role in emergency management [171]. Transit agencies should coordinate in advance to avoid this.

Mutual Aid Agreements: Mutual aid agreements are agreements made in advance of an emergency between agencies who agree to assist one another in the event that one experiences an emergency, by for instance loaning vehicles and equipment. Mutual aid agreements solve problems upfront in the areas of reimbursement, licensure, and liability. A national level model is the Emergency Management Assistance Compact (EMAC). FEMA recognizes EMACs so a state that aids another during a disaster is eligible for reimbursement. Only three state departments of transportation have transit specific mutual aid agreements and two states include transit as part of a broader mutual aid agreement [172].

Insurance: Clearly, acquiring insurance coverage that will meet the agency's needs following extreme weather events is key. Insurance agencies tend to be at the forefront of incorporating climate change into their business practices, as increased claims from extreme weather events affects their core business. Working with the insurer, transit agencies may be able to lower their rates by taking protective actions. Some agencies form mutual insurance pools to spread risk. Transit agencies take advantage of a wide range of insurance practices. Further investigation into insurance best practices for transit agencies insuring against weather related losses is needed.

Evacuation, Especially Serving Transit-Dependent Populations

Public transportation serves a critical role in evacuations, especially for transit-dependent populations. This role becomes all the more important as extreme weather events such as storms, hurricanes, heat waves and wildfires are projected to increase as the climate changes. General best practices include:

- Establishing evacuation routes and bus assignments in advance of a storm to allow the passengers to be aware of service that will be available in event of a disaster and to expedite implementation.
- Coordinating with local school bus fleets and human service transportation providers to expand the pool of resources.
- Establishing an Access and Functional Needs Coordinator position in the Emergency Operations Center, to coordinate with service delivery systems.
- Establishing a point of contact at each shelter to focus on transportation needs.

To provide a balance of extending the mass evacuation time period as long as possible, while not overly jeopardizing transit personnel, passengers, and vehicles, most transit agencies establish a maximum threshold at which operations are ceased and the buses and support vehicles return to the garage or seek other shelter. For example, for wind, the use of 39 or 40 mph sustained winds as the threshold at which bus services should be ceased is considered a reasonable standard. Transit buses offer a large profile for the wind that makes them susceptible to unsafe operation for the driver, the passengers and the public. Thresholds are also important for wildfires and other extreme events.

Transit's unique role in facilitating the evacuation of people with disabilities and others with access and functional needs before and after an event should be coordinated and planned for in advance and procedures and protocols should regularly be tested for implementation. These populations include individuals with disabilities, older adults, low income populations, persons with limited English proficiency, and persons living in households without vehicles. Hurricane Katrina provided stark evidence of the need to plan for emergency evacuation of these populations, as 70,000 individuals were left behind. One survey found that 17 percent of the respondents could not afford to leave, 15 percent were unable to leave their jobs, 12 percent lacked transportation, 12 percent had physical or medical needs that made it difficult to leave, 16 percent had to take care of someone who was physically unable to leave, and 18 percent said that they did not know where to go [173]. Overall, 10 percent of U.S. households do not own any cars. This percentage varies greatly between and within metropolitan areas. For instance, in some high poverty Baltimore neighborhoods, 44 percent or more of households have no cars [174]. This concentration means that individuals cannot rely on neighbors for sharing vehicles for evacuation.

An FTA-sponsored study found that only one of 25 transit agencies surveyed had conducted evacuation planning for the focus populations of racial and ethnic minorities, persons with low incomes, persons with limited English proficiency, and persons living in households without vehicles. The report found that:

> *With some exceptions, the agencies reviewed in the study have taken very limited steps towards involving populations with specific mobility needs in emergency preparedness planning, identifying the locations of and communicating emergency preparedness instructions to these populations, or coordinating with other agencies to meet the specific needs of these populations in an emergency. While many agencies have conducted important outreach, analysis, and coordinating activities to address the needs of their general population in emergencies, few have targeted these activities to assist their region's most vulnerable people [175].*

To better plan and execute emergency evacuations, particularly for transit-dependent populations, transit agencies can implement a range of best practices:

- Pre-establish pick up locations for transport to shelters.
- Prior to an emergency, create procedures to ensure existing government systems are coordinating with emergency managers and first responders regarding passengers requiring transportation assistance.

- Prior to an emergency, create a matrix of public and private assets within a jurisdiction that includes wheelchair accessible vehicles.
- Develop Memoranda of Understanding (MOU) and Memoranda of Agreement (MOA) with transportation providers within and outside the jurisdiction for the purpose of mutual aid assistance.
- Plan scheduling, dispatching, and rider notification processes in advance.
- Encourage and secure the participation of people with disabilities and others with access and functional needs in the planning process when developing emergency preparedness plans.
- Identify areas with high concentrations of minority and low-income persons, persons with limited English proficiency, persons with disabilities, and older adults who may require additional assistance in an emergency, including evacuation.
- Partner with faith- or cultural-based, social service, and other nonprofit organizations that are active in local communities to link residents with emergency preparedness information and services.
- Conduct exercises and drills that include first responders, providers, people with disabilities, and others with access and functional needs.
- Provide information regarding emergency evacuation and transportation with local partnering agencies and organizations.

