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GUIDELINE

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Urban Design Working Group

Transit Resilience Guidelines

A Compendium of Adaptive Design and Operations Strategies for Extreme Weather

Abstract: These guidelines are a compendium of resilience strategies for designing and operating transit to reduce transit's risk to climate hazards such as flooding, sea level rise, extreme heat, extreme cold and wildfire.

Keywords: acute hazard, adaptation, alignment, climate hazard, disaster, extreme cold, extreme heat, facilities, fleet, flooding, frameworks, funding, hazard, hazard mitigation, infrastructure, managed retreat, operation and maintenance, physical risk, resilience, right-of-way, sea level rise, strategies, wildfire.

Summary: This document provides an overview of selected climate hazards and their impacts on transit systems and facilities. Case studies on extreme weather impact and adaptation from U.S. and Canadian public transit and transportation agencies are presented to demonstrate best practices.

APTA Standards

Foreword

The American Public Transportation Association is a standards development organization in North America. The process of developing standards is managed by the APTA Standards Program's Standards Development Oversight Council (SDOC). These activities are carried out through several standards policy and planning committees that have been established to address specific transportation modes, safety and security requirements, interoperability, and other topics.

APTA used a consensus-based process to develop this document and its continued maintenance, which is detailed in the manual for the APTA Standards Program. This document was drafted in accordance with the approval criteria and editorial policy as described. Any trade name used in this document is information given for the convenience of users and does not constitute an endorsement.

This document was prepared by the Urban Design Working Group as directed by the Sustainability Steering Committee.

This document represents a common viewpoint of those parties concerned with its provisions, namely transit operating/planning agencies, manufacturers, consultants, engineers and general interest groups. The application of any recommended practices or guidelines contained herein is voluntary. APTA standards are mandatory to the extent incorporated by an applicable statute or regulation. In some cases, federal and/or state regulations govern portions of a transit system's operations. In cases where there is a conflict or contradiction between an applicable law or regulation and this document, consult with a legal adviser to determine which document takes precedence.

This is a new document.

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Introduction

This introduction is not part of APTA SUDS-UD-GL-011-26, "Transit Resilience Guidelines: A Compendium of Adaptive Design and Operations Strategies for Extreme Weather."

Designing and operating resilient transit requires a forward-thinking view in an era when infrastructure is facing not only the present consequences of extreme weathers but also future consequences. The IPCC Sixth Assessment Report notes that the frequency and intensity of extreme weather events, such as heatwaves, heavy precipitation, and droughts, have increased with more significant impacts expected to continue as global temperatures rise. For the transit industry to improve its resilience to climate hazards, it must take a proactive, systematic approach toward what a transit agency can and should do.

This document is intended for practitioners tasked with making transit systems more resilient to climate hazards. Such practitioners may include engineers, consultants, policymakers, designers, planners, maintenance staff, operations staff, project and program managers, and emergency managers.

APTA recommends the use of this document by:

- individuals or organizations that operate transit systems;
- individuals or organizations that contract with others for the operation of transit systems; and
- individuals or organizations that influence how transit systems are operated (including but not limited to consultants, designers and contractors).

Scope and purpose

Climate and weather disruptions are creating new challenges for transit operators. While the transit industry has operated its systems under varied natural conditions for a very long time, the impact resulting from more frequent and severe climate events such as sea level rise, flooding, wildfire, and extreme heat or cold has created new challenges. To be adaptive and resilient to these climate impacts, the transit industry must go beyond "business as usual" patterns for planning, designing, constructing and operating their systems.

This document provides guidance and recommendations that can be adopted by transit agencies seeking to develop and implement adaptation and resilience strategies. The guidelines are intended to address all aspects of the transit system—including infrastructure, facilities, rolling stock, and operations and maintenance—as well as best practices such as partnerships among federal, state and local governments and utility providers. This document does not cover non-weather events such as earthquakes or pandemics.

This recommended practice covers a wide spectrum of climate resilience best practices for transit to comprehensively lead to the realization of the objectives below. It reflects a compilation and curation of knowledge drawn from transit agency experiences and documented guides and best practices. Authoritative sources include those at the national level from FTA, FEMA, ASTM, FHWA, NOAA and EPA, as well as regional and local sources. It focuses on physical and non-physical strategies that are organized by transit element (sections 3 through 6) and implementation considerations such as partnerships, funding and frameworks (section 7).

The intent is for practitioners to use this document as a starting point for identifying resilience strategies and measures. Practitioners are encouraged to use this document in concert with other available sources when identifying and evaluating resilience strategies. It is assumed that practitioners will have carried out a climate vulnerability assessment before reviewing this document. There is a wealth of other guidance available on how to carry out such an assessment (see Section 7.1).

Resilience strategies should aim to achieve the following objectives:

- Reduce the risk of loss of life, property damage and environmental degradation.
- Ensure reliability of services (including a fast recovery after an event).
- Protect public investment.
- Support economic recovery.

For those transit agencies embarking on capital expansions, major rehabilitation programs or infrastructure upgrades, incorporating climate resilience measures that will support infrastructure to perform effectively and efficiently over the long term.

Transit Resilience Guidelines: A Compendium of Strategies

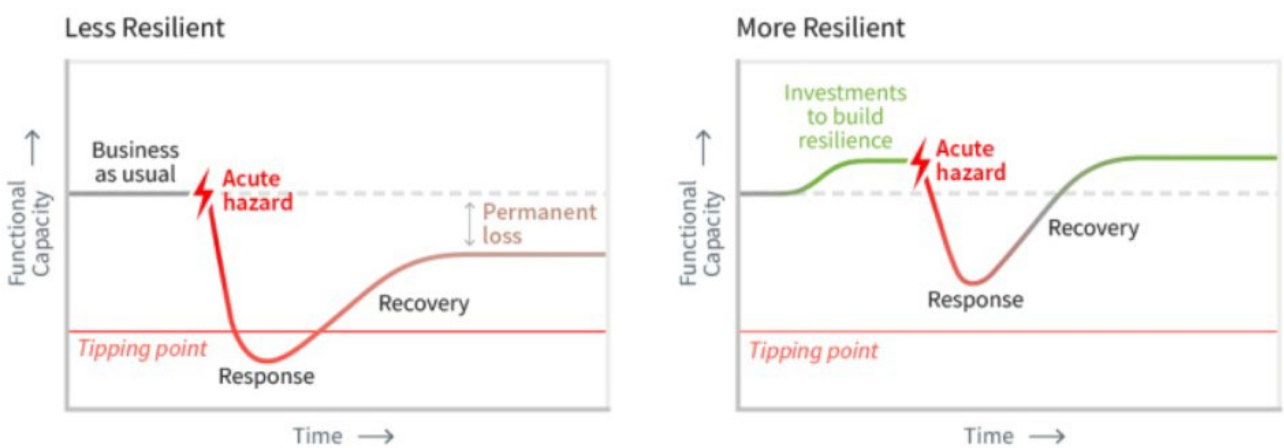
1. Approach

1.1 What is resilience?

Resilience is the capacity of an individual, community, organization or natural system to respond to disruptions, recover from stresses and adapt to hazards. Investments for building resilience should be made to improve an entity's ability to adapt to climate hazards and disruptions. An entity that invests beyond a "business as usual" approach to climate hazards is more resilient, with faster recovery and less permanent loss. **Figure 1** visualizes this concept.

Resilience in a transit system refers to its ability to absorb shocks (disturbances) while retaining the transit system and its operations, as well as its capacity to adapt to stress and change. Resilience reflects the ability of a transit system to "bounce back" and return to normal levels of transit service after a hazard event. A more resilient transit system works proactively, not reactively, to address its risks and impacts from disturbances. Resilience is often associated with adaptation, which in this context refers to actions reducing the vulnerability of a transit agency to existing or future hazards. A less resilient system can reach a tipping point in its functional capacity (or level of service) if a hazard results in permanent or irreversible loss or damage and inability to fully recover. For example, a tipping point for a transit agency could be a flood event that permanently damages electrical equipment. This could result in the closure or partial closure of the system for an extended period after the event.

FIGURE 1
How Resilience Affects Functional Capacity[1]



1. U.S. Climate Resilience Toolkit, Resilience Graphs. https://toolkit.climate.gov/image/3144

1.2 Transit elements

Each section of this document reflects various aspects of the transit system: planning, designing, constructing, and operating and maintaining a transit system. Transit systems of all modes have certain common elements and functions; this recommended practice organizes the elements and functions as follows (see **Figure 2**):

Policy and management (Section 2) refers to strategic policies and management practices at the enterprise level. Policy and management practices focus on governance opportunities, strategic decision-making, metrics and developing solutions at a broader scale.

System route, transit mode and node (Section 3) refers to the physical siting, site planning and alignment of public transportation routes. Examples:

- Rail transit operates on track right-of-way (guideway) and fixed station site properties.
- Bus transit uses shared or dedicated roadways and stops.
- Ferry transit has routes across designated waterways and accesses terminal ports.

Infrastructure and facilities (Section 4) refers to the planning, design and construction of the physical elements (excluding fleet), including stations, terminals, supporting facilities and systems, and corridors. Examples:

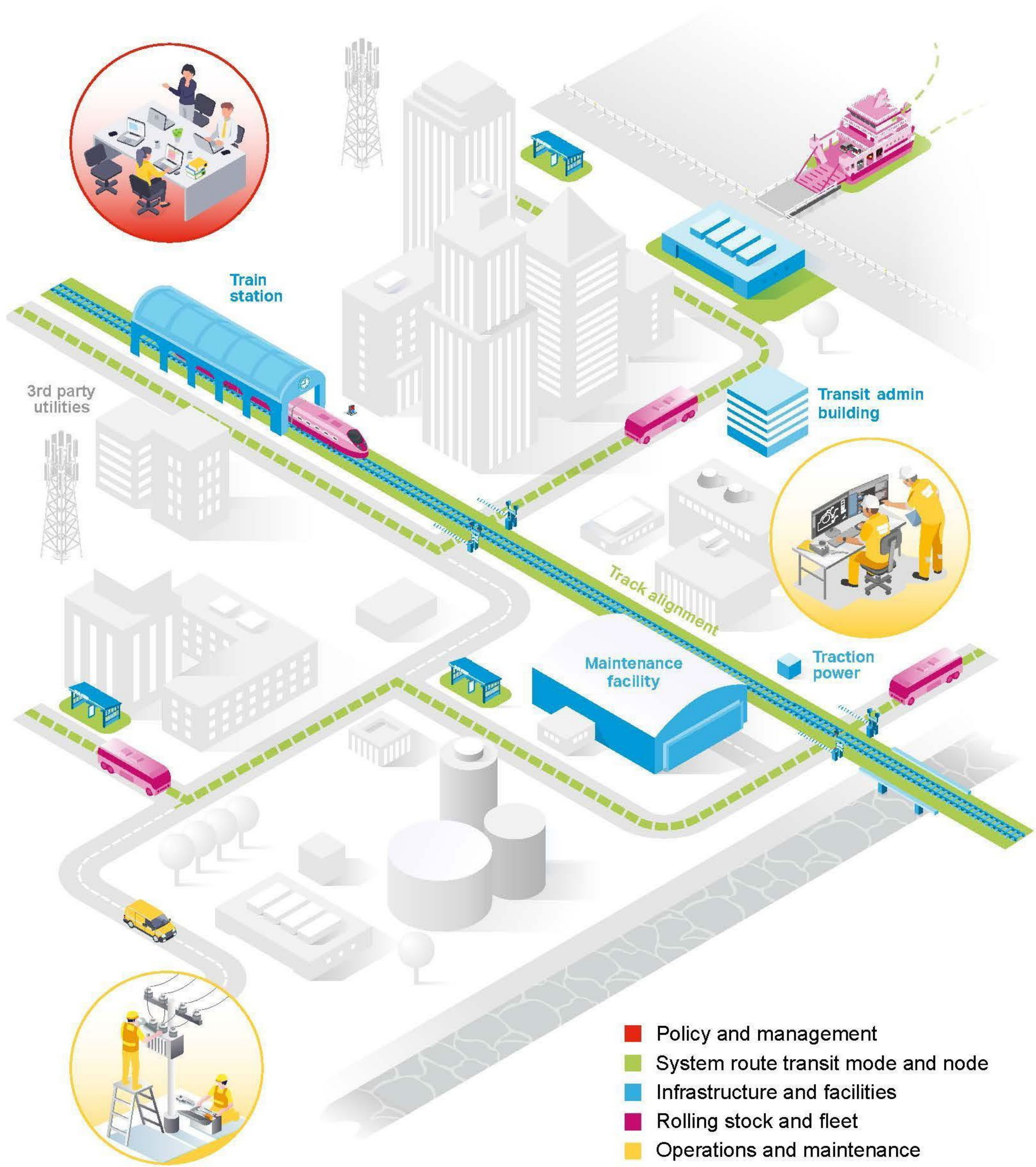
- Rail transit includes track and right-of-way infrastructure, power and communication systems, and revenue and nonrevenue facilities supporting transit operations.
- Bus transit includes shared or dedicated roadways or guideways, communication systems, and revenue and nonrevenue facilities supporting bus operations.
- Ferry transit includes power and communication systems and revenue and nonrevenue facilities supporting ferry services.

Rolling stock and fleet (Section 5) refers to planning, procurement, design, fabrication and operation of rolling stock and fleet. Examples:

- Rail transit has trains (assemblies of rail cars) for revenue service and nonrevenue rail and rubber-tire vehicles supporting maintenance and operations.
- Bus transit has buses and supporting vehicles.
- Ferry transit has vessels and supporting vehicles.

Operations and maintenance (Section 6) refers to opportunities during the operational phase of a transit system (i.e., after the system is designed, constructed and commissioned). It includes tactical measures within existing operations.

FIGURE 2
Transit Elements Covered by This Document



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1.3 Climate hazards

Transit systems face myriad of hazards. This document focuses on climate hazards. Failing to adapt to climate threats can have a direct and lasting negative impact on the livability, environmental quality and economic prosperity of a community. This compendium focuses on the following five climate hazards that transit systems are commonly facing:

- **Sea level rise** is a permanent increase in sea level due to global warming impacts, which includes the melting of glaciers and ice sheets and the expansion of seawater as it warms. Sea level rise has potential to cause more frequent and longer flooding of coastal flood-prone areas, erode shorelines, elevate groundwater, and permanently inundate coastal zones.
- **Flooding** refers to a temporary condition of a partial or complete inundation of land that is normally dry. For purposes of this compendium, flooding includes two types: *fluvial* and *pluvial*. Fluvial flooding occurs when streams, rivers, lakes, reservoirs or coastal water bodies are abnormally high and overflow into adjacent low-lying areas. Areas at risk of recurring floods are known as floodplains. Pluvial flooding occurs when an extreme rainfall event creates a flood independent of an overflowing water body. Flooding of infrastructure typically results from heavier precipitation than designed for but can also occur from dam failures.
- **Wildfire** refers to any free-burning vegetative fire that initiates from an unplanned ignition, whether natural (e.g., lightning) or human-caused (e.g., powerline failure, escaped prescribed fire). Drought conditions increase the fire hazard risk.
- **Extreme heat** occurs when the heat index, a function of heat and relative humidity, is high. The threshold is typically the 98th percentile of historic maximum temperature for a given region. Extreme heat can lead to health emergencies, including heat exhaustion and heatstroke. Vulnerable populations including the elderly, children and people with disabilities are particularly prone to heat emergencies. Extreme heat also places a strain on infrastructure including electrical equipment (e.g., overheating) and rail (e.g., buckling).[2]
- **Extreme cold** refers to sustained temperatures near or below freezing. An extreme cold event often occurs in tandem with a winter storm, resulting in snow, sleet, freezing rain or a mix. Icy conditions can lead to dangerous driving conditions and create a pedestrian slip-and-fall hazard. Human exposure to extreme cold may cause frostbite, hypothermia or even heart attack during physically demanding activities. Extreme cold impacts infrastructure, including water pipe bursts, power outages, and road and rail closures.

