Overcoming Barriers to Institutionalize Climate Change Resiliency Practices: MassDOT

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ABSTRACT

The most pronounced climate change effects in northeastern United States will be increased precipitation events, more frequent heat waves, and substantial sea level rise. These temperature and flooding outcomes place substantial risk on vital infrastructure that supports economic development, public health, and access to resources and amenities within the state of Massachusetts. As such, there is a need to mitigate these risks through long-range planning and climate change adaptation strategies. The Massachusetts Department of Transportation (MassDOT) recognizes that infrastructure must be fortified through these methods but has yet to establish a systematic approach for quantifying climate change impacts, evaluating the costs and benefits of selective intervention, and implementing adaptation strategies. However, MassDOT operates within a complex political setting of constraints and conditions that may or may not be conducive to particular implementation mechanisms. Additionally, the hydrologic modeling and spatial analysis needed to identify specific areas of transportation infrastructure that are especially vulnerable to climate change effects will not be completed until late 2018.

Cognizant of these constraints, this thesis aims to (1) synthesize the best climate change resiliency strategies from other large infrastructure owners/DOTs and (2) draw upon lessons learned from other agencies to recommend strategies for overcoming barriers to institutionalization at MassDOT. In this way, the department will have a roadmap to addressing existing gaps and barriers to implementation once the climate adaptation and vulnerability assessment tool has been developed. By strategically protecting infrastructure that will have the greatest benefit to MassDOT's constituents at the least cost, the department will be able to minimize the impacts of climate change and maintain a satisfying level of service despite increasing climate stresses on infrastructure and operations.

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DISCLAIMER

This report was prepared by a graduate student in partial fulfilment for the degree Masters in City Planning. It does not necessarily represent the views of MassDOT, its employees or the supervisor of this project.

Introduction

Because of rapid industrial expansion over the past 150 years, the combustion of fossil fuels and global deforestation have altered the carbon cycle and affected the climate by increasing the concentration of heat trapping greenhouse gases (CO_2, CH_4, and NO_x) in the atmosphere. In addition to a global warming effect, these drive other climate changes: some regions have experienced increased precipitation, others decreased; increased frequency, intensity, and duration of precipitation events, winter storms, and hurricanes; rising sea levels; and ocean acidification (Melillo et al. 2014). Though data from the past 50 years supports these findings, it is not simply sufficient to rely on historical observations to predict future climate trends. Rather, climate models vary in complexity and reflect great uncertainty. Take, for instance, the future of global emissions; will population continue to grow in an economy that still very much depends on fossil fuel combustion or will population balance in a transformed, information-based economy that deemphasizes material intensity? Because these questions are impossible to answer and greatly affect the magnitude of climate change effects, climate scientists use a range of scenarios to best estimate impacts in near-future time horizons.[1]

Extreme weather events threaten public health nationwide, damaging infrastructure and displacing thousands to accrue billions of dollars in damages (see Figure 1). In the northeastern region of the United States, climate change's most substantial impacts will be an increased frequency of heatwaves and extreme weather events, as well as sea level rise (Melillo et al. 2014). Climate scientists estimate that New England will witness a 30% increase in precipitation in winter months, 13% increase in extreme precipitation events, 60 of more 90-degree days, and 11 to 79 inches of sea level rise (The Commonwealth of Massachusetts 2018). Each of these climate change effects has the potential to dramatically influence people's daily lives. An increase in 90-degree days, for example, can cause public health crises in vulnerable populations, such

[1] The IPCC Special Report on Emissions Scenarios identifies 4 potential narratives. The A1 storyline and scenario family describes a future world of very rapid economic growth, global population that peaks in mid-century and declines thereafter, and the rapid introduction of new and more efficient technologies. The three A1 groups are distinguished by their technological emphasis: fossil intensive (A1FI), non-fossil energy sources (A1T), or a balance across all sources (A1B).

The A2 storyline and scenario family describes a world of self-reliance and preservation of local identities where population increases continuously and economic development/technological change is slow.

The B1 storyline and scenario family describes an A1 world with rapid change in economic structures toward a service and information, reductions in material intensity, and the introduction of clean and resource-efficient technologies.

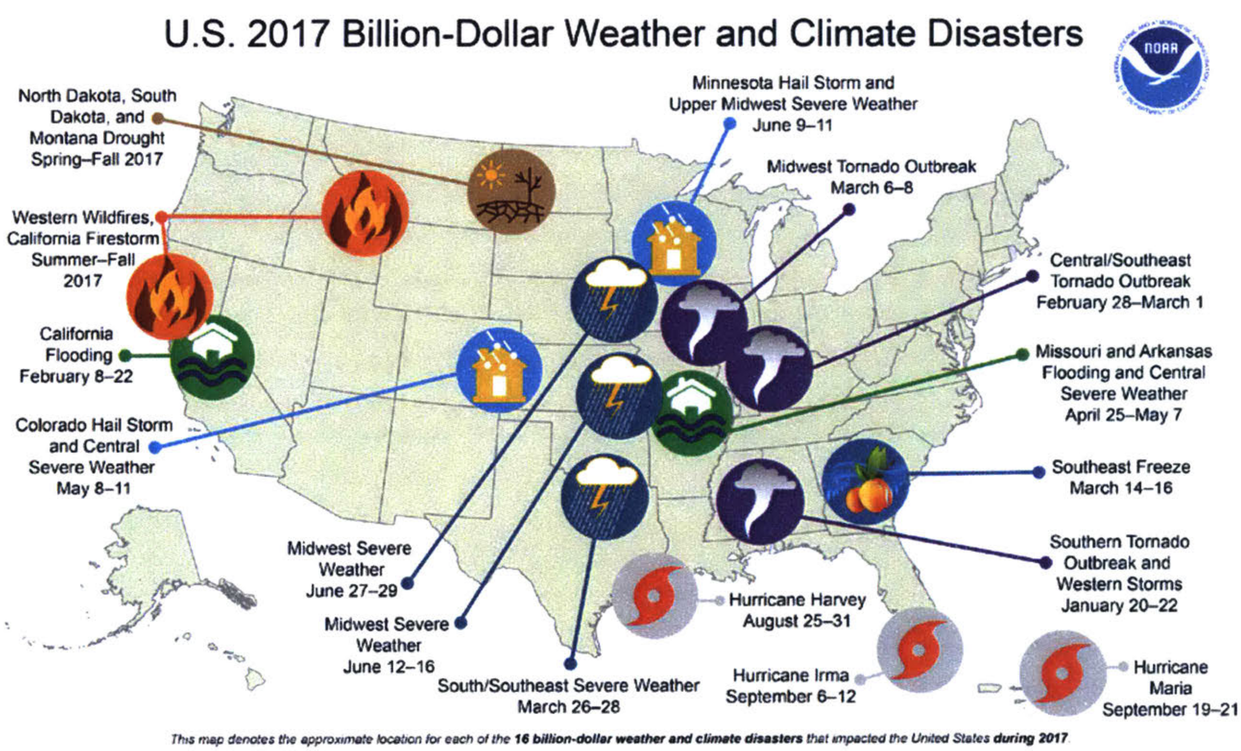
The B2 storyline and scenario family describes a world in which the emphasis is on local solutions to economic, social and environmental sustainability leads to a slowly increasing global population, intermediate levels of economic development, and less rapid technological change.

Source: Nakicenovic et al 2000

as increased rates of morbidity and mortality in the elderly (Aström et al. 2011). Within the scope of transportation infrastructure alone, climate change has the potential to interrupt service. Higher temperatures can cause light rail equipment to overheat and create transit delays. Sea level rise and extreme weather events, such as nor'easters, can cause significant flooding, rendering roadways impassable.

Transportation infrastructure failures are critical within the state of Massachusetts because their interconnection to economic activity, as well as its direct affect residents' ability to access resources, which contributes to social quality of life improvements. Those living within the state depend on roads, bridges, highways, and tunnels to get to work, to school, to the grocery store, to the doctor's office, to their family and friends. The list goes on. The Boston Metropolitan Area alone is responsible for $422 billion in GDP annually (BEA n.d.); these are jobs manned by the state's residents, serving in sectors from healthcare to professional, scientific, and technical industries. Beyond economic arguments, however, there is a moral duty to provide quality access to the state's natural resources and other basic human services, like food and shelter.

Figure 1: Billion-Dollar Weather and Climate DIsasters (2017)



Source: NCEI 2018

As development and extreme environmental events increase, the extent of impacts also increase. Disruptions to urban and rural fabric caused by climate change threaten economic productivity as well as public health.

Thus, the agency responsible for providing, managing, and maintaining the state's transportation infrastructure, the Massachusetts Department of Transportation, is in a strategic position to consider, plan for, and adapt to climate change. By inventorying threats and enacting resiliency practices that anticipate disasters, MassDOT can decrease the area's social and economic vulnerability to impact by addressing transportation infrastructure impacts, listed below. The agency, thus, has a stake in mainstreaming climate considerations across planning, construction, and operation and maintenance programs to most completely and effectively serve their constituency.

Notable Potential Impacts:

- More frequent/severe flooding or underground tunnels and low-lying infrastructure, requiring drainage and pumping, due to more intense precipitation, sea level rise, and storm surge
- Increased numbers and magnitude of storm surges and/or relative sea level rise potentially shorten infrastructure life
- Increased thermal expansion of paved surfaces, potentially causing degradation and reduced service life due to higher temperatures and increased duration of heat waves
- Higher maintenance/construction costs for roads and bridges, due to increased temperatures, or exposure to storm surge
- Culvert and drainage infrastructure design damage, due to changes in precipitation intensity of snowmelt timing
- Increased risk of vehicle crashes in severe weather
- System downtime, derailments, and slower travel times, due to rail buckling during extremely hot days
- Air traffic disruptions, due to severe weather and precipitation events that impact arrival and departure rates
- Reduced shipping access to docks and short equipment and navigational aid damage
- Restricted access to local economies and public transportation

Source: USDOT 2014

Background

As the climate shifts, there is a need to quantify predicted impacts in order to better plan and thereby adapt to the aforementioned effects. Fundamentally, climate change threatens infrastructure owners' ability to achieve goals, such as maintaining a state of good repair while providing safety and reliability to its constituents. Because these predictions greatly affect public health, economic activity, resource availability, energy demand, and natural amenities, city, regional, and state plans account for strategies to adapt to climate change. The National Institute of Building Structures reports that there is a $6 return for every $1 spent on resilience strategies (NIBS 2016); as such, there is a clear need to mainstream climate resilience strategies within government entities, especially those that will be impacted by increased frequency and magnitude weather events. Despite these benefits, though, there are challenges to transitioning policy interventions into implementation. Structural and organizational barriers within public agencies prevent time- and resource-sensitive responses to climate threats. As such, public agencies need to adopt a framework conducive to uncertainty planning, including the efficient adoption and implementation of adaptation and mitigation policies. This thesis examines the aforementioned problem through the lens of one public agency, the Massachusetts Department of Transportation (MassDOT).

MassDOT is a component of the Massachusetts Commonwealth, though the Department acts as an authority guided by the executive office of the governor. The Secretary of Transportation, also the Chief Executive Officer, is responsible for administration of policies and practices, while the Board of Directors serves as the primary governing body for MassDOT; the Governor appoints both the Secretary and Board. Together, the Department is responsible for transportation related capital planning, asset management, project design, and regular operations and maintenance. Here, transportation includes that by road, rail, air, bus, water, bike, and foot; MassDOT oversees approximately 2,800 miles of roadway and supports the fifth largest transit system in the United States, the Massachusetts Bay Transit Authority (MassDOT 2015). Each of these modes prioritize current and future economic viability, residential quality of life, and environmental objectives of the State. Climate change directly impedes the agency from fulfilling its mission.

State legislation establishes MassDOT's governance structure, funding, and policy mandate as given in the General Laws, Part I, Title II, Chapter 6c: Massachusetts Department of Transportation. Section 10 of this chapter provides for transportation planning, including climate change mitigation and adaptation:

The office of transportation planning shall be responsible for research and planning in support of the implementation of chapter 21N [Climate Protection and the Green Economy]. The office shall undertake planning and research tasks and coordinate with the executive office of energy and environmental affairs on issues related to historic, current, and projected future transportation-generated emissions of carbon dioxide and other greenhouse gases and technology, policy, and legal issues related to developing and implementing market-based compliance mechanisms for transportation-generated greenhouse gases. Such planning shall include comprehensive climate change adaptation planning to ensure that the commonwealth's transportation infrastructure is designed to tolerate increased environmental stress due to climate change, including, but not limited to increased temperatures, increased stormwater runoff, and extreme weather events

While the department's statutory mandate does address climate change planning, the language does not present a project prioritization mechanism, a standardized set of projections around which to base planning efforts, acceptable levels of risk, vulnerability, or loss tolerance, or budgetary considerations and tradeoffs, nor does national policy. Conversations with MassDOT personnel identified similar shortcomings as barriers to integrating climate change adaptation planning strategies, adding that the uncertainty of future impacts increases the difficulty of allocating portions of an already sparse budget to protect against events that may not even come to fruition. State transportation professionals echo these frustrations across the country. During a Resiliency Peer Exchange on Extreme Weather and Climate Impacts hosted by the American Association of State Highway and Transportation Officials, the group agreed that limited funding is a significant barrier to making transportation systems more resilient (AASHTO 2017). As a result, many DOTs fail to devote sufficient staff to climate adaptation activities. Additionally, these transportation agencies struggle to prioritize resiliency projects that involve high-importance, critical infrastructure and a long-term timeline over competing shorter-term activities. In short, there is a need to incorporate climate change concerns into agency decision making in a meaningful way.

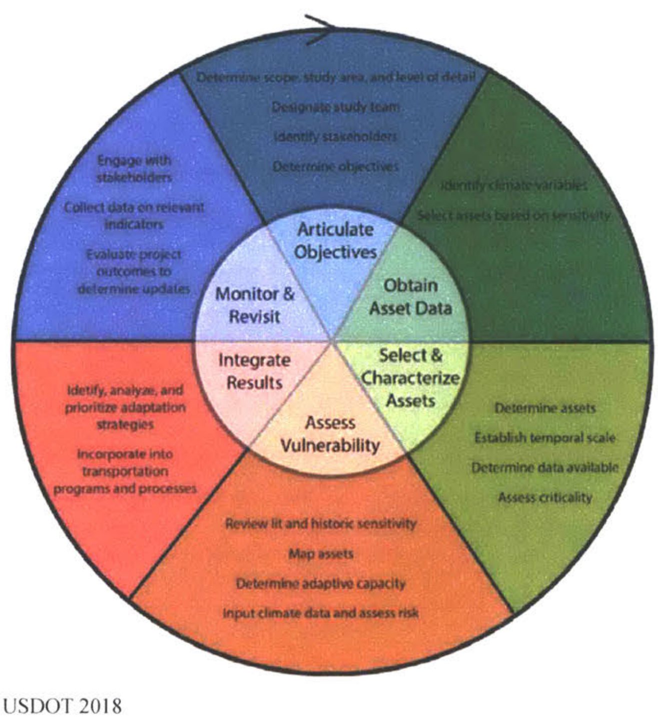
Measuring and Addressing Transportation Infrastructure Vulnerability

The Federal Highway Administration (FHWA) is an agency within the US Department of Transportation tasked with aiding smaller governing bodies, such as State DOTs and local municipalities, in their efforts to design, construct and maintain the national highway system. Though the FHWA's primary source of support is financial, the agency also contributes technical assistance within core highway topics. As part of the Administration's work within the environmental realm, the Vulnerability Assessment and Adaptation Framework (2018) guides DOTs looking to incorporate climate change planning into their operations.

The first step towards safeguarding transportation infrastructure against costly damage caused by climate related impacts is by articulating the Department's objectives. As part of this undertaking, the agency should define the project scope, study area, and level of detail required. Next, the FHWA recommends designating a study team, identifying stakeholders and engaging them in the planning process, and explicitly enumerating the vulnerability assessment objectives. Key to thoroughly defining the assessment's purpose and goals is identifying the desired outcomes and deciding how the results will be used.

Second, the FHWA suggests that the agency undertaking the vulnerability assessment identify key climate variables. After reviewing possible climate stressors to determine which are relevant to the study area, the agency should select those based on transportation asset sensitivity. Here, sensitivity is a component of vulnerability and refers to the ability of an asset to withstand exposure to an impact. The other two components of vulnerability are exposure and adaptive capacity; in other words, the duration and intensity of an asset's subjugation to a climate stressor and its ability to adjust to said exposure.

Figure 2: FHWA Vulnerability Assessment Adaptation Framework



To effectively assess and address climate vulnerabilities, an agency must articulate its objectives, use asset data to characterize and quantify vulnerabilities, integrate the findings into standard practice and periodically amend their efforts to address any gaps.