Expedited funding mechanisms for recovery

Finally, transit agencies must be able to obligate and spend funds in an expedited fashion if there is an emergency requiring immediate spending to retrofit, reconstruct, or replace assets, as well as to operate and maintain assets during emergency periods. States, MPOs, and transit agencies need to be sure that they will be able to access funds for repair, procurement, etc. through expedited procedures. This would include consideration of an expedited and/or exceptional environmental review processes so as to facilitate expedited application of financial resources to spending needs.

Performance Measures

Measuring the effectiveness of adaptation strategies requires choosing appropriate performance metrics. A process oriented approach focused specifically on climate adaptation could include for instance measuring the percent of capital projects for which adaptation was considered, or the number of recommendations met in a climate adaptation plan. As with all performance measures however, outcome measures are generally preferred as they indicate progress towards the end goal rather than only the process. In this case, the end goal is resilience of transit assets and systems to climate change impacts. Adjusting existing measurement systems to gauge progress on adaptation goals provides a streamlined approach. For instance, transit agencies can use asset condition and quality of service measurements already conducted as part of measuring progress on adaptation goals. This could include for example station condition or vehicle condition. Climate stressors such as high heat and flooding will impact asset condition along with other factors such as age and maintenance. Successful adaptation strategies will reduce the vulnerability and improve the resilience of transit assets to climate change impacts, thus maintaining asset condition. Agencies may need to change some of the monitoring processes to gather the relevant information and add new data elements. For example, for bridge condition agencies could monitor stream conditions and not just the joint conditions of the bridge. This allows for monitoring how close environmental factors are getting to design thresholds.

SECTION 6

Conclusion

Responsible risk management calls for reducing vulnerability and improving resilience of transit assets and services to the impacts of climate change. Understanding climate impacts and how to adapt to them will be crucial to the nation's ability to bring transit assets up to and maintain a state of good repair over the long-term. While infrastructure and assets are a key part of the equation, service provision is equally important. Transit will be challenged to operate emergency evacuation service as well as regular service under shifting climate conditions and a broader range of extremes.

Few transit agencies domestically and internationally have begun thinking about adaptation. This is a new area for the transit industry and much work remains to be done. There is a lack of specific information on the impact of climate changes on transit infrastructure and operations, beyond a few systems that have begun work in this area. Multiple guidebooks and tools on adaptation planning are available, though none are specific to transit. The literature lacks information on design standards and engineering solutions for dealing with climate impacts on transit assets. Information that is available tends to be from agencies that have experienced severe weather events and are changing in response to these events. These literature gaps point to potential future areas of research.

The transit industry can leverage climate change adaptation work that is going on outside of the industry by participating in State and local efforts and capitalizing on existing climate data and partnerships. Several research efforts have produced climate data for particularly populous metropolitan regions while in other areas, reliance on Federal climate science data for larger geographic regions is advisable as data is not yet available at a higher resolution.

Mainstreaming climate change considerations into existing transit agency processes offers a streamlined approach. By assessing both existing and planned infrastructure and services, we can ensure that vital assets are protected, and that future investments are guided by the best available information about future climate conditions. As one transit manager noted: "We can anticipate where there will be recurring problems and make adjustments to accommodate changes. We have a service imperative" [176]. We hope this report provides a useful departure point to help place the transit industry on the track to climate resilience.

APPENDIX

FTA Policy Statement on Climate Change Adaptation Federal Transit Administration

Integration of Climate Change Adaptation into FTA Planning, Operations, Policies, and Programs

The Federal Transit Administration (FTA) will integrate consideration of climate change impacts and adaptation to the extent practicable into the planning, operations, policies, and programs of the agency in order to ensure proper stewardship of the federal investment in public transportation systems, for the safety of the traveling public, mobility, and to maintain a state of good repair. FTA is committed to adaptation planning to address the challenges posed by climate change.

Purpose and Background

Climate-related changes are already observed in the United States and will increase in the future, according to the Federal government's Global Change Research Program. These include rising temperature and sea levels, increases in both extreme downpours and droughts, and stronger hurricanes. Reducing greenhouse gas emissions will lower the severity of these impacts over the long-term. However, even with aggressive action immediately to reduce emissions going forward, past emissions will continue to cause climate change impacts for many years. An effective response to climate change must therefore include both mitigation (reducing greenhouse gas levels) and adaptation (reducing the vulnerability of human and natural systems to climate impacts).

