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FEDERAL TRANSIT ADMINISTRATION

Transit and Climate Change Adaptation: Synthesis of FTA-Funded Pilot Projects

AUGUST 2014

FTA Report No. 0069
Federal Transit Administration

PREPARED BY

Office of Budget and Policy
Federal Transit Administration
U.S. Department of Transportation

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1200 New Jersey Avenue, SE
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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	liter	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^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)				
°F	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	°C

REPORT DOCUMENTATION PAGE	*Form Approved* *OMB No. 0704-0188*

1. AGENCY USE ONLY	2. REPORT DATE August 2014	3. REPORT TYPE AND DATES COVERED October 2011–October 2013

4. TITLE AND SUBTITLE Transit and Climate Change Adaptation: Synthesis of FTA-Funded Pilot Projects	5. FUNDING NUMBERS

6. AUTHOR(S)

Brian Alberts, Mazhar Ali Awan, and Kimberly A. Gayle, Office of Budget and Policy

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESSE(ES) U.S. Department of Transportation Federal Transit Administration Office of Budget and Policy and Office of Policy Review and Development Washington, DC 20590	8. PERFORMING ORGANIZATION REPORT NUMBER FTA Report No. 0069
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) U.S. Department of Transportation Federal Transit Administration East Building 1200 New Jersey Avenue SE Washington, DC 20590	10. SPONSORING/MONITORING AGENCY REPORT NUMBER FTA Report No. 0069

11. SUPPLEMENTARY NOTES [http://www.fta.dot.gov/research]

12A. DISTRIBUTION/AVAILABILITY STATEMENT Available from: 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

Public transit agencies play a critical role in providing safe, reliable, and cost-effective transportation to the communities they serve. In the face of increased frequency and intensity of extreme weather events, several public transit and other transportation agencies have taken the initiative to adapt their systems to make them more resilient to changing climate conditions, and a growing number of public transit agencies that are aware of the climate risks they face have identified their vulnerable assets and are prioritizing improvements to develop a more robust and resilient system. In 2011, the Federal Transit Administration (FTA) announced its Climate Change Adaptation Initiative and committed $1 million in research funding to pilot projects in seven geographically-diverse locations, including nine transit agencies. This report is a synthesis of the final reports of those seven pilot studies.

14. SUBJECT TERMS Climate change, adaptation, vulnerability, flooding, extreme heat, extreme precipitation, tropical storms, sea level rise.	15. NUMBER OF PAGES 27

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT Unclassified	18. SECURITY CLASSIFICATION OF THIS PAGE Unclassified	19. SECURITY CLASSIFICATION OF ABSTRACT Unclassified	20. LIMITATION OF ABSTRACT

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ACKNOWLEDGMENTS

The Federal Transit Administration, Office of Budget and Policy staff team of Brian Alberts, Mazhar Ali Awan, and Kimberly A. Gayle served as the primary authors of this synthesis report. Robert J. Tuccillo, Katherine A. Mattice, Dan Ngo, and Sharon Pugh of the Office of Budget and Policy also contributed. The authors acknowledge the work of the Project Managers of the Transit Climate Change Adaptation Assessment Pilot Projects.

ABSTRACT

Public transit agencies play a critical role in providing safe, reliable, and cost-effective transportation to the communities they serve. In the face of increased frequency and intensity of extreme weather events, several public transit and other transportation agencies have taken the initiative to adapt their systems to make them more resilient to changing climate conditions, and a growing number of public transit agencies that are aware of the climate risks they face have identified their vulnerable assets and are prioritizing improvements to develop a more robust and resilient system. In 2011, the Federal Transit Administration (FTA) announced its Climate Change Adaptation Initiative and committed $1 million in research funding to pilot projects in seven geographically-diverse locations, involving nine transit agencies. This report is a synthesis of the final reports of those seven pilot studies.

SECTION 1

Introduction

Public transit agencies play a critical role in providing safe, reliable, and cost-effective transportation to the communities they serve, and climate change-related issues place substantial operating and financial burdens on these agencies. In the face of increased frequency and intensity of extreme weather events, several public transit and other transportation agencies are taking the initiative to adapt their systems to make them more resilient to changing climate conditions. A growing number of public transit agencies that are aware of the climate risks they face have identified their vulnerable assets and are prioritizing improvements to develop a more robust and resilient system. As a result, they will be in a better position to withstand climate hazards while providing cost-effective service to their customers.

The Federal Transit Administration (FTA) invests billions of dollars every year in assets across the U.S., many of which are at risk from the adverse impacts of climate change. Reducing the impacts of weather events and long-term climate change on transit service is a key goal for transit agencies and FTA.