Additional hazards, such as high winds or landslide potential, may be considered in future updates to this document.

1.4 Opportunities for building resilience

Table 1 conceptualizes the opportunities for building resilience for each climate hazard in each of the transit elements. The matrix indicates the potential under each transit element to maximize opportunity and achieve resilience.

2. Federal Transit Administration, "Flooded Bus Barns and Buckled Rails: Public Transportation and Climate Change Adaptation," FTA Report No. 001, August 2011, page 21. https://www.transit.dot.gov/sites/fta.dot.gov/files/FTA_0001_-_Flooded_Bus_Barns_and_Buckled_Rails.pdf

TABLE 1
Matrix of Opportunities for Building Resilience

	Transit Element			
Hazard	**System Route Transit Mode and Node**	**Infrastructure and Facilities**	**Rolling Stock and Fleet)**	**Operations and Maintenance**
Sea level rise	***	**	*	**
Flooding	***	**	*	**
Wildfire	**	**	*	**
Extreme heat	*	***	*	**
Extreme cold	*	***	*	**

2. Policy and management

1. **Resilience officer.** Establish a resilience officer or equivalent role to drive resilience. The officer coordinates action across various departments and external parties, leads effective processes and decision-making, and supports capacity-building to proactively prepare for disruptions.[3]
2. **Policy.** Establish a climate resilience policy that articulates the organization's commitment to climate resilience. A climate resilience policy may be standalone or embedded within an organization's strategic plan, vision or policy. It is not uncommon for climate resilience to be integrated into sustainability policies.[4,5,6]
3. **Risk assessment.** Conduct risk assessments to understand vulnerability to climate hazards. Leverage existing hazard data and GIS to map the risk of various hazards. Include future conditions and changes resulting from climate change, such as sea level rise. ISO 14091 is a global standard for conducting climate risk assessment. Refer also to Section 7.1 of this document for frameworks that include risk assessment methods. Where possible, work with other infrastructure or utility owners (e.g., energy, water/wastewater, communications, roads) to identify critical interdependencies, risks, and vulnerabilities.
    a. **Best available science.** Stay informed on the latest available science on climate change and updates to projections and other relevant data. This may include use of the internationally recognized business as usual greenhouse gas emissions scenario, "Representative Concentration Pathway 8.5 (RCP8.5)" and lower emissions scenarios (RCPs 4.5 and 2.6) for sensitivity analysis, or region-specific climate models and resources.
4. **Adaptation planning.**
    a. **Conduct adaptation planning.** Refer to ISO 14092 for global standard on adaptation planning for local government and communities.
    b. **Adaptation plan.** Develop an adaptation plan that identifies climate risks and resilience actions.[7,8]

3. The Rockefeller Foundation, What a Chief Resilience Officer Does, September 2014. https://www.rockefellerfoundation.org/blog/what-a-chief-resilience-officer-does/
4. San Francisco Bay Area Rapid Transit District, BART Sustainability Policy, April 2017, Goal 5. https://www.bart.gov/sites/default/files/docs/BART%20Sustainability%20Policy%20Apr17_v2.pdf
5. Washington Metropolitan Area Transit Authority, Our Sustainability Vision. https://www.wmata.com/initiatives/sustainability/Our-Sustainability-Vision.cfm
6. Maryland Department of Transportation, Maryland Transit Administration, Sustainability Program, Goal 17. https://www.mta.maryland.gov/sustainability
7. SamTrans, SamTrans Adaptation and Resilience Plan, February 2021. https://www.samtrans.com/media/28139/download
8. Metrolink, "Climate Vulnerability Assessment and Adaptation Plan, A Roadmap to Implementation," February 2022. https://metrolinktrains.com/globalassets/about/agency/sustainability/metrolink_cva_adaptplan_final_220330.pdf

   c. **Local hazard mitigation plan (LHMP).** Leverage an LHMP to address climate hazards.[9]

NOTE: Participation in an LHMP provides eligibility to FEMA hazard mitigation assistance programs; see Section 7.2.

5. **Agency integration.** Integrate climate risk and opportunities into policies, programs, projects and plans.[10,11,12,13] Examples include regional plans, capital improvement programs, system expansion plans, modernization plans, master plans, transit-oriented developments, asset management programs, and sustainability or climate action plans.[14] Establish policies to ensure that climate risks are part of the planning process.
   a. **Asset management.** Refer to ISO 55001 for global standard on asset management.[15] See also Section 7.7 of this document.
6. **Resilient design standards.** Adopt or upgrade design standards to be more resilient.[16,17,18]
   a. Require new and renovation projects to account for future conditions of climate hazards. Specify climate hazards specific to the agency's region. Leverage findings from agency or local vulnerability assessments into design standards.
   b. Consider referencing the International Building Code, which includes provisions for resilience.[19] Design codes and standards should ensure that infrastructure and facilities are resilient to hazard events and consider the ability to adapt to changing conditions over the life of the asset.[20]
   c. Refer to the American Society of Civil Engineers' "Pathways to Resilient Communities,"[21] which summarizes available codes, standards and manuals of practice for resilient infrastructure design.

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9. San Francisco Bay Area Rapid Transit District, Local Hazard Mitigation Plan, 2022. https://www.bart.gov/about/planning/policies/hazard
10. Federal Emergency Management Agency, "Mitigation Ideas: A Resource for Reducing Risk to Natural Hazards," MU-6, page 78, January 2013. www.fema.gov/sites/default/files/2020-06/fema-mitigation-ideas_02-13-2013.pdf
11. City and County of San Francisco, OneSF, Sea Level Rise Guidance. https://onesanfrancisco.org/sea-level-rise-guidance
12. U.S. General Services Administration, "Climate Change Risk Management Plan," September 2021. https://www.sustainability.gov/pdfs/gsa-2021-cap.pdf#:~:text=describes%20steps%20GSA%20will%20take%20to%20develop%20a,money%2C%20and%20develop%20healthy%2C%20just%20and%20prosperous%20communities. See appendixes for example policy statement, draft decision diagrams and governance structure.
13. United Nations, "Managing Infrastructure Assets for Sustainable Development, A Handbook for Local and National Governments," Chapter 6 Improving Climate Resilience, 2021. https://www.un-ilibrary.org/content/books/9789210051880/read
14. San Francisco Bay Area Rapid Transit District, BART Sustainability Action Plan, Chapter 8, December 2017. https://www.bart.gov/sites/default/files/docs/BART_SustainabilityActionPlan_Final.pdf
15. International Organization for Standardization, ISO/TC 251 Asset Management. https://committee.iso.org/home/tc251
16. American Society for Testing and Materials, E3032, Standard Guide for Climate Resilience Planning and Strategy, 2015 edition, Article 6.5.5.5 and 6.3.4.4
17. Massachusetts Bay Transportation Authority, "Design Guidelines for Bus Maintenance Facilities," Section 2.1.3, March 2023. https://cdn.mbta.com/sites/default/files/2023-04/2023-03-31-bus-maintenance-facility-design-guideline-second-edition_accessible.pdf
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21. American Society of Civil Engineers, "Pathways to Resilient Communities: Infrastructure Design for the Environmental Hazards in Your Region." https://www.asce.org/-/media/asce-images-and-files/advocacy/documents/pathways-to-resilient-communities-asce-toolkit.pdf

Case Study: Miami-Dade County's SMART Program Integrates Sea Level Rise Adaptation and Greenhouse Gas Reduction Needs

The Strategic Miami Area Rapid Transit (SMART) Program,[22] a transit development program led by Miami-Dade County, is helping the region become future-ready[23] by addressing sea level rise and mitigating GHG emissions. As a cornerstone for the county's Sea Level Rise Strategy and Climate Action Strategy, the SMART Program will densify development on high ground around rapid transit corridors, thereby reducing flood risk and encouraging use of public transportation.

As part of the county requirements, projects under the SMART Program "shall consider sea level rise…using regional consistent unified sea level rise projections, during all project phases...to ensure that infrastructure projects will function properly for fifty (50) years or the design life of the project, whichever is greater."

Resilience is integrated into the requests for proposals, ensuring that project planning and design stages will be informed by a climate risk assessment. The risk assessment includes looking at project components (e.g., guideways, stations, light maintenance facilities, park-and-ride lots), design life, criticality of each component, and current and future flood hazard scenarios. Projects must evaluate the components and relative risk tolerance, taking into account the need to often add 1 to 3 ft of elevation to comply with county requirements. Where there are limitations for elevating assets or where the assets are highly critical, floodproofing might also be recommended.

Early in the SMART Program, the county's Office of Resilience held training sessions in collaboration with Miami-Dade's Department of Transportation and Public Works to expand the knowledge base of project teams. As projects developed, the Office of Resilience provided comments on design reports and deliverables from consultants. Throughout the process, teamwork has been critical in helping the county meet current and future climate and transit challenges while also creating a healthier, more integrated community along the way.

- **Operational response plans or continuity of operations plans (COOPs).**[24] Establish response plans or COOPs, including rerouting or alternative service plans to circumvent disabled assets and minimize disruption to patrons (e.g., bus bridges, mutual aid agreements with other operators). Establish backup plans, systems and procedures to ensure that critical functions are maintained and supported. Update existing plans to account for increase in frequency or intensity of hazard events. COOPs may also be referred to as business continuity plans. The following are available resources for continuity planning:
    a. FEMA National Continuity Programs, "Guide to Continuity Program Management"[25]
    b. FEMA Continuity Resource Toolkit[26]
    c. ISO 22301, Security and Resilience, Business Continuity Management Systems

7. **Regional planning.**
    a. Engage in regional adaptation planning efforts (e.g., Bay Adapt for sea level rise).[27][28] Certain climate hazards, such as sea level rise, are better addressed at the regional scale.
    b. In conjunction with the relevant metropolitan planning organization or other regional planning organization, develop an integrated transit/land-use plan that discourages or prohibits development that is not adaptive to high-risk hazard-prone zones.

22. Miami-Dade County, The Strategic Miami Area Rapid Transit (SMART) Program. https://www.miamidade.gov/global/transportation/corridor-plans.page
23. Miami-Dade County, Office of the Mayor, "Future Ready." https://www.miamidade.gov/mayor/library/future-ready.pdf
24. Federal Transit Administration, "Emergency Relief Manual, Reference Manual for States, and Transit Agencies on Response and Recovery from Declared Disasters and FTA's Emergency Relief Program," Version 2.0, page 15, March 2023. https://www.transit.dot.gov/sites/fta.dot.gov/files/2023-03/FTA-Emergency-Relief-Manual-March-2023.pdf
25. FEMA National Continuity Programs, "Guide to Continuity Program Management," May 2020. https://www.fema.gov/sites/default/files/2020-10/fema_national-continuity-programs_guide-continuity-program-management.pdf
26. Federal Emergency Management Agency, Continuity Resource Toolkit. https://www.fema.gov/emergency-managers/national-preparedness/continuity
27. San Francisco Bay Conservation and Development Commission, Bay Adapt. https://www.bayadapt.org/
28. National Academies, Incorporating Resilience into Transportation Network. http://nap.nationalacademies.org/27919

c. Work with jurisdictional partners to coordinate and integrate with local adaptation planning and efforts. Avoid siloed, uncoordinated efforts, which may end up being more costly and maladaptive.
d. Consider financial and zoning controls (in partnership with regional authorities) to regulate or influence land use patterns. Examples of controls include conservation easements, special assessments, zoning restrictions, buyouts and transfer of development rights programs.[29]

3. System route transit mode and node

3.1 General

1. **Avoidance.** Avoid siting of alignments and new critical infrastructure in (current and future) high-risk hazard-prone areas. For example, avoid siting in floodplains or landslide zones.[30]
2. **Relocation.** When undertaking major upgrade or rehabilitation of existing infrastructure in identified high-risk zones, and where feasible, relocate infrastructure and facilities away from hazard-prone areas.[31] This is likely to require extensive effort with adjacent jurisdictions and landowners.
3. **Alternative routes and modes.** Plan for alternative routes and modes for rerouting to allow for continuity of services (see Section 6.1 for more detail on emergency response).
4. **Grid independence.** Reduce reliance on the local electrical grid. Assess the potential for on-site renewable energy generation, energy storage (i.e., batteries), and microgrids at facilities or stations to provide more reliable, decentralized grid-independent renewable energy.

3.2 Sea level rise

3.2.1 Adaptation planning

1. If alignments or critical infrastructure must be sited in zones vulnerable to sea level rise, plan for adaptation at appropriate time horizons.
2. Evaluate for spacing availability to plan for barriers or other hardening measures.

3.2.2 Shoreline adaptation

Shoreline adaptations[32,33] are most likely achieved through regional partnerships, as transit operators would not likely have the full jurisdiction to implement them. Shoreline adaptations can be conventional (gray infrastructure) or nature-based, though nature-based solutions are preferred for their ecological co-benefits.

3.2.2.1 Nature-based solutions

1. **Nearshore reefs.** Nearshore reefs dissipate wave energy, reducing coastal flood risk. Nearshore reefs also create a natural habitat for aquatic plants and animals.
2. **Submerged aquatic vegetation.** SAV refers to underwater flowering plants. SAV can contribute to trapping sediment and slowing shoreline erosion.

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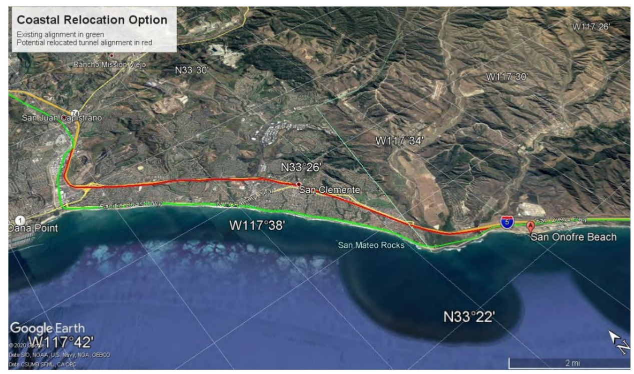
29. San Francisco Estuary Institute, “Adaptation Atlas,” Version 1.0, pages 104–112, April 2019. https://www.sfei.org/documents/adaptationatlas
30. Federal Transit Administration, “Flooded Bus Barns and Buckled Rails: Public Transportation and Climate Change Adaptation,” FTA Report No. 001, August 2011, page 65. https://www.transit.dot.gov/sites/fta.dot.gov/files/FTA_0001_-_Flooded_Bus_Barns_and_Buckled_Rails.pdf
31. ASTM E3032, Article 6.5.4.1, 6.5.7.2
32. San Francisco Estuary Institute, “Adaptation Atlas,” Version 1.0, April 2019. https://www.sfei.org/documents/adaptationatlas
33. ASTM E3032, Article 6.5.7.3

Case Study: OCTA Evaluates Coastal Rail Line Relocation in Response to Coastal Hazards

The Orange County Transportation Authority, the transportation planning commission of Orange County, completed a risk and vulnerability study in early 2021, evaluating the Orange County rail corridor, a 25-mile segment of rail in Southern California.[34,35] The rail corridor is at risk for existing and future climate hazards, including mudslides, slope erosion, flooding and sea level rise. In particular, a portion of the segment is along the California coast, which makes sea level rise a critical issue.