In fact, public transportation plays a key role in climate change mitigation by offering a low-emissions alternative to driving and by facilitating compact land use that enables reduced vehicle miles traveled. Yet public transportation must also adapt to the impacts of climate change. Subway tunnels, busways, tracks, and maintenance facilities are vulnerable to an increase in flooding from more intense rain storms, sea-level rise, and storm surge. Also, extreme heat can deform rail tracks, stress materials, reduce asset life, and jeopardize customer and worker health and safety. And, more broadly, public transportation must be positioned and prepared to serve a vital role in providing essential mobility options as communities adapt to the impacts of climate change. Public transportation also provides evacuation services during the extreme weather emergencies that become more common with climate change. Transit dependent populations are particularly vulnerable.

FTA is responsible for the stewardship of tens of billions of dollars in taxpayer investments in public transportation assets. But this is more than a fiscal responsibility: tens of millions of Americans rely on these resources and the services they provide every day. We must build upon and share our knowledge of climate change impacts on transit and the best response strategies if we are to protect these assets and the mobility they provide. In addition, through FTA grant programs, many communities are building new transit infrastructure or rehabilitating older systems. Better awareness of the future environmental stressors these assets will encounter is instrumental to sound planning and design.

Process

FTA will use the following process to coordinate adaptation planning across programs and operations within the agency.

- An interdisciplinary, inter-office adaptation working group will analyze the impact of climate change on FTA's mission and operations, then develop strategies to incorporate climate change adaptation considerations into FTA policies, programs, and operations.
- The working group will propose strategy options for consideration to senior executives through the FTA Policy Council.
- FTA will coordinate with other agencies on climate change adaptation matters of common interest through the U.S. DOT Center for Climate Change.
- FTA will also coordinate with the Environmental Protection Agency, the Department of Housing and Urban Development, and other related agencies through the Council on Environmental Quality Communities Adaptation Working Group.

Programs and Resources

FTA will use the following programs and resources to support the climate change adaptation planning process: 1) Discretionary funding from FTA research programs to support adaptation research, technical assistance, and outreach; and, 2) Staff resources from headquarters and regional offices.

Public transportation agency grantees already have access to FTA's major capital programs, which fund capital investments such as asset rehabilitation and acquisition, as well as construction. Funding from FTA's major capital programs can support capital investments that increase resilience of transit assets and services to the impacts of climate change. Planning activities such as climate change vulnerability and risk assessments are also eligible under FTA's current statewide and metropolitan transportation planning programs.

Guiding Principles and Framework

FTA adopts the guiding principles and framework for adaptation planning established by the Interagency Climate Change Adaptation Task Force. These guiding principles are:

- Adopt integrated approaches.
- Prioritize the most vulnerable.
- Use the best available science.
- Build strong partnerships.

- Apply risk management methods and tools.
- Apply ecosystem-based approaches.
- Maximize mutual benefits, and
- Continuously evaluate performance.

Authority

This policy is based on Executive Order (E.O.) 13514—*Federal Leadership in Environmental, Energy, and Economic Performance*. The E.O. includes direction to address climate adaptation planning. Additionally, the Secretary of Transportation has authority under 49 United States Code (U.S.C.) Section 322 – General Powers. This FTA Policy is consistent with and complementary to the department-wide Policy Statement on Climate Change Adaptation of the Secretary of Transportation. This Policy is effective immediately and will remain in effect until it is amended, superseded, or revoked. This Policy does not alter or affect any existing duty or authority of individual components or offices. FTA will review and update this policy as necessary.

References

[1] National Academy of Sciences, *America's Climate Choices*, 2011; U.S. Global Change Research Program, *Global Climate Change Impacts in the United States*, June 2009; Intergovernmental Panel on Climate Change, *Climate Change 2007: Synthesis Report: Summary for Policymakers*, 2007.

[2] U.S. Global Change Research Program, *Global Climate Change Impacts in the United State*s, June 2009.

[3] The White House Council on Environmental Policy, *Progress Report of the Interagency Climate Change Adaptation Task Force: Recommended Actions in Support of a National Climate Adaptation Strategy*, October 2010.

[4] Federal Transit Administration, "Mississippi Valley Flooding Disaster: Public Transportation Situational Report, May 15, 2011.

[5] Metropolitan Transportation Authority, *August 8, 2007 Storm Report*, 2007.

[6] Nashville Metropolitan Transit Authority & Regional Transportation Authority, Nashville Flood 2010," http:// www.nashvillemta.org/PDF/NashvilleMTAFlood2010.pdf

[7] Marder, Jenny. "Heat Wave Causes Kinks in Rail Tracks," PBS NewsHour, July 7, 2010.

[8] Author interview with TriMet staff, March 31, 2011.

[9] U.S. Department of Transportation, Impacts of Climate Change and Variability on Transportation Systems and Infrastructure: Gulf Coast Study, 2009.

[10] New York City Panel on Climate Change, *Adaptation Assessment Guidebook: Appendix B*, 2010.

[11] New York State Energy Research and Development Authority (NYSERDA), ClimAID: Responding to Climate Change in New York State, Draft Version, 2010.

[12] San Francisco Bay Conservation and Development Commission, *Living with a Rising Bay: Vulnerability and Adaptation in San Francisco Bay and on its Shoreline*, April 7, 2009.