In 2011, FTA announced its Climate Change Adaptation Initiative and committed $1 million in research funding for seven pilot projects aimed to identify and address climate change impacts. This report synthesizes these pilot projects and presents the collective findings. The pilot projects cover seven geographically-diverse locations involving nine transit agencies:

1. San Francisco Bay Area Rapid Transit (BART)
2. Chicago Transit Authority (CTA)
3. Gulf Coast (Houston Metro, Tampa HART, and Island Transit)
4. Los Angeles County Metropolitan Transportation Authority (LACMTA)
5. Metropolitan Atlanta Rapid Transit Authority (MARTA)
6. Southeastern Pennsylvania Transportation Authority (SEPTA), Philadelphia
7. Central Puget Sound Regional Transit Authority (Sound Transit), Seattle

Figure 1-1 shows a map of the systems included in the pilot projects.

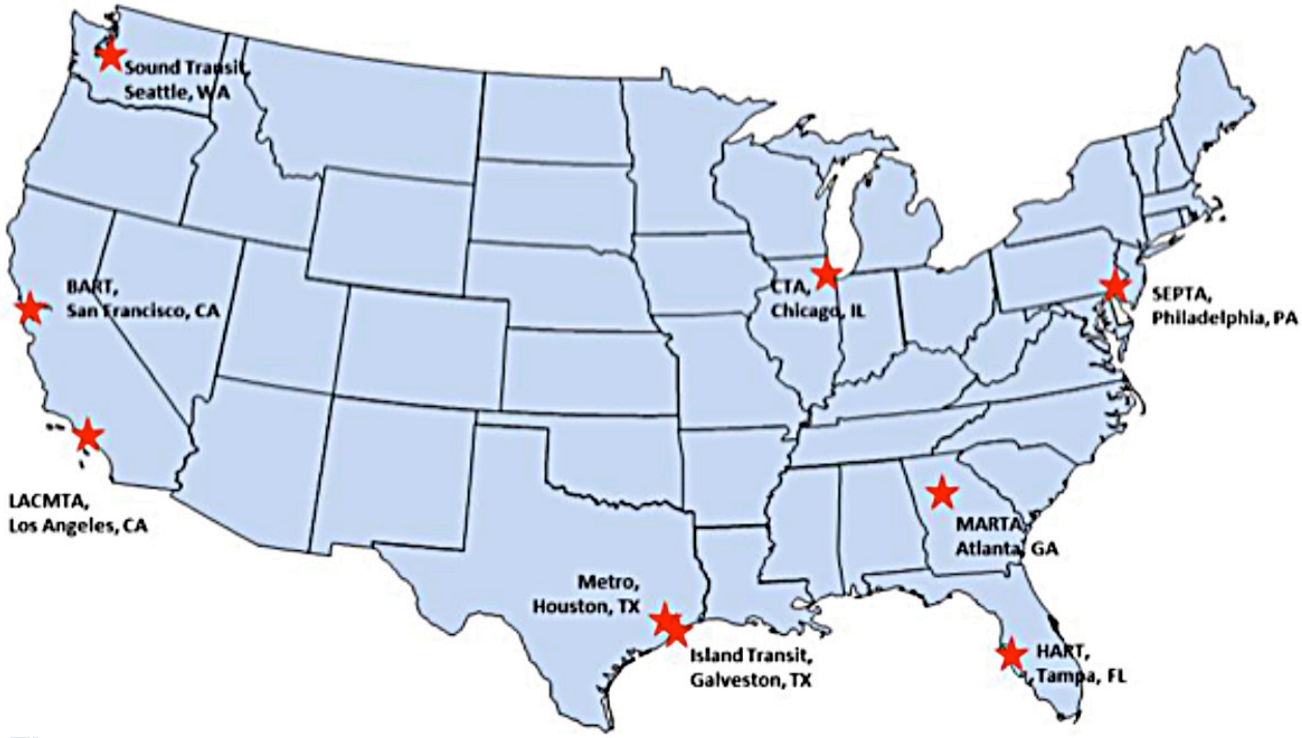

Figure 1-1

Systems included in Climate Change Adaptation Pilot Projects

Each of the pilot studies sought to identify current and future climate hazards, assess transit system vulnerabilities, and develop adaptation strategies, as appropriate to the geography and the system, in the following primary areas:

- Flooding and extreme precipitation
- Extreme heat
- Sea level rise
- Tropical storms and hurricanes

Evident in the analyses was that the impacts of flooding and extreme precipitation (of varying forms), heat-related effects, rising sea levels, and increases in tropical storms and hurricanes were expected to grow in the 20- to 50-year time horizon. System vulnerabilities from these climatic hazards were generally similar for each of the studied areas and include suspension of and delays in service and damage to infrastructure (rail, buses, equipment, right-of-way, and facilities). Among the adaptation strategies identified are:

- Developing disaster operations plans
- Proactively designing new and more resilient facilities and infrastructure and reassessing existing facilities

- Integrating vulnerabilities to climate change impacts into asset management practices
- Working with local public works departments
- Proactively inspecting and maintaining assets
- Adding backup power/generator capacity
- Relocating critical assets prior to damage or impact
- Upgrading cooling systems
- Improving storm drain capacity
- Communicating plans and information with the public and stakeholders
- Documenting and disseminating institutional knowledge
- Integrating the adaptation and analysis solutions developed into current management practices.