In addition to near- and midterm adaptations, the study identified and evaluated relocating the alignment inland as a potential long-term option to address coastal hazards. The study found that relocating would provide the most benefits by eliminating rail's exposure to coastal hazards. However, it would also be the costliest, estimated at $5.3 billion. The study determined the benefit-cost ratio for relocation to be far below 1. However, as sea level rise gets higher and more beach erodes, the benefits and costs of relocation could become more favorable. In line with the California Coastal Commission's recommendations, OCTA will undertake a subsequent study to further explore long-term potential solutions, including relocation.



Left: Metrolink on rail corridor. Right: Existing alignment (green) and potential relocation (red).

3. **Mudflat augmentation.** Direct or indirect placement of fine sediments to increase mudflat elevation relative to the tides can help protect adjacent marshes or other shoreline types.
4. **Beaches.** Beaches can be created to attenuate waves. Preference is for coarse gravel or cobble beaches that can dissipate wave energy over shorter distances.
5. **Tidal marsh.** Protecting, maintaining and restoring tidal marshes and associated tidal flats is critical for sustaining their flood control benefits. Tidal marshes mitigate flood risk from storm surges, waves and tidal currents through a combination of shoaling and friction effects.
6. **Polder management.** Polders refer to low-lying areas of land that would normally be inundated by regular tides if they were not protected by dikes. Managing existing polders includes maintaining dikes, water control structures and pumps.
7. **Ecotone levees.** Ecotone levees (also referred to as living levees) are gentle slopes or ramps that provide flood protection and habitat for species. Ecotone levees are characteristically flatter than normal levees, with length-to-height ratios of 20:1 or more.

34. Orange County Transportation Authority, "OCTA Rail Defense Against Climate Change Plan," Agreement No. C-8-2072, Final Report, January 2021. https://www.octa.net/pdf/OCTA_RailDefAgainstCC_FinalReport_wAppendix.pdf?n=202103
35. Orange County Transportation Authority, Coastal Rail Planning Framework, File 23-4801, February 2023. https://octa.legistar.com/LegislationDetail.aspx?ID=6035693&GUID=6FA94472-09B8-4C55-9943-7FD9199A2E6C&Options=&Search=

8. **Migration space preparation.** Migration space preparation refers to identifying natural wetland-upland transition zones to be protected for marshes. This allows existing marshes to migrate landward as sea level rises and preserve marsh functions. Expand setbacks to allow for migration of seawater.[36]
9. **Creek-to-bayland reconnection.** Reconnection refers to connecting through levee breaching or removal, which would improve sediment, nutrient and freshwater delivery to bayland and support flood risk management. Often creeks are hydrologically disconnected from floodplains and baylands due to water supply, flood control and development.

3.2.2.2 Conventional solutions

1. **Super levees.** Super levees are extremely tall (up to 9 m) and wide (up to 300 m) levees.
2. **Elevate land.** Elevating land is most suitable for undeveloped or minimally developed areas and would require a significant amount of fill.
3. **Floodwalls.** Floodwalls can be permanent or temporary. They may be more suitable than levees in urban locations where space is limited. Floodwalls are typically constructed no more than 1 m above grade. Floodwalls are not designed to manage waves or strong erosive forces. Where groundwater rise is an issue, floodwalls may not eliminate flooding.[37]
4. **Seawalls.** Seawalls are large stone, rock or concrete structures and designed to withstand large storms. Seawalls are designed to protect from overtopping and wave run-ups.
5. **Bulkheads.** Bulkheads are vertical retaining structures built to stabilize existing shoreline and limit shoreline erosion. Bulkheads are most suitable for sites with already hardened shorelines, to improve waterfront access and maritime use.
6. **Revetments and riprap.** Revetments are hardened structures made of concrete, rocks, wood or other materials to stabilize waterways against waves and erosion. Riprap is made of rock or concrete rubble and provides the same function as a revetment.
7. **Levees and dikes.** Levees and dikes are earthen embankments. Levees are best suited for low-lying areas that need protection from occasional surges, storm-related flooding or extreme tides. They are not well-suited for areas of high wave action.

3.2.3 Managed retreat or relocation

Recognize that sea levels will continue to rise in the foreseeable future. Proactively move structures and infrastructure out of inundation zones into inland areas. Managed retreat is a complex regional adaptation measure and must be addressed with the existing community and local and regional policymakers. Refer to Georgetown Climate Center's Managed Retreat Toolkit for more information.[38]

36. ibid., Article 6.5.4.2
37. San Francisco Estuary Institute, Shallow Groundwater Response to Sea Level Rise, Version 2, 2022. https://www.sfei.org/documents/shallow-groundwater-response-sea-level-rise-alameda-marin-san-francisco-and-san-mateo
38. Georgetown Climate Center, Managed Retreat Toolkit. https://www.georgetownclimate.org/adaptation/toolkits/managed-retreat-toolkit/introduction.html?chapter

SWEL vs. TWL

There are many approaches and terms associated with characterizing sea level rise, including the stillwater elevation level (SWEL) and total water level (TWL). The distinction between SWEL and TWL is important to note, and designers should select based on project goals.[39]

Stillwater Elevation Level (SWEL)

What it is: SWEL includes the astronomical tide, storm surge and tsunamis over the period of observation. It represents a static water surface elevation that persists for a prolonged period (several minutes to hours at a time). SWEL excludes wave run-up.

When to use it: Use SWEL as a design basis when the goal is to prevent inundation but allow for periodic overtopping from wave action.

Total Water Level (TWL)

What it is: TWL includes the superposition of wind waves, ocean swell and wave run-up at any given SWEL. The TWL represents a dynamic water level that may occur for only a few seconds at a time, albeit repeatedly over the period of a storm. It is the highest elevation reached by the water however short-lived it is.

When to use it: Use TWL as a design basis when the goal is to prevent any overtopping.

The distinction between SWEL and TWL is especially important to note along coastal areas, because a shoreline exceeded by the SWEL constitutes an inundation or large-scale flooding scenario, whereas embankments exceeded by TWL elevation constitute an overtopping scenario that could lead to short-term flooding if the storm duration is prolonged.[40]

3.3 Flooding

3.3.1 Avoidance[41]

Avoid siting critical infrastructure and alignments in floodplains (e.g., 100- and 500-year flood zones), understanding that these may change due to climate change impacting future rainfall locally, as well as high in the watershed. Utilize FEMA Flood Insurance Rate Maps (FIRMs) and consult local flood management districts or authorities on floodplains.

3.3.2 Minimize low points

Design for horizontal track wherever possible and locate pump sites at any low points.

3.3.3 Stormwater management planning[42]

1. Conduct a stormwater drainage study to understand problem areas and identify culverts and retention areas that are undersized to accommodate future climate conditions.
2. Develop a stormwater drainage and grading plan to address current and anticipated future deficiencies.
3. For existing/planned rail alignments situated or crossing over waterways, increase culvert capacity to accommodate more extreme rainfall events.[43]

39. Sea Level Risk Assessment SF Downtown Ferry Terminal Expansion, March 2016, page 4
40. ibid.
41. ASTM E3032, Article 6.5.7.3
42. Federal Emergency Management Agency, "Mitigation Ideas: A Resource for Reducing Risk to Natural Hazards," F-5, page 24, January 2013. www.fema.gov/sites/default/files/2020-06/fema-mitigation-ideas_02-13-2013.pdf
43. Federal Highway Administration, TechBrief, "Climate Change Adaptation for Pavements," FHWA-HIF-15-015, August 2015. https://www.fhwa.dot.gov/pavement/sustainability/hif15015.pdf

3.4 Wildfire

3.4.1 Avoidance

Avoid siting alignments and critical infrastructure in wildland areas, including the wildland urban interface, which contains large amounts of fuel source.

3.4.2 Defensible space

Plan for firebreaks, defensible space or setbacks between critical infrastructure and surrounding area.[44]

3.4.3 Vegetation management

Plan for vegetation management in the right-of-way in high wildfire exposure areas. Depending on the location and vegetation, this can mean either complete clearing of vegetation or appropriate management for wildfire resilience. Consider use of fire-resistant (and drought-resistant) vegetation, and select/plant vegetation that will do well in future climate conditions.

3.5 Extreme heat

3.5.1 Tangent tracks

Prioritize alignments that minimize curves in the track. Curved tracks have reduced resistance to additional bending and are subject to lateral forces from rail operations.

3.5.2 Solar gain

Evaluate site planning and building massing with regard to solar gain.

3.5.3 Optimize site layout

Segregate heat-sensitive equipment (e.g., electronic computer control systems) from heat generating equipment (e.g., transformers) where permissible.

3.6 Extreme cold

Refer to Section 3.1.

4. Infrastructure and facilities

4.1 General

4.1.1 Redundancy

Design for system redundancy to account for climate hazard disruption.[45] Redundant systems, equipment and components ensure that critical operations are not interrupted. Examples of redundancy include the following:

1. **Uninterrupted power for critical loads.** Implement backup power or uninterrupted power supplies (UPS) for those prioritized loads. Employ batteries and electrical generators. At a minimum, backup power should power critical systems including fueling systems, radio communications, computerized scheduling and dispatching systems, lights, electrical outlets, and shop equipment.
2. **Backup operation centers, including backup communications.**
3. **Alternative egress routes.**

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44. Federal Emergency Management Agency, "Mitigation Ideas: A Resource for Reducing Risk to Natural Hazards," WF-7, page 72, January 2013. www.fema.gov/sites/default/files/2020-06/fema-mitigation-ideas_02-13-2013.pdf
45. Amtrak, "Extreme Heat Preparations Factsheet," July 2016. http://media.amtrak.com/wp-content/uploads/2015/10/Extreme-heat-fact-sheet-7_22_16-1.pdf

4. **Emergency lighting.**
5. **Backup power feed cables, transfer switches.**
6. **Water tanks or wells for water outages.**[46]
7. **Sewage service backup (i.e., porta potties).**

4.1.2 Separated backups

When feasible, locate primary and backup assets in separate locations to avoid failure of both during a hazard event.

4.1.3 Early warning detection and remote monitoring systems

Early detection and monitoring systems can help early response to hazards. Sensor indicators may include temperature, humidity, barometric pressure, solar radiation, precipitation, wind speed, water level, seismic activity. Examples of systems include the following:

1. Mini weather and temperature stations[47]
2. Rail temperature probes[48]
3. Remote water level sensors[49]
4. Smoke alarms
5. CCTVs
6. Services that provide flood, storm, wind forecasting and alerts

4.1.4 Design and manage power supply and distribution reliability and redundance

Provide surge protection.

4.2 Sea level rise

4.2.1 Elevate assets

1. Elevate critical infrastructure and openings (e.g., entrances, vent grates)[50] above the flood stage.[51] Refer to American Society of Civil Engineers (ASCE) 24 for Flood Resistant Design and Construction standards. Critical facilities should be built at least 1 foot above the 500-year flood stage.[52]
2. Elevate electrical and mechanical equipment.
3. Add or increase freeboard (feet above base elevation).[53]

46. Federal Emergency Management Agency, "Mitigation Ideas: A Resource for Reducing Risk to Natural Hazards," MU-13, page 81, January 2013. www.fema.gov/sites/default/files/2020-06/fema-mitigation-ideas_02-13-2013.pdf
47. Network Rail, How We Prevent Tracks from Getting Too Hot, https://www.networkrail.co.uk/stories/how-we-prevent-tracks-from-getting-too-hot/
48. Amtrak, "Extreme Heat Preparations Factsheet," July 2016. http://media.amtrak.com/wp-content/uploads/2015/10/Extreme-heat-fact-sheet-7_22_16-1.pdf
49. City of Savannah, Sea Level Sensors. https://www.savannahga.gov/2937/Sea-Level-Sensors
50. Federal Transit Administration, "Flooded Bus Barns and Buckled Rails: Public Transportation and Climate Change Adaptation," FTA Report No. 001, August 2011, page 65. https://www.transit.dot.gov/sites/fta.dot.gov/files/FTA_0001_-_Flooded_Bus_Barns_and_Buckled_Rails.pdf
51. Federal Emergency Management Agency, "Mitigation Ideas: A Resource for Reducing Risk to Natural Hazards," page 5-28, 5-30, January 2013. www.fema.gov/sites/default/files/2020-06/fema-mitigation-ideas_02-13-2013.pdf
52. ibid., F-18, page 29
53. ibid., F-4, page 23

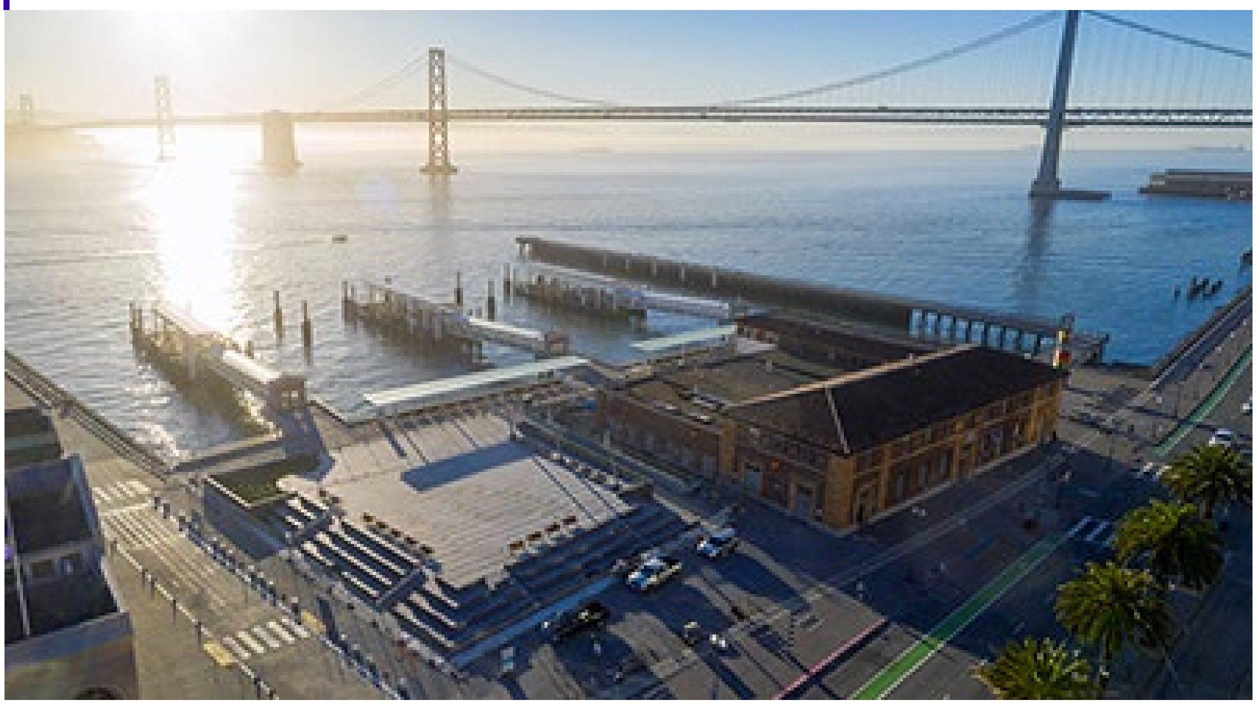
4. Use dry floodproofing.[54,55] See also ASCE 24, Chapter 6.
    a. Use continuous impermeable walls. Seal building's exterior with waterproof membranes.
    b. If the entire building cannot or does not need to be floodproofed, then floodproof critical rooms.
    c. Seal openings such as doors, windows and utility penetrations.
    d. Use flood shields for openings in exterior walls such as entrances.
    e. Install check valves, backflow prevention valves for drainage outfalls and interior drains.
    f. Include pump stations or sump pumps.
    g. Use permanent floodwalls that create a barrier surrounding a building. Floodwalls are permanent and freestanding structures from the building.[56]