Source: USDOT 2018

Third, agencies should select and characterize relevant transportation assets. This step requires that the party conducting the vulnerability assessment determine which assets to evaluate, determine the temporal scope of the assets, and determine the availability of asset data. After, the study team should further delineate assets by conducting a criticality assessment.

Fourth, the agency should assess vulnerabilities by developing information on asset sensitivity to climate by reviewing relevant literature and investigating historical sensitivity. After an agency maps relevant assets, the assets' adaptive capacity should be identified, climate inputs should be considered, and risk should be assessed by identifying and rating potential vulnerabilities.

These vulnerabilities should be integrated into decision-making by identifying, analyzing, and prioritizing adaptation options. The assessment results should be incorporated into transportation programs and processes, strategically protecting critical infrastructure from climate stressors. Strategies to mitigate climate impacts and reduce vulnerabilities include: maintaining and managing infrastructure, strengthening and protecting existing assets, enhancing system redundancy, and retreat. Additionally, the study team should engage with stakeholders to communicate about climate change vulnerability.

Finally, the FHWA suggests that DOTs continually monitor and revisit the vulnerability assessment and implementation. A reasonable monitoring and evaluation plan should include engaging with stakeholders, collecting data on relevant indicators, and evaluating the project's outcomes to make any needed updates given emerging information.

Vulnerability assessments for transportation infrastructure can be conducted at various effort levels, given the budget and capacity of a DOT's study team. The first level is minimal effort and relies on existing data and resources to measure vulnerability. The second level of analysis involves original modeling of storm surges and waves. The third level of assessment effort includes using probabilistic risk framework to evaluate potential scenarios and modeling outcomes.

The planning division within MassDOT is undertaking the second level of vulnerability assessment, using GIS data and modeling to determine which assets are at risk for flooding. However, this modeling work will not be complete until late 2018. Nonetheless, MassDOT can take strides to incorporate climate change planning while awaiting the data needed to complete a vulnerability assessment; interventions can be made across various domains of the transportation agency in a long-term strategy that focuses on "not so much doing entirely different things, but doing some of the same things in a different way" (Hodges 2011).

Transportation Domains

Climate change vulnerability can be addressed throughout an agency, over varying time horizons, based on the strengths, weaknesses, and resources of the entity undertaking adoption. This thesis will consider vulnerability and resilience through six lenses, identified and mapped to their respective division within MassDOT below:

Policy and Administration: Overarching

The policy and administration domain includes but is not limited to (1) existing local, state, and national legislation regarding statutory mandates, funding mechanisms, and implementation tools, (2) editing, updating, or creating policy directives, (3) the structure of the agencies carrying out transportation planning functions as mandated by relevant legislation, and (4) individual agents within the existing structure, current and future. Examples of increasing resilience to climate related impacts within this domain include explicitly addressing climate change as a priority of the DOT and taking strides to promote climate change adaptation practices as the "new norm" within mid- and upper-level management.

Long-Term Planning: Office of Transportation Planning

Long-term planning refers to existing physical infrastructure and its use, as well as coordination between internal departments and external partners to develop future priorities and projects. Conducting a corridor study to identify strategic interventions, such as roadway elevation or green infrastructure implementation, is an example of reducing vulnerability to climate change impacts.

Project Development: Dept. of Design and Engineering -- Project Management

Project development is the holistic process that follows a transportation project from conception to completion. The goals of project development within MassDOT are to ensure context sensitivity, consider innovative interventions that support multimodal transportation, conserve resources by proactive planning, outreach and evaluation, achieve consistent project goals as understood by the project's stakeholders, and prioritize projects that address local, regional, and statewide needs. Relying on design standards that incorporate resiliency within project development is an instance of reducing a system's vulnerability to climate change impacts.

Capital Programming: Office of Performance Management and Innovation

The capital programming domain refers to the overall strategy used by an agency to determine near and long term investment; capital programming reflects the goals and priorities of a DOT. Vulnerability to climate change impacts can be addressed through capital programming by shifting priorities to emphasize resilience.

Maintenance and Operations: Dept. of Operations and Maintenance

Maintenance and operations is the domain responsible for the continued servicing of infrastructure and systems to ensure functionality throughout its lifecycle. One mechanism within the maintenance and operations domain to bolster resilience is instituting more thorough and frequent reporting following extreme weather events to better detect and predict future climate change related impacts.

Emergency Preparedness: Dept. of Operations and Maintenance -- Highway Operations Center

Emergency preparedness is a department's ability to plan, respond, and recover from extreme weather events. Examining historical events and related infrastructure failure to determine the root cause of malfunction and posit solutions is one mechanism within the emergency preparedness domain to reduce vulnerability to climate change impacts.

By taking meaningful action across each domain, MassDOT can help to protect its infrastructure from excessive loss during future, increasingly more frequent extreme weather events. While adopting one or two best practices in each category is certainly a step forward, it is far from institutionalizing climate change resiliency. As such, this thesis will examine individual, domain-specific actions for reducing vulnerability, while also analyzing the efficacy of adopting an overarching strategy that will enable climate resiliency integration across core practices: transportation asset management. As the Federal Transit Administration notes, "climate change adaptation is essentially responsible risk management" and transportation asset management is a risk-based framework for strategic investment (Hodges 2011).

Transportation Asset Management Plans

Transportation Asset Management (TAM) is a long term, proactive practice that aims to minimize life cycle costs and ensure the longevity of transportation infrastructure while accounting for potential risk and threats. TAM is driven by policy that reflects an infrastructure owner's vision for the future and supported by high quality, performance based data. The decision-making process relies on value-based trade-offs accounting for varying scenarios and total lifetime costs. The 2012 bill, Moving Ahead for Progress in the 21st Century (MAP-21), requires states to develop Transportation Asset Management Plans (TAMPs) that are risk-based and provide guidance for infrastructure operation, maintenance, and improvement.

State DOTs are tasked with developing an initial asset management plan to improve or preserve the condition of the national highway system approved by the department's head by April 30, 2018. By June 30, 2019, state DOTs must submit a complete plan for a 10-year period with documentation demonstrating implementation of the asset management plan. This plan, made available to the public, includes:

- A summary listing of all national highway system pavement and bridge assets, regardless of ownership, and a description of the asset's condition based on performance measures
- An identification of asset management objectives, which are chiefly concerned with achieving and sustaining the desired state of good repair over the life cycle of assets at a minimum practicable cost
- Asset management measures and state DOT targets for asset condition for national highway system pavements and bridges
- Performance gap identification
- Life-cycle planning
- Risk management analysis of the periodic evaluations of facilities repeatedly damaged by emergency events
- A financial plan including funding mechanisms
- Investment strategies that support:
    - Achieving and sustaining a desired state of good repair over the life-cycle of the assets
    - Improving or preserving the condition of the assets and the performance of the national highway system relating to physical assets
    - Achieving the state DOT targets for asset condition and performance
    - Achieving goals including safety, infrastructure condition, congestion reduction, system reliability, freight movement and economic vitality, environmental sustainable, and reduced project delivery dates
- A description of how the analyses required by the state processes collected data and used best available practices

State DOTs are encouraged, but not required, to include all other national highway system infrastructure assets within the right-of-way corridor and assets on other public roads. If a state elects to include these assets within the transportation asset management plan, the report must inventory the condition of the assets, address asset management measures and relevant targets include a performance gap analysis, rely on lifecycle planning, evaluate risk, and detail a financial plan, as well as investment strategies.

Because TAMPs are forward looking and risk-based, they are excellent candidates for climate change response and resiliency measures. The AASHTO Peer Exchange concluded that DOTs should be considering risk tolerance for climate stressors, which includes integrating uncertainty into planning and decision-making. These transportation professionals argue that asset management programs "provide an opportunity to integrate resiliency concepts into agency decision-making" (AASHTO 2017).

Because MassDOT will publish their TAMP in mid-2018, it is too late to integrate further climate change concerns into the present iteration, which will include conceptual and qualitative efforts. However, the TAMP is a living document that must be updated and expanded on a regular basis. Therefore, it is beneficial to look to other states' efforts to learn from first movers.

Research Question

TAMPs are federally mandated plans that aim to minimize lifecycle costs and future losses to potential vulnerabilities, risks, and threats by inventorying and analyzing state transportation agency's current stock of vertical and horizontal assets. Because of their forward-looking, risk-based nature, TAMPs can be a point of intervention regarding the institutionalization of climate change adaptation practices. In this regard, some states have more developed TAMPs than others. Because MassDOT's first TAMP will be released in April 2018 -- prior to the completion of hydrologic modeling and spatial analysis needed to identify specific areas of transportation infrastructure that are especially vulnerable to climate change effects -- and will need to undergo additional iterations, this thesis aims to lay the groundwork for more efficiently including climate change adaptation provisions by building off the successes and failure of other state DOT's efforts. By incorporating climate resilience at various stages throughout a project's lifecycle and instilling principles of resilience throughout the processes and practices of the agency, MassDOT can mitigate future risk posed by extreme events and shifting weather patterns. As such, this thesis asks: How are comparable transportation agencies addressing climate change throughout the policy and administration, system planning, capital programming, project development, operations and maintenance, and emergency preparedness? How can MassDOT learn from the strategies, organizational insights, and institutional knowledge of other agencies to incorporate findings into the next TAMP iteration?

This thesis aims to answer these questions by (1) establishing a sound methodology, (2) identifying barriers to climate resiliency institutionalization within MassDOT and other large infrastructure owners, (3) inventorying lessons from other transportation agencies, and (4) recommending strategies that align with agency departments and their processes.

Methodology

To most thoroughly and succinctly provide MassDOT with recommendations for institutionalizing climate resiliency practices, I first identified the needs of the agency, then compiled best practices and barriers to implementation, and ensured that these strategies were relevant to the agency before making final recommendations.

While working as a climate policy extern for MassDOT within the Secretary's office, I gained access and developed professional relationships with staff. These staff members were vital to my research, helping to identify agency climate resilience needs and information gaps through informal conversations and interviews, as well as connecting me with other key stakeholders. Through these conversations and informational planning documents published by MassDOT, I was able to assess the current state of research and need for more clear pathways towards climate resiliency; specifically, interviewees identified the need for integration through implementation guidance, design standards, cost-benefit analysis, and asset management.

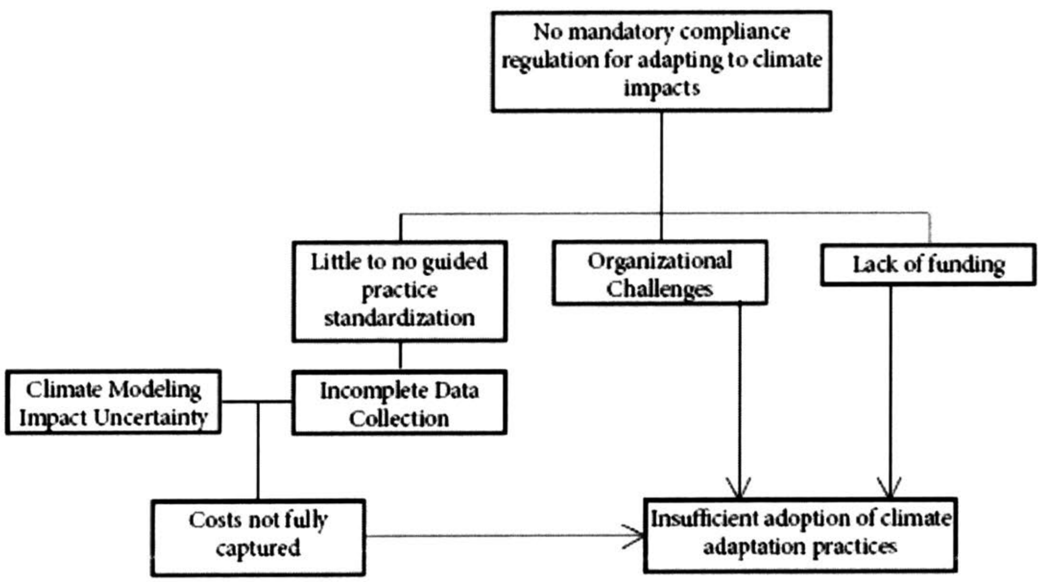
With these needs in mind, I surveyed other state departments of transportation and regional transportation agencies, as well as material produced by the US Department of Transportation, Transportation Research Board, and academics, to determine best practices and potential barriers to implementation. Following the progress of first movers -- strategically chosen because of their similarities to MassDOT whether in terms of size, scope, or vulnerabilities faced -- helped distill the efforts that were successful and identify "lessons learned" from those that were not. Similarly, identifying barriers to implementation allowed me to predict challenges not previously identified through interview and tailor recommendations to MassDOT.

Final recommendations are based on literature review, case studies, and interviews with staffers and mid-to-upper-level management at MassDOT. These findings were presented in the form of a thesis towards the fulfilment of requirements for my Masters of City Planning degree, a condensed report and presentation will be made to MassDOT leadership. However, it is worth addressing limitations to this methodology and research: time and data availability, and scope. First, because of time limitations on both my part and that of MassDOT employees, I did had limited access to interviews and, therefore, likely attained an incomplete record of strengths and gaps within MassDOT's efforts. Second, because case study data came from the transportation agency websites, it is likely I was not able to assess a complete record of climate adaptation strategies taken by state DOTs and regional transportation entities. These limitations are limited in nature and do not discredit findings, rather emphasize the greater need to devote resources to consolidating existing information on transportation agencies' climate resilience strategies.

Barriers to Institutionalizing Climate Resiliency

Prior to effectively synthesizing the best climate resiliency practices of other transportation agencies and state DOTs, it is critical to understand the barriers and constraints within which the authorities act. Identifying the challenges that face other agencies and the respective actions taken to adapt and overcome these issues will provide a lens with which to view best practices; in other words, MassDOT can use or repurpose other agencies' strategies to overcome their own barriers to make strides towards institutionalizing resiliency. The following section will give an overview of the most significant barriers to implementing climate change adaptation and resilience measures (visualized below) for MassDOT and other large infrastructure owners: lack of funding, model uncertainty, costs not fully captured, and organizational challenges.

Figure 3: Barriers to Institutionalizing Climate Resiliency



Because climate change resilience is not mandated, there is little to no practice standardization, a lack of funding to support efforts, and resulting organizational challenges. Climate modeling uncertainty and incomplete data collection lead to the costs of intervention being insufficiently captured and a lack of prioritization.

Lack of Funding

State DOTs and regional transportation agencies face significant funding challenges. State taxes, tolls, and fees generate revenue; the federal government provides additional funding for these agencies, which also finance projects through bonds. These fixed and limited sources must cover all of the operational and maintenance costs of the transportation authorities, with the exception of grants and special-circumstance funding, such as post-disaster recovery. As such, priority is given to those functions that are vital to everyday operation and directly affect the agency's ability to achieve their mission in the present. The scarcity of funding opportunities, then, contributes to spending habits that support current service continuation (AASHTO 2017, Dodws and Aultman-Hall 2015). Capital programming looks to the future to forecast costs aligned with future development that contributes to the agency's ability to maintain and, if possible, enhance service to their constituents. Agencies have varying prioritization mechanisms to determine funding allocation and balance competing considerations. Activities that are imperative to immediate functionality, are front facing, and/or are directly provided for by state or national legislation are favored over alternative projects. The remaining funding is often allocated by cost-benefit determination. Because the implementation of climate resiliency strategies is not compulsory, models are uncertain, and full-costs are not captured, climate resiliency efforts often fail to capture significant funding.

Modeling Uncertainty

Issues with climate modeling scenarios, their impact on vulnerable infrastructure, and translating these scenarios into information engineers can incorporate into standards prevent the institutionalization of climate resiliency strategies. The first problem faced by agencies is their capacity to produce original models that will generate meaningful data. Because most agencies do not prioritize resiliency funding, few have the ability to produce models in-house and must rely on previously constructed scenarios assuming a set of climate projections or rely on historical data, which is often incomplete and of inconsistent detail (ten Sienthoff et. al. 2017). If an agency can produce original models demonstrating the impacts of most concern within the region, the modelers must rely on climate projections that are uncertain (Savonis et. al. 2014). The models are tested against inventories of infrastructure, which can take significant time to compile or populate gaps in data, to determine vulnerability (Adapting to Rising Tides 2018). Because of funding restrictions, agencies opt to protect the infrastructure that is most critical and most vulnerable to climate impacts; however, criticality is not often explicitly defined and therefore subjective. Both the model uncertainty and subjectivity in this process challenge an agency's ability to effectively argue for climate resiliency's prioritization against other projects or efforts, whose impacts are more certain and readily measured. Additionally, it is uncertain how much risk agencies are willing to tolerate and, therefore, which design and engineering standards to build or maintain. Because there is unclear communication of model outputs, engineering decisions have difficulty becoming standardized (Hyman et. al. 2014, ICF International 2013). Finally, there exist no evaluation techniques to determine the efficacy of these resiliency practices, which inhibits arguments for future prioritization.