As a result of these pilot studies, transit agencies are in a better position to understand and prepare for climate change effects while providing cost-effective service to their customers. These pilot projects provide a positive step towards accounting for and integrating climate affects into regular transit agency practices.

This report is a synthesis of the final reports of the seven pilot projects:

- *An Integrated Approach to Climate Adaptation at the Chicago Transit Authority (CTA)*
- *A Vulnerability and Risk Assessment of SEPTA's Regional Rail*
- *Gulf Coast Climate Change Adaptation Pilot Study*
- *LACMTA Climate Change Adaptation Pilot Project Report*
- *San Francisco Bay Area Rapid Transit District (BART) Climate Change Adaptation Assessment*
- *Sound Transit Climate Risk Reduction Project*
- *Transit Climate Change Adaptation Assessment/Asset Management Pilot for the Metropolitan Atlanta Rapid Transit Authority (MARTA)*

The following sections present summaries of each of the seven pilot project assessments.

SECTION

2

San Francisco Bay Area Rapid Transit (BART) Pilot Study

The BART system serves the San Francisco Bay area (the city of San Francisco and San Francisco, Alameda, Contra Costa, and San Mateo counties). In operation since September 1972, BART operates 5 heavy-rail routes covering 104 miles with 44 stations and 534 vehicles. In 2012, the system provided 367,505 average weekday unlinked trips, resulting in annual fare revenue of $342 million. It is the 5th largest heavy-rail system by ridership.

The BART pilot study concluded that climate change is expected to have very significant impacts in California and is predicted to impact temperature, precipitation, wildfire, sea-level rise, and coastal marine upwelling and currents. For this study, three major climate hazards were selected for evaluation—sea-level rise, downpours, and flooding.

Sea-level rise in the Bay area has the potential to severely disrupt operations and damage critical infrastructure. The Independent Science Board recommended adopting an estimated rise in sea level in the Bay area of 16 inches by 2050 and 55 inches by 2100. Sea-level rise maps developed for the study by the National Oceanic and Atmospheric Administration include different scenarios with either 16 or 55 inches of sea-level rise combined with daily high tides, 100-year storms, or 100-year storms plus wind waves.

The seasonal precipitation trends in the Bay Area are expected to generally remain unchanged, with a modest increase in the frequency and magnitude of intense storm events. Flooding patterns in the East Bay are not anticipated to change drastically because of climate change; however, increases in precipitation intensity may lead to longer durations of flooding and higher peak flows in rivers and storm drain systems. For year 2100 conditions, the study considered areas within the 100- and 500-year FEMA floodplains and areas within ½ mile of either floodplain type as potentially vulnerable to flood events.

To address these potential risks, BART developed an exhaustive list of adaptation strategies on a system-wide and asset-specific basis, including hazards exposure, implementation priority, and costs. System-wide strategies include addressing local storm drain capacity and storm drain backflow prevention, identifying potential flooding problems through maintenance reporting, and active testing of roofs and drain systems to detect potential problems proactively. Also presented in the report are asset-specific strategies for station entrances, track portals, and power substations, as well as rain exposure retrofits, flood control measures, track portal retrofits, sediment removal/reduction, waterproofing, and monitoring of equipment exposed to flooding and extreme precipitation.

BART developed a cost-benefit matrix and implementation time component to assess adaptation strategies using low-, moderate-, and high-cost designations.

BART is taking a holistic approach to climate change. In addition to climate change adaptations outlined in the study, it has focused efforts on climate change mitigation to lessen future impacts by taking steps to reduce greenhouse gas (GHG) emissions in its agency.

The BART study determined that the vulnerability related to climate change is real, the risks are high, and resiliency is attainable. Many adaptation strategies, structural and non-structural, will take a significant time period to implement. The findings of this pilot provide sufficient and critical insights that urge BART, as an indispensable transportation provider to the mobility of the San Francisco Bay Area region, to respond in a timely manner and adapt to the impacts of climate change.