54. Federal Emergency Management Agency, FEMA P-2181, "Hurricane and Flood Mitigation Handbook for Public Facilities," page 5-27, March 2022. https://www.fema.gov/sites/default/files/documents/fema_p-2181-fact-sheet-5-2-transit-facilities.pdf
55. Federal Emergency Management Agency, "Floodproofing Non-Residential Buildings," P-936, Chapter 3, July 2013. https://wbdg.org/FFC/DHS/femap936.pdf
56. ibid., page 4-1

Case Study: Downtown San Francisco Ferry Terminal Elevated to Address Sea Level Rise

In 2020, to address rising sea level, the Water Emergency Transportation Authority (WETA), a ferry service operator in the San Francisco Bay Area, elevated its San Francisco Ferry Terminal by nearly 5 ft.[57] The project is designed to withstand the projected 50-year rise in sea level and features an elevated 13,000 sq. ft public plaza that is also resilient to rising sea level. The cross-section for the project design shows how tidal elevations and flood levels would increase over time relative to the upper range of sea level rise estimates. The design addresses the anticipated water elevations across the project's design life (year 2068). The deck elevation is designed to be above not only the SWEL, but also the TWL.

The terminal is also designed intentionally to allow for additional adaptation to address water elevations beyond the project design life. The design can support construction of an additional low wall along the perimeter of the ferry terminal that could add an additional 1.5 ft of protection (up to 17 ft total crest elevation). WETA can implement the adaptation when future conditions require increasing protection.



4.2.2 Wet floodproofing

Wet floodproofing[58] differs from dry floodproofing in that it modifies a building to allow floodwater to enter it. See also ASCE 24, Chapter 6.

1. Flood-proof doors for entrances and flood-proof enclosures or walls.
2. Use noncorrosive materials for flood-exposed environments. Seawater has a high concentration of salts that make it corrosive. For example, composite materials such as cross-linked polypropylene provide improved durability over stainless steel. Alternatively, consider the use of anti-corrosion coatings.

57. Water Emergency Transportation Authority, Press Release: Mayor London Breed, Senator Scott Wiener, Assemblymember David Chiu, WETA and Port of San Francisco Open Expanded Downtown San Francisco Ferry Terminal, August 2020. https://sanfranciscobayferry.com/downtown-san-francisco-ferry-terminal-press-release
58. ibid., page 4-14

4.2.3 Groundwater

1. Waterproof underground structures to resist hydrostatic pressures and negative groundwater infiltration.
2. Waterproofing systems may include water stops, gaskets, membrane waterproofing, liquid-applied sealants.[59]

4.2.4 Underground assets

1. Use vent covers or elevate street-level vent grates and utility hole openings.[60] Vent covers can be manual or automatic.
2. Use inflatable plugs for subway tunnels.[61]

4.2.5 Conduits and openings

Seal (waterproof) conduits and openings.[62]

4.2.6 Erosion

Enhance facility foundations, embankments, bridge abutments and ballast shoulders to protect from erosion and stabilize slope.

4.2.7 Pump capacity

Add or enhance pump capacity (such as sump pumps) at locations to remove floodwater.[63]

4.3 Flooding

Refer also to Section 4.2.

4.3.1 Storm drainage systems

Increase design size and capacity of storm water drainage to prevent overflow.[64,65] Drainage elements include detention and retention basins, relief drains, spillways, ditches, culverts, bridge clearances, dike setbacks, flood gates, and pumps.

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59. Federal Transit Administration, "Research Report and Findings: Specifications and Guidelines for Rail Tunnel Design, Construction, Maintenance and Rehabilitation," FTA Report No. 0231, page 25, October 2022. https://www.transit.dot.gov/sites/fta.dot.gov/files/2022-10/FTA-Report-No-0231.pdf
60. Federal Emergency Management Agency, FEMA P-2181, "Hurricane and Flood Mitigation Handbook for Public Facilities," page 5-24, March 2022. https://www.fema.gov/sites/default/files/documents/fema_p-2181-fact-sheet-5-2-transit-facilities.pdf
61. ibid., page 5-23
62. ibid., page 5-28
63. Federal Transit Administration, "Flooded Bus Barns and Buckled Rails: Public Transportation and Climate Change Adaptation," FTA Report No. 001, August 2011, page 65. https://www.transit.dot.gov/sites/fta.dot.gov/files/FTA_0001_-_Flooded_Bus_Barns_and_Buckled_Rails.pdf
64. Federal Emergency Management Agency, FEMA P-2181, "Hurricane and Flood Mitigation Handbook for Public Facilities," page 5-31, March 2022. https://www.fema.gov/sites/default/files/documents/fema_p-2181-fact-sheet-5-2-transit-facilities.pdf
65. Federal Emergency Management Agency, "Mitigation Ideas: A Resource for Reducing Risk to Natural Hazards," F-13, page 27, January 2013. www.fema.gov/sites/default/files/2020-06/fema-mitigation-ideas_02-13-2013.pdf

4.3.2 Low impact development (LID)

LIDs, also referred to as green infrastructure, mitigate storm water runoff and localized flooding.[66,67,68] LID is a stormwater best management practice that mimics natural hydrologic conditions and results in greater infiltration and evapotranspiration than conventional development. Examples of LID include rain gardens, retention basins, bioswales, permeable pavement and vegetated roofs. These may be most appropriate for station or facilities parking lots. LID can also help reduce local extreme heat effects; see Section 4.5.

4.3.3 Elevate assets

Elevate electrical components of signal/communications systems along flood-prone track that are sensitive to water damage, either by elevating the concrete pads or attaching the equipment on poles above the design flood elevation. If elevating is not feasible (i.e., the equipment must be at track level), waterproof the equipment itself. For the track, the bottom of the wheel flange must remain above the water level for automated operations.

4.3.4 Roadways or pavements

Specify materials that:

1. Increase surface friction, focusing on surface texture and maintaining adequate skid resistance.[69]
2. Increase resistance to rutting.[70]
3. Improve visibility and pavement marking demarcation.[71]
4. Reduce moisture susceptibility of unbound base/subgrade materials through stabilization.[72]
5. Ensure resistance to moisture susceptibility of asphalt mixes.[73]

4.3.5 Design for temporary measures

Include space allowances for temporary flood protection measures (e.g., sandbags, water-filled bladders, and shield structures). Include space to deploy the measure and space to store when not in use.

4.4 Wildfire

4.4.1 Firebreaks

Provide firebreaks or barriers along the right-of-way to prevent the spread of wildfires to and from the tracks.

4.4.2 Noncombustible materials

Select noncombustible (ignition-resistant) construction materials. Noncombustible materials include metals (steel, aluminum, copper), masonry, fiber cement, and concrete.

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66. Federal Transit Administration, “Flooded Bus Barns and Buckled Rails: Public Transportation and Climate Change Adaptation,” FTA Report No. 001, August 2011, page 69. https://www.transit.dot.gov/sites/fta.dot.gov/files/FTA_0001_-_Flooded_Bus_Barns_and_Buckled_Rails.pdf
67. Federal Emergency Management Agency, “Mitigation Ideas: A Resource for Reducing Risk to Natural Hazards,” F-6, page 24, January 2013. www.fema.gov/sites/default/files/2020-06/fema-mitigation-ideas_02-13-2013.pdf
68. San Francisco Estuary Institute, “Adaptation Atlas,” Version 1.0, page 94, April 2019. https://www.sfei.org/documents/adaptationatlas
69. Federal Highway Administration, TechBrief, “Climate Change Adaptation for Pavements,” FHWA-HIF-15-015, August 2015. https://www.fhwa.dot.gov/pavement/sustainability/hif15015.pdf
70. ibid.
71. ibid.
72. ibid.
73. ibid.

4.4.3 Fire-retardant materials

Where wooden elements cannot be avoided, use fire-retardant coating (e.g., cementitious fireproofing or intumescent), or use fire-retardant treated wood.[74,75]

4.4.4 Fire protection

Employ fire detection and suppression systems (e.g., fire extinguishers, automatic sprinkler systems, alarm systems).

4.4.5 Air filtration

Add high-performance air filtration systems to indoor stations/facilities to manage poor air quality from wildfire smoke.

4.4.6 Roofs[76]

1. Select for Class A rated roof assemblies (using test method ASTM E108).
2. Install noncombustible gutters.
3. Install bird stops at eaves to prevent debris accumulation.
4. Install metal flashing and fire-resistant underlayment in areas that may accumulate debris.
5. Limit size of roof overhangs and eave openings that can trap embers and hot gases.
6. Construct boxed eave assembly.

4.4.7 Exterior walls[77]

1. Install fire-resistant or noncombustible cladding.
2. Install siding with less penetrable joints to hinder passage of embers.
3. Install Type X gypsum board compliant to ASTM C1177 between studs and coverings.
4. Eliminate gaps in wall penetrations.

4.4.8 Vents[78]

1. Install noncombustible screens with small openings.
2. Install noncombustible louvers and adjustable slats.

4.4.9 Exterior doors[79]

1. Use fire-rated door assemblies compliant to UL 10C. Fire rating should not be less than 20 minutes.
2. Install noncombustible insulated sectional and rolling doors and frames. Insulation protects against radiant heat. Seal gaps between garage door and the pavement/framing with weatherstripping.

4.4.10 Exterior structures (e.g., ramps, decks)[80]

1. Install flashing or screen between building and attached exterior structure.
2. Cover underside of joists with fire-resistant panels.
3. Enclose underside of structure if less than 6 in. above grade with screens.

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74. Federal Emergency Management Agency, "Wildfire Hazard Mitigation Handbook for Public Facilities," P-754, October 2008. https://wbdg.org/FFC/DHS/femap754.pdf
75. ASTM E3032-15 Standard Guide for Climate Resiliency Planning and Strategy, Article 6.4.3
76. Federal Emergency Management Agency, "Wildfire Hazard Mitigation Handbook for Public Facilities," P-754, Section I.A, October 2008. https://wbdg.org/FFC/DHS/femap754.pdf
77. ibid., Section I.B
78. ibid., Section I.C
79. ibid., Section I.D
80. ibid., Section I.E

4. Enclose underside of structure with skirting with 1 hr fire rating.
5. Construct noncombustible patio around footprint of exterior structure.

4.4.11 Windows and skylights[81]

1. Install fire-resistant glazed window or skylight panels.
2. Install fire-resistant framing.
3. Install permanent or temporary fire-resistant shutters.
4. Install fire-resistant screens.

4.4.12 Foundations[82]

1. Enclose crawl space with fire-resistant cripple wall.
2. For open foundations, protect the underside of exposed floor framing with fire-resistant panels.
3. Install fire-resistant skirting.

4.4.13 Utilities[83]

1. Use fire-rated enclosures for outdoor equipment.
2. Use flashing to shield exposed electrical components.
3. Place utilities (e.g., power lines, catenary wires) underground, except in flood prone areas; see Section 4.2.

4.5 Extreme heat

4.5.1 Rail tracks

1. Design track system to handle high operating temperatures to prevent thermal misalignment or track buckling (sun-kinking).
2. Set and maintain high "rail-neutral temperatures."[84]
3. Add expansion joints to rails in heat-prone areas.[85]
4. Replace wood ties with concrete ties, which are heavier and more resistant to movement, reducing chances of thermal misalignment.
5. Re-tamp ballast to increase ballast density, increasing lateral resistance and reducing chances of thermal misalignment. Disturbed track is more prone to movement until compaction is reestablished. Reduce and monitor speeds until compaction is established.
6. Increase the width of the ballast shoulder, which increases lateral resistance and reduces the chances of thermal misalignment.
7. Reduce tie spacing, which provides additional weight to the track structure and increases lateral resistance, reducing chances of thermal misalignment.
8. Consider installing sensors to actively monitor conditions with active warnings to indicate potential misalignment or track defects.

81. ibid., Section I.F
82. ibid., Section I.G
83. ibid., Section II
84. Federal Transit Administration, "Flooded Bus Barns and Buckled Rails: Public Transportation and Climate Change Adaptation," FTA Report No. 001, August 2011, page 73. https://www.transit.dot.gov/sites/fta.dot.gov/files/FTA_0001_-_Flooded_Bus_Barns_and_Buckled_Rails.pdf
85. ibid., page 75

9. Paint webs of the rail with UV-resistant white coating to increase albedo and reduce thermal stress. Rail painted white can be cooler by 5 to 10 °C.[86]

Case Study: Southern California Regional Rail Authority Track Adaptations to Extreme Heat

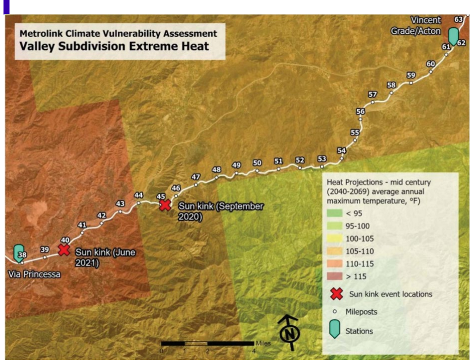
In 2022, the Southern California Regional Rail Authority (SCRRA), which owns and operates the Metrolink rail system, prepared a systemwide Climate Vulnerability Assessment and Adaptation Plan.[87] As part of the plan, SCRRA conducted a study on a 23.6-mile rail segment that experienced a number of thermal misalignment events (sun kinks) and identified physical interventions to reduce the risk of future thermal misalignment.

The assessment found increased vulnerability of thermal misalignment in track sections that 1) are curved, 2) have weak track beds or 3) have ties in poor condition. Curved sections of track have reduced resistance to additional bending and are subject to significant lateral forces from rail operations. A weak track bed structure could affect lateral resistance to movement depending on the nature of the weakness. Ties in poor condition (failed or marginal) reduce the effectiveness of rail fasteners to prevent displacement of the rail (loose tie plates reduce the effectiveness of rail anchors).