Costs Not Fully Captured

An incomplete assessment of the costs and benefits of implementing climate resiliency practices can hinder the prioritization of these strategies. For instance, varying the expected lifetime of an asset and the discount rate can produce wildly different costs and benefits in terms of net present value, as can the projected number of extreme events and climate conditions. Additionally, valuing non-monetary goods, such as ecosystem services or impact on citizens, can be subjective, challenging, and incomplete (Savonis 2014). The larger the scope of impact, the greater benefit society derives from moving forward with climate resiliency measures, however, the cost-benefit analyses do not often consider a wide lens. In a dense, urban region with many interdependent systems, such as Boston and the Commonwealth, cascading impacts can intensify rapidly. By ignoring these effects, cost-benefit analyses can influence decision-making that does not completely capture current and future conditions to make the most economically rational decision.

Organizational Challenges

Lack of regulatory prioritization and funding create immense organizational barriers to agencies attempting to institutionalize climate resiliency. Sparse funding significantly limits agencies from developing in-house capacity to address climate impacts through the hiring of new staff members to fill newly created positions devoted to populating climate divisions. Without dedicated staff, roles in addressing climate impacts often become muddled with other task priorities. Additionally, the lack of standardization in climate scenarios, determining criticality, and adopting engineering best practices can delay or disrail effective implementation. Because climate change is a complex phenomenon that will span many jurisdictions and affect many stakeholders, public and private, the issue requires tremendous cross-agency coordination and the formation of new, strong partnerships. The interdependencies of these stakeholders necessitate a cohesive, holistic approach but gaps in knowledge, funding, and standard practice can prove challenging to overcome.

Lessons from Other Transportation Agencies

Policy and Administration:

Efforts to incorporate climate change resiliency into transportation planning at the agency and state DOT level often begin as policy initiatives as propagated by leadership within an administration. There is flexibility within this domain; based on the resources available, internal structure of agencies, and climate threats, departments pursue varying strategies.

Policy

Many states and transportation agencies have yet to plan for climate change impacts by incorporating resilience into policy initiatives, whether because of competing priorities, limited funding opportunities, and/or lack of political support. However, those entities that have adopted a resiliency effort are not uniform in policy framework.

In select instances, transportation agencies are able to more successfully able to incorporate climate resiliency practices into overarching strategy guiding the entity by rebranding the effort, using terminology that is more politically favorable to advance climate change adaptation efforts. Agencies such as Hillsborough Area Regional Transit Authority (HART, Florida), Honolulu Department of Transportation Services (HDTS, Hawaii), Kansas City Area Transit Authority (KCATA, Kansas/Missouri), Southeastern Pennsylvania Transit Authority (SEPTA, Pennsylvania), Idaho Valley Regional Transit (IVRT, Idaho), and Nashville Metropolitan Area Transit (NMAT, Tennessee) have dubbed their resiliency efforts as "preparedness" or "event readiness" (Amdal et al. 2017). Other states and regional transit authorities focus on "safety" and "recovery." These terms shift the focus away from climate change, which can help agencies overcome arguments about the variability of climate modeling and uncertainty of event frequency and intensity. Instead, transportation agencies can use these words to rely on a familiar, accepted vocabulary to argue for adaptation mechanisms, by emphasizing past exposure and socioeconomic consequences of being "unprepared" for extreme weather events.

Other transportation agencies, such as the New Orleans Regional Transit Authority (NORTA) and San Francisco based-authorities (Bay Area Rapid Transit (BART), San Francisco Municipal Transit Authority (Muni), and Metropolitan Transportation Commission (MTC)), have adopted climate resiliency specific policies. In the wake of Hurricane Katrina, NORTA was able to incorporate resilience holistically; federal funding has enabled the agency to rebuild its entire system with "a philosophy of resilience… woven into all their investment and operational decisions" (Amdal and Swigart 2010). Because the hurricane is still very much in the memory of NORTA staff and residents, the agency has the political will to prioritize resilience and ensure that the agency is properly equipped to recover from future climate events. The San Francisco Bay Area, though not recent victim of large-scale storm events, is familiar with a different type of resilience: preparing for and mitigating the impacts of earthquakes. These frequent, intense seismic events have forced transportation agencies to develop the capacity to adapt and respond to emergency events. As such, these entities are familiar with identifying vulnerabilities, establishing design guidelines, and addressing risk during project development and routine maintenance. The region's situation along the California coastline and progressive political base have enabled the agencies to codify climate resilience through planning efforts, such as Muni's Climate Action Strategy which focuses on mitigation and adaptation. In this Strategy, mitigation of climate impacts is actively addressed through measuring reductions in greenhouse gas emissions. Adaptation efforts are realized through focused program areas and goals pertaining to education capacity and communication, capital planning, vulnerability assessment, adaptation strategies, plans, and policies, and collaboration (see Table 1). In establishing tangible goals with associated target dates, Muni has reinforced the agency's commitment to climate resiliency and established a replicable starting framework that can be adopted by other agencies or adapted to further advance goals that are more ambitious.

Leadership

Enthusiasm for addressing climate resiliency within senior staff members have been instrumental in progressing policy efforts at HART, BART, KCATA, the New Jersey Transit Corporation (NJTC), and the Metropolitan Atlanta Regional Transit Authority (MARTA) . Upper management supports policy efforts, encouraging the integration of resiliency considerations throughout departments and, in the case of BART, successfully convincing the board to allocate increased funding to resiliency projects (Amdal 2017). At MARTA, senior staff engage with frontline employees to determine the current climate impacts on infrastructure and predict future projects and sites that will require resiliency measures. Similarly, KCATA provides forums for frontline staff to express feedback and management to address concerns. In each of these agencies, the commitment of senior staff to climate change resiliency practices contributes towards institutionalization.

Table 1: SFMTA's Climate Action Strategy

Program Area	Goal	Strategies
Education Capacity and Communication	By 2020, increase awareness of climate impacts and capacity of agency staff, the public, and decision makers	• Coordinate with city partners to establish climate change communication working group • Engage local communities and stakeholders on cc/future impacts • Establish/maintain slr working group that spans units and divisions to provide strategic guidance and direction
Capital Planning	By 2020, integrate climate risk principles and resiliency features into capital planning efforts	• Conduct a pilot project that examines resiliency of projects (orient project managers to climate risks as they develop projects) • Provide technical assistance (Capital Planning Committee SLR Guidance and Checklist) • Understand variety of financial tools/mechanisms (like resilience bonds)
Vulnerability Assessment	By 2020, conduct a SLR vulnerability and risk assessment of multimodal transportation system	• Identify system wide vul/risk • Identify impacts to disadvantaged communities • Identify and assess transportation system data/info gaps
Adaptation Strategies, Plans, and Policies	By 2020, develop adaptation strategies and integrate into transportation plans, policies, projects, and operations	• Build on initial planning efforts • Monitor and document climate related impacts
Partnerships and Collaborations	By 2020, build strong and diverse partnerships that enable the development of a more resilient transportation system	• Maintain active role on relevant climate adaptation working groups • Build and maintain strong working partnerships (city, regional, domestic/international)

Source: SFMTA 2017

Administration

The bulk of climate resiliency efforts at transportation agencies are integrated holistically throughout departments, rather than stand-alone subgroups, such as an "Office of Resiliency." BART's Climate Change Adaptation Assessment Pilot, for example, addresses climate change at a staff level: executive managers apportion resources and funding to adaptation efforts, planners integrate climate change at a plan's inception, engineers and designers modify facilities specifications, maintenance managers and staff modify relevant protocols, and asset managers incorporate climate considerations into asset management programming (FTA 2013). Similarly, LA Metro relies on a comprehensive strategy to address climate change across all departments within the agency using an Environmental Management System (EMS). The EMS identifies processes and practices that reduce the impacts of climate change on transportation infrastructure and users, as well as opportunities to increase efficiency, by establishing two groups of staff members: the administrative and core teams. The former identifies a comprehensive strategy for the organization on environmental issues. The latter is comprised of frontline employees, with a functional knowledge of EMS. The core team is directly responsible for EMS implementation and maintaining the core principles, as established by the administrative team, but adapting solutions to work within site-specific context. The two groups meet to address feedback and incorporate findings into EMS (LACMTA 2012). Addressing resiliency through continuous integration of lessons learned from existing processes and practices, as well as at on-the-ground and management levels, enable a sustained and evolving discussion of climate change adaptation that strengthen the system's infrastructure through more cost, labor, and energy efficient practices.

Takeaways: Policy and Administration

- Large infrastructure owners operating in regions already facing extreme events (such as hurricanes, earthquakes, and tornadoes) have a framework for institutionalizing resiliency practices that can be drawn upon to support climate change adaptation
- Supportive agency leadership and rebranding climate resiliency efforts as "event readiness" or "preparedness" has helped to prioritize efforts, motivate staff to incorporate practices, and ingrain a sense of urgency around adopting resilient practice
- Resiliency teams that are integrated throughout the agency more holistically address stand-alone climate divisions
- Establishing a resiliency plan that outlines an agency's present and future efforts increases transparency, builds accountability, and serves as a metric for tracking progress

System Planning

To ensure that infrastructure is resilient to climate impacts and that the system's function remains intact well into the future, transportation agencies must address climate mitigation and adaptation efforts through system planning; that is, viewing the transportation network as a whole to identify and confront vulnerability. First, current assets and risk are assessed. Then, after vulnerability has been evaluated, strategic decisions are made to protect critical infrastructure. Asset management encapsulates this process and, in turn, informs capital planning, project development, and operations and maintenance.

Assessing Current Conditions and Future Risk

Obtaining a complete inventory of transportation assets is critical to determining current condition, future risk, and overall vulnerability to climate impacts. As the Maryland State Highway Administration notes, data on roads and bridges is more readily available than smaller culverts and drainage systems (FHWA 2015). Indeed, most states have compiled an inventory, including current conditions, on highways and bridges, due to TAMP requirements. However, assets are not limited to the aforementioned infrastructure. A complete record includes not only horizontal but vertical considerations; for a comprehensive inventory of infrastructure types, please see Table 2.

The next step is to determine asset criticality. LA Metro assesses the criticality of transit facilities based on ridership, interconnection to the system network, and the presence of joint development. For other facilities, the agency relies on expert opinions of Metro staff (LACMTA 2012). The Long Beach Transit Authority measures criticality based on the likelihood of failure (relying on percentage of useful life consumed data) and severity of failure, measured in terms of impact to people, environment, costs, and operations (GAO 2013). Other agencies, such as the Washington State DOT (WSDOT), rely on stakeholders to determine criticality.[2]

Third, agencies rely on historic conditions and future risk scenarios based on modeling supported by relevant climate and geospatial data to determine vulnerability. As a baseline, risk can be projected based on previous weather events, as is the case with HART (Amdal 2017). Other agencies rely on existing data and in-house modeling capabilities; for instance, an assessment conducted in the San Francisco Bay Area entitled "Rising to Rising Tides" considered two scenarios -- the IPCC's high-end estimate of sea level rise

[2] For a more thorough review of criticality assessments to protect critical infrastructure, please see Risk Assessment Methodologies for Critical Infrastructure Protection (Giannopoulos, Filippini, and Schimmer).

for mid-century and mid-end estimate for end of century -- using a bathtub method to determine vulnerable assets (Adapting to Rising Tides 2018). Further developed climate vulnerability assessment efforts model

Table 2: Asset Inventory Types

Asset Category	Assets
Highway	• Pavement • Interchanges • Intersections • Tolling Gantries
Structure	• Bridges (Deck, Superstructure, Substructure) • Tunnels (Roof, Walls, Floor, Columns, Pavement, Fencing, Ventilation Ducts and Fans, Struts, Hanging Panels, Lighting, Pumps, Fire Suppression, Electrical Gear, Pump Stations) • Culverts • Retaining Walls • Ditches • Catch Basins • Under/Edge Drains • Vegetation
Safety	• Barriers (Guard Rails) • Signals (Traffic, Pedestrian, Subway) • Traffic Control Facilities • CCTV • HVAC • Signs and Signposts • Lighting Systems (Fixtures, Poles, Controllers) • Pavement Markings (Raised Pavement Markers, Stripping, Rumble Strips and Stripes, Sidewalks, ADA Assets) • Weight in Motion Scales • Rest Areas
Multimodal	• Railways and Yards • Ports and Docks • Bikeways • Airport Runways and Heliports • Intermodal Facilities
Real Estate	• Right-of-Way • Excess Land

Source: ODOT 2011, CalTrans 2018, GDOT 2014 original data; in Mobile, Alabama storm surge flood elevation and wave height maps were used to produce an array of simulations for various sea level rise and storm scenarios to evaluate asset vulnerability. More advanced efforts rely on probabilistic risk framework to evaluate scenarios; a study of the Florida coast simulated hundreds of storm scenarios and reduced the events to a suite of dynamic storms representative of a majority of inundation coverage.

Evaluating Potential Adaptation Efforts

Generally, decision-making regarding investment in climate change adaptation efforts involves consideration of vulnerability and risk analysis, safety priorities, likelihood of weather event and related impact, and cost. In some transportation agencies effort this is an informal process; for instance, KCATA collaborates with a regional planning authority, which gathers stakeholders to discuss best practices (Amdal 2017). Other agencies, such as BART, rely on criticality to determine investment priorities; decision-making is a product of an asset's traffic flow, interregional travel, emergency management, potential loss of life, adaptability, classification as a lifeline route structure, and economic costs. MARTA, however, relies on lifecycle asset management principles to evaluate potential adaptation efforts. MARTA considers climate risks to an asset throughout each phase: (1) design and procure, (2) use and operate, (3) maintain and monitor, (4) rehabilitate, and (5) disposal, reconstruction, or replacement, as well as the costs of climate- related strategies and the value or benefit of the measure to facilitate prioritization. By adding a field to their Enterprise Asset Management System to denote an asset's sensitivity to climate, incorporating a climate-related objective to their resource allocation decision-making software, and weaving these processes into their transportation asset management program, MARTA holistically integrates resiliency into system planning (Springstead et al n.d.).

Takeaways: Long-Term Planning

- To account for the full extent of costs related to future climate impacts, an agency must have a full asset inventory, including data on location and condition
- Establish a measure of criticality based on: ridership, interconnection to the system network, the presence of joint development, likelihood of failure, severity of failure, and/or the opinions of experts and stakeholders
- Partnerships with other institutions can build capacity at relatively low cost
- Evaluate build scenarios using lifecycle considerations

Capital Programming

Because capital programming reflects an agency's priorities and vision for the future, successfully integrating climate adaptation and resiliency principles in this domain is imperative. Within capital plans, agencies can rely on decision-making tools to institutionalize resilient practices.

Decision-Making

Establishing resiliency as a priority within capital programming is another mechanism to support the institutionalization of climate adaptation practices. Though agencies that have faced significant extreme weather events in the past, such as SEPTA, recognize that "resilience is the new reality" (APTA 2016 Sustainability Workshop 2016), other transportation entities have yet to recognize proactively planning for climate impacts as a necessity. Because agencies reassess priorities on a one-to-ten year cycle, there is opportunity for resilience to be woven into the decision-making fabric of capital programming. While some transit authorities, such as HART, simply give items relating to resilience extra consideration, others, such as BART, embrace the criticality view (Amdal 2017); the agency is acting preemptively to protect its most crucial infrastructure and ensure future functionality.

Another mechanism to support the integration of climate adaptation into capital programming is through cost-benefit-analysis. A simple form of climate cost accounting, as employed by HART, is to add a 15% contingency to each analysis to address climate impacts (Amdal 2017). The Chicago Transit Authority's (CTA) lifecycle analysis, however, more accurately reflects costs. Beginning with a 2050 time horizon and a 3.5% discount rate, the agency considers a "no-build" scenario to estimate the impacts on customers and service, including: the operating costs for slow zones, single tracks, and bus shuttles, the revenue costs forfeited when passengers opt for other modes of transportation during service disruption, the passenger value of time, and the no-build maintenance/repair costs. The agency also considers the "build" scenario, accounting for one-time capital costs and routine maintenance. The CTA's model can reflect 2050 net present values for projects for a given baseline and disruption frequency (FTA 2013b). In this way, projects that account for resiliency can be recommended based on lifecycle cost data, ultimately cutting costs for the agency. For a more detailed life cycle cost model, please see Appendix 1.