For more detailed information on the BART pilot project, refer to the final project report, *San Francisco Bay Area Rapid Transit District (BART) Climate Change Adaptation Assessment Pilot.*

SECTION

3

Chicago Transit Authority (CTA) Pilot Study

The CTA system serves the Chicago metropolitan area and 40 surrounding suburbs. In operation since October 1947, CTA operates 140 bus routes covering 2,230 miles and 8 rail routes covering 222 miles with 144 stations. The CTA system provided more than 1.7 million average weekday unlinked trips resulting in annual fare revenue of $551 million in 2012. It is the 3rd largest heavy-rail transit system by ridership and the 3rd largest local bus system by ridership.

The pilot study concluded that historical climate data observations and projected future increases in extreme heat and precipitation events are likely to have significant impacts on CTA's infrastructure, transit operations, and customer experience. Localized climate models predict that prolonged heat events (e.g., three or more days exceeding 90˚F) will increase in the Chicago area under both low- and high-emissions scenarios.

Extreme heat will increase rates of rail buckling and signal equipment failures and increase vehicle energy consumption. CTA rail system operations are vulnerable to disruptions and greater costs from flooding and extreme precipitation and can affect rights-of-way. Bus services are vulnerable to flooding from troubled viaducts within the city, and water intrusion into subway portals has a high potential for service disruptions and infrastructure impacts. Such incidents will continue to inflict significant capital, operating, and maintenance cost impacts.

CTA developed adaptation strategies to address repeated flooding in subway tunnels and at-grade rail crossings, including proposed barriers around ventilation shafts to prevent water infiltration into the subway system and installation of an underground cistern that would capture water from track portals and release it into the drainage system as capacity becomes available. Build options for track susceptible to heat kinks include upgrading ballasted track sections with improved materials and installation methods and replacing track sections by placing the running rail on a structural concrete base. Signal house overheating options include installing a second parallel A/C unit in each signal house to increase overall cooling capacity and provide redundancy in the case of failure of the primary A/C unit and providing secondary power sources to signal houses by installing switch gear or traction power convertors to connect to the Commonwealth Edison regional electrical grid.

CTA developed a life-cycle cost analysis (LCCA) model to evaluate proposed adaptation solutions for three different rail system vulnerabilities: right-of-way flooding, rail heat kinks, and signal house overheating. The LCCA demonstrated a positive return-on-investment (ROI) for the majority of model runs at higher weather-event frequencies than have been predicted in the baseline climate models. The study recommended, however, that prioritization of the improvements should not be performed exclusively from an LCCA analysis; additional factors must be considered to ultimately prioritize climate-adaptive improvements based on historical performance and available projection data.

Two alternative approaches were proposed to incorporate climate impacts into CTA's enterprise asset management (EAM) system, in concert with the ongoing build-out of the EAM framework and ongoing engineering condition assessments: 1) develop qualitative risk assessment tables for major asset groups driven by severe weather impacts; and 2) incorporate fields in the EAM database to indicate the climate vulnerability of a given asset, defined as a function of exposure, sensitivity, and adaptive capacity. A framework model was developed for forecasting operational and budgetary impacts.

Overall, the CTA pilot project established a baseline for observed and projected climate impacts based on available data and climate models and provides a set of flexible tools to allow testing of multiple scenarios and demonstrates the sensitivity of outputs to varying input assumptions.

For more detailed information on the CTA pilot project, refer to the final project report, *An Integrated Approach to Climate Adaptation at the Chicago Transit Authority (CTA).*

SECTION

4

Gulf Coast (Houston Metro, Tampa HART, Island Transit) Pilot Study

The Gulf Coast pilot project included three transit systems: Houston Metro, Tampa HART, and Galveston Island Transit.

Houston Metro serves the Houston metropolitan area (the city of Houston and Harris and Fort Bend County). It began operations in January 1979 and operates 75 local bus routes and 32 commuter bus routes with nearly 10,000 posted bus stops, as well as 1 light-rail route with 24 stations. The system provided almost 275,000 average weekday unlinked trips resulting in annual fare revenue of $73 million in 2012. It system is the 14th largest light-rail system by ridership and the 12th largest local bus system by ridership.

Tampa's Hillsborough Area Regional Transit (HART) system began operation in October 1979 and includes 30 local bus routes and 13 express bus routes, as well as 1 streetcar system with 11 stops. The system provided more than 49,000 average weekday unlinked trips resulting in annual fare revenue of $14 million in 2012. The HART system is the 32nd largest light-rail system by ridership.

Galveston Island Transit (Island Transit) serves Galveston Island and has been in operation since the mid-1960s, operating 7 bus routes and generating almost 709,000 annual unlinked trips resulting in annual fare revenue of $ 0.33 million in 2012. It is primarily a small bus and commuter bus system.