Adaptation recommendations (which are also applicable beyond the study area) include the following:

- Replace failed/marginal wood ties, focusing first on the sections identified as having high sensitivity to thermal misalignment, and then the sections identified as having medium-high sensitivity.
- Increase ballast shoulder width for high sensitivity stretches, from 9 in. (as currently required for wood ties) to 12 in. (as currently required for concrete ties). Prioritize stretches of track where substandard track bed has been identified based on ballast scans. These sections also may need to be re-tamped.
- Selectively upgrade to concrete ties. Although replacing all wood ties in the study area with concrete ties may not be feasible, a subset of stretches should be prioritized, focusing on high-sensitivity stretches that are between or adjacent to existing stretches of concrete ties.
- Consider reducing tie spacing for stretches with wood ties on tight curves.

At the time of this writing, SCRRA is replacing wood ties with concrete ties and is seeking grants to accelerate implementation of adaptation strategies.



Crosstie Type	Alignment	Sun kink Sensitivity	Adaptation Strategies (in order of priority)
Wood ties with spikes and anchors	Curved (gentle and tight)	High	Replace failed and marginal ties with elastic fasteners Increase ballast shoulder width Reduce tie spacing Replace with concrete ties
	Tangent	Medium-High	Replace failed and marginal ties with elastic fasteners Increase ballast shoulder width Replace with concrete ties
Wood ties with Pandrol plates	Curved (gentle and tight)	Medium-High	Replace failed and marginal ties with elastic fasteners Increase ballast shoulder width Reduce tie spacing
	Tangent	Medium	Replace failed and marginal ties with elastic fasteners Increase ballast shoulder width
Concrete	Curved (gentle and tight)	Low	Not necessary
	Tangent	Low	Not necessary

Left: Midcentury heat projections for the 23.6-mile rail segment. Right: Prioritized adaptations strategies by crosstie type and alignment type.

4.5.2 Human heat stress

1. Add station amenities to help riders and staff cope with extreme heat.
2. Install air conditioning or cooling and ventilation systems in enclosed spaces.[88]

86. Network Rail, How We Prevent Tracks from Getting Too Hot, https://www.networkrail.co.uk/stories/how-we-prevent-tracks-from-getting-too-hot/
87. Metrolink, "Climate Vulnerability Assessment and Adaptation Plan, A Roadmap to Implementation," February 2022. https://metrolinktrains.com/globalassets/about/agency/sustainability/metrolink_cva_adaptplan_final_220330.pdf
88. Federal Transit Administration, "Flooded Bus Barns and Buckled Rails: Public Transportation and Climate Change Adaptation," FTA Report No. 001, August 2011, page 75. https://www.transit.dot.gov/sites/fta.dot.gov/files/FTA_0001_-_Flooded_Bus_Barns_and_Buckled_Rails.pdf

3. Provide shade (e.g., canopies, trees, bus shelters) to mitigate heat exhaustion. Consider shading in parking lots and plazas. Use light colored or reflective shelter and canopy materials.
    a. If glass must be used, use fritted glass where possible to reduce glare.
    b. Orient station seating and shelter to maximize shade during peak sunlight hours.
4. Install misting in bus shelters and on station platforms.[89]
5. Insulate conditioned spaces. Use weather strips on doors and sills to keep cool air in.[90]
6. Provide hydration facilities at stations.

4.5.3 Building energy audit, retro-commissioning

1. Conduct energy audit of existing buildings including evaluation of building envelope to ensure temperature control systems are performing optimally and eliminate pathways for heating and cooling losses. Refer to ASHRAE 211 for standards on energy audits. Retro-commission to enhance building energy performance.

4.5.4 Outdoor equipment

Provide shade canopies or covers (sun shields) for outdoor equipment.

4.5.5 Urban heat island effect

1. Provide landscaping at shelters and pedestrian corridors.[91] Vegetation can create microclimates with temperatures that are cooler than the surrounding area.
2. Use high albedo materials to maximize reflectivity and minimize absorptivity for pavements and building roofs.[92]
3. Refer also to LEED Sustainable Sites Credit: Heat Island Reduction.[93]

4.5.6 Roadways and pavement

1. Design pavement to handle high operating temperatures to prevent asphalt buckling.
2. Flexible pavement:[94]
    a. Utilize or increase utilization of binder polymerization and/or improved aggregate structure in asphalt mixes.
    b. Increase use of rut-resistant designs including thin, rut-resistant surfaces.
    c. Implement binders that age more slowly or expand use of asphalt pavement preservation techniques to address binder aging.
3. Rigid pavement:[95]
    a. Consider the concrete coefficient of thermal expansion and drying shrinkage.

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89. City of Phoenix, Misted Bus Shelter Installed Near Uptown Phoenix, August 2018. https://www.phoenix.gov/newsroom/public-transit/367
90. Federal Emergency Management Agency, "Are You Ready? An In-Depth Guide to Citizen Preparedness," page 87, September 2020. https://www.fema.gov/pdf/areyouready/natural_hazards_2.pdf
91. Federal Transit Administration, "Flooded Bus Barns and Buckled Rails: Public Transportation and Climate Change Adaptation," FTA Report No. 001, August 2011, page 79. https://www.transit.dot.gov/sites/fta.dot.gov/files/FTA_0001_-_Flooded_Bus_Barns_and_Buckled_Rails.pdf
92. ibid., page 76
93. U.S. Green Building Council, LEED V4.1, "Building Design and Construction," pages 64–66, July 2023. https://build.usgbc.org/bd+c_guide
94. Federal Highway Administration, TechBrief, "Climate Change Adaptation for Pavements," FHWA-HIF-15-015, August 2015. https://www.fhwa.dot.gov/pavement/sustainability/hif15015.pdf
95. ibid.

   b. Incorporate design elements to reduce damage from thermal effects including shorter joint spacing, thicker slabs, less rigid support and enhanced load transfer.
   c. Use shorter joint spacing in new design.
   d. Keep joints clean or install expansion joints in existing pavement.

4.5.7 Catenary lines

1. Employ catenary-less system.[96]
2. Use auto-tensioning or constant tension to prevent cable sag. Weights or hydraulic tensioners can be installed at specific points across the line to maintain tension.[97]

4.5.8 Equipment and systems

Procure equipment and system with a higher range of maximum operating temperature.

4.6 Extreme cold

4.6.1 Buildings and structures

1. Retrofit structures to handle snow loads and prevent collapse.[98]
2. Add building insulation to walls and attics.[99]
3. Avoid flat roofs, which can result in a buildup of heavy snow loads.[100]
4. Install wind screens at bus shelters.

4.6.2 Building energy audit, retro-commissioning

1. Conduct energy audit of existing buildings including evaluation of building envelope to ensure temperature control systems are performing optimally and eliminate pathways for heating and cooling losses. Refer to ASHRAE 211 for standards on energy audits. Retro-commission to enhance building energy performance.

4.6.3 Utilities

1. Protect power lines from winter storm events.[101]
   a. Bury power lines.[102]
   b. Use designed-failure mode that allows for power lines to fail in small sections rather than the complete system for faster restoration.
2. Install heat wires around water pipes to prevent the water from freezing.
3. Bury water supply pipes below ground frost line to prevent freezing and cold weather impacts.

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96. Mass Transit, "The Future is Here: Catenary-less Power for Light Rail," June 2011. https://www.masstransitmag.com/rail/article/10262406/the-future-is-here-catenaryless-power-for-light-rail
97. Railway Technology, Tension and Strain on Overheated Trains, October 2011. https://www.railway-technology.com/features/featuretension-and-strain-on-overheated-trains/
98. Federal Emergency Management Agency, "Mitigation Ideas: A Resource for Reducing Risk to Natural Hazards," WW-2, page 52, January 2013. www.fema.gov/sites/default/files/2020-06/fema-mitigation-ideas_02-13-2013.pdf
99. ibid., WW-2, page 52
100. ibid., WW-1, page 52
101. ibid., WW-3, page 52
102. Mass Transit, "The Future is Here: Catenary-less Power for Light Rail," June 2011. https://www.masstransitmag.com/rail/article/10262406/the-future-is-here-catenaryless-power-for-light-rail

4.6.4 Roads

1. Protect roadways:[103]
    a. Use snow fences or "living snow fences" such as a row of trees or shrubs to limit blowing and drifting of snow over roads.
    b. Install roadway heating technology to prevent snow or ice buildup.
2. Pavement materials:
    a. Flexible pavement.[104] Consider the thermal fatigue characteristics of asphalt binders.
    b. Rigid pavement.[105] Potential increase for de-icing may require concrete materials that are more resistant to freeze–thaw cycling and de-icer applications, particularly as related to joints.

4.6.5 Rail

Install contact rail heat systems and switch point heaters to prevent ice and snow on rails, and ensure that switch points remain movable.

5. Rolling stock and fleet

5.1 General

1. Ensure that emergency exits on vehicles are maintained.
2. Ensure that onboard communication systems are operational.

5.2 Sea level rise

See guidelines in Section 5.3.

5.3 Flooding

Test vehicles for watertightness.

5.4 Wildfire

Install advanced HVAC filters to enhance indoor air quality when operating in wildfires impacted areas; see Section 6.1.

5.5 Extreme heat

1. Design for high operating temperatures. In vehicle procurement, consider including operating temperatures that account for future climate scenarios in the performance specifications.
2. Use reflective and light-colored roof coating on transit vehicles to reduce solar heat gain.
3. Comply with transit operator's specified cooling capacity requirements.
4. An automated temperature control system can adjust to ambient temperatures, balancing riding comfort and energy efficiency. Internal and external temperature sensors provide signals for cooling when above 75 °F and heating when below 65 °F.

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103. Federal Emergency Management Agency, "Mitigation Ideas: A Resource for Reducing Risk to Natural Hazards," WW-4, page 52, January 2013. www.fema.gov/sites/default/files/2020-06/fema-mitigation-ideas_02-13-2013.pdf
104. Federal Highway Administration, TechBrief, "Climate Change Adaptation for Pavements," FHWA-HIF-15-015, August 2015. https://www.fhwa.dot.gov/pavement/sustainability/hif15015.pdf
105. ibid.

5.6 Extreme cold

1. For trolleys or rail vehicles with overhead wires, attach steel shoes (also known as ice cutters) to the collector heads of the first few coaches deployed for service to strip the ice from the overhead wires. Depending on the severity of ice accumulation and frequency of service, a transit operator may choose to equip ice-cutting equipment dispersed throughout its fleet.
2. Invest in a deicer truck for winter operations.
3. Explore possible solutions for thermal deicing of overhead wire.
4. Invest in fiberglass body cutaways to protect vehicles from damage during a hailstorm.
5. An automated temperature control system can adjust to ambient temperatures, balancing riding comfort and energy efficiency. Internal and external temperature sensors provide signals for cooling when above 75 °F and heating when below 65 °F.
6. Invest in floor heaters at bus entrance and exit doors to prevent ice buildup.
7. Invest in winter tires for articulated buses to help with traction.
8. Invest in heated headlamps.

6. Operation and maintenance

6.1 General

6.1.1 Inspections

Regularly maintain and inspect facilities and response measures (e.g., sump pumps, barriers, deployable measures, drain systems, and culverts) to ensure functionality. Adjust frequency of inspection and maintenance regimens according to risk level.

6.1.2 Operations and maintenance

Update operations and maintenance (O&M) manuals to reflect adaptation-related procedures.

6.1.3 Supplies and equipment

Review, adjust and maintain supplies and equipment for emergency repairs, replacements and other responses (given likely increase in extreme events). This includes identifying alternative supply and equipment sources if current sources become unavailable.

1. In the event of power outages, portable generators may be deployed to keep critical systems running.[106] If power outages are known beforehand, power generators may be staged in advance.
2. Mobile water pumps may be used to remove floodwater.
3. Advanced HVAC filters may be used for rolling stock and buildings during wildfire events.

6.1.4 Emergency planning

Incorporate climate hazard scenarios in emergency planning (e.g., emergency plans and procedures, evacuation maps, service rerouting, warning communications, practice drills, disaster recovery procedures).

1. Train staff in disaster preparedness.[107]
2. Implement drills and exercise programs to test preparedness, including coordinated drills with local, regional, state and federal emergency response entities, as applicable.

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106. San Francisco Bay Area Rapid Transit District, BART Gears Up to Prevent Service Disruptions from Public Safety Power Shutoffs, August 2021. https://www.bart.gov/news/articles/2021/news20210817
107. Federal Transit Administration, "Emergency Relief Manual, Reference Manual for States, and Transit Agencies on Response and Recovery from Declared Disasters and FTA's Emergency Relief Program," Version 2.0, page 10, March 2023. https://www.transit.dot.gov/sites/fta.dot.gov/files/2023-03/FTA-Emergency-Relief-Manual-March-2023.pdf

3. Develop operational responses depending on level of alert.
4. Add detail to emergency procedures sufficient for execution.
5. Have plans for special needs populations.[108]
6. Review emergency response budget needs.
7. Include criteria for requesting "state of emergency" declaration.

6.1.5 Patron education and outreach

Provide education and outreach to patrons on disaster preparedness.[109] Education and outreach to patrons may include public awareness campaigns, in-station real-time digital displays, in-station announcements, online promos, station/vehicle ads, in-station staff, social media, app feeds, website, emails and letters.

6.1.6 Communications

1. Maintain evacuation and communication systems for climate hazard scenarios to keep patrons and staff informed on active emergencies.
2. Maintain redundant communication systems in the event of communication disruptions; see also Section 4.1.1.[110] Power outages may limit telephone communications.
3. Have backup copies of electronic files of communication protocols, contacts and other information.
4. Have chargers and extra batteries for radios and cell phones.

6.1.7 Operations Control Center

Establish a dedicated climate hazards desk in the Operations Control Center to enable centralized inventorying, dispatching, tracking and reporting of climate hazard incidents.[111] This can improve deployment of resources to high-priority areas; improve contractor oversight; improve documentation; improve utilization; and increase situation awareness, accountability and responsiveness. Refer also to Section 4 to ensure Operation Control Center facilities are resilient.

6.1.8 Recordkeeping

Develop recordkeeping policies and protocols for emergencies. Recordkeeping is essential during emergencies to document the uses and losses of assets and necessary for recovery funding.[112]

6.1.9 Weather watch

Monitor weather forecasts for hazardous events (e.g., storms, significant snowfall, heat waves) and participate in regional weather advisory and preparedness briefings with state/provincial, meteorological services, city and county emergency management teams.

6.1.10 Fare suspension

Consider fare suspension or a no-fare policy during emergencies or evacuations to facilitate vehicle boarding, eliminate money handling, and eliminate other security problems related to fare collection.[113]

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108. ibid., page 13
109. ibid., page 12
110. ibid., page 12
111. Massachusetts Bay Transportation Authority, MBTA Winter Operations, Winter Resiliency Overview, August 2015.
112. Federal Transit Administration, "Emergency Relief Manual, Reference Manual for States, and Transit Agencies on Response and Recovery from Declared Disasters and FTA's Emergency Relief Program," Version 2.0, page 10, March 2023. https://www.transit.dot.gov/sites/fta.dot.gov/files/2023-03/FTA-Emergency-Relief-Manual-March-2023.pdf
113. ibid., page 15

6.1.11 Reporting

Report hazardous conditions (e.g., accumulated ice or snow, water pooling) to supervisor.

6.1.12 Debriefs or after-action review

Conduct debriefs after a hazardous event is over. Review responses, plan effectiveness and lessons learned. Make corrective actions and ensure continuous improvement.

6.1.13 Manual mode

Switch from automated to manual train operations for essential emergency responses as needed.