Additionally, several transit authority's capital programming accounts for resiliency as a criteria for evaluation. As previously noted, MARTA's "Expert Choice" Enterprise Risk Management System accounts for cost and strategy to provide a clear view of risk and resiliency, including trade-offs between project alternatives (ICF International 2013). Other agencies, such as NORTA and SEPTA have identified resilience as part of the evaluation process leading to capital programming decisions. In emphasizing resilience as a leading principle guiding development, these agencies have embedded climate adaptation principles into future projects and fund allocation.

Takeaways: Capital Programming

- Options for integrating climate resiliency into capital program decision-making include:
    - Allocating extra consideration (additional points in a score-based system) for those projects which include adaptive mitigation aspects and/or design considerations that account for climate projections
    - Emphasis on critical infrastructure and climate impacts' ability to impede an agency from fulfilling its mission
    - Lifecycle cost considerations for projects to reflect future climate scenarios

Project Development

Because development that proactively plans for impending climate impacts will require less maintenance and repair in the future, integrating resilient practices into a project from the onslaught can help to prevent lengthy delays in service, bolster safety, and decrease costs over an asset's lifecycle. Transportation agencies have started to pursue this strategy at varying effort levels.

Some transit authorities have instituted relatively weak policies to institutionalize climate resilience during project development. For instance, IVRT uses "common sense" to plan for adaptation needs, identifying resiliency opportunities through conversations. KCATA also plans for climate resilience indirectly, by explicitly emphasizing sustainability through efficiency and mitigation, while also seeking projects with adaptive cobenefits, such as green infrastructure. Additionally, the Utah Transit Authority (UTA) does not promote resilience through project specific cost-benefit-analysis, but does use a generalized model with locally adjusted estimates to account for historic weather trends (Amdal 2017). Though the aforementioned policies and points of intervention do not explicitly promote resiliency in project development, implementing small measures can help build a path towards resilience, especially in resource constrained or politically challenging climates.

More progressive transit authorities have instituted explicit resiliency requirements for project development. LA Metro's Environmental Compliance and Sustainability Department, for example, has authority over design standards and ensures the implementation of resiliency strategies in the design and construction phases of a project. Not only must each project address sustainability, but full lifecycle cost analyses are also required. Additionally, HDTS requires projects use resilient materials in the rehabilitation, reconstruction, and new construction of projects vulnerable to extreme weather (Amdal 2017). BART requires plans to address climate vulnerability, unless the designers can prove that the project's performance is not affected by climate threats and will cut costs. In addition to these policy interventions, transit agencies have identified physical interventions based on climate stressors, see Table 3.

Table 3: Adaptation Strategies for Extreme Weather Events

Weather Event	Affected Asset	Impact	Adaptation Strategy
Extreme Heat	Overhead Line	Sagging Wire	• Modernize to constant tension system • Check, maintain, reduce rail speeds
	Rail Tracks	Buckling Tracks	• Invest in rail temperature monitoring stations to determine when and where there is risk • Improve shading in outdoor track areas
	Rail Signalling	Equipment Stress	• Install more ventilation • Acquire alternative energy sources • Reduce energy demand through increased energy efficiency
	Utilities	Brown-Outs	• Acquire back-up power sources • Upgrade HVAC units • Use heat-resistant construction materials
	Employees	Dehydration, Heat Exhaustion	• Shift work schedule to cooler times of the day during extreme heat events • Educate workers about dehydration and heat stress
	Customers	Potential Adverse Health Effects	• Install green roofs • Expand shade cover

Weather Event	Affected Asset	Impact	Adaptation Strategy
Heavy Rain, Storms	Equipment	Flooding	• Place specialty equipment on standby • Move portable equipment to higher elevation
	Roadways	Flooding	• Install stream gauges to proactively close roads • Elevate roads when possible • Build dikes, breakwaters, and levees, including living levees • Increase culvert size or providing flexible armouring of culvert ends to maintain end conditions • Decrease area of impervious surfaces • Improve drainage • Install green infrastructure • Slope stabilization using reinforced soil, retaining walls, or densely rooted vegetation • Flexible armouring of approach embankments to prevent erosion • Sacrificial embankment sections to enhance flow capacity during extreme flooding • Evaluating watershed for debris production potential and planning for debris transport • Living shorelines • Renourish beaches and riverbanks • Wetland restoration and improving interconnection of wetlands • Seawalls
	Rail Track	Flooding	• Elevate rails when possible • Install debris screens along key sections of track • Increase pumping capacity • Improve drainage

			- Redirect runoff away from tracks: tilting platforms, installing rain gardens or green roofs - Increased stormwater management via green infrastructure - Infrastructure upgrades: vent grates, entrances, seals - Require moisture intrusion and pest/decay resistance measures to improve material durability
	Utilities	Flooding	- Elevate select assets when possible, convert electric lines to run underground - Acquire backup generators
	Customers	Service Delays	- Increase bus service in advance of predicted flood events to service flooded stations - Improve customer communication
	Bridges	Overtopping	- Perching bridges to engage weir flow over embankments prior to bridge overtopping - Restraining slab units, bridge spans to prevent lifting of substructure if inundated - Bridge protection that accounts for scouring patterns - Raise bridge landings and approaches to shorelines

Weather Event	**Affected Asset**	**Impact**	**Adaptation Strategy**
	Utilities	Loss of Functionality	Acquire backup generators
	Customers	Discomfort	Platform heaters

Sources: Committee on Climate Change and US Transportation… 2008, ICF International 2013, Meyer n.d., Radow and Neudorff 2011, FTA 2013a, IDOT Fall Planning Conference 2014

Standards

Within project development, standards can involve procedures or design. For instance, Transport for London's Crossrail project has an elongated design-life of 120 years and is designed to withstand a one-in-two-hundred-year flood (Amdal 2017). However, not all agencies plan to such a capacity. The Transportation Research Board addresses design standards through four options. The first strategy is to build to a more resilient standard, assuming more frequent and powerful extreme weather events; this high-cost option is most suitable for projects in particularly vulnerable areas. The second strategy upgrades parallel routes, given right-of-way and amenable cost conditions. The third strategy is to build projects with shorter lifespans and retrofit these assets when projected climate impacts are more certain. The final strategy is to build to current standards and accept the risk of major upgrades in the future. Most agencies rely on a combination of strategies, balancing cost-risk tradeoffs within the given parameters of operation, as demonstrated by *Design Standards for US Transportation Infrastructure: The Implications of Climate Change.* This manual guides planners to assign a likely occurrence probability for environmental changes that will occur during the facility's lifespan, estimate the cost of design to various standards, and apply the hazard occurrence probability to the cost components of each design to choose the alternative with the lowest net present value (Meyer 2008).

Progressive agencies have updated design standards to ensure a minimum risk tolerance. For instance, Muni requires that capital projects within the sea level rise vulnerability zone must be reviewed before recommendation with an eye to the project's lifespan and planning horizon. In other words, before a project can be approved, it must fully address future climate impacts deemed relevant by the transit agency to ensure resiliency. Other agencies, such as SEPTA, rely on physical design standards that must be met prior to approval within the capital programming process (FTA 2013a). To address higher temperatures, bridges have updated joint seal design criteria, railways have increased temperature thresholds to account for expansion and contraction, and landscape design provides for drought resistant plants. SEPTA accounts for increased precipitation impacts by requiring submersible pumps for mechanical systems and increased drainage pipe sizes to reflect increased expected rainfall. Similarly, the agency adjusts groundwater tables to account for storm water outfall water level elevation and an increase in design flood elevation to withstand higher flood levels. For a detailed example of adaptive design for culverts, see Figure 4:

Figure 4: Adaptive Design for Culverts

First-Order Climate Variable (Columns B and C)		Second-Order Climate Variable (If Applicable) (Column D)	Method for Estimating the Second-Order Climate Variable (If Applicable) (Column E)	Affected Design Input (Column F)	Typical Source(s) of Referenced Design Input (Column G)	What Future Value to Use for the Affected Design Input? (Column H)
Precipitation	***More extreme rainfall events***	Stream flows (2-100 year recurrence intervals)	Theoretical models (TR-20, TR-55, HEC-HMS, rational method)	24-hour precipitation for given recurrence interval	NOAA Atlas 14 or TP-40	**Preferred**: Utilize downscaled projected climate change precipitation values **Alternative**: Use relative increases in precipitation amounts following the Clausius–Clapeyron relationship[1]
				IDF curves	NOAA Atlas 14, TP-40, or state-specific sources	**Preferred**: Utilize projected IDF curves reflecting projected climate change if available[2] **Alternative**: Use relative increases in precipitation totals following the Clausius–Clapeyron relationship[1]
				Precipitation distribution[3]	NRCS type curves or state-specific curves	**Preferred**: Utilize projected precipitation distribution type curves from climate models **Alternative**: Assume no changes and utilize existing curves
			Regional regression curves	Shape of regional curve[4]	USGS or state-specific sources	**Preferred**: Utilize regional curves with considerations for climate non-stationarity **Alternative**: Utilize theoretical models instead
			Stream gauge analysis	Shape of historical data curve[5]	USGS or local sources	**Preferred**: Utilize stream gauge analyses with data adjustments using regional curves with considerations for climate non-stationarity **Alternative**: Utilize theoretical models instead
	Greater snowfall depths	Stream flows (2-100 year recurrence intervals)	Regional regression curves	Shape of regional curve[4]	USGS or state-specific sources	**Preferred**: Utilize regional curves with considerations for climate non-stationarity **Alternative**: Adjust results of existing regression analyses by a percentage correlated to anticipated snowpack increase
			Stream gauge analysis	Shape of historical data curve[5]	USGS or local sources	**Preferred**: Utilize stream gauge analyses with data adjustments using regional curves with considerations for climate non-stationarity **Alternative**: Adjust results of historical gauge analysis by a percentage correlated to anticipated snowpack increase
Water Level / Chemistry	***Sea-level rise***	-	-	Base tidal elevation	NOAA tidal buoys	**Preferred**: Increase local tidal datums by projected SLR
				Fresh vs. saline water	Local knowledge	**Preferred**: Increase local tidal datums by projected SLR and determine whether freshwater is likely to become saline
	Lake-level rise	Base lake level	Theoretical water budget models	Water depth	Historical data	**Preferred**: Increase average local lake level by the projected lake-level rise as forecast from a revised water budget model **Alternative**: Investigate historical response of lake levels to years with high annual precipitation. Extrapolate lake level trends to projected annual precipitation levels
	Lake-level decrease	Stream channel geomorphology	Theoretical considerations and historical data evaluation	Long-term bed scour	Historical surveys, observed channel characteristics and/or geomorphic surveys	**Preferred**: Adjust stream channel profiles with considerations for lake-level decrease determined from a climate change–influenced water budget model **Alternative**: Investigate historical response of lake levels to droughts and years with lower annual precipitation. Extrapolate lake-level trends to projected maximum drought periods or lower annual precipitation projections
	Increase in ocean salinity	-	-	Water chloride level	Water samples	**Preferred**: Use projected chloride levels over asset life span based on climate research
	Ocean acidification	-	-	Water pH	Water samples	**Preferred**: Use projected maximum pH over asset life span from climate research

Source: Meyer et al 2014

SEPTA's integration of multi-level climate variables into design considerations maps affected design inputs to current, preferred, and alternative practices.

Takeaways: Project Development

- Especially in vulnerable regions, new projects should require pre-established resilient materials and design standards to ensure a minimum risk tolerance while balancing cost-tradeoffs identified through lifecycle cost analysis
- Seeking adaptive cobenefits is a low-cost way to bolster resilience
- Physical interventions have been identified above

Operations and Maintenance

Resiliency can be woven into existing transportation infrastructure through operations and maintenance. As climate impacts and extreme weather events become more frequent, there is an increased need to assess the state of infrastructure not designed to withstand prevailing conditions and address gaps in functionality to maintain appropriate levels of safety. This process of upkeep can be ingrained within a transportation agency through culture, personnel, and practice.

Culture

The culture of maintenance and operations at transit authorities, such as SEPTA, UTA, HART, IVRT, and others, is one of preventative action; in other words, these agencies address potentially threatening issues with infrastructure to "fix before failure" (Amdal 2017). In that way, those working in operations and maintenance departments are the authority's eyes and ears. Frontline staff are those most familiar with current conditions and have a working knowledge of the impacts caused by extreme weather events. At the CTA, these considerations help to model future maintenance costs and resource needs to support budgeting and planning (FTA 2013b). Engaging frontline staff to continuously update operations and maintenance strategies can generate cost savings through proactive practice, especially as climate impacts will continue to grow in frequency and magnitude.

Personnel

The "on-the-ground" staff at transit agencies have institutional knowledge about locational and procedural tactics used to combat climate impacts. For instance, at HART, service workers often know where it is going to flood prior to an event (Amdal 2017). The knowledge that comes from repeat prior exposure can help to color predictive models and bolster agency-wide resiliency efforts. The Maryland Transit Authority (MdTA) harnesses this unique working understanding of the system by including on-the-ground staff on safety committees that address hazards. Similarly, at HART, staffers have the information and training to identify and include resiliency practices into their work responsibilities. By addressing climate resiliency incrementally through these collaborative efforts, agencies build capacity and ensure the long-term viability of such strategies.

Practice

Routine maintenance and inspections are used to collect resilience data at LA Metro; the data collected informs the agency's Environmental Management System that, in turn, informs capital programming. At Muni, operations and maintenance functions similarly: based on previous exposure and impacts, the agency has delineated specific assets to be monitored and maintained more frequently as a form of preventative action. At theMdTA, monthly meetings are used to address maintenance concerns and workshops help to identify problematic site plans and hazardous project elements based on field observations (Maryland Transit Authority 2010). Table 4 identifies operations and maintenance practices.

Table 4: Operations and Maintenance Best Practices

Weather Event	Impact	Operations/Maintenance Strategy
Shifting rain/snow line	Fewer snow and ice precipitation events	Reduced need for winter maintenance operations resources and staff
	Increased snowmelt/rain during the winter season increases the likelihood of flooding, which will generally affect specific roadways and locations, as opposed to the whole network	Shift in resources from winter maintenance to winter flooding monitoring and traveler information
	Temperatures in some areas may shift to or more frequently hover at the freezing point, increasing the probability of ice precipitation instead of snow	Shift in resources from snow to ice management
	Long-term shifting of snow/ice precipitation necessitates reassessment of winter maintenance needs	Monitoring trends to identify and forecast trends of increasing or decreasing snow/ice and frequency of extreme precipitation events
	Longer construction season due to higher temperatures, fewer days with	Altered construction and maintenance schedules

	temperatures below freezing, and less snow/ice precipitation	
Changes in the freeze/thaw cycle	Potential for longer duration and/or shifting of freeze/thaw period	Increased staff to monitor vulnerable areas to post seasonal weight restrictions and make repairs
Increased coastal and inland flooding; increases in intense precipitation events	Greater frequency of flooded, blocked, damaged, and washed out roads	Mandatory diversion to more robust alternate routes, reducing route options/redundancy
		Increased staff and resources to monitor vulnerable routes and provide traveler information
		Broader preparedness for potential evacuation
		Review and update culvert maintenance, stormwater management, and tree trimming programs
		Maintain and update automated system for detecting traffic signals affected by power outages and monitor the battery back-ups at the intersections that would require officers in case of outages
		Reduced (and variable) speed limits
		Contraflow lane operations and ramp management
		Monitor, track, and trim trees regularly
		Increase coordination with utilities that require regular tree trimming services
	Erosion of bridge supports	Increased bridge scour monitoring
Increased frequency, duration, and intensity of	Roadside vegetation dies off	Changes to vegetation management activities

droughts; increase in average air temperature		
	Increased probability of wildfires	Increased staff and resources to monitor vulnerable areas and provide traveler information
Increase in magnitude and duration of severe heat waves	Greater risk of structural damage to bridge joints, rail track, and pavement	Mandatory diversion to robust alternative routes
		Require higher rail-neutral temperatures during track replacement
		Deploy quick maintenance patrols to address potholes and buckling issues
		Reduced (and variable) speed limits
		Truck restrictions
		Plan for the increase in incident management activities
	Higher temperatures may inhibit construction activities	Altered construction and maintenance schedules
	Increase in energy demand for air conditioning	Increased need for more resilient communications and backup power to maintain real-time information feeds
		Maintain HVAC systems

Sources: Committee on Climate Change… 2008, ICF International 2013, Gopalakrishna et al 2013, Amekudzi et al 2013, Meyer et al 2014, New Jersey Climate Adaptation Alliance 2014, Meyer n.d., Radow and Neudorff 2011

Overarching operation and maintenance strategies to incorporate resiliency include:

- Increased and flexible monitoring system
- Integration of sophisticated weather information at transportation operations centers
- Rapid mobilization and deployment teams; flexible resource allocation
- Incorporate technology, such as sensors, that can detect changes in pressure and temperatures in materials to alert when damage thresholds are near approaching.
- Review and augment cross training in emergency response and maintenance tasks.
- Use archival data of macro and micro trends to improve prediction and prepare for long-term trends, which will support the development of effective decision support technology

Takeaways: Operations and Maintenance

- Engaging with frontline staff can capture institutional knowledge and bolster impact forecasting for more robust operations and maintenance practices
- Enhanced data collection can also contribute to more accurate modeling
- Operations and maintenance strategies have been identified above

Emergency Preparedness

Climate impacts to transportation infrastructure are expected to be both chronic and acute; as such, resiliency involves long-term strategies that address the everyday function of facilities and equipment in shifted climates and plans that address system needs during extreme events. To manage hazards, Security and Emergency Management practices identify four stages of emergency preparedness: (1) mitigation, (2) preparedness, (3) response, and (4) recovery. Mitigation through adaptive practice has been largely discussed through modified design standards and resilient operations and maintenance processes. Preparedness concerns hazard identification, planning, training, after action improvements to make alterations to ensure better future response operations, and creating an emergency operations plan. Effective response involves a tiered, scalable, and flexible response backed by a unity of effort. Authorities typically operate under Security Emergency Plans, which delineate standard operating procedure, decision making, project prioritization, and communications. Agencies will often temporarily harden infrastructure or move assets. Finally, recovery is the process by which the agency can resume operations and is often achieved through collaboration with other agencies, outside funding, and rebuilding with an eye towards future resilience. In this vein, entities plan for redundancy, whether communication or physical system planning, to protect the welfare of transportation infrastructure and users. For a checklist transportation assets and resources, please see Appendix 2.