Transit agencies near the Gulf of Mexico are particularly vulnerable to natural hazards such as extreme heat, flooding, and high winds. Climatic trends in the Gulf Coast indicate that the temperature has increased by 2°F since 1970, with conservative estimates predicting an additional increase of 4.5°F by 2080. Heavy rainfall events and droughts have increased and are expected to continue, with longer dry days between rainfall events. Damage from hurricanes has increased, with likely increases in future storm intensities. Sea levels and storm surges have risen higher than the global average along the Gulf of Mexico coastline, with the projected rise in sea levels up to 4 feet within 50–100 years, putting 2,400 miles of major roadways and 246 freight lines at permanent risk of flooding.

These changes are particularly important when considering that 37 percent of the U.S. population lives within the Gulf Coast region, with an expected increase estimated at 15 percent by 2020, and substantial implications for hurricane-, surge-, and flood-related damages. In addition, 7 of the 10 largest U.S. ports are located on the Gulf Coast, which provide nearly 30 percent of the nation's crude oil production and 20 percent of its natural gas production, all of which are extremely vulnerable to storm surge.

The study identified Gulf Coast rail system vulnerabilities from heavy precipitation, including submerged tracks, flooding of low-lying underpasses, and erosion of bridges. Bus operation vulnerabilities include power outages, road flooding, and damaged or poorly maintained drainage facilities. Impacts from increasing temperatures include increased energy consumption, rail buckling, derailments, failure of ventilation/cooling systems, increased maintenance costs, and concerns for human health and safety. Increases in sea level will affect highways, ports, bridge crossings, rail, roads, tunnels, equipment, and facilities. Low-lying areas, highways, bridges, and coastal infrastructure are particularly vulnerable to tropical storms and hurricanes.

Adaptation strategies identified in the Gulf Coast study to deal with climate change include ensuring that all new operations/vehicle maintenance facilities are outside the 100-year floodplain or at another higher level of flood resistance or designing site plans with buildings raised sufficiently high as to avoid all foreseeable flood risk; working with public works departments from local jurisdictions to ensure that storm sewers for flood prone areas are kept clear; using agency and management operations experience to identify flood-prone route segments and identify standard/ preferred alternatives or procedures; educating riders about typical reroutes or agency procedures using route brochures, public service announcements, and operator/rider dialogue; identifying standard operating procedures to reduce the impact of street flooding on vehicle maintenance (slow speeds, avoid known trouble areas), agency property (passenger amenities), and private property (reducing vehicle speed to limit forcing water up onto/into private property); and establishing methods of recording useful information to quantify the impacts of street flooding on facilities, vehicle maintenance, and operating costs to inform future decisions.

The Gulf Coast report concludes with a section on how to use GIS to assess transit asset vulnerability to climate change.

Gulf Coast transit agencies can use the information from this pilot study as a baseline guide to renew and improve planning for the impacts of finite weather events and long-term climate change. Climate change vulnerability planning and adaptation will increase agency staff capabilities, protect valuable assets, and improve rider safety.

For more detailed information on the Gulf Coast pilot project, refer to the final project report, *Gulf Coast Climate Change Adaptation Pilot Study.*

SECTION 5

Los Angeles County Metropolitan Transportation Authority (LACMTA) Pilot Study

The LACMTA system serves the Los Angeles metropolitan area. Formed via a merger of the Southern California Rapid Transit District and the Los Angeles County Transportation Commission in 1993, LACMTA operates 191 bus routes as well as 2 subway (heavy-rail) and 4 light-rail routes, covering 87.8 miles with 80 stations. The LACMTA system provided almost 1.5 million average weekday unlinked trips resulting in annual fare revenue of $359 million in 2012. Based on ridership, it is the 9th largest heavy-rail system, the 3rd largest light-rail system, and the 2nd largest local bus system.

In this pilot study, LACMTA drew on historical data on temperature, rainfall, and sea-level rise, as well as climate models, to examine future climate conditions in Los Angeles County through the end of the century. It was determined that temperatures are projected to continue to rise, possibly in excess of 10°F, and the frequency of extremely hot days is expected to increase. There is some evidence of a recent increase in the frequency of events of heavy precipitation, but it is unclear if such a trend might continue into the future. Sea levels are expected to rise 1 foot by the mid-21st century and between 20 inches and 5 feet by the end of the century. However, the risk of impacts from sea-level rise is low due to the inland location of most transit assets.

In light of these conditions, LACMTA developed a Climate Action and Adaptation Plan (CAAP) to assess the vulnerability of its rolling assets (rail operations, bus operations, and projects under construction) and provided a series of general adaptation options for the agency to consider, including new technologies to withstand extreme heat, such as heat-resistant track materials and white “cooling” boxes for equipment, which are being tested for effectiveness and efficiency.