6.2 Sea level rise

See Section 6.3.

6.3 Flooding

1. Improve flood risk assessment for emergency response.[114]
    a. Track high-water marks following flood events.
2. Develop and implement a maintenance plan for storm drainage systems and flood control structures.[115] Implement routinely prior to the wet season.
    a. Routinely remove sediment and debris from drains, downspouts, bracing under low-lying bridges, riverbank near aerial lines, culverts and other locations.
    b. Routinely inspect and repair drains.
    c. Inspect bridges for repairs and retrofits to prevent scouring.
3. In addition to safeguarding the power supply systems from water damage, provide protective measures for the transit vehicle body to waterproof critical components.
4. If operating a rail vehicle where the floodwater level is above its wheel flange bottom, follow instructions from the agency's control center, such as activating the manual operation system to drive the train. This would come with strict conditions, such as the following:
    a. Ensuring traction power is monitored to avoid electrical hazards.
    b. Having a contingency plan for rapid response in case of emergencies.
5. Reduce train speeds during heavy downpours and flash flooding conditions.
6. Deployable equipment:
    a. Employ the use of deployable flood mitigation supplies. Store and maintain flood mitigation supplies near flood-prone areas. Examples of flood mitigation supplies include sandbags,

114. Federal Emergency Management Agency, "Mitigation Ideas: A Resource for Reducing Risk to Natural Hazards," F-7, page 25, January 2013. www.fema.gov/sites/default/files/2020-06/fema-mitigation-ideas_02-13-2013.pdf
115. ibid., F-14, page 27

tarps or sheets, portable pumps, deployable temporary flood barriers.[116,117,118] Train staff in use of supplies.

b. For subway tunnels, consider the use of resilient tunnel plugs.[119]

> **Considerations in using deployable measures**
>
> **Ease of operation.** Staff must be trained in use of any deployable measure; they must have familiarity. Training and regular deployment drills are critical. Consider measures that can be deployable by staff with limited lifting capabilities.
>
> **Speed of deployment.** Consider how long it takes for a measure to be fully deployed, including mobilization and setup. Also consider how quickly the measure can be deconstructed and returned to normal operations.
>
> **Manual backups.** If a measure is an automated system, make sure that backup (manual) options are present and effective for operation in the event of failure of the automated capabilities.

6.4 Wildfire

1. Weed vegetation and remove debris that are potential fuel sources.[120] Maintain firebreaks and defensible spaces clear of overgrowth. Consider integrated vegetation management.[121]
2. Remove combustible debris that may accumulate on roofs or in gutters.
3. Review and update train operation protocol to address operation in wildfire impacted areas.
4. Maintain agency's emergency operating plan to address operating conditions subject to fire incidents.

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116. Federal Emergency Management Agency, FEMA P-2181, "Hurricane and Flood Mitigation Handbook for Public Facilities," page 5-25, March 2022. https://www.fema.gov/sites/default/files/documents/fema_p-2181-fact-sheet-5-2-transit-facilities.pdf
117. Federal Emergency Management Agency, "Floodproofing Non-Residential Buildings," P-936, Chapter 3, page 4-24, July 2013. https://wbdg.org/FFC/DHS/femap936.pdf
118. Federal Transit Administration, "Flooded Bus Barns and Buckled Rails: Public Transportation and Climate Change Adaptation," FTA Report No. 001, August 2011, page 65. https://www.transit.dot.gov/sites/fta.dot.gov/files/FTA_0001_-_Flooded_Bus_Barns_and_Buckled_Rails.pdf
119. Federal Transit Administration, "Research Report and Findings: Specifications and Guidelines for Rail Tunnel Design, Construction, Maintenance and Rehabilitation," FTA Report No. 0231, page 50, October 2022. https://www.transit.dot.gov/sites/fta.dot.gov/files/2022-10/FTA-Report-No-0231.pdf
120. Federal Emergency Management Agency, "Mitigation Ideas: A Resource for Reducing Risk to Natural Hazards," WF-8, page 72, January 2013. www.fema.gov/sites/default/files/2020-06/fema-mitigation-ideas_02-13-2013.pdf
121. U.S. Environmental Protection Agency, "Integrated Vegetation Management," EPA 731-F-08-010, October 2008. https://www.epa.gov/sites/default/files/2016-03/documents/ivm_fact_sheet.pdf#:~:text=ntegrated%20Vegetation%20Management%20%28IVM%29%20is%20generally%20defined%20as,of%20appropriat%20e%2C%20environmentally-sound%2C%20and%20cost-effective%20control%20methods.

Case Study: BART Reduces Wildfire Risk with Vegetation Management and Backup Power

The San Francisco Bay Area Rapid Transit District, a heavy rail system that serves the San Francisco Bay Area, reduces its risk to wildfire impacts via vegetation management and maintaining backup power supplies.

Weed management reduces the availability of wildfire fuel and helps to prevent fires from starting or spreading. The BART system operates in some high wildfire potential zones that contain vegetated habitat. Uncontrolled wildfires pose a risk to BART assets and other nearby built structures. BART proactively manages overgrowth of vegetation on its properties employing goats to provide weed management.[122] Goats have many advantages over mowers and other power tools. For example, motors from mowers can spark fires. Goats also reduce BART's reliance on fossil-fuel-powered equipment.

Wildfire risks in California have led to power outage challenges for BART. In California, a power utility provider may preemptively turn off power temporarily to specific areas to reduce the risk of fires caused by utility's electric infrastructure; this action is known as a public safety power shutoff.[123] BART takes precautionary steps to address these power outages by maintaining backup generators that may be deployed in advance at stations that are at risk to a power shutoff event.[124] Mobile backup generators serve as an important source of backup power at locations where there isn't a fixed backup generator. Together, backup and fixed backup power sources protect critical safety systems such as tunnel fans and radio communications systems from disruption.[125] In 2019 and 2020, BART was able to maintain regular train service despite the power shutoff events.

Goats providing weed management on BART property in Fremont that serves as a firebreak.

122. San Francisco Bay Area Rapid Transit District, BART Uses Goats to Reduce Fire Danger on Right-of-Way Property, July 2021. https://www.bart.gov/news/articles/2021/news20210708
123. California Public Utilities Commission, Public Safety Power Shutoffs. https://www.cpuc.ca.gov/PSPS/
124. San Francisco Bay Area Rapid Transit District, BART Gears Up to Prevent Service Disruptions from Public Safety Power Shutoffs, August 2021. https://www.bart.gov/news/articles/2021/news20210817
125. Mass Transit, "How BART kept the power on during PG&E's power shutoff," October 2019. https://www.masstransitmag.com/rail/article/21111430/how-bart-kept-the-power-on-during-pges-power-shutoff

6.5 Extreme heat

6.5.1 Rail

Utilize weather forecasting technologies, predictive weather models and weather-related action plans.[126] Consider utilizing rail temperature prediction models to target locations for heat inspections or potential heat-related slow orders. This will significantly reduce impact to train operations and revenue.

1. Install temperature sensors along the rail alignment to monitor for rail buckling issues.
2. Implement speed restrictions or slow-work order for high-heat days to reduce risk of derailment.[127,128]
3. Check track stability each winter as part of ongoing maintenance, and strengthen any weak parts before summer.[129]
4. If sensors are not an option, increase visual inspections during the hottest part of the day to identify track movement.

6.5.2 Human heat stress

1. Establish cooling buses to provide citizens a space for relief from heat and avoid health emergencies.[130]
2. Pre-cool trains stored in yards in extreme hot weather.

[126]. Federal Rail Administration, FRA Safety Advisory 2023-07, https://www.federalregister.gov/documents/2023/11/24/2023-25924/safety-advisory-2023-07-review-and-implement-new-predictive-weather-modeling-and-proactive-safety
127. Network Rail, How We Prevent Tracks from Getting Too Hot, https://www.networkrail.co.uk/stories/how-we-prevent-tracks-from-getting-too-hot/
128. Amtrak, “Extreme Heat Preparations Factsheet,” July 2016. http://media.amtrak.com/wp-content/uploads/2015/10/Extreme-heat-fact-sheet-7_22_16-1.pdf
129. Network Rail, How We Prevent Tracks from Getting Too Hot, https://www.networkrail.co.uk/stories/how-we-prevent-tracks-from-getting-too-hot/
130. Whyy, Philly Opens Four Cooling Bus Locations to Help Beat the Heat This Weekend, July 2022. https://whyy.org/articles/philadelphia-four-cooling-bus-locations-heat-health-emergency/

Case Study: WMATA Heat Rides Program

In 2020, the Washington Metropolitan Area Transit Authority, which operates transit services in the Washington, D.C., metropolitan area, formally adopted a process for heat ride inspections to help prevent rail defects that may occur during heat waves. These heat ride inspections serve to identify potential track buckles and heat kinks. The process is triggered when ambient temperatures reach 90 °F. Heat ride inspections are conducted from the cab of revenue trains to verify rail temperatures. During these cab inspections, the rail temperature is taken at the top of every hour, and the time and temperature are recorded in track inspection heat ride forms. Anytime rail temperatures reach 135 °F, above-ground speed restrictions are issued until the rail temperature decreases. Additional mitigation measures include removing the track from service. The program includes rigorous documentation, which allows WMATA to track incidents and identify patterns that can inform future capital investments.

Heat-related issues are expected to increase as climate change worsens. The number of heat emergency days each year (i.e., days above 95 °F) is expected to more than triple by 2050.[131] As the number of heat emergency days increase in the District, it will become increasingly imperative to safeguard the region's transportation infrastructure.

6.6 Extreme cold

6.6.1 General

1. Develop and implement an annual checklist for winter storm readiness.
2. Prune trees around power lines.
3. Maintain on-call contracts for snow and ice removal services.
4. Temporarily remove stops that have historically been impacted by ice or snow conditions from service on routes.

6.6.2 Slips, trips and falls[132]

1. Wear appropriate footwear that is well-insulated; waterproof; and has a good tread and a wide, low heel.
2. Wipe shoes before entering building or climbing steps.
3. Use designated walkways and available handrails.
4. Report hazardous conditions (e.g., slippery surfaces, black ice, damaged or obstructed paths).

6.6.3 Operating on-road vehicles[133]

1. Adjust vehicle speed to maintain safe following distance and allow for more reaction time for pedestrians and other drivers.
2. Reduce speed when turning, and maintain two hands on wheel.
3. Clear windshield, windows and mirrors of snow, condensation and ice.
4. Ensure that vehicle wipers are in good condition and that washer fluid is available. Slush and spray can obstruct windshield and mirrors and impede visibility.
5. Consider idling vehicles at terminals to maintain comfortable thermal conditions for customers.
6. Train operations staff on how to properly install snow chains on vehicle tires or snow socks.
7. If snowbanks, slush or ice build up, position vehicles in a safe location before and after stops.
8. Be aware of water/slush accumulation on road, and slow vehicle to avoid splashing customers and pedestrians.

131. Department of Energy and Environment, "Keep Cool DC: The District of Columbia's Heat Adaptation Strategy," June 2023. https://storymaps.arcgis.com/stories/7692809a1d6a498482d3fed431f432f9
132. Toronto Transit Commission, Winter Operations
133. ibid.

6.6.4 Operating streetcars[134]

1. Observe, check and verify position of switches. Clean switch if necessary to ensure it is fully set.
2. Operate vehicle slowly when traveling through overhead components.
3. Salt can produce slippery rail conditions and result in spin or slide. Slow down and operate to conditions.

6.6.5 Operating rail vehicles[135]

1. Operate vehicle at lower speeds when visibility is reduced.
2. Test braking distance for snowy conditions, and reduce speed appropriately.

6.6.6 Rail transit track

In extreme cold weather, or when rail temperatures fluctuate between warm and cold, there is potential for rail breaks, stripped joints, etc. due to the thermal stress induced. In addition to utilizing signal circuits for alerting broken rails, consider establishing inspection protocol to detect breaking openings triggered by low temperatures and rapid temperature swings. Consider pre-heating or pre-cooling for trains stored in yards in extreme cold and extreme hot weather.

6.6.7 Bus operations

1. Prepare a Bus Contingency Plan including Notification/Communication Plan (website, TV/radio, news release or social media).
2. Notify municipality of unplowed or unsalted roads impacting service.
3. Place temporary bus stops at top/bottom of hills.
4. Provide indoor bus garage storage.
5. If stored outside, start buses prior to start of service to ensure that each bus is fully operational.

134. ibid.
135. ibid.

Case Study: DART Light Rail Winterization Program

Dallas Area Rapid Transit, which provides multimodal transportation services for the Dallas–Fort Worth region, evaluated the impact and effects of winter weather incidents (snow and ice) and developed mitigations for six major transit elements, including traction electrification, system signal system, track and right-of-way, light rail vehicles, rail operating facilities, and operations and maintenance.

The following are findings for signaling system.

Frozen track switch externals: During a winter storm event, ice can build up on movable switch points or the associated throw and gauge rods. Mitigation options include introducing switch point heaters.

Frozen track switch internals: Internal components seize when water accumulates inside the switch and freezes. Mitigation options include introducing submersible track switches and blower heaters.

Gate crossing and signal house power outage: Backup gate crossing system and signal house power is limited to about one hour in some locations. Mitigation options include increasing capacity with battery backups, UPS, power from the OCS, and permanent standby generators.

DART track and right-of-way in winter weather conditions

7. Implementation

This section includes resources and considerations to support practitioners in implementing the resilience practices provided in this document.

7.1 Resilience planning frameworks

Frameworks are structured roadmaps for practitioners to follow in building resilience. Elements of resilience planning frameworks typically include setting objectives, identifying hazards of concern, identifying assets, assessing the risk, investigating and prioritizing options, and taking action. The following are prominent frameworks available.

7.1.1 U.S. Climate Resilience Toolkit

The U.S. Climate Resilience Toolkit, an interagency initiative among U.S. federal governments launched in 2014 and managed by NOAA, is a site that offers tools, information and subject matter expertise from the federal government for building resilience. The site serves to centralize federal information and resources that support resilience-building into one convenient location.

The site's framework is referred to as Steps to Resilience, which define the following steps:

1. Understand exposure.
2. Assess vulnerability and risk.
3. Investigate options.
4. Prioritize and plan.
5. Take action.

Link: Climate Resilience Toolkit

7.1.2 FHWA Vulnerability Assessment and Adaptation Framework, Third Edition

The FHWA's framework, third edition (FHWA-HEP-18-020), published in 2017, provides a transportation-specific framework for building resilience.

The framework defines the following steps:

1. Set objective, define the scope.
2. Obtain asset data.
3. Obtain climate data.
4. Assess vulnerability.
5. Identify, analyze and prioritizing adaptation options.
6. Incorporate assessment results in decision-making.

Link: Vulnerability Assessment and Adaptation Framework

7.1.3 NOAA Implementing the Steps to Resilience, A Practitioner's Guide

In 2022, NOAA published a guide to help climate adaptation practitioners work with local governments and community organizations to incorporate climate risk and impacts on disadvantaged communities into their long-term decision-making. The NOAA Steps to Resilience (StR) outlines the following steps:

1. Get started.
2. Understand exposure.
3. Assess vulnerability and risk.
4. Investigate options.
5. Prioritize and plan.
6. Take action.