[13] Author Interview with Helen Woolston, Transport for London, April 4, 2011.

[14] Horgan, Daniel, "Flood Protection: A Comparison," viewed April 22, 2011, http://www.pbworld.com/news_ events/publications/network/issue_65/pdf/050.pdf

[15] U.S. Global Change Research Program, *Global Climate Change Impacts in the United States*, June 2009.

[16] Federal Transit Administration, *Public Transportation's Role in Responding to Climate Change*, 2010; Center for Transit Oriented Development, *Transit Oriented Development and the Potential for VMT-related Greenhouse Gas Emissions Reduction*, 2010

[17] The White House Council on Environmental Quality, *Progress Report of the Interagency Climate Change Adaptation Task Force: Recommended Actions in Support of a National Climate Adaptation Strategy*, October 2010.

[18] U.S. Global Change Research Program, *Global Climate Change Impacts in the United States*, June 2009, p.23.

[19] Ibid.

[20] Ibid, p.32.

[21] Northeast Climate Impacts Assessment (NECIA). C*onfronting Climate Change in the U.S. Northeast: Science, Impacts, and Solutions*. Union of Concerned Scientists. July 2007.

[22] U.S. Global Change Research Program, *Global Climate Change Impacts in the United States*, June 2009, p.32.

[23] Metropolitan Transportation Authority, *August 8, 2007 Storm Report*, 2007.

[24] Email communication with Projjal Dutta, Director of Sustainability Initiatives, MTA, March 31, 2011.

[25] Nashville Metropolitan transit Authority & Regional Transportation Authority, Nashville Flood 2010," http:// www.nashvillemta.org/PDF/NashvilleMTAFlood2010.pdf

[26] Author interview with James Burke, Chief of Public Transit Division, Honolulu, April 5, 2011. Author interview with TriMet staff, March 31, 2011.

[27] The Washington Post, "To save Louisiana's lowlands, officials want to re-engineer Mississippi," May 17, 2011.

[28] Federal Transit Administration, "Mississippi Valley Flooding Disaster: Public Transportation Situational Report, May 15, 2011.

[29] Author interview with TriMet staff, March 31, 2011.

[30] Author Interview with Helen Woolston, Transport for London, April 4, 2011.

[31] Yang, C Y David, "Trends in Transit Bus Accidents and Promising Collision Countermeasures," *Journal of Public Transportation*, Volume 10, No. 3, Center for Urban Transportation Research, 2007. This analysis of major bus collisions from 2002 and 2003 found 76 percent of them were on clear days, 10 percent on rainy days, 8 percent on cloudy days, 1 percent foggy/misty days, and 3 percent under snow/sleet conditions.

[32] Union of Concerned Scientists, *Confronting Climate Change in the U.S. Northeast: Science, Impacts, and Solutions*, July 2007.

[33] Walker, Lindsay; Figliozzi, Miguel; Haire, Ashley Raye; MacArthur, John, "Identifying Surface Transportation Vulnerabilities and Risk Assessment Opportunities under Climate Change: Case Study in Portland, Oregon," Sub-mitted for presentation and publication to the 90th Annual Meeting of the Transportation Research Board, August 2010.

[34] Author interview with James Burke, Chief of Public Transit Division, Honolulu, April 5, 2011.

[35] Email communication with Projjal Dutta, Director of Sustainability Initiatives, MTA, March 31, 2011.

[36] Washington Metropolitan Area Transit Authority, "Using Metro in a Snow Storm," http://www.wmata.com/getting_around/snowmap.cfm, viewed April 22, 2011.

[37] New York Metropolitan Transportation Authority, MTA Adaptations to Climate Change: A Categorical Imperative, October 2008.

[38] Author Interview with Helen Woolston, Transport for London, April 4, 2011.

[39] U.S. Global Change Research Program, *Global Climate Change Impacts in the United States*, June 2009, p.27.

[40] Ibid, p.29.

[41] Ibid, p.34.

[42] U.S. Environmental Protection Agency, "Heat Island Effect," http://www.epa.gov/heatisld/, downloaded April 22, 2011.

[43] TriMet, "SOP 434 Weather Operating Instructions," April 28, 2010.

[44] Marder, Jenny. "Heat Wave Causes Kinks in Rail Tracks," PBS NewsHour, July 7, 2010.

[45] Dobney, K. et al., "The Future Cost to the United Kingdom's Railway Network of Heat-related Delays and Buckles Caused by the Predicted Increase in High Summer Temperatures Owing to Climate Change," *Journal of Rail and Rapid Transit*, Vol. 224 Issue F1, 2010.

[46] Author interview with TriMet staff, March 31, 2011.

[47] U.S. Department of Transportation, *Impacts of Climate Change and Variability on Transportation Systems and Infrastructure: Gulf Coast Study*, 2008, pp.4-15.