To address climate change effects on rail operations related to extreme heat, adaptation strategies include pre-emptive maintenance or inspection and weather/climate-related monitoring of equipment such as electrical systems and AC and increased shading of railways to address railway buckling. Strategies for dealing with effects on bus operations including pre-emptive maintenance or inspection and weather/climate-related monitoring of equipment and facilities. For new construction projects, extreme heat and heavy rainfall effects may be mitigated by integration of climate considerations in siting and alternatives decisions and modification of construction schedules, especially during the summer months.

To address flooding of underground stations and tracks, adaptation strategies include improved stormwater management systems, infrastructure upgrades in stations (ventilation grates, entrances, seals), and increased pumping capacity. Flooding of at-grade railways and bus rapid transit rights- of way also may be mitigated by upgraded stormwater management systems.

LACMTA's pilot project also engaged in evaluating how climate adaptation principles align with overall agency goals and projects by developing a comprehensive set of metrics that would enable Metro to gauge past progress while also identifying new targets and guide the direction of growth of climate adaptation work. More than 100 metrics were developed in the categories of Planning, Operations, Ridership, and Adaptation, and seven were considered for adoption. These ranked highly in the metrics selection process and will provide valuable information and direction in tracking Metro's performance in the implementation of its climate adaptation strategies and developing action plans for continual improvement, and will serve as a guide for further work .

Next steps as Metro moves toward evaluating specific options for adapting to climate change include investigating climate vulnerabilities at a higher level of specificity, exploring the monetary and social costs of climate impacts and adaptation options, developing a communications strategy for the adaptation component of the CAAP and subsequent adaptation activities, and exploring implementation of climate adaptation principles at the operations level.

For more detailed information on the LACMTA pilot project, refer to the final project report, *LACMTA Climate Change Adaptation Pilot Project Report*.

SECTION

6

Metropolitan Atlanta Rapid Transit Authority (MARTA) Pilot Study

The MARTA system serves the Atlanta metropolitan area (the city of Atlanta and the counties of Fulton, DeKalb, and Cobb). With buses in operation since February 1972 and rail in operation since June 1979, MARTA operates 91 bus routes covering 1,000+ miles and has 4 rail routes covering 47.6 miles with 38 stations. The MARTA system provided almost 430,000 average weekday unlinked trips resulting in annual fare revenue of $130 million in 2012. It is the 8th largest heavy- rail system by ridership and the 15th largest local bus system by ridership.

The pilot study indicated that higher extreme temperatures for longer periods of time and higher-intensity rainfall have been an issue for MARTA's operations and assets in the past. Atlanta will most likely not experience sea-level rise nor storm surge given its location, but the types of climate/weather stresses that could affect its operations include higher levels of more intense precipitation (and thus flooding), higher maximum temperatures, and drought.

Vulnerabilities due to extreme precipitation and flooding include flooding on tracks and facilities and disruptions in bus service; vulnerable assets include poorly-maintained culverts, channels, and storm-water retention ponds in high runoff areas. Among the adaptation strategies identified are establishing plans for assets in floodplains, establishing temporary rerouting and rescheduling of services plan for flood prone areas, relocating and/or hardening maintenance facilities against flooding, establishing emergency shutdown and restart plans for maintenance facilities, conducting more frequent inspections of drainage systems for tracks and facilities, increasing drainage and pumping capacity at problem locations, implementing strategies to prevent mudslides, developing generator capacity to address power failures, and monitoring new floodplain data to reassess the network..

Temperature increases and extreme heat waves will be of longer duration, which could affect MARTA operations in two major ways. First, the high levels of heating of key electrical instrumentation (signals, communication relays, passenger information systems, etc.) could lead to higher levels of failure of these devices. Second, heat-related passenger and worker comfort could become a more important factor in how MARTA schedules and protects its labor force and the way it assures a comfortable traveling experience to its passengers.

Adaptation strategies include conducting more frequent inspections of AC systems on hot days, updating design standards for heat-resistant bus materials, installing more efficient and durable engine cooling systems, evaluating existing policies on worker safety on hot days, and educating customers on how to stay cool.

The occurrence of drought could be an issue in the future. Strategies to address drought conditions include reducing vehicle washing during extreme heat episodes, increasing the use of reclaimed water, replacing bus-washing equipment with more efficient systems, investigating new paints or coverings requiring less washing, removing vegetation that poses fire hazards, incorporating water saving technology (low-flow toilets, faucets, water fountains, and cleaning apparatus), and designing water saving technology into new construction.