Link: Implementing the Steps to Resilience, a Practitioner's Guide

7.1.4 ISO Standards

The International Organization for Standardization has developed several standards for adaptation planning and implementation. Adaptation-related standards for practitioners include the following:

1. ISO 14090, Adaptation to Climate Change - Principles, Requirement and Guidelines
2. ISO 14091, Adaptation to Climate Change - Guidelines on Vulnerability, Impacts and Risk Assessment
3. ISO 14092, Adaptation to Climate Change - Requirements and Guidance on Adaptation Planning for Local Governments and Communities
4. ISO 22301, Security and Resilience - Business Continuity Management Systems

7.1.5 The National Academies, Incorporating Resilience into Transportation Networks

In 2024, the National Academies published a guide for state departments of transportation and other transportation agencies seeking to define and strategically integrate resilience into transportation networks and network planning. Guidance is provided in the form of a "playbook" detailing the following resilience plays:

1. Define the transportation resilience ecosystem.
2. Build and prepare the resilience team.
3. Define disruptions, risks, and vulnerabilities.
4. Identify critical "hard" and "soft" assets.
5. Invest in resilience.
6. Play to Win: Build a resilience program and learn from experience.
7. The future of network resilience.

Link: Incorporating Resilience into Transportation Networks

7.2 Funding

Funding resilience presents one of the biggest challenges for many entities. Entities will need to consider a range of funding options and strategies (e.g., state and federal grant funding, public/private partnerships, local taxes) to improve resilience. The following are some noteworthy recurring grant funding options for resilience for U.S. transit operators:

1. **FEMA Hazard Mitigation Assistance** (HMA) is a set of programs that provide funding assistance to states, territories, federally recognized Indian tribal governments, and communities to reduce risk to individuals and property from natural hazards. Transit agencies may be eligible as a sub-applicant to the state.
    a. **Building Resilient Infrastructure and Communities** provides grants for hazard mitigation projects that reduce the risk from natural hazards. BRIC's aim is to shift federal focus from reactive disaster spending to proactive investment in community resilience.
    b. **Hazard Mitigation Grant Program** provides grants for long-term hazard mitigation measures after a major disaster declaration in a given state. HMGP aims to reduce loss of life and property as a result of natural disasters and to enable implementation of mitigation measures during the recovery from a disaster.
    c. **Flood Mitigation Assistance** provides grants for certain flood mitigation projects to reduce or eliminate flood risk to buildings, manufactured homes, and other buildings that are National Flood Insurance Program (NFIP) insured.
2. **Emergency Management Performance Grant Program** (EMPG) managed by FEMA, provides grants for disaster financial management, resilient communications, debris removal and protection against the effects of climate change.
3. **National Oceanic and Atmospheric Administration Coastal Resilience Grants Program** provides grants for protecting coastal property and infrastructure.
4. **U.S. Department of Housing and Urban Development Community Development Block Grant Disaster Recovery** (CDBG-DR) grant funds provide grants for increased resilience to disasters and reduced or eliminated long-term risk.
5. **U.S. Department of Transportation and Federal Transit Administration Emergency Relief Program** provides funding for capital costs incurred by a transit agency to protect from and/or respond to a disaster.

6. **The Consolidated Rail Infrastructure and Safety** (CRISI) improvements program administered through the FRA provides funding that improves regional railroad infrastructure, among other areas.
7. **State governments** may provide specific grants, loans and/or direct funding to support climate resilience efforts (e.g., California, New York, Washington)
8. **Additional funding opportunities:**
    a. Adaptation Clearinghouse
    b. Funding Opportunities | U.S. Climate Resilience Toolkit

Another important strategy is to integrate resilience into the agency budgeting strategy, such as creating a budget that can support adaptation investments as well as preparation and post-disaster response activities through allocation of a portion of its annual operating budget to specifically fund climate change actions.

7.3 Community impact

Building climate resilience requires understanding not only the transit infrastructure at risk but also the communities that may be affected. While climate and weather-related disruptions impact everyone, some communities, particularly those that are economically or socially disadvantaged, face greater challenges and have fewer resources to recover. These considerations should be integrated throughout all stages of transit planning and decision-making to ensure fair and effective outcomes. By prioritizing projects that strengthen adaptive capacity and reduce exposure for disadvantaged populations, transit agencies can help build more resilient communities. Refer to Georgetown Climate Center's Equitable Adaptation Legal and Policy Toolkit for practical guidance.

7.4 Cost-effectiveness tools

Cost-effectiveness tools allow practitioners to understand the cost and benefits of the mitigation and help prioritize among mitigation options. These tools offer a systematic approach for comparing a mitigation option against the baseline (business as usual) or other alternatives. Generally, cost-effectiveness tools take into consideration:

- implementation and operational costs;
- benefits in terms of reduced or avoided damages;
- time frame that benefits will be received; and
- current condition or life span of infrastructure being altered.

The following are cost-effectiveness tools that are available. Cost-effectiveness tools are typically required for federal funding applications to demonstrate that benefits outweigh the costs. While these tools were developed specifically for funding applications, practitioners can leverage these tools for effective decision-making regardless of the project's funding situation:

1. **FEMA's benefit cost analysis (BCA).** FEMA's BCA is a method that determines the future risk reduction cost and benefits of a hazard mitigation project. The FEMA BCA is an application requirement for HMA programs. FEMA considers a project to be cost-effective if its benefit-cost ratio (BCR) is 1 or greater. **Link:** Benefit-Cost Analysis
2. **FTA Hazard Mitigation Cost-Effectiveness (HMCE).** FTA published the HMCE tool in 2014 and updated in 2017. This benefit-cost analysis tool was developed for purposes of funding applications under the Public Transportation Emergency Relief Program and the Disaster Relief Appropriations Act of 2013. The HMCE framework outlines costs associated with infrastructure damage, response and recovery and economic impacts because of service disruption. **Link:** Hazard Mitigation Cost Effectiveness Tool

3. **USDOT Benefit-Cost Analysis Guidance for Discretionary Grant Programs.** The USDOT published this guidance in 2023. This guidance specifically targets surface transportation infrastructure projects for various modes. **Link:** Benefit-Cost Analysis Guidance for Discretionary Grant Programs

7.5 Engagement and partnerships

Successful hazard mitigation often means working beyond jurisdictional boundaries.[136] Proactive and strong linkages and collaboration with public, private, not-for-profit and community-based organizations improve coordination, accelerate and bolster resilience, build greater capacity for adaptation, and result in more successful hazard mitigation outcomes. Positioning projects for grants, especially federal grants, is likely to be more successful with support from a widespread coalition of related agencies, county and city governments, and stakeholders. In a coalition, members can benefit from aligning resources (e.g., time, capital, equipment), sharing expertise, and reducing chances of risk transfer and maladaptation.

Case Study: Houston METRO Enhances Resilience of Emergency Management Through Partnerships

The Metropolitan Transit Authority of Harris County is a proactive partner within the Southeast Texas Region for emergency management. Houston METRO engages in both public and private partnerships, performs community outreach, and participates in the Homeland Security Program Urban Area Security Initiative (UASI). Houston METRO maintains memorandums of agreement with the City of Houston and Harris County, serving as the primary emergency transportation partner. Houston METRO's participation in the UASI enables it to establish connections with cities, utilities, hospitals located within the service area and neighboring counties.

Partnerships with local governments and communities have played a crucial role in improving emergency management and support. For example, the Houston region endures severe heat waves in the summer months, resulting in heat stress emergencies. Houston METRO, in coordination with the Houston Fire Department, provides critical support by sending cooling buses that serve as an environment for the victims to cool down in and reduce heat stress. Houston METRO, in partnership with the City of Houston's Office of Emergency Management, serves as a backup support partner to citizens who call the 311 helpline for requests to transport to a cooling center. And during hurricane emergencies, Houston METRO is an emergency partner in providing hurricane evacuation transportation to shelter hubs.

Cooling bus support for the Houston Fire Department in July 2023.

136. American Society of Adaptation Professionals and Climate Resilience Consulting, "Ready-to-Fund Resilience Toolkit," "Characteristic 1: Use multi-scale, cross-sector partnerships to increase project capacity," March 2022. https://adaptationprofessionals.org/ready-to-fund-resilience-toolkit/

Engagement or partnerships may include the following:

- Local/State government and municipal agencies such as cities, utilities, counties and water districts in the same or adjoining communities.
- Local community including community-based organizations and local businesses.
- Indigenous/Indian peoples and communities.
- Utility providers (e.g., water supplier, electricity utility).
- Operational partners (e.g., emergency services, other transportation operators).
- Weather and natural disaster agencies (e.g., CalOES, CalFIRE, USGS, NOAA).
- Academic institutions.
- Committees, forums and boards. Examples include resilience forums.

For ongoing or long-term partnerships, parties may formalize under an agreement. Examples of formalization include mutual aid agreements, memorandums of agreement or memorandums of understanding, or a joint powers authority.

7.6 Recognizing co-benefits

Implementing resilience practices can open up opportunities for co-benefits. For example, nature-based solutions for flood protection (e.g., ecotone levees, nearshore reefs, green stormwater infrastructure) not only provide flood protection, but can also create new recreational opportunities and habitat for native species.[137] Co-benefits may include benefits to

- underserved communities,
- public health,
- reduction in emergency incidents,
- natural ecosystem,
- air quality,
- heritage or cultural significance,[138]
- economy, or
- GHG emission levels.

Leveraging co-benefits can gain broader stakeholder buy-in to the mitigation and are typically more favorable in competitive grant applications. Recognizing the importance of co-benefits, funding agencies often include co-benefits as additional points in their scoring criteria. Due to the challenges in quantifying co-benefits, cost-effectiveness tools often do not capture or only partially capture the co-benefits.

7.7 Addressing climate risk through asset management

Integrating climate risk or "mainstreaming" them into planning and decision-making processes[139] can support adaptation and help ensure long-term resilience. Climate risks can impact asset replacement schedules, expected useful service life of capital assets,[140] operational and continuity planning involving at-risk assets, and identification of hardening needs. Integration of climate considerations should occur through all phases of

137. San Francisco Estuary Institute, "Adaptation Atlas," Version 1.0, April 2019. https://www.sfei.org/documents/adaptationatlas
138. ASTM E3032-15 Standard Guide for Climate Resiliency Planning and Strategy, Article 7.1.6
139. Metropolitan Transportation Commission, Climate Change and Extreme Weather Adaptation Options for Transportation Assets in the Bay Area: Pilot Project, Chapter 8, December 2014. https://mtc.ca.gov/tools-resources/digital-library/mtc-clmtechng-extrmwthr-adtpn-report-finalpdf
140. Federal Transit Administration, "Emergency Relief Manual, Reference Manual for States, and Transit Agencies on Response and Recovery from Declared Disasters and FTA's Emergency Relief Program," Version 2.0, page 17, March 2023. https://www.transit.dot.gov/sites/fta.dot.gov/files/2023-03/FTA-Emergency-Relief-Manual-March-2023.pdf

the asset lifecycle (i.e., investment planning and prioritization, project planning, design, construction or acquisition, asset onboarding, operations, and maintenance).

Example planning and decision-making processes where climate risks can be considered include but are not limited to:

- strategic planning;
- risk management planning;[141]
- asset-related policies or policy and standards development;
- asset management plans;
- asset life cycle plans and strategies;
- emergency response plans or business continuity plans; and
- investment planning and prioritization.

141. ASTM E3032 Standard Guide for Climate Resiliency Planning and Strategy

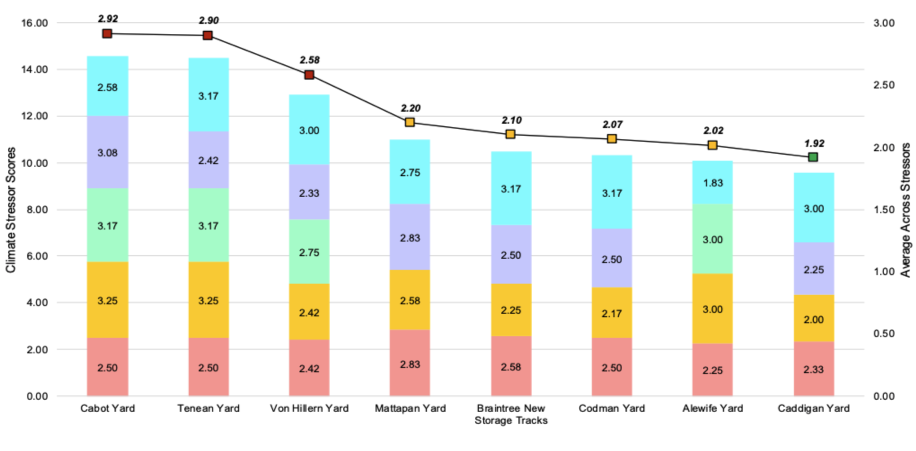
Case Study: MBTA Integrates Vulnerability Assessments and Scoring in Asset Management and Capital Planning

The Massachusetts Bay Transportation Authority, which operates the public transit system for the greater Boston region, systematically mainstreams resilience into its asset management program through climate hazard vulnerability assessments and scoring.[142] Assessments and scoring improve capital planning and decision-making by informing asset management of the parts of the system of highest risk and where to prioritize investment.

MBTA includes assessment scores in its asset prioritization framework. The prioritization framework develops risk scores based on condition and criticality. Assessment scores are included as a criticality factor, which directly influences the overall risk score. Assessment scores are developed for extreme heat, heavy precipitation and inland flooding, sea level rise and storm surge, snow and ice, and wind stressors across key MBTA transit assets. These scores were then averaged to produce vulnerability scores for two different planning horizons (near-term 2030; long-term 2070) and assigned to each rapid transit station, guideway segment and maintenance facility.

In addition, assessments have improved MBTA decision-making in various areas, including:

- capital needs assessment (including project identification and development);
- capital improvement plans and projects;
- emergency response planning;
- standard operating procedures; and
- strategic planning.



Top: Flood protection project at Aquarium Station. Bottom: Scoring of vulnerability of maintenance yards from the Red Line assessment.

Integration of these considerations should not be limited to the agency level. Interagency coordination and collaboration may be necessary at the regional level or even across jurisdictions, especially where transit assets may be owned and managed by multiple agencies, or where there are interdependencies to delivering transit service (e.g., electric utility for rail transit).