Takeaways: Emergency Preparedness

- Engage in increased data collection efforts to monitor emergency response in order to proactively modify protocol based on previous events and outcomes

Recommendations

Previous sections identified the common barriers facing transportation agencies attempting to institutionalize climate resiliency strategies, as well as the best practices adopted to overcome these challenges. Lessons learned emerge from this comparison. This section will detail domain-specific recommendations for integrating climate resiliency strategies throughout MassDOT and describe mechanisms for incorporating climate considerations in the agency's TAMP.

Barrier-Specific Strategies to Prioritize Climate Adaptation

To institutionalize climate resiliency practices, it is imperative that strategies be adopted across divisions within the agency. That is to say, one-off interventions will not have the support needed to ensure longevity. Rather, actions taken within one branch of the agency should be complemented by actions taken in others.

Lack of Funding

Because there is no climate resiliency policy mandate, large infrastructure owners cite difficulty acquiring funding to sponsor adaptation projects. Arguing that transportation dollars should be spent on climate considerations rather than more public-facing, immediate projects is an uphill battle. To address these concerns, I recommend that (1) leadership renew their commitment to addressing climate concerns, which will ultimately impede the agency's ability to achieve their mission, (2) capital programming shift future funding allocation to reflect climate impacts as a priority, and (3) the agency compile a list of resiliency funding opportunities.

Table 5: Recommendations to Address a Lack of Funding

Strategy	Reasoning	Mechanism
Renewed commitment from upper- and mid-level management	Effective leadership can: • Instill climate resiliency principles in mid-level management and staff • Motivate employees to seek cobenefits during project planning and development or further integrate resiliency strategies into current practice • Prioritize actions that have the potential to address climate impacts, such as applying for resilience-related grants or seek partnerships that contribute to knowledge transfer From review of best practices of other transportation agencies, there is a need to start conversations around incorporating uncertainty into the planning process and determining acceptable levels of risk tolerance; MassDOT leadership is in an advantageous position to begin this process	Reframing the conversation around climate resiliency into one of safety and preparedness may help to convey proactive practice in terms that resonate with staff, especially those who have experienced extreme events first-hand Leadership can initiate conversations around uncertainty an acceptable risk tolerance through more formal venues such as staff meetings and memos, or through everyday conversations emphasizing a common, straightforward language
Address climate impacts proactively through updates to the Capital Investment Plan	Enumerating the agency's commitment to increasing its resiliency to climate impacts through the CIP will ensure that future funding is allocated to efforts	Updating the cost-benefit analysis to reflect lifecycle costs, such as adopting CTA or MARTA's framework, could be instrumental in realizing the costs of proactive vs. reactive climate adaptation implementation and impacting the agency's resource allocation framework
Compile a database of resiliency funding opportunities	Increased knowledge of funding opportunities translates to increased capacity to enact strategies through fund acquisition	Delegate a staff member to building a database detailing relevant funding mechanisms Potential characteristics to note include: funding amount, spending requirements, one-time or cyclic application window, application materials, characteristics of previously successful applicants

Organizational Challenges

Resiliency has yet to become standard practice for state DOTs or regional transit authorities due to sparse funding, which also inhibits an agency's ability to institute comprehensive, climate-specific divisions. MassDOT is no different. As such, I recommend that the agency integrate climate resilience staff throughout existing divisions and encourage new collaborations for knowledge capture.

Table 6: Recommendations to Address a Organizational Challenges

Strategy	Reasoning	Mechanism
Integrated climate resilience dedicated staff	Tasking team members and/or creating several new positions to address climate resiliency measures and assess progress within their division is less costly than establishing a comprehensive team and has been proven to capture institutional knowledge	Realize the need to dedicate additional staff to addressing climate impacts Secure funding through CIP or other mechanisms Hire qualified applicants or train existing employees to ensure the implementation and monitoring of strategies across divisions
Establish new collaborations for knowledge capture	Seeking new partnerships with other agencies and institutions can boost capacity without requiring additional funding Working with partners to compound on existing climate change adaptation and resiliency foundations is more comprehensive and efficient than working independently	Compile a database of ongoing local, regional, and statewide efforts to address climate impacts Reach out to universities to establish partnerships with transportation, planning, and engineering departments, staff members, and/or students

Little-to-No Practice Standardization

Lack of mandated climate resiliency efforts translates to a lack of standard practice in addressing impacts through adaptation strategies. As a result, implementation of efforts are piecemeal. Standardized practices and results enables infrastructure owners to monitor and assess the efficacy of interventions, which combats arguments of climate impact uncertainty and designating funds to resiliency efforts. To address this barrier, I recommend MassDOT update design guidelines more frequently, actively seek cobenefits during project design, and standardize cost accounting for resiliency efforts.

Table 7: Recommendations to Address a Standardization

Strategy	Reasoning	Mechanism
More frequent update of design guidelines	Because climate patterns are shifting, infrastructure will need to withstand different weather events than previously Updating design standards can extend the life of infrastructure and reduce costs by proactively addressing increased maintenance needs of infrastructure designed to historic standards	Review best practices to determine relevant design standards Consult with other transportation agencies to identify relevant standards for heat, precipitation, and ice Periodically update standards to incorporate new climate science/ lessons learned and incorporate lifecycle cost analysis
Actively seek cobenefits during project development stages	Adaptive cobenefits can reduce the strain on infrastructure, mitigate energy consumption, and reduce impacts on ecosystems Less strain on infrastructure reduces maintenance and/or rebuild costs "Two-birds-with-one-stone" mentality is a method of accomplishing goals without requiring extra funding	Identify cobenefit opportunities, present strategies in a manual, establish period in project development window to ensure that designs seek cobenefits Incorporation of resiliency strategies through cobenefits can be implemented in varying effort levels: low (voluntary compliance) or high (regulated mandatory compliance)
Standardize cost accounting for resiliency strategies	Ensures uniform conditions across asset types for decision-making Resulting data can be used to support future arguments regarding cost-effectiveness	Normalize climate impact baseline assumptions to determine lifespan for asset classes Enumerate economic and ecosystem costs, including cascading impacts, in a replicable manner to promote uniform incorporation

Incomplete Data Collection

Without a complete inventory of assets -- including their location, condition, expected lifetime, and criticality -- it is very challenging to fully address climate vulnerability and allocate funds towards those assets that will produce the most benefit for the least cost. Though MassDOT already practices thorough operations and maintenance, the agency should focus on expanding the scope and scale of data collected, especially post-extreme weather event, and training frontline staff to recognize climate-related impacts.

Table 8: Recommendations to Address a Data Collection

Strategy	**Reasoning**	**Mechanism**
Expand the scope and scale of data collected	Obtaining more thorough and complete data following post-extreme weather events will expand the agency's knowledge of impacts and ability to model future scenarios	Integrate with standard operations and maintenance procedures by increasing the frequency following select events Incorporate climate impacts by adding a checkbox on existing reporting paperwork
Train frontline staff to recognize climate-related impacts	Enhanced quality of data collected will enable more accurate forecasting and provide evidence for the efficacy of investing in climate resilience strategies	Training sessions with frontline staff

Modeling Uncertainty

Climate change projections are uncertain due, in large part, to scientific capability and unknown future behavior. As a result, modeled climate impacts severity and probability of occurrence can vary based on underlying assumptions. These model outputs, then, are not readily expressed in engineering terms. For these reasons, I recommend that MassDOT rely on institutional knowledge, modify models periodically to reflect the best available science and technology, and provide a mechanism for translating model outputs to engineers.

Strategy	Reasoning	Mechanism
Reliance on institutional knowledge	Institutional knowledge can supplement gaps in quantitative knowledge and fill holes in modeling efforts	Interview key staff members and inventory knowledge not already captured
Modify models often to reflect best available science and technology	Science-backed prioritization of critical infrastructure builds credibility, especially when competing for limited funding Frequent updates ensure that costs are most accurately accounted for in the decision making process	Periodic monitoring and revision of plans and standards
Translate modeling outputs to engineers	Addressing gaps in communication will allow for more successful implementation of climate resiliency efforts	Establish guidelines on translating modeling outputs to engineering standards based on conversations with research teams

Costs Not Fully Captured

Climate change resiliency efforts are not prioritized in part because the full extent of potential costs given future impacts are not captured. To account for this barrier to prioritization, I recommend that the agency modify their cost benefit analysis practice, expand data collection, and pursue adaptive cobenefits.

Table 9: Recommendations to Address Cost Capture

Strategy	Reasoning	Mechanism
Modify cost-benefit analysis	Updating the cost-benefit analysis to could be instrumental in realizing the costs of proactive vs. reactive climate adaptation implementation and impacting the agency's resource allocation framework	Adopt lifecycle cost techniques, such as adopting CTA or MARTA's framework
Expand data collection	Obtaining more thorough and complete data following post-extreme weather events will expand the agency's knowledge of impacts and ability to model future scenarios	Integrate with standard operations and maintenance procedures by increasing the frequency following select events Incorporate climate impacts by adding a checkbox on existing reporting paperwork
Pursue adaptive cobenefits	Cost-minimizing strategy to reduce impacts	Identify cobenefit opportunities and present strategies in a manual Establish period in project development window to ensure that designs seek cobenefits Incorporation of resiliency strategies through cobenefits can be implemented in varying effort levels: low (voluntary compliance) or high (regulated mandatory compliance)

There is an overarching need for a resiliency plan with measurable outcomes that touches on all domains and enables MassDOT to set goals, measure the agency's progress, and evaluate success systematically; such a plan can be found below and should be updated periodically based on the outcome of resiliency indicator framework.

Approaching Climate Resiliency through TAMP

One of the important characteristics of TAM as it relates to extreme weather events is the emphasis on life-cycle costs, considering the costs and benefits of an asset over its entire useful life from project inception to asset removal. Thus, any hazard or stressor that affects the future condition and performance of an asset becomes an important consideration in the timing of rehabilitation and replacement. Effective TAM requires a history of good data, including knowledge about the assets, their condition, performance, and other characteristics that relate to the life of the asset and its ability to continue to provide reliable, safe service. The focus on monitoring asset condition, evaluating performance, and data-driven decision-making reinforces the relevance of TAM as a platform for mitigating the impacts of extreme weather events on transportation infrastructure.

- Michael Meyer (PhD MIT '78), AASHTO, "Integrating Extreme Weather Risk into Transportation Asset Management"

Transportation asset management is a risk-based program that incorporates lifecycle planning to operate, maintain, and improve physical assets at a minimum cost. However, current regulation does not require agencies to investigate climate-related impacts or identify and plan for assets other than pavement and bridges, changing climate conditions threaten a variety of assets. The systematic approach to decision-making that ensures bridges and pavement maintain a state of good repair in TAM anticipates and responds to threats, not unlike climate hazards. For these reasons, AASHTO and TRB have identified asset management practices as an opportunity to institutionalize climate resiliency within transportation agencies. As risk assessment and climate models develop, considerations can be phased in over iterations of an agency's TAMP. For these reasons, I suggest MassDOT incorporate climate considerations into the next update of their transportation asset management plan.

Among other requirements, TAMPs must: inventory assets, assess conditions, and determine potential risk, promote through maintenance practices to achieve a state of good repair, establish priorities for asset repair, and develop cost data for maintenance. These practices provide framework for agencies to monitor vulnerability, asses changing climate conditions and their impact on asset performance, determine risk over time with changing conditions, change design standards, and adopt flexible adaptation pathways. MARTA has identified opportunities to integrate climate change adaptation into asset management plans. Similarly, the National Cooperative Highway Research Program has mapped climate resiliency strategies to TAMP sections (Table 10). For a sample of a standalone template to address climate change as a section with the TAMP report, please see Appendix 5.

Table 10: Integrating Climate Resiliency into TAMP

TAMP Component	Opportunity to Integrate Climate Resiliency
Asset inventory and conditions	Summarize and identify climate conditions
Asset management objectives and measures	Define objectives, level of service, types of assets, and short to long term targets for resiliency, redundancy, evacuation and recovery
Performance gap assessment	Define short and long-term planning horizons; illustrate performance gap
Lifecycle cost considerations	Quantify tradeoffs associated with minimizing vulnerability proactively
Risk management analysis	Identify risk and most vulnerable assets; include risk register
Financial plan	Determine funding mechanisms to reduce system risk
Investment strategies	Describe approaches to minimizing risk
Investment process strategies	Identify priorities and incorporate lessons learned from disruptions

Source: FTA 2013c, Meyer and Flood 2015

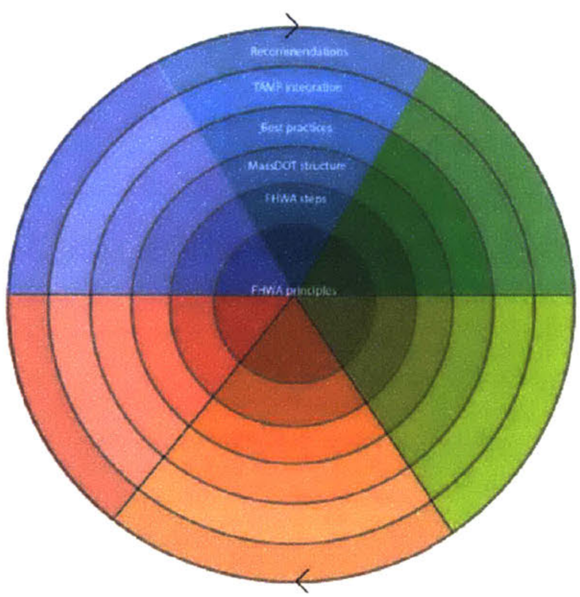
There is significant crossover between domain-specific recommendations and the mechanisms through which to integrate climate resiliency into MassDOT's next TAMP update. Pursuing both within the context of a larger resiliency plan will help to systemize implementation, measure progress, and generate accountability moving forward.

Conclusions

MassDOT, like many other transportation agencies, faces tremendous barriers to implementing climate resiliency strategies. A lack of funding inhibits the agency in two key ways: an understaffed climate resiliency team and a lack of project prioritization in the face of short-term, highly visible projects. Because climate-modeling forecasts are for a range of scenarios and are largely uncertain, projects can face substantial arguments regarding the variability of impact and the need to prioritize climate resiliency. In part, this is because costs and benefits of adaptation and mitigation are not fully realized in the analyses that support decision-making.

Using the FHWA's vulnerability assessment adaptation framework, MassDOT can integrate the recommendations described previously to overcome the barriers to institutionalizing climate resiliency. These actions span various departments to holistically address barriers. Additionally, strategies include a framework for incorporating actions through the TAMP process, which can provide a systematic structure for (1) evaluating climate risks, (2) identifying operational and maintenance interventions to support a state of good repair in the face of elevated climate impacts, and (3) accounting for lifecycle costs and criticality as a decision-making framework. This system can be visualized in Figure 5, below, and more comprehensively in Figures 6-11.