[48] National Oceanographic and Atmospheric Administration (NOAA), "Many of the 1995 Heat Wave Deaths Were Preventable According to NOAA Report," April 11, 1996. http://www.publicaffairs.noaa.gov/pr96/apr96/noaa96-21.html

[49] U.S. Environmental Protection Agency, "The Plain English Guide to the Clean Air Act, Cleaning Up Commonly Found Air Pollutants," http://www.epa.gov/air/peg/cleanup.html, downloaded May 19, 2011.

[50] Transport Workers, AFL-CIO, *Safety News: Working in the heat*, undated.

[51] Washington Metropolitan Area Transit Authority, "Excessive heat affects Metrorail Service," July 6, 2010. http:// wmata.com/about_metro/news/PressReleaseDetail.cfm?ReleaseID=4555)

[52] National Research Council, *Climate Stabilization Targets: Emissions, Concentrations, and Impacts over Decades to Millennia*, 2010.

[53] Author Interview with Chris Liban, Environmental Compliance and Services Department Manager, March 17, 2011.

[54] Author interview with David Gillespie, NJ Transit, March 30, 2011.

[55] Intergovernmental Panel on Climate Change, Fourth Assessment Report, 2007.

[56] U.S. Global Change Research Program, *Global Climate Change Impacts in the United States*, June 2009.

[57] Ibid.

[58] Ibid.

[59] Weiss JL et al. "Implications of recent sea-level rise science for low-elevation areas in coastal cities of the conterminous U.S.A." *Climatic Change Letters*, 2011.

[60] San Francisco Bay Conservation and Development Commission, *Living with a Rising Bay: Vulnerability and Adaptation in San Francisco Bay and on its Shoreline*, April 7, 2009.

[61] Ibid, p.70.

[62] Weiss JL et al. "Implications of recent sea-level rise science for low-elevation areas in coastal cities of the conterminous U.S.A." *Climatic Change Letters*, 2011.

[63] Climate Change Advisory Task Force (CCATF), "Initial Recommendations," April 2008; http://www.miamidade. gov/derm/climatechange/taskforce.asp As cited in Center for Clean Air Policy, *The Value of Green Infrastructure for Urban Climate Adaptation*, 2010.

[64] U.S. Global Change Research Program, *Global Climate Change Impacts in the United States*, June 2009, p.27.

[65] Ibid.

[66] Ibid.

[67] TriMet, "SOP 434 Weather Operating Restrictions," April 2010.

[68] American Association of State Highway and Transportation Officials (AASHTO), *AASHTO LRFD Bridge Design Specifications*, 2004. As cited in Meyer, Michael, "Design Standards for U.S. Transportation Infrastructure: The Implications of Climate Change," 2011.

[69] Meyer, Michael, "Design Standards for U.S. Transportation Infrastructure: The Implications of Climate Change," 2011. http://onlinepubs.trb.org/onlinepubs/sr/sr290Meyer.pdf

[70] WRECO, Bridge Hydraulic and Scour Studies, http://www.wreco.com/projects/bridgescour/smart.html, downloaded May 31, 2011.

[71] Suarez, Pablo et al. "Impacts of flooding and climate change on urban transportation: A systemwide performance assessment of the Boston Metro Area," *Transportation Research Part D: Transport and Environment*, Volume 10, Issue 3, May 2005, pp.231-244.

[72] New York Metropolitan Transportation Authority, "*Greening Mass Transit & Metro Regions: The Final Report of the Blue Ribbon Commission on Sustainability and the MTA*," 2009. http://www.mta.info/sustainability/pdf/SustRptFinal.pdf

[73] New York State Metropolitan Transportation Authority, http://www.mta.info/mta/network.htm, downloaded June 13, 2011.

[74] New York State Metropolitan Transportation Authority, *MTA Adaptations to Climate Change: A Categorical Imperative*, October 2008.

[75] Klaus, Jacob, personal communication, May 4, 2011.

[76] New York State Energy Research and Development Authority (NYSERDA), *ClimAID: Responding to Climate Change in New York State*, Draft Version, 2010.

[77] Klaus, Jacob, et al, in preparation, 2011.

[78] Ibid.

[79] Ibid.

[80] National Institute of Building Sciences, Multihazard Mitigation Council, *Natural Hazard Mitigation Saves: An Independent Study to Assess the Future Savings from Mitigation Activities*, 2005. http://www.nibs.org/index.php/mmc/projects/nhms/

[81] New York State Energy Research and Development Authority (NYSERDA), ClimAID: Responding to Climate Change in New York State, Draft Version, 2010. http://www.nyserda.org/programs/environment/emep/clim-aidsynthesis-draft.pdf

[82] City of New York, "Press Release: Mayor Bloomberg Launches Task Force to Adapt Critical Infrastructure to Environmental Effects of Climate Change," August 12, 2008.