7.8 Performance indicators

Transit operators must monitor the performance of resilience strategies in order to understand how effective they are in addressing climate hazard risks. Transit operators may monitor a number of indicators to evaluate performance and may also set thresholds as alerts when tolerances are exceeded and additional decision-making is required. The following are potential performance indicators with links to climate impacts, that practitioners may consider.[143]

7.8.1 Outcome indicators

1. System delay time
2. Response time and recovery time
3. Asset damage (dollars)
4. Asset useful life (years)
5. Number and duration of facility closures
6. Number and duration of slow work
7. Number and duration of fleet in need of repair
8. Frequency and severity of safety incidents (patron and employee)
9. Frequency of derails (due to extreme heat)
10. Frequency of equipment failures

7.8.2 Climate indicators

1. Flood elevation level and frequency
2. Frequency of excessive heat warnings
3. Frequency of windchill or snowstorm warnings
4. Duration, temperature and frequency of heat waves
5. Frequency and duration of power and other utility outages (e.g., public safety power shutoffs)[144]

7.8.3 Process indicators

1. Number of projects with climate resilience objectives included
2. Number of assets or facilities assessed for climate risk
3. Identification and list of critical assets
4. Regular and timely update of climate adaptation plans (e.g., local hazard mitigation plan)
5. Number of actions implemented and complete under climate adaptation plans.
6. Community engagement in planning process
7. Grant funding awarded for climate resilience projects
8. Regular and timely update of emergency plans
9. Frequency of testing and drills of emergency plans
10. Staff training on climate resilience measures and procedures

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142. Massachusetts Bay Transportation Authority, Climate Change Resiliency. https://www.mbta.com/sustainability/climate-change-resiliency
143. Duke University Nicholas Institute, Method Brief Resilience Roadmap, Developing Key Performance Indicators for Climate Change Adaptation and Resilience Planning, August 2022. https://nicholasinstitute.duke.edu/sites/default/files/publications/developing-key-performance-indicators-for-climate-change-adaptation-and-resilience-planning.pdf
144. California Public Utilities Commission, Public Safety Power Shutoffs. https://www.cpuc.ca.gov/PSPS/

7.9 More information and resources

7.9.1 Adaptation Clearinghouse

The Adaptation Clearinghouse, by the Georgetown Climate Center, serves to centralize and make available to the public information and resources that support adaptation planning and implementation. The content is a collection of published work from around the nation and is intended to help practitioners at all levels of government reduce or avoid impacts of climate change to communities in the United States.

Link: Adaptation Clearinghouse

7.9.2 Georgetown Climate Center Adaptation Program

The Georgetown Climate Center Adaptation Program is a leading source of practical strategies for preparing and responding to the impact of climate change.

Link: Helping Communities Prepare for Climate Change

7.9.3 U.S. Climate Resilience Toolkit

Refer to Section 7.1.1. In addition to its framework, the U.S. Climate Resilience Toolkit includes case studies, guidance for using GIS, and climate projections and models.

Link: U.S. Climate Resilience Toolkit

7.9.4 FEMA Mitigation Best Practices

FEMA maintains a register of stories, articles and case studies of successful mitigation work. The register aims to inspire and highlight proven practices.

Link: Mitigation Best Practices

7.9.5 Ready-to-Fund Resilience Toolkit

In partnership between the American Society of Adaptation Professionals and Climate Resilience Consulting, the toolkit provides guidance for designing fundable resilience projects.

Link: Ready-to-Fund Resilience Toolkit

7.9.6 BC Ministry of Transportation, Systems Based Approach for Climate Resilient Infrastructure

In partnership between the BC Ministry of Transportation & Infrastructure and Infrastructure Canada, the guidebook outlines methodologies for integrating systems-based approaches into existing infrastructure development processes.

Link: Systems-Based Approaches to Climate Resilient Infrastructure

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Definitions

adaptation: Adjusting to actual or expected future climate, which includes taking actions to change the physical landscape of the environment or prepare communities to respond to future impacts of climate change. It is focused on addressing climate hazards impacts to human life, property, economic continuity, ecological integrity and community function.

co-benefits: The positive effects that a policy or measure aimed at one objective might have on other objectives, irrespective of the net effect on overall social welfare. Co-benefits are often subject to uncertainty and depend on local circumstances and implementation practices, among other factors.

community: The people living in a specific locality (urban, suburban or rural area) where there are common destinations for households such as workplaces, schools, medical facilities, shops, and commercial and cultural establishments. A community may bridge governmental jurisdictions. Community is "society at large" in a particular area.

hazard: The potential occurrence of a natural or human-induced physical event or trend or physical impact that may cause loss of life, injury or other health impacts, as well as damage and loss to property, infrastructure, livelihoods, service provision, ecosystems and environmental resources. In this document, hazard refers to climate-related physical events or trends or their physical impact.

[climate change] mitigation: Reducing the amount of greenhouse gases going into the atmosphere in order to limit the severity of future climate change and its impacts. FEMA uses the term "mitigation" to refer to mitigation of hazards.

passenger transport: All modes of motorized transportation systems for moving people via air, land and water. In the United States, the majority of passenger transport is based on the automobile.

transit: A motorized passenger transportation system capable of carrying a mass of people operating in a fixed route, openly accessible by the general public.

resilience: The capacity of any entity-individual, community, organization or natural system—to prepare for disruptions, to recover from shocks and stress, and to adapt and grow from a disruptive experience.

risk: The potential for consequences where something of value is at stake and where the outcome is uncertain, recognizing the diversity of values. Risk is often represented as probability of occurrence of hazardous events or trends multiplied by the impacts if these events or trends occur. Risk results from the interaction of vulnerability, exposure and hazards.

transit node: A location at which a passenger boards or alights transit services. Examples include a rail station, bus stop, transit center or ferry terminal. There are also intermodal nodes where various public transit modes share a common node.

vulnerability: The propensity of predisposition to be adversely affected. Vulnerability encompasses a variety of concepts and elements, including sensitivity or susceptibility to harm and lack of capacity to cope and adapt.

Abbreviations and acronyms

ASCE	American Society of Civil Engineers
ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers
ASTM	American Society of Testing and Materials
BCA	benefit cost analysis
CCTV	closed circuit television
COOP	continuity of operations plan
FEMA	Federal Emergency Management Agency
FHWA	Federal Highway Administration
FIRM	Flood Insurance Rating Maps
FRA	Federal Rail Administration
FTA	Federal Transit Administration
GHG	greenhouse gas
GIS	geographic information systems
HMCE	Hazard Mitigation Cost-Effectiveness
IPCC	Intergovernmental Panel on Climate Change
ISO	International Organization for Standardization
LEED	Leadership and Environmental Energy Design
LHMP	local hazard mitigation plan
LID	low impact development
NOAA	National Oceanic and Atmospheric Administration
O&M	operations and maintenance
SAV	submerged aquatic vegetation
SCRRA	Southern California Regional Rail Authority
SWEL	still water elevation
TWL	total water level
UASI	Urban Area Security Initiative
UL	Underwriters Laboratories
UPS	uninterrupted power supply
UV	ultra violet

Document history

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Appendix A: Quick reference for implementation resources

Resilience frameworks

U.S. Climate Resilience Toolkit

FHWA Vulnerability Assessment and Adaptation Framework

NOAA Implementing Steps to Resilience

Funding

FEMA Hazard Mitigation Assistance Grants

FEMA Emergency Management Performance Grant

NOAA National Coastal Resilience Fund

HUD Community Development Block Grant Disaster Recovery Grant Funds

FTA Emergency Relief Program

Cost-effectiveness tools

FTA Hazard Mitigation Cost Effectiveness Tool

FEMA Benefit-Cost Analysis

USDOT Benefit-Cost Analysis Guidance for Discretionary Grant Programs

Asset management/risk management

FTA Transit Asset Management Resources

APTA Transit Asset Management Resources

FHWA Asset Management Resources

ISO Technical Committee 251 Asset Management Resources

UN Managing Infrastructure Assets for Sustainable Development: A Handbook for Local and National Governments

More information

Adaptation Clearinghouse

Helping Communities Prepare for Climate Change - Georgetown Climate Center

U.S. Climate Resilience Toolkit

FEMA Mitigation Best Practices

Ready-to-Fund Resilience Toolkit

Appendix B: Additional case studies

Resilient design standards (Section 2):

Case Study: Massachusetts Bay Transportation Authority Incorporates Resilience into Its Design Standards

The Massachusetts Bay Transportation Authority updates its design standards, with the Office of the Chief Engineer, to include resilience considerations and help address flood protection, stormwater management and other forces that can affect the infrastructure. For example, resilient design considerations have been included in the MBTA's 2023 "Design Guidelines for Bus Maintenance Facilities."[145] The MBTA also requires mandatory consideration of climate-related risks in the design and construction of new projects; all new designs will apply new engineering practices according to LEED standards and the Institute for Sustainable Infrastructure's Envision standards.

Case Study: Southern California Regional Rail Authority Design Criteria Manual Update for Resilience

The Southern California Regional Rail Authority commissioned a Climate Vulnerability Assessment and Adaptation Plan (CVA), published in February 2022, to better understand the vulnerability of the Metrolink rail system, its assets (track, stations, communications, signals, facilities, culverts and bridges) and its passengers to current and future changes in the climate. The assessment included exposure and sensitivity for sea level rise, precipitation flooding, extreme heat, wildfire, drought, landslides/mudslides, seismic/earthquake and electrical outages. Strategies to address climate vulnerability were developed and categorized as part of the CVA and include recommendations relating to policy, programs and procedures.

One immediate outcome of the CVA was to update the SCRRA Design Criteria Manual (DCM) with the climate adaptation strategies outlined in the CVA, as consideration of future climate conditions is essential for project planning, design and delivery to safeguard future investments in SCRRA assets over their useful lives, which range from 20 to 100-plus years. The strategies identified in the CVA for each asset category and type of climate hazard were integrated as appropriate into the chapters for the DCM (including track work, stations, drainage and grading, facilities mechanical facilities, etc.). In addition, a new section was added to guide project teams on how to identify climate hazards for their particular project site and vulnerable asset types. This section is referred to in all other chapters. An additional question was added to Appendix E to require designers to document the climate vulnerability of the project and the adaptation strategies included to reduce the vulnerability.

Due to other forthcoming changes, the updated DCM is not yet posted to SCRRA's website. However, it is provided to consultants and internal staff and must be followed for SCRRA projects and has been in use since June 2022. It is planned to be posted online by the end of 2023.

145. Massachusetts Bay Transportation Authority, "Design Guidelines for Bus Maintenance Facilities," March 2023. https://cdn.mbta.com/sites/default/files/2023-04/2023-03-31-bus-maintenance-facility-design-guideline-second-edition_accessible.pdf

Adaptation planning and regional planning (Section 2):

Case Study: BART's Local Hazard Mitigation Plan and Regional Planning

The San Francisco Bay Area Rapid Transit District, a heavy rail system that serves the San Francisco Bay Area, advances infrastructure resilience by incorporating adaptation planning into its Local Hazard Mitigation Plan (LHMP) and participating in regional planning.[146]

BART recognizes that it must adapt to the consequences of global warming by preparing and protecting the region from climate hazards. In 2022, BART updated the Local Hazard Mitigation Plan (LHMP) which identifies the risks of natural hazards and climate change and identifies actions for reducing those risks.[147] The LHMP is a planning document required by FEMA in order to maintain eligibility to hazard mitigation funding grant programs. Examples of BART LHMP actions include slope stabilization, water intrusion mitigation and power redundancy. The LHMP reflects BART's commitment to maintain and enhance a disaster-resilient system by reducing the long-term risks of natural hazards and protecting human life, property and environment.

BART also builds resilience through participation in regional planning efforts. BART participates in the Bay Adapt Joint Platform, a regional consensus-driven strategy for how the Bay Area must adapt to the growing urgency of rising sea levels. In 2022, BART's Board of Directors endorsed the Joint Platform, joining 55 other cities, counties and organizations to affirm its support for regional adaptation to sea level rise. The BART Board of Directors recognizes the importance of regional adaptation and the need for local and regional governments and communities to cooperatively implement successful adaptation projects and protect the region.

Cost-effectiveness (Section 7):

Case Study: Southern California Regional Rail Authority Cost of Inaction

To understand the potential economic impact of specific climate or extreme weather events, the Southern California Regional Rail Authority analyzed three case study areas in its service area as part of its Climate Vulnerability Assessment and Adaptation Plan.[148] The cost of inaction studies are intended to help SCRRA understand the potential magnitude of costs related to flooding and extreme heat in different parts of the rail system, to guide future planning for adaptation. In addition, understanding the "cost of inaction" is an important step in establishing a business case for investments needed to minimize the impacts of hazards and economic consequences for SCRRA, its riders, and Southern California's general economy.

To assess the potential cost of inaction, a model was developed to estimate both direct costs to SCRRA—including infrastructure damage, emergency response and recovery costs—and the broader economic consequences from the loss of service (i.e., the cost of rider delays). The general framework for the model was based on the FTA's Hazard Mitigation Cost-Effectiveness (HMCE) tool. Infrastructure damages were calculated using a variety of resources, including FEMA's HAZUS (desktop software program) flood model, academic literature and historical reports from the National Train Safety Board. Ridership disruptions were calculated using origin-destination data for 2019. Infrastructure replacement, maintenance and repair costs came from the 2020 Rehabilitation Plan, service invoices provided by SCRRA, and infrastructure assessment data published by FEMA.

To estimate the economic impact of different disaster scenarios, an economic model was adapted from FTA's HMCE framework (but didn't include cost of the adaptation strategies and uses 2021 dollars). The HMCE framework outlines three types of costs associated with natural disasters:

Infrastructure damage: The cost of damage to capital assets owned and operated by an agency (in this case, SCRRA), including damage to fixed structures (e.g., stations, track, bridges, maintenance facilities) and rolling stock.

146. San Francisco Bay Area Rapid Transit District, Calendar Year 2022 Annual Report: Sustainability, pages 9–10. https://www.bart.gov/sites/default/files/2023-08/2022%20Sustainability%20Report-072023-Final.pdf
147. San Francisco Bay Area Rapid Transit District, Local Hazard Mitigation Plan, 2022. https://www.bart.gov/about/planning/policies/hazard
148. Metrolink, "Climate Vulnerability Assessment and Adaptation Plan, A Roadmap to Implementation," pages 67–75, February 2022. https://metrolinktrains.com/globalassets/about/agency/sustainability/metrolink_cva_adaptplan_final_220330.pdf

Response and recovery costs: Emergency repairs, cleanup and other costs associated with an agency's response during and immediately after the event.

Economic impacts because of service disruption: These impacts include the monetized value of increased travel time because of rider delays, the cost of shuttling stranded riders and increases in vehicle miles traveled. Although service interruptions may result in loss of ridership and decreased fare revenue, the FTA typically does not include loss of fare revenue in cost-effectiveness calculations, and fare revenue impacts are not included in the economic cost estimates. In addition, the health and productivity impacts on riders or maintenance workers because of heat are not included in the overall costs.

The estimates are high-level, based on a number of assumptions, and are intended to represent a range of possible costs rather than to predict the costs associated with any specific event. This work effort did not analyze or account for the probability of the events described. For each study area, two scenarios were assessed:

- Minor damage scenarios outline the economic consequences associated with events with limited damage, such as minor flooding or a thermal misalignment (sun kink) that is located and fixed without any injuries or cleanup. For the flood scenarios, a 100-year flood event is assumed.
- Major damage scenarios outline the economic impact associated with events that cause severe damage to the Metrolink system, such as a 500-year flood or a derailment caused by an undetected sun kink.

	Damage Scenario	Infrastructure Damage	Response and Recovery Costs	Economic Impacts from Loss of Transit Service	Modeled Scenario Totals
Study Area 1: Rancho Cucamonga (riverine flooding)	Minor	$3,055,000	$133,000	$48,000	$3,236,000
	Major	$11,523,000	$433,000	$279,000	$12,235,000
Study Area 2: Santa Clarita (riverine flooding)	Minor	$1,939,000	$133,000	$37,000	$2,108,000
	Major	$10,177,000	$433,000	$191,000	$10,802,000
Study Area 3: San Bernardino (extreme heat)	Minor	$94,000	$83,000	$10,000	$187,000
	Major	$13,921,000	$865,000	$51,000	$14,837,000

Above: Economic Impact, USD.