Figure 5: Visualizing Recommendations within the FHWA Framework



Within each FHWA principle of vulnerability assessment are corresponding steps, departments within MassDOT, best practices, TAMP process intervention, and overarching recommendation. The vulnerability assessment's first step is to articulate objectives; then the agency must obtain asset data, select and characterize assets, assess vulnerabilities, integrate the results into decision-making, and monitor and revisit.

Figure 6: Articulating Objectives

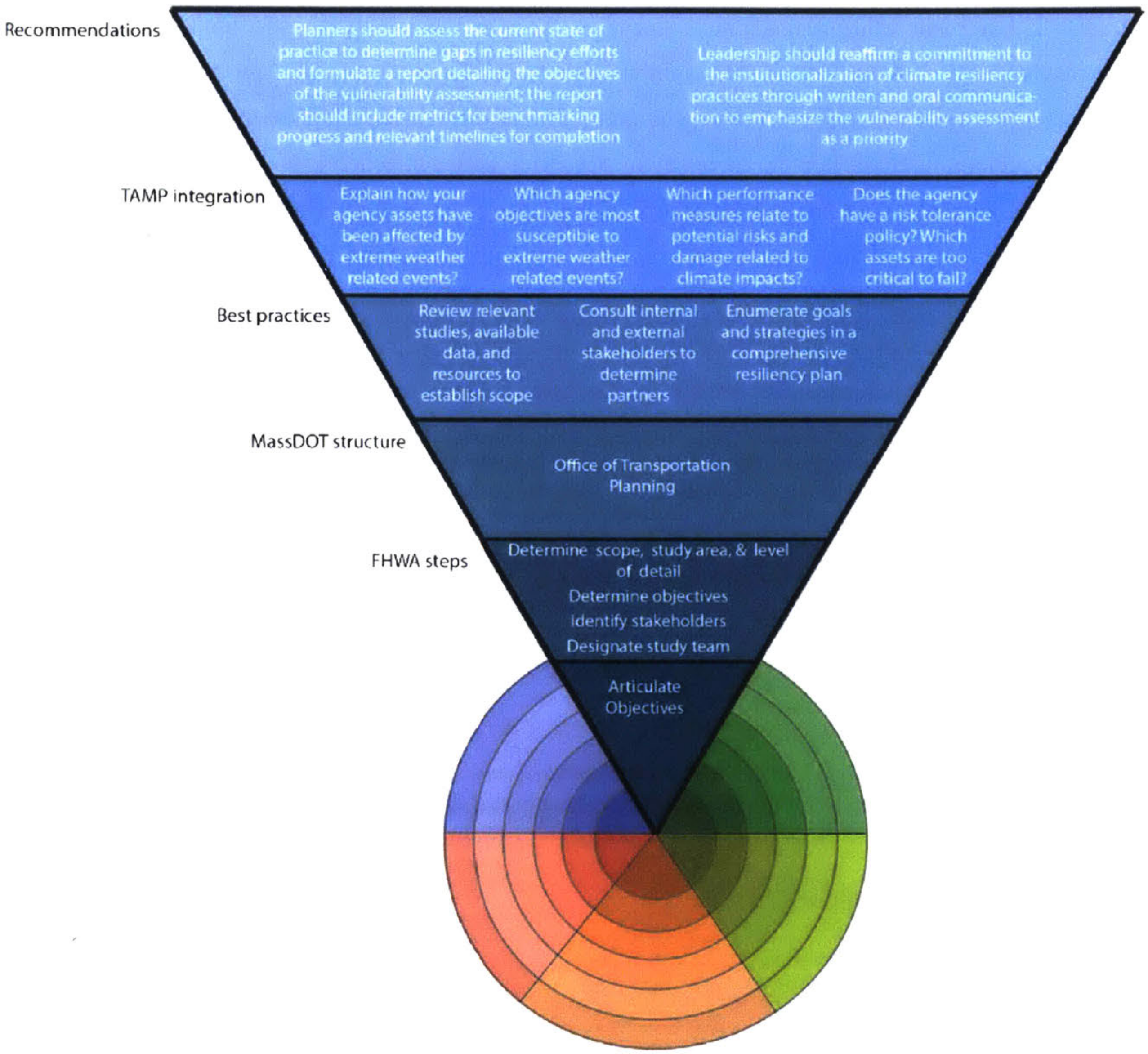


Figure 7: Obtaining Asset Data

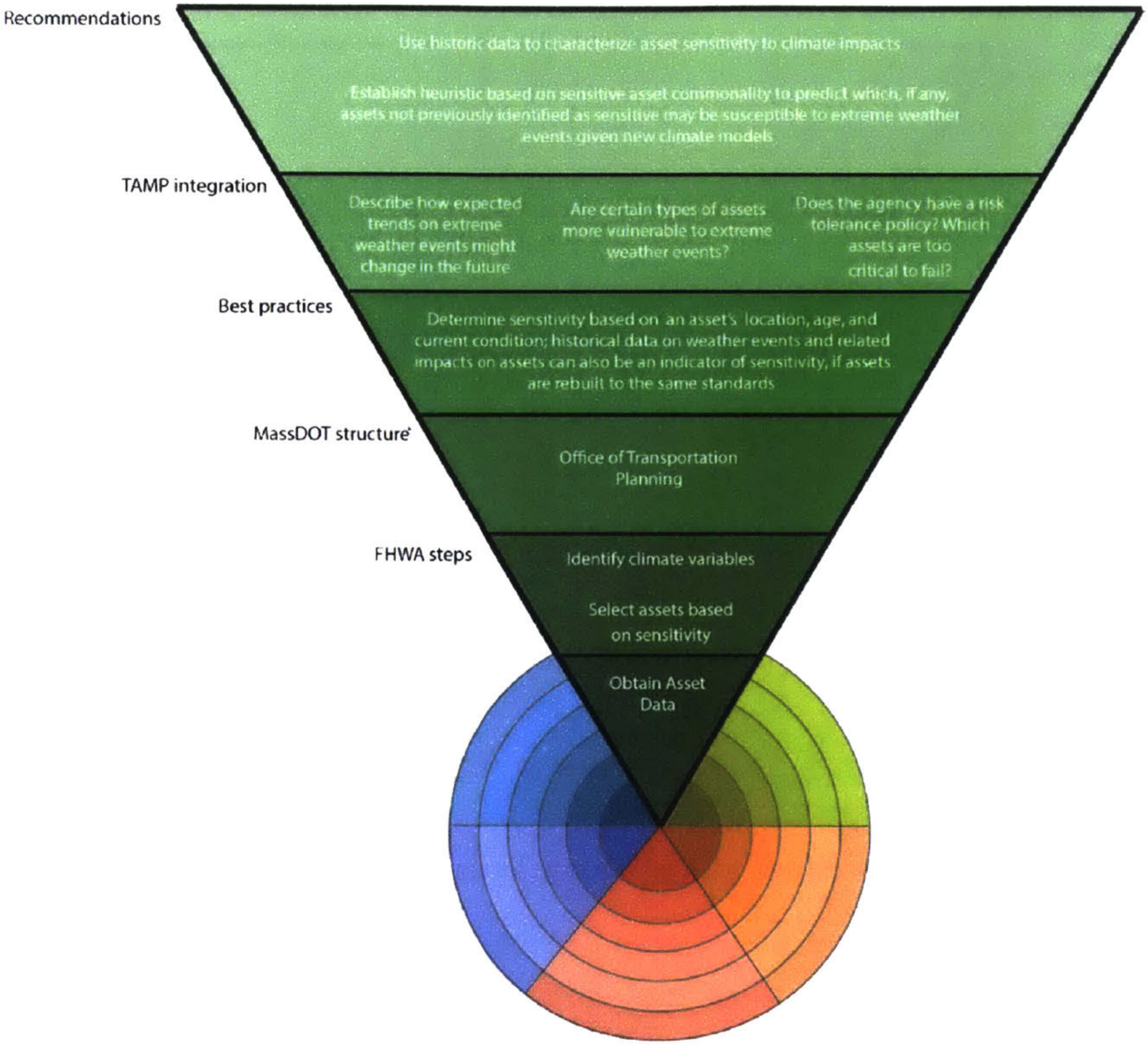


Figure 8: Selecting and Characterizing Assets

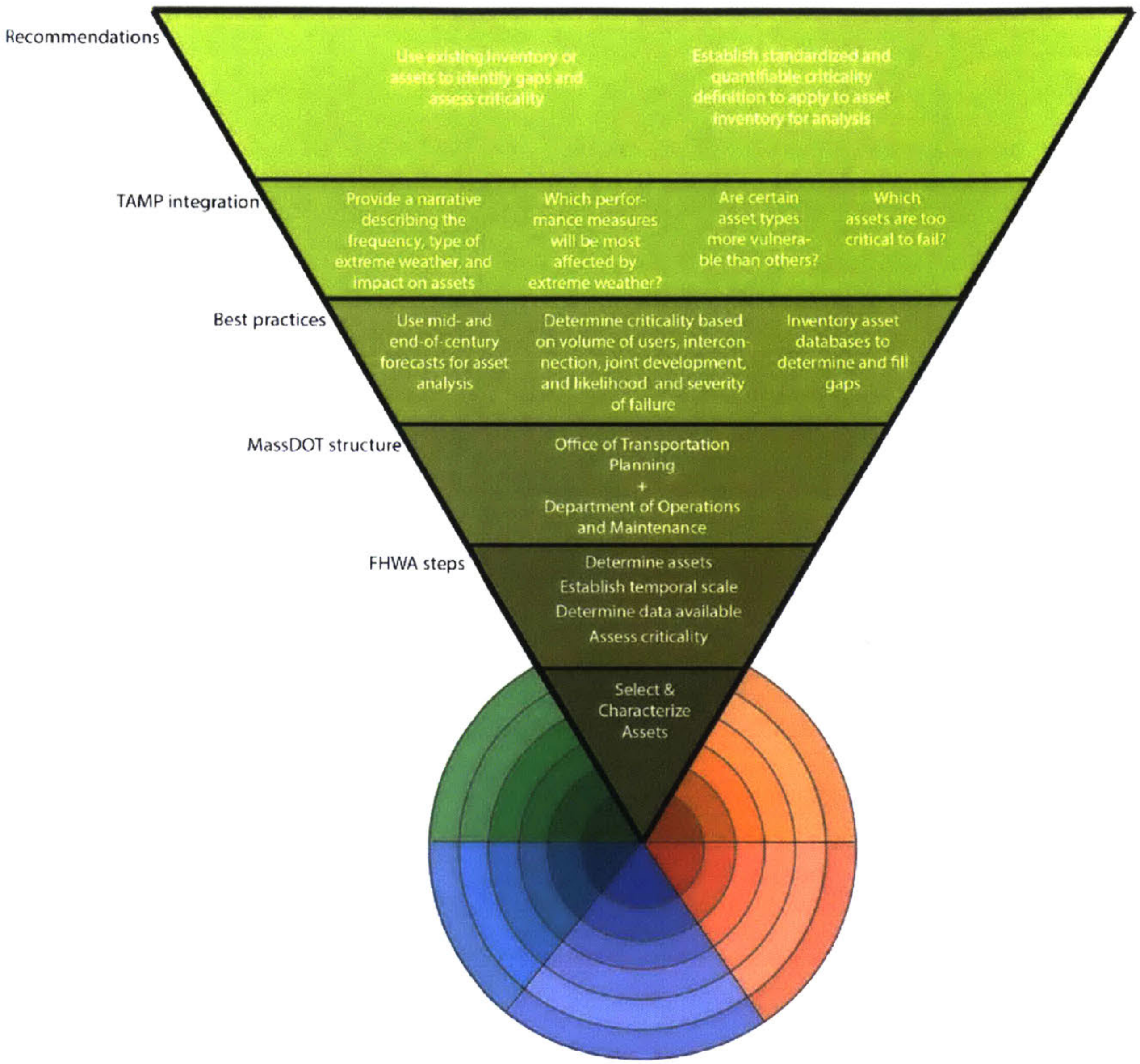


Figure 9: Assessing Vulnerabilities

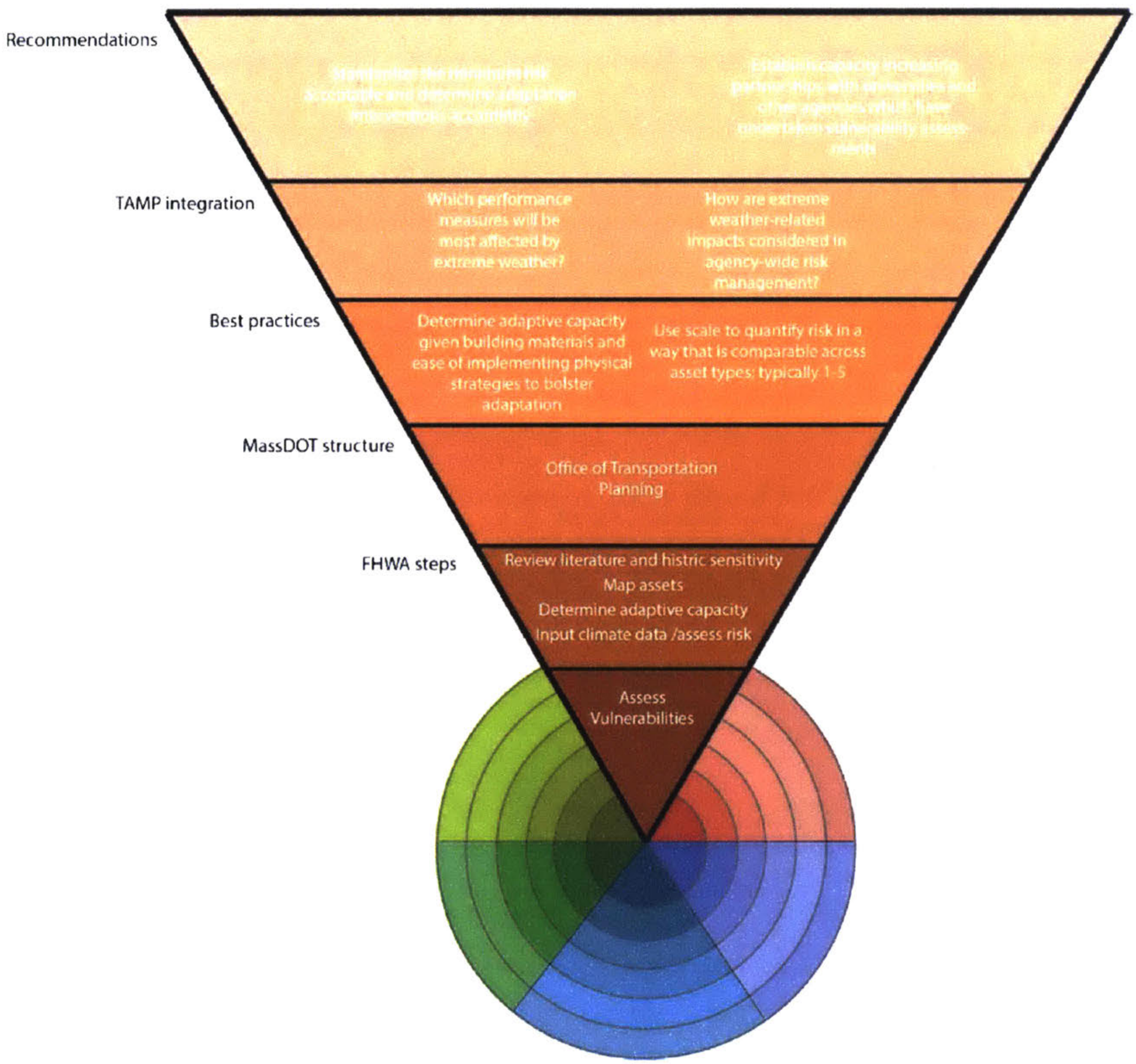


Figure 10: Integrating Results into Decision-Making

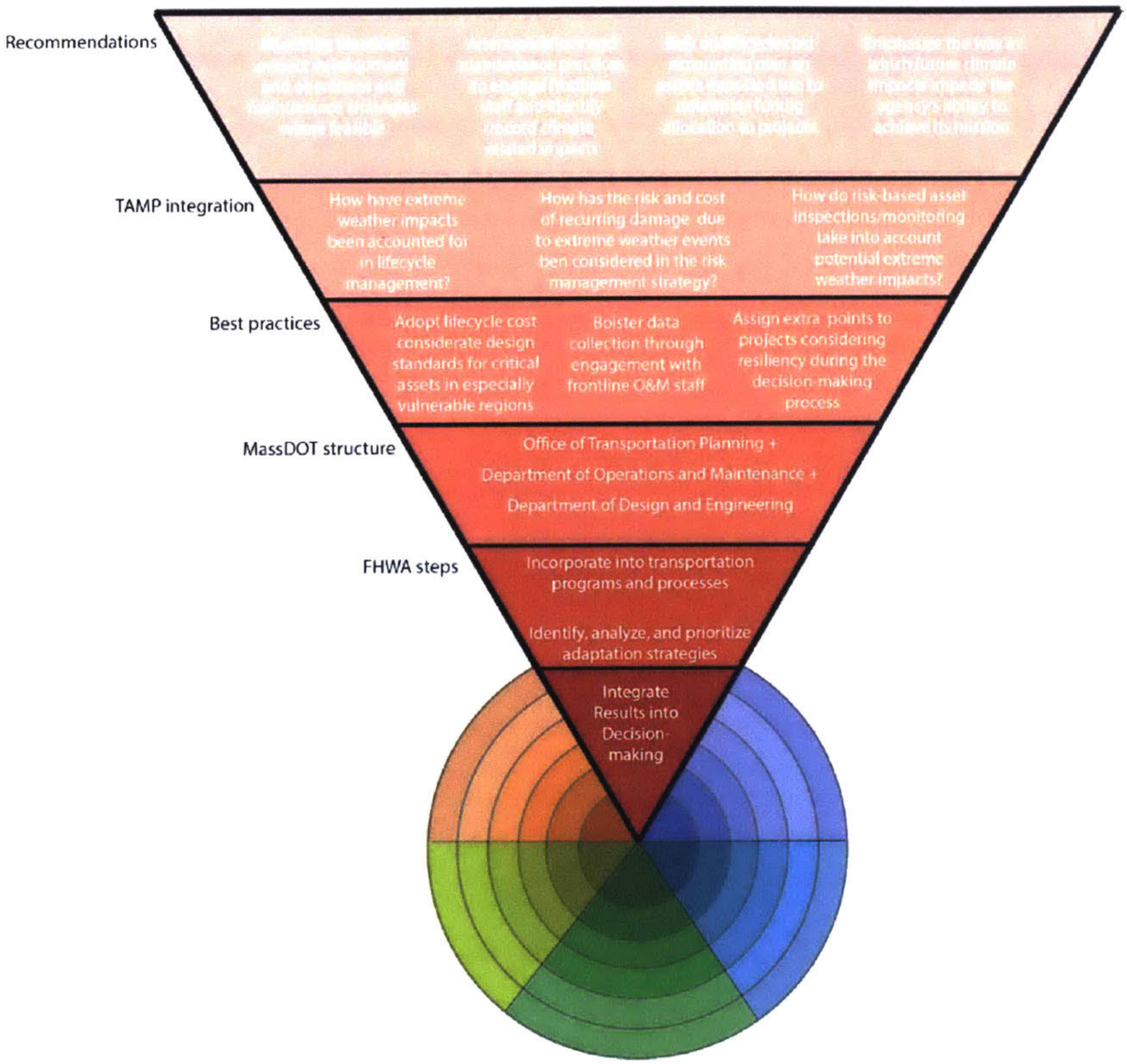
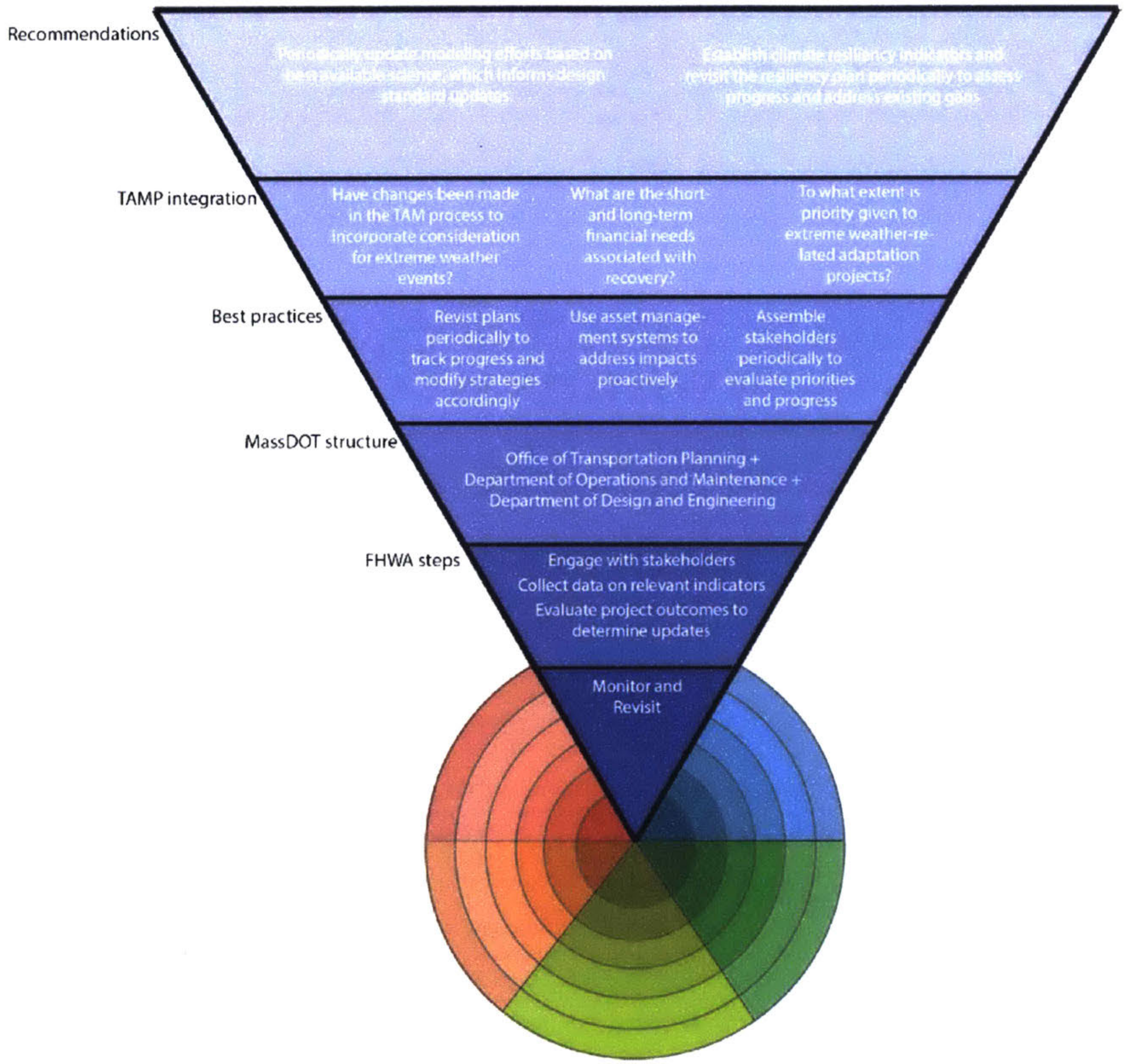


Figure 11: Monitor and Revisit



MassDOT, and other large transportation infrastructure owners concerned with the impacts of climate change, can identify, assess, and integrate adaptation measures using the FHWA's vulnerability assessment framework to adopt department- and division-wide initiatives. Moving forward, I recommend the agency prioritize three strategies, each at varying effort levels.

The highest priority initiative is for MassDOT to build a resiliency framework strategy (see Figure X for an example). Dedicating a team within the Office of Transportation Planning to explicitly enumerating agency-wide goals, mechanisms for reaching targets, and relevant progress indicators will enable the adoption of a comprehensive set of strategies. Additionally, the process of goal setting and monitoring will allow the team to account for available resources, identify gaps in knowledge and abilities, and determine a context-specific scope. Enabling progress monitoring will increase transparency and promote accountability, in addition to identifying regions for improvement and mechanisms for improving. This visible, mid-level effort will strategically position the agency to move forward with a comprehensive strategy.

Additionally, the agency should adopt lifecycle cost analysis to determine project standards, funding, and prioritization. By integrating forecasted climate impacts with the expected lifetime of an asset, the net present value of project will reflect the cost of adopting practices that do not reflect resiliency principles. Using lifecycle cost analysis to frame resource allocation decisions is a financially and politically sound mechanism for promoting resiliency institutionalization and will require updating cost-accounting software and/or consulting agencies that have adopted similar strategies (MARTA and CTA) to integrate the changes into the existing system. Though this process will require high levels of effort upfront, cost accounting is critical to decision-making across the agency and, therefore, adopting lifecycle cost analysis has the greatest opportunity to institutionalize resiliency efforts.

Finally, the Department of Operations and Maintenance should adopt a practice of increased data collection. Not only should the frequency of data inventory and condition assessment be more frequent following extreme weather events, but frontline staff should be trained to identify and record climate-specific impacts on assets. These alterations are low cost and low effort, as the strategy can be integrated into the existing frontline operations and maintenance paperwork. More comprehensively tracking data will enable better forecasting of future climate impacts, which will not only validate climate models, but provide historic data on which to base future lifecycle cost analysis.

In establishing an overarching resiliency framework strategy, addressing lifecycle costs, and updating operations and maintenance processes, MassDOT can address and overcome barriers to institutionalizing climate resilience.

Appendix 1: CTA's Life-Cycle Cost Model

Life-Cycle Cost Model

Description of Model

A life-cycle cost analysis (LCCA) model was constructed to compare the infrastructure investment costs (i.e., build scenarios) against the costs of no action (no-build scenarios) for each of the three issues described above. The model was developed in a manner to provide flexibility to allow for different weather event frequencies and cost assumptions to be tested to determine the sensitivity of the model to inputs for a given scenario. This flexibility also allows for future modification of inputs by CTA or peer agencies to support additional case studies.

Principles of Good Practice

Principles of good practice are based upon the application of an LCCA to various infrastructure projects as promoted by the USDOT and the Office of Management and Budget.

The LCCA level of detail should be consistent with the level of detail of investment. LCCA need only consider differential costs among alternatives, as costs common to all alternatives are effectively canceled out. However, all LCCA factors and assumptions should be addressed, even if limited to an explanation of the rationale for not including eliminated factors in detail. Sunk costs should not be included.

The LCCA time horizon should be sufficient to reflect long-term cost differences associated with reasonable design strategies. For this project, a time horizon of 2050 was used, which is the equivalent to the general lifespan of proposed capital improvements before major repairs or upgrades would be required.

Net present value (NPV) is the economic efficiency indicator of choice as it compares the value of money today to money in the future, allowing for an accurate comparison of the value of an initial capital cost against future operating costs. Future cost and benefit streams are be estimated in constant dollars and discounted to the present using a real discount rate.

Discount rates employed in LCCA should reflect historical trends. Although long-term trends for real discount rates hover around 4 percent, with 3–5 percent considered an acceptable range. For public agencies, a 3–3.5 percent discount rate is typically applied; this analysis applied a 3.5 percent discount rate for a more conservative estimate of future benefits.[17]