[83] New York City Panel on Climate Change, "Climate Change Adaptation in New York City: Building a Risk Management Response," *Annals of New York Academy of Sciences*, May 2010. http://onlinelibrary.wiley.com/doi/10.1111/ nyas.2010.1196.issue-1/issuetoc

[84] City of New York, *PlaNYC: A Greener, Greater New York*, April 2011. http://www.nyc.gov/html/planyc2030/html/theplan/theplan.shtml

[85] New York State Climate Action Council, http://www.nyclimatechange.us/, downloaded May 9, 2011.

[86] National Cooperative Highway Research Program (NCHRP), *#20-83, Task 2.3: Synthesis Report Review of Key Climate Impacts to the Highway System and Current Adaptation Practices and Methodologies*, 2011.

[87] New York State Metropolitan Transportation Authority, *MTA Adaptations to Climate Change: A Categorical Imperative*, October 2008.

[88] Meyer, Michael, "Design Standards for U.S. Transportation Infrastructure: The Implications of Climate Change," 2011. http://onlinepubs.trb.org/onlinepubs/sr/sr290Meyer.pdf

[89] National Cooperative Highway Research Program (NCHRP), *#20-83, Task 2.3: Synthesis Report Review of Key Climate Impacts to the Highway System and Current Adaptation Practices and Methodologies*, 2011; Federal Highway Administration, *Literature Review: Climate Change Vulnerability Assessment, Risk Assessment and Adaptation Approaches*, 2009.

[90] New York City Panel on Climate Change, *Adaptation Assessment Guidebook: Appendix B*, 2010.

[91] Ibid.

[92] Climate Change Science Program, *Preliminary Report of Adaptation Options for Climate-Sensitive Ecosystems and Resources*, 2008.

[93] Kirshen, Paul, et al., *Final Report: Infrastructure Systems, Services, and Climate Change: Integrated Impacts and Response Strategies for the Boston Metropolitan Area*, 2004. http://cfpub.epa.gov/ncer_abstracts/index.cfm/fuseac-tion/display.abstractDetail/abstract/285/report/F

[94] Author Interview with Helen Woolston, Transport for London, April 4, 2011.

[95] Crawford, David, "After the Storm," *ITS International*, Vol. 13 Issue 6, November 2007, pp.26-27.

[96] American Public Transportation Association (APTA). *Guidelines for Transit Climate Action Planning*, 2011. http://www.apta.com/resources/hottopics/sustainability/Documents/Guidelines_for_Climate_Action_Planning_ APTA.pdf

[97] Meyer, Michael, "Design Standards for U.S. Transportation Infrastructure: The Implications of Climate Change," 2011, http://onlinepubs.trb.org/onlinepubs/sr/sr290Meyer.pdf

[98] Northeast Climate Impacts Assessment (NECIA). *Confronting Climate Change in the U.S. Northeast: Science, Impacts, and Solutions*. Union of Concerned Scientists. July 2007. http://www.climatechoices.org/ne/resources_ne/nereport.html

[99] Metropolitan Transportation Authority, "Appendix 3: Discussion of Storm Impacts, Summary of Findings, prepared by Region II University Transportation Research Center," in *August 8, 2007 Storm Report*, 2007.

[100] Ibid.

[101] Author communication with Heather Allen, Sustainability Manager, International Association of Public Transport (UITP), February 22, 2011.

[102] National Cooperative Highway Research Program (NCHRP), *#20-83, Task 2.3: Synthesis Report Review of Key Climate Impacts to the Highway System and Current Adaptation Practices and Methodologies*, 2011.

[103] Paaswell, Robert and Pillich, Jose, "MTA Storm Task Force Peer Property Comparisons," September 5, 2007.

[104] Ibid.

[105] Horgan, Daniel, "Flood Protection: A Comparison," viewed April 22, 2011, http://www.pbworld.com/news_ events/publications/network/issue_65/pdf/050.pdf

[106] Department of Rapid Transit Systems, Tapei City Government, "FAQ: What are your flood prevention criteria?" August 2009. http://english.dorts.taipei.gov.tw/ct.asp?xItem=205848&ctNode=15951&mp=115002

[107] Horgan, Daniel, "Flood Protection: A Comparison," viewed April 22, 2011. http://www.pbworld.com/news_ events/publications/network/issue_65/pdf/050.pdf

[108] Ibid.

[109] Paaswell, Robert and Pillich, Jose, "MTA Storm Task Force Peer Property Comparisons," September 5, 2007.

[110] Author interview with TriMet staff, March 31, 2011.

[111] Center for Clean Air Policy, *The Value of Green Infrastructure for Urban Climate Adaptation*, 2010; Nisensen, Lisa, "Using Smart Growth Techniques as Stormwater Best Management Practices," U.S. Environmental Protection Agency, 2005.

[112] New York City Transit, "Memo to File: Contract C40455 New Mother Clara Depot – Green Roof," October 6, 2010.

[113] Center for Clean Air Policy, *The Value of Green Infrastructure for Urban Climate Adaptation*, February 2011.

[114] U.S. Department of Transportation, *Transportation's Role in Reducing U.S. Greenhouse Gas Emissions*, April 2010. Federal Transit Administration, *Public Transportation's Role in Responding to Climate Change*, January 2011.