MARTA makes the case for integrating climate change vulnerabilities into an agency's overall asset management system. Agencies can integrate climate change risks into the ongoing systematic decision-making on the state of good repair (SGR) of their assets. Based on the vulnerability of the assets to climate hazards, the relative criticality of those assets to the agency achieving its goals, the potential magnitude of the impacts on the system users and surrounding community, and the costs of appropriate retrofits, appropriate climate change retrofits can be prioritized to make the system more resilient. MARTA provides a case study on how climate change risks can be incorporated into an asset management system.

For more detailed information on the MARTA pilot project, refer to the final project report, *Transit Climate Change Adaptation Assessment/Asset Management Pilot for the Metropolitan Atlanta Rapid Transit Authority (MARTA).*

SECTION 7

Southeastern Pennsylvania Transportation Authority (SEPTA) Pilot Study

The SEPTA system serves the Philadelphia area (Philadelphia City-County and Delaware, Montgomery, Bucks, Chester, New Castle, and Mercer counties). In operation since February 1964, it is one of two transit agencies that operate all five major types of transit services: commuter rail, heavy-rail, light-rail, electric trolleybuses, and buses. In aggregate, SEPTA operates 196 lines with 290 stations. The system provided almost 1.2 million average weekday unlinked trips resulting in annual fare revenue of $451 million in 2012. It is the 6th largest heavy-rail system by ridership, the 5th largest light-rail system by ridership, and the 4th largest local bu s system by ridership.

SEPTA reviewed a wide range of extreme weather events from January 2005 to February 2012 and found that flooding and precipitation have had a moderate to significant effect on its operations, concluding that extreme precipitation in the form of snow is the biggest factor affecting the system. Anticipated is a future that will be wetter, with heavy precipitation events more common (increases up to 13%) by the end of the century; however, days with a possibility of snow will decrease in the future. Extreme heat events will be more frequent by 2050 and longer in duration.

Parts of the SEPTA system that are susceptible to flooding and extreme precipitation include culverts, and added runoff from streams and creeks can increase the vulnerability, which can result in flooding at stations, debris on tracks, and washed out tracks and embankments. Catenaries and signal structures are liable to flood and rain damages and could cause closure of tracks, causing major disruptions in service. The system also is vulnerable to delays stemming from snow removal from infrastructure and vehicles, staff availability, limited parking availability due to snow piles, and increased susceptibility to injuries and accidents. Vulnerabilities due to snowstorms and cold temperatures also come in the form of downed power lines, power outages, signal failures, interlocking failures, broken track, and broken wires.

Among SEPTA's adaptation strategies related to extreme precipitation and flooding are moving equipment to strategic and safer locations, pre-screening trouble areas, trimming trees regularly, and renting generators. Service disruptions may be avoided by installing turn-backs on flood prone locations, increasing the monitoring of water levels, employing bus service prior to flooding, improving coordination with local authorities and partners, and improving customer communication. The study also suggested that SEPTA elevate assets in certain areas, build flood protection structures, increase culvert sizes and pumping capacity, and improve drainage capacity in key areas and recommended attention to the deployment of new assets to ensure that they are resistant to flood and extreme precipitation.

Strategies to deal with snow include putting contractors on call for snow removal, prepping facilities pre-storm, deploying platform heaters, trimming trees, deploying backup power systems, monitoring staff and working conditions, and improving customer communication strategies.

Among the extreme heat adaptation strategies are modernizing the catenary system to be more heat resistant, addressing track buckling by increasing rail-neutral temperatures for rail, increasing inspections during periods of high heat events, installing rail temperature monitoring systems at prone locations and additional ventilation and cooling for key electronics, as well as temporary or permanent backup power generation for blackouts and brownouts. The study also considered non-infrastructural issues from extreme heat such as staff, schedules, and budget concerns and operational adaptation, including reduced train speeds.

The results of this study will be used to inform SEPTA's planning as it relates to extreme weather and climate change. SEPTA is already implementing many of the recommended strategies to better maintain service during and after extreme weather events.

For more detailed information on the SEPTA pilot project, refer to the final project report, *A Vulnerability and Risk Assessment of SEPTA's Regional Rail.*

SECTION 8

Central Puget Sound Regional Transit Authority (Sound Transit) Pilot Study

The Sound Transit system serves the Seattle area (the city of Seattle and the counties of Snohomish, King, and Pierce). In operation since September 1999, its services include express bus (25 routes), light rail (2 lines, 16.2 miles, 19 stations), and commuter rail (1 line, 12 stations). The system provided almost 95,000 average weekday unlinked trips resulting in annual fare revenue of $54 million in 2012. It is the 16th largest light-rail system by ridership, 14th largest commuter rail system by ridership, and 31st largest streetcar system by ridership.