Routine annual maintenance costs have only a marginal effect on NPV and should be equivalent across the alternatives. For these analyses, the maintenance costs that would be incurred above the basic preventative maintenance procedures are included to evaluate the effectiveness of different alternatives over the lifespan of the improvement.

Basic Model Architecture

The basic model architecture was developed an Excel spreadsheet format to allow adjustment of input assumptions as cost information and climate projections are refined. The model run template shown in Table 2-19 consists of four main input areas:

- Results
  - Inputs are given for baseline and multiple frequencies for severe weather events
  - Outputs are given as 2050 NPV values based on different event frequencies
- Model No-Build Cost Assumptions
  - No-Build Service Costs
    - CTA Service Costs are the operating costs calculated for slow zones, single tracks, and bus shuttles.
    - CTA Revenue Costs is the lost revenue from passengers opting for other modes of transportation during service disruptions.
    - Passenger Value-of-time is the value of passenger time for the delays associated with bus shuttles and slow zones.

[17] This is consistent with values historically reported from the Office of Management and Budget (OMB) [26].

  - No-Build Maintenance Costs are costs beyond routine preventative maintenance that would be necessary in the absence of proposed capital improvements.
  - No-Build Repair Costs are the costs of repairs due to a severe weather event that would be necessary in the absence of proposed capital improvements.
- Model Capital Cost Assumptions
  - One-Time Capital Improvement Costs are the costs developed as part of the engineering analysis necessary to adapt infrastructure to severe weather events.
  - Ongoing Capital Improvement Costs are maintenance costs incurred after construction are complete; used only if there is a difference among build scenarios.
- Model Base Assumptions
  - Discount rate assumed to calculate NPV
  - Baseline year to be used as basis for NPV cost analysis

Subsequent tabs of the LCCA model calculate the "savings" and "costs" for each given year of the model run, and final "NPV" column indicated when the return on investment turns from negative to positive (see Tables A-2 and A-3). The model run template is given in Table 2-18; elements highlighted in green are inputs, elements highlighted in blue are calculations, and elements highlighted in yellow are outputs.

Model Run - Template			
Results	Frequency Increase	Events / Year	2050 NPV
Baseline	1.0	2	$ 8,631,090
Frequency 1	1.5	3	$ 10,350,480
Frequency 2	2.0	4	$ 12,069,870
Frequency 3	3.0	6	$ 15,508,649
Model No Build Cost Assumptions			
No-Build Service Costs	Weekday Cost / Day	Days	Cost / Incident*
CTA Service Costs			
Slow Zones	$ 2,500	120	$ 300,000
Bus Bridges	$ 250,000	0.25	$ 62,500
CTA Revenue Costs	$ 10,000	0.25	$ 2,500
Passenger Value of Time	$ 10,000	0.25	$ 2,500
Total			$ 367,500
No-Build Maintenance Costs	Cost / Year		
Work Involved	$ 20,000		
No-Build Repair Costs	Cost / Incident		
Work Involved	$ 15,000		

Model Capital Cost Assumptions			
One-Time Capital Improvement Costs			
Work involved	$ 500,000		
On-Going Capital Improvement Costs			
Work involved	$ 50,000		
Model Assumptions			
Discount Rate	3.5%		
Baseline Year	2013		

After each base model run was completed, sensitivity testing was performed on no-build and build inputs (as defined earlier in this report) to determine the variability of the outputs. With each model run, a single test variable is altered, while all other variables are held constant.

Results of LCCA Model Runs

ROW Flooding

The baseline model run for right-of-way flooding is shown in Table 2-19.

Model Run - ROW Flooding (Base)			
Results	Frequency Increase	Events / Year	2050 NPV
Baseline	1.0	0.04	$ (58,836)
Frequency 1	1.5	0.06	$ 79,467
Frequency 2	2.0	0.08	$ 217,770
Frequency 3	3.0	0.12	$ 494,376
Model No Build Cost Assumptions			
No-Build Service Costs	Weekday Cost / Day	Days	Cost / Incident
CTA Service Costs			
Slow Zones	$ 2,600	0	$ -
Bus Bridges	$ 59,286	1.00	$ 59,286
CTA Revenue Costs	$ 29,391	1.00	$ 29,391
Passenger Value of Time	$ 173,127	1.00	$ 173,127
Total			$ 261,804
No-Build Maintenance Costs	Cost / Year		
None	$ -		
No-Build Repair Costs	Cost / Incident		
Labor to dry out and restore systems	$ 70,000		
Model Capital Cost Assumptions			
One-Time Capital Improvement Costs			
Construction of drainage retention system	$ 287,940		
On-Going Capital Improvement Costs			
Pump annualized maintenance	$ 2,880		
Model Assumptions			
Discount Rate	3.5%		
Baseline Year	2013		

Flooding Event Frequency Sensitivity

Using the baseline value of one event of four inches of rain in a single day every 25 years (= 0.04 events/year) from the CCAP projection data results in a negative return on investment over the specified time horizon. By increasing the anticipated frequency by 1.5 times (one event every 16.7 years), the model yields a positive return by 2050 Looking at the highest modeled frequency of a severe precipitation event every 8.33 years yields significant positive return. In recent decades, storm events of this magnitude have been occurring less than every eight years, so it is feasible that observed flooding events will exceed CCAP projections and trend toward the higher end of the frequency range.

No-Build Cost Sensitivity

For the No-Build Service Costs, the highest value is the passenger value-of-time. While this cost is a common input to LCCA and cost-benefit analyses, it is instructive to test sensitivity from removing this less tangible variable. Table

2-21. Column 5 shows the impact of removing the passenger value-of-time from the model, which results in a positive return on investment only for the highest flooding frequency.

Capital Cost Sensitivity

Another model run illustrates a scenario in which the proposed improvement required twice the capital costs originally estimated, with results shown in Table 2-20, Column 3. In this scenario, the return is positive only for the highest frequency.