[115] Adaptation Technical Work Group, New York Climate Action Council, "Full Descriptions of Adaptation Recommendations," http://www.nyclimatechange.us/ewebeditpro/items/O109F24268.pdf, downloaded May 18, 2011.

[116] Houston-Galveston Area Council, *Foresight Panel on Environmental Effects Report*, 2008.

[117] Author communication with Peter Brown, San Francisco MTA, June 3, 2011.

[118] Walker, Lindsay; Figliozzi, Miguel; Haire, Ashley Raye; MacArthur, John, "Identifying Surface Transportation Vulnerabilities and Risk Assessment Opportunities under Climate Change: Case Study in Portland, Oregon," Sub-mitted for presentation and publication to the 90th Annual Meeting of the Transportation Research Board, August 2010.

[119] Author Interview James Burke, Chief of the Public Transit Division in the City and County of Honolulu, April 5, 2011.

[120] Kish, Andrew and Samavedam, Gopal, "Improved Destressing of Continuous Welded Rail for Better Management of Rail Neutral Temperature," *Transportation Research Record: Journal of the Transportation Research Board*, 2005, pp. 56-65.

[121] Ibid.

[122] Federal Railroad Administration, "Development of Rail Temperature Prediction Model," Research Results, RR08-06, June 2008. http://www.fra.dot.gov/downloads/Research/rr0806.pdf

[123] Author Interview with Leith Al-Nazer, February 3, 2011.

[124] U.S. Department of Transportation, Impacts of Climate Change and Variability on Transportation Systems and Infrastructure: Gulf Coast Study, 2009, pp.4-15.

[125] Ibid.

[126] Dobney, K. et al., "The Future Cost to the United Kingdom's Railway Network of Heat-related Delays and Buckles Caused by the Predicted Increase in High Summer Temperatures Owing to Climate Change," *Journal of Rail and Rapid Transit*, Vol 224 Issue F1, 2010.

[127] U.S. Department of Transportation, Impacts of Climate Change and Variability on Transportation Systems and Infrastructure: Gulf Coast Study, 2009, pp.4-15.

[128] Rail Safety and Standards Board, *Tomorrow's Railway and Climate Change Adaptation*, 2010.

[129] Author Interview with TriMet staff, March 31, 2011.

[130] TriMet, "Conserving Fuel and Reducing Emissions," downloaded May 17, 2011. http://trimet.org/sustainable/fuel-emissions.htm#emissions

[131] Author communication with Heather Allen, Sustainability Manager, International Association of Public Transport (UITP), February 22, 2011.

[132] Author interview with Thomas Abdallah, Chief Environmental Engineer, New York City Transit, March 15, 2011.

[133] City of Tucson, Department of Transportation, Transit Services Division, "ADA Bus Stop Accessibility Study," January 2009.

[134] Author interview with Tom Fisher and Shellie Gin, Tucson Department of Transportation, April 29, 2011.

[135] University of Arizona, College of Architecture and Landscape Architecture, Drachman Design Build Coalition, *Bus Shelter Prototypes*, 2011.

[136] R. Unternmann, *Accommodating the Pedestrian: Adapting Towns and Neighborhoods for Walking and Bicycling*, Van Nostrand Reinhold, New York, 1984.

[137] National Institute of Building Sciences, Multihazard Mitigation Council, *Natural Hazard Mitigation Saves: An Independent Study to Assess the Future Savings from Mitigation Activities*, 2005. http://www.nibs.org/index.php/mmc/projects/nhms/

[138] Author interview with Carol Roalkvam, Sandy Salisbury, and Mark Maurer, Washington Department of Transportation, April 20, 2011.

[139] Federal Transit Administration, *Rail Modernization Study Report to Congress*, April 2009.

[140] Meyer, Michael Amekudzi, Adjo, O'Har, John "Transportation Asset Management Systems and Climate Change Adaptive Systems Management Approach," November 2009.

[141] Ibid.

[142] Slater, Gregory I., "Climate Change Adaptation: Maryland State Highway Administration," Presentation to U.S. Department of Transportation, March 30, 2011.

[143] Author Interview with Helen Woolston, Transport for London, April 4, 2011.

[144] Ibid.

[145] Transport for London, "Risk Management," http://www.tfl.gov.uk/corporate/about-tfl/investorrelations/4718. aspx, accessed May 17, 2011.

[146] Arkell, B.P. and Darch, G.J.C., "Impact of climate change on London's transport network," *Proceedings of the Institution of Civil Engineers: Municipal Engineer 159*, December 2006, pp.231-237.

[147] Author communication with Helen Woolston of Transport for London, May 12, 2011.

[148] Ibid.

[149] Arkell, B.P. and Darch, G.J.C., "Impact of climate change on London's transport network," *Proceedings of the Institution of Civil Engineers: Municipal Engineer 159*, December 2006, pp.231-237.