Projected changes in climate relevant to Sound Transit services include increased average annual temperature of 2.0°F by the 2020s, 3.2°F by the 2040s, and 5.3°F by the 2080s; more frequent and longer extreme heat events; increases in winter precipitation and extreme precipitation events; decreased summer precipitation; increased slope instability and sediment loading in rivers and streams; increased winter flooding in many rivers; and sea-level rise of 4–56 inches for Seattle.

Vulnerabilities related to increased temperature include rail buckling and heat stress on electrical and safety equipment, overhead catenary systems, pavement and structures, and landscaping and environmental mitigation sites. Impact of increased precipitation include mudslides and slope instability, larger and/or more frequent river and stream flooding, increased localized flooding due to more stormwater runoff or poor drainage, seepage due to higher groundwater tables, and summer drought. Related to sea-level rise, there is an increased potential for temporary flooding and permanent inundation of low-lying areas, higher tidal and storm surge reach, erosion, drainage problems, and corrosion from more frequent or prolonged exposure to saltwater.

Sound Transit identified potential adaptation priority ratings for specific services and identified more than 70 possible options for action if and when Sound Transit determines that adaptation is warranted. These options were generally categorized as 1) adjustments to infrastructure—retrofitting, replacing, or relocating infrastructure; 2) adjustments to operations and maintenance—changes in maintenance frequency or standard operations; 3) design changes—changes in design criteria (specifications) for new and existing infrastructure; and 4) decision support and capacity-building activities—implementing new tools to gather additional information related to climate impacts on the system, using partnerships to address impacts.

Among the strategies for adapting to heat impacts are re-installing expansion joints in areas prone to buckling, using thermocouples to directly monitor actual rail temperatures, adjusting auto tension and fixed-termination set points to a higher average temperature, increasing the use of shading around structures, and increasing visual monitoring for premature wear related to heat stress on structures. Strategies for adapting to precipitation impacts include planning for the increased use of bus bridges, increased visual monitoring of river banks and areas with drainage problems, raising or relocating sensitive underground or ground-level infrastructure, and increased maintenance frequency of pumps and drained used to manage seepage. Sea-level rise adaptation strategies include modifying design standards and drainage patterns, updating service interruption plans, improving and upgrading sea walls and raising track elevations and relevant overhead clearances.

Deciding when, where, and how Sound Transit will adapt to the impacts of climate change ultimately will depend on the nature of the impacts and vulnerabilities that need to be addressed, how quickly climate changes, individual and institutional risk tolerance, ownership of the potentially affected infrastructure, available resources, and other factors. Effective adaptation will require integrating adaptive thinking into Sound Transit agency processes, and, in pursuing near-term actions, the agency will begin to formally address adaptation and integration opportunities to strengthen its resilience to climate change.

For more detailed information on the Sound Transit pilot project, refer to the final project report, *Sound Transit Climate Risk Reduction Project.*

SECTION

9

Conclusion

It was evident from these seven pilot studies that the impacts of flooding and extreme precipitation (of varying forms), extreme heat, rising seal levels, and increases in tropical storms and hurricanes are anticipated to grow in the 20- to 50-year time horizon, with the potential to significantly affect transit operations and assets.

Although system vulnerabilities from these climatic hazards are generally similar for each agency or geographic area, including suspension of and delays in service and damage to infrastructure, the adaptation strategies each has developed are varied based on a number of factors. Among these strategies are:

- Developing disaster operations plans
- Proactively designing new facilities and infrastructure
- Reassessing existing facilities with respect to updated floodplain data
- Working with local public works departments
- Proactively inspecting and maintaining assets
- Adding backup power/generator capacity
- Relocating critical assets prior to damage or impact
- Upgrading cooling systems
- Improving storm drain capacity
- Communicating plans and information with the public and stakeholders
- Documenting and disseminating institutional knowledge
- Integrating the adaptation and analysis solutions developed into current management practices.

As a result of these pilot projects, transit agencies should be in a better position to address and adapt to climate hazards while providing cost-effective service to their customers. These pilot projects provide a positive step towards accounting for and integrating climate affects into regular transit agency practices.

For more detailed information, refer to the final reports of the seven pilot projects:

- *An Integrated Approach to Climate Adaptation at the Chicago Transit Authority (CTA)*
- *A Vulnerability and Risk Assessment of SEPTA's Regional Rail*
- *Gulf Coast Climate Change Adaptation Pilot Study*

- *LACMTA Climate Change Adaptation Pilot Project Report*
- *San Francisco Bay Area Rapid Transit District (BART) Climate Change Adaptation Assessment Pilot*
- *Sound Transit Climate Risk Reduction Project*
- *Transit Climate Change Adaptation Assessment/Asset Management Pilot for the Metropolitan Atlanta Rapid Transit Authority (MARTA)*

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