ROW Flooding Model Runs			Base	Double Capital Cost	No Passenger Value of Time
Results	Multiplier	Events / Year	2050 NPV	2050 NPV	2050 NPV
Baseline	1.0	0.04	$ (58,836)	$ (337,039)	$ (203,163)
Frequency 1	1.5	0.06	$ 79,467	$ (198,736)	$ (137,023)
Frequency 2	2.0	0.08	$ 217,770	$ (60,433)	$ (70,883)
Frequency 3	3.0	0.12	$ 494,376	$ 216,173	$ 61,398

Summary

Event frequency has a significant sensitivity impact on the model runs to quantify potential flooding impacts. None of the model runs displayed a positive return on investment by 2050 using the CCAP baseline flooding event frequency; however, all scenarios displayed a positive return at the high end of the frequency scale. Thus, it is necessary to closely monitor frequency trends for flooding events to determine cost-effectiveness of the proposed improvements.

The passenger value of time resulted in the largest impact to the cost-effectiveness of the project. While this factor may be less tangible than other variables, it is critical to the core mission of a transit agency, and thus should be appropriately reflected in the analysis. Doubling capital costs has a less significant impact than removing passenger value of time, but careful estimation of capital costs is still required to ensure that the project is cost-effective.

Rail Heat Kinks

Two model templates were developed for the rail heat kink analysis reflecting the two different build scenarios: upgraded ballasted track (Table 2-21) or direct fixation track (Table 2-22). Both templates shared common data values, with the exception of initial capital costs, and the lack of ongoing maintenance costs for the direct fixation scenario.

Model Run - Rail Kinks Ballasted Construction (Base)			
Results	Frequency Increase	Events / Year	2050 NPV
Baseline	1.0	2	$ 7,728,387
Frequency 1	1.5	3	$ 13,216,997
Frequency 2	2.0	4	$ 18,705,607
Frequency 3	3.0	6	$ 29,682,826
Model No Build Cost Assumptions			
No-Build Service Costs	Weekday Cost / Day	Days	Cost / Incident*
CTA Service Costs			
Slow Zones	$ 3,315	60	$ 198,900
Bus Bridges	$ 28,359	0.25	$ 7,090
CTA Revenue Costs	$ 7,666	0.25	$ 1,917
Passenger Value of Time			
Slow Zones	$ 3,801	60	$ 228,060
Bus Bridges	$ 45,156	0.25	$ 11,289
Total			$ 447,255
No-Build Maintenance Costs	Cost / Year		
Additional surfacing	$ 137,000		
No-Build Repair Costs	Cost / Incident		
Repairing damaged rail	$ 15,000		
Model Capital Cost Assumptions			
One-Time Capital Improvement Costs			
New ballasted track structure	$ 9,199,000		
On-Going Capital Improvement Costs			
Annual surfacing	$ 68,500		
Model Assumptions			
Discount Rate	3.5%		
Baseline Year	2013		

* For slow zones, the cost is per year

Model Run - Rail Kinks Direct Fixation Construction (Base)			
Results	Frequency Increase	Events / Year	2050 NPV
Baseline	1.0	2	$ 7,008,659
Frequency 1	1.5	3	$ 12,497,268
Frequency 2	2.0	4	$ 17,985,878
Frequency 3	3.0	6	$ 28,963,098
Model No Build Cost Assumptions			
No-Build Service Costs	Weekday Cost / Day	Days	Cost / Incident
CTA Service Costs			
Slow Zones	$ 3,315	60	$ 198,900
Bus Bridges	$ 28,359	0.25	$ 7,090
CTA Revenue Costs	$ 7,666	0.25	$ 1,917
Passenger Value of Time			
Slow Zones	$ 3,801	60	$ 228,060
Bus Bridges	$ 45,156	0.25	$ 11,289
Total			$ 447,255
No-Build Maintenance Costs	Cost / Year		
Additional surfacing	$ 137,000		
No-Build Repair Costs	Cost / Incident		
Repairing damaged rail	$ 15,000		
Model Capital Cost Assumptions			
One-Time Capital Improvement Costs			
New ballasted track structure	$ 11,353,000		
On-Going Capital Improvement Costs			
None	$ -		
Model Assumptions			
Discount Rate	3.5%		
Baseline Year	2013		

* For slow zones, the cost is per year

Frequency Sensitivity

Available CTA Control Center data showed that in 2011 there were seven heat kink incidents on the CTA rail system, with two slow orders implemented on the Orange Line. It is assumed that the heat related incidents were grouped into the two slow-order areas, based on data provided by CTA Infrastructure. For this analysis, the baseline assumes two heat kinks impacting operations per year, and according to CCAP data, the frequency of consecutive days over 90° is predicted to double. Therefore, for purposes of this analysis, the baseline was set at 2 incidents per year, and additional scenarios of 1.5, 2, and 3 times baseline frequencies were examined to determine the sensitivity due to projected increases in prolonged heat events.

Capital Cost Sensitivity

Columns 2 and 3 of Table 2-23 compare returns on investment for the upgraded ballasted track solution and the novel direct-fixation solution. Despite lower initial capital costs for the former and lower annual maintenance costs for the latter, returns on investment within the time horizon are nearly identical; thus, capital cost sensitivity under this scenario is extremely low.

No-Build Cost Sensitivity

Slow zones in 2011 lasted for a total of four months each, but a slow-zone service cost accumulation at higher frequencies would exceed the total days per year. Therefore, the base model assumes 60 days as a baseline duration for all slow zones. Bus shuttles were limited to 0.25 days per incident, as these repairs are typically performed under traffic (or in the case of the Orange Line, after service hours).

An alternative model run compares results if the average slow zone duration is reduced to 30 days (Table 2-23, Column 4); this scenario reduces overall benefits, as adverse impacts are also reduced. A final model run illustrates the effect of removing passenger value-of-time from consideration; this scenario yields a negative return on investment for all event frequencies, underscoring the passenger impacts of a combined service disruption and prolonged slow zone.

Rail Kink Model Runs			Ballasted (Base)	Direct Fixation (Base)	Ballasted (30 Day Impact)	Ballasted (No PVT)
Results	Frequency Increase	Events / Year	2050 NPV	2050 NPV	2050 NPV	2050 NPV
Baseline	1.0	2	$ 7,728,387	$ 7,008,659	$ 902,723	$ (2,248,200)
Frequency 1	1.5	3	$ 13,216,997	$ 12,497,268	$ 4,014,823	$ (1,747,883)
Frequency 2	2.0	4	$ 18,705,607	$ 17,985,878	$ 7,126,924	$ (1,247,567)
Frequency 3	3.0	6	$ 29,682,826	$ 28,963,098	$ 13,351,125	$ (246,934)

Summary

The rail kink build scenarios show potential significant returns on investment due to the high costs incurred by CTA for each rail buckling incident. A subsequent sensitivity analysis reveals a low sensitivity to capital costs (i.e., ballasted vs. direct fixation scenarios), a moderate sensitivity to slow zone duration, and a high sensitivity to passenger value of time, due to extended slow zone durations.

Signal House Overheating

Signal house overheating build scenarios have the lowest capital costs of the three situations analyzed, and also pose the lowest operation costs, since slow zones imposed by signal failures do not cause a total disruption of service.

Base case assumptions include a lower-end capital cost estimate of $30,000, a quarter-day slow zone (including one rush period) required to resolve the signal house failure, and passenger value of time incurred for the duration of the slow zone (see Table 2-24).

Model Run - Signal House Overheating ($30,000 Capital Cost)			
Results	Frequency Increase	Events / Year	2050 NPV
Baseline	1.0	1	$ 228,084
Frequency 1	1.5	1.5	$ 356,619
Frequency 2	2.0	2	$ 485,154
Frequency 3	3.0	3	$ 742,223
Model No Build Cost Assumptions			
No-Build Service Costs	Weekday Cost / Day	Days	Cost / Incident
CTA Service Costs			
Slow Zones	$ 3,315	0.25	$ 829
Bus Bridges	$ -	0.00	$ -
CTA Revenue Costs	$ -	0.00	$ -
Passenger Value of Time (Noon - 6pm)	$ 11,206	1.00	$ 11,206
Total			$ 12,035
No-Build Maintenance Costs	Cost / Year		
None	$ -		
No-Build Repair Costs	Cost / Incident		
Labor to fix A/C unit	$ 300		
Model Capital Cost Assumptions			
One-Time Capital Improvement Costs			
New A/C only (low)	$ 30,000		
On-Going Capital Improvement Costs			
None	$ -		
Model Assumptions			
Discount Rate	3.5%		
Baseline Year	2013		

Sensitivity to Severe Weather Event Frequency

Based on available CTA Control Center data, failures were either linked to A/C units not working due to deferred maintenance or to disruptions in ComEd service. The data as currently aggregated are not specific enough to reliably correlate signal failures and severe weather events; thus, for purposes of the current analysis, it is assumed that there is one failure per cooling season per signal house.

The projected increase in temperatures will place a larger load on individual A/C units and the broader ComEd system, with a prediction that the number of cooling degree days will increase by 1.25 times. Given the uncertainty of the base data, the same relative frequency multiplies are used as with the previous two case studies.

Capital Cost Sensitivity

Capital cost sensitivity was tested by comparing the lowest capital cost assumption (i.e., install backup A/C system) against the highest capital cost assumption (i.e., install new dual A/C system & generator tap box) for signal house improvements, as illustrated in Table 2-25, Columns 2 and 3, which yields a very slight margin for 2050 NPV in each of these cases.

No-Build Cost Sensitivity

Passenger loads are a major factor for the signal house overheating analysis. The base model run represents ridership for a high-ridership segment of the Blue Line. If the number of riders were reduced by 50 percent, as reflective of some lower volume rail branches (e.g., CTA Yellow, Pink, Orange, and Green Lines), the model run shows a moderately reduced return on investment, as shown in Table 2-25, Column 4.

Finally, as for previous cases, an additional model run illustrates 2050 NPV without incorporating passenger value of time (Table 2-25, Column 5). This run yields a positive return for all but the baseline frequency, revealing relatively lower sensitivity for this variable than rail heat kinks.

Signal House Overheating Model Runs			Low Capital Cost	High Capital Cost	Low Capital Cost (Low Ridership)	Low Capital Cost (No PVT)
Results	Multiplier	Events / Year	2050 NPV	2050 NPV	2050 NPV	2050 NPV
Baseline	1.0	1	$ 228,084	$ 175,910	$ 111,311	$ (5,461)
Frequency 1	1.5	1.5	$ 356,619	$ 304,445	$ 181,460	$ 6,301
Frequency 2	2.0	2	$ 485,154	$ 432,980	$ 251,608	$ 18,063
Frequency 3	3.0	3	$ 742,223	$ 690,049	$ 391,905	$ 41,588

Summary

Signal house overheating model runs reveals a low sensitivity to capital costs (i.e., ballasted vs. direct fixation scenarios), and a moderate sensitivity to passenger loads and passenger value of time. By selecting a specific signal house location for investigation, this analysis necessarily generalizes variables that are to be modified for other signal house locations to determine the appropriate level of capital investment.

CTA should monitor individual signal houses for A/C-related service disruptions. Any signal house showing more than two failures per year should be evaluated

for appropriate capital improvements based on relative capital costs and expected level of service impacts.

Summary of Life-Cycle Cost Analysis

This research presents a life-cycle cost analysis (LCCA) model and evaluates alternative solutions to three different climate adaptation strategies, providing a flexible tool and a high level of customization of inputs to allow multiple scenarios to be tested. The following table summarizes results for each of the three project areas investigated above.

Table 2-26 *Summary of LCCA Model Runs and Payback Periods*

	No Build Scenario		Build 1 Scenario			Build 2 Scenario		
	Capital Costs (cost per event)	*Ongoing Costs (annual cost)*		*2050 NPV (by frequency)*	*Break Even (from 2013)*		*2050 NPV (by frequency)*	*Break Even (from 2013)*
ROW Flooding	$332,000	-	Base	-$59,000	2089 (76 years)	Base	-$337,000	n/a
			High	+$494,000	2021 (8 years)	High	+$216,000	2034 (21 yrs)
			Install storage system to capture & detain storm-water at portal entrance			Install storage system with double base construction costs		
Rail Heat Kinks	$462,000	$137,000	Base	+$7,700,000		Base	+$7,700,000	2030 (17 yrs)
			High	+$29,700,000		High	+$29,700,000	2019 (6 yrs)
			Replace with tighter tie spacing, granite ballast & new anchoring system			Replace the entire structure with concrete direct fixation track		
Signal House Overheating	$12,000	-	Base	+$228,000	2015 (2 years)	Base	+$176,000	2020 (7 yrs)
			High	+$742,000	2013 (immediate)	High	+$690,000	2015 (2 yrs)
			Install single backup A/C unit to provide redundancy for primary unit failure ($30,000 capital cost)			Install dual A/C units & connect to traction power in case of grid failure ($84,000 capital cost)		

The LCCA demonstrated a positive return on investment for all model runs at the higher event frequencies than have been predicted in the baseline climate models. Many did not show a positive return for the baseline climate prediction scenario. Downscaling global climate models to local conditions is a complex task, and thus it is necessary to revise event frequencies as more sophisticated climate forecasting tools are developed.

All model runs demonstrated sensitivity to various input assumptions. This indicates that extrapolation to other locations must be done carefully and all inputs correctly calculated for each unique situation. Changes in location of a potential project would dramatically affect CTA service costs.[18] Overall, the variables tested in this report did not take any of the model runs to all negative return on investment scenarios, which indicates that as a general rule, the capital investment scenarios selected can be justified in the context of other key decision variables.

The LCCA analysis demonstrates that certain investments made today are projected to offset the future costs associated with climate change, given the appropriate assumptions for frequency, no-build costs, and capital costs for a specific scenario. However, prioritization of the improvements should not be performed exclusively from an LCCA analysis; additional factors (as outlined in the following section) must be considered to ultimately prioritize climate-adaptive capital improvements based on historical performance and available projection data.

Appendix 2: Transportation Resource Checklist

Resources	Number	Emergency/ Disaster	Planned Event	Does Not Apply	Comments/ Contact Information
Department of Transportation					
Equipment and Assets					
Barricades					
Emergency Management Agency (EMA) units for inter-operable communication					
Fixed traffic cameras that feed into the emergency operations center (EOC)					
Installations at selected sites that can be activated as needed					
Laptops to control fixed camera tilt, zoom, and timing					
Mobile units to cover dead zones					
Portable units for network operations					
Real-time traffic counters					

Resources	Number	Emergency/ Disaster	Planned Event	Does Not Apply	Comments/ Contact Information
Reflector cones					
Traffic control equipment					
Variable message signs (VMS) (permanent and portable)					
Situational Awareness					
Flow maps for traffic capacity and time					
GIS maps					
Lidar					
Traffic management centers (TMCs)					
Security cameras for critical infrastructure					
Intrusion detection systems for critical infrastructure (e.g., bridges, hatches, control centers)					
Management					
Communication –Intra-agency, –Interagency and external with the public –Web-based EOC or similar software program –Website and other electronic communication –Satellite phones					
Evacuation maps (updated annually)					

Resources	Number	Emergency/ Disaster	Planned Event	Does Not Apply	Comments/ Contact Information
Strategies like toll waive policy, reverse lanes, traffic management (e.g., turn prohibitions)					
Personnel					
ICS training					
NIMS compliance					
First responder standard identification					
Maintenance personnel					
Mid-level staff or administrative staff to sit in the EOC					
National Guard to assist with traffic control, security, crowd control					
Operations personnel in the EOC					
People at barricades					
Person(s) in the field to assess actual conditions and remain in contact with the EOC					
Traffic officers at key inter-sections					
Routes					
Arterial roads					
Freeways					
Highways (Interstate, federal, state, and county)					
Bridges					
Tunnels					
Rail lines					
Waterways					

DOT and police sport-utility vehicles with cameras					
Heavy equipment [e.g., earth movers, backhoes, bulldozers (may be through contractors); debris removal, reconstruction]					
Mobile command centers					
Police helicopters with cameras					
Snow plows, other snow removal equipment					
Trucks equipped with radios					
Vehicles equipped with reflector cones and VMS in the field					
Emergency Management					
Equipment and Assets					
NTAS/ Reverse 9-1-1® emergency alert notification					
Event radio channels to communicate with people in the field					
Hardwired, secure telephone lines with direct links to regional municipalities					

Resources	Number	Emergency/ Disaster	Planned Event	Does Not Apply	Comments/ Contact Information
Voice Interoperable Program for Emergency Response (VIPER) on mobile phones on same frequency					
Situational Awareness					
Satellite phones					
Critical infrastructure adjacent to facilities					
Threats to special events					
Maps of hurricane and surge zones, flood zones, wildfire areas, etc.					
Possibly a registry listing populations with access and functional needs, medical or other special needs, or pets or livestock (updated every 2 years)					
State Medical Asset Resource and Tracking Tool—a Web-