[150] Author communication with Helen Woolston of Transport for London, May 12, 2011.

[151] Arkell, B.P. and Darch, G.J.C., "Impact of climate change on London's transport network," *Proceedings of the Institution of Civil Engineers: Municipal Engineer 159*, December 2006, pp.231-237.

[152] 49 USC Chapter 53, Section 5303(a).

[153] Federal Transit Administration, *Transit at the Table: A Guide to Participation in Metropolitan Decisionmaking*, 2005; Federal Transit Administration, *Transit at the Table II: A Guide to Participation in Metropolitan Transportation Decisionmaking for Transit Agencies in Small- and Medium-sized Metropolitan Areas*, 2010.

[154] Federal Highway Administration, *Integrating Climate Change into the Transportation Planning Process*, July 2008; Schimdt N. and Meyer, M., "Incorporating Climate Change Considerations into Transportation Planning," *Transportation Research Record: Journal of the Transportation Research Board*, No. 2119, 2009, pp.66-73.

[155] Ibid.

[156] Connecticut DOT. *Connecticut On the Move: Strategic LRTP 2009-2035*, adopted June 2009, pages 3-14: Mandates, Issues & Actions. As cited in FHWA, "Climate Change - Model Language in Transportation Plans," May 2010. http://www.fhwa.dot.gov/hep/climate/model_language/index.htm

[157] The Resource Innovation Group, *Building Climate Resiliency in the Lower Willamette Region of Western Oregon*, January 2011.

[158] Adaptation Technical Working Group, New York State Climate Action Council, "Full Descriptions of Adaptation Recommendations," 2011. http://www.nyclimatechange.us/ewebeditpro/items/O109F24268.pdf

[159] Federal Highway Administration, *Integrating Climate Change into the Transportation Planning Process*, July 2008.

[160] Liban, Cris, "Environmental Management System (EMS) as a Climate Change Management Tool," Presentation to 2010 Sustainability Summit, Los Angeles County Metropolitan Transportation Authority, June 9, 2010. http:// www.metro.net/about_us/sustainability/images/2010/D3-Cris-Liban-Summit-Presentation.pdf

[161] California Climate Action Team, "State of California Sea-level Rise Interim Guidance Document," October 2010.

[162] Washington Department of Transportation "Guidance for Project-Level Greenhouse Gas and Climate Change Evaluation," October 2010. http://www.wsdot.wa.gov/NR/rdonlyres/73ADB679-BDA6-4947-93CA-87C157862DD7/0/GreenHouseGasGuidanceOct2010.pdf

[163] Federal Transit Administration, "Floodplains," http:// www.fta.dot.gov/planning/environment/planning_environment_2237.html, downloaded June 15, 2011. Additional information is available on the FEMA website at: http://www.msc.fema.gov/ and from US Department of Transpor-tation Order 5650.2, "Floodplain Management and Protection," April 23, 1979.

[164] Ibid.

[165] National Cooperative Highway Research Program (NCHRP) #20-83, Task 2.3 "Synthesis Report Review of Key Climate Impacts to the Highway System and Current Adaptation Practices and Methodologies," 2011.

[166] Meyer, Michael, "Design Standards for U.S. Transportation Infrastructure: The Implications of Climate Change," 2011. http://onlinepubs.trb.org/onlinepubs/sr/sr290Meyer.pdf

[167] Ibid.

[168] London Underground, *Chief Maintenance Officer Asset Performance Arrangements for Dealing with Heavy Rain and Flooding Events*, Updated April 2010.

[169] FTA, "Disaster Response and Recovery Resource for Transit Agencies", August 2006. http://transit-safety.volpe.dot.gov/publications/safety/DisasterResponse/HTML/DisasterResponse.htm

[170] Federal Transit Administration, An Introduction to All-Hazards Preparedness for Transit Agencies, 2010. http:// transit-safety.fta.dot.gov/Publications/order/singledoc.asp?docid=1122

[171] National Cooperative Highway Research Program, "Research Results Digest 326: State Public Transportation Division Involvement in State Emergency Planning, Response, and Recovery" (NCHRP Project 20-65 (13), May 2008.

[172] Ibid.

[173] Blendon, R.J., et al. "High-Risk Area Hurricane Survey." Technical Report, Harvard School of Public Health, Cambridge, MA, 2007. As cited in: FTA, *Hurricane Evacuation Planning for Special Needs Populations*, May 2010.

[174] Federal Transit Administration, "Transportation Equity in Emergencies: A Review of the Practice of State Departments of Transportation, Metropolitan Planning Organizations, and Transit Agencies in 20 Metropolitan Areas," National Technical Information Services / NTIS, May 2007.

[175] Ibid.

[176] Author interview with TriMet staff, March 31, 2011.

U.S. Department of Transportation
Federal Transit Administration

U.S. Department of Transportation
Federal Transit Administration
East Building
1200 New Jersey Avenue, SE
Washington, DC 20590
http://www.fta.dot.gov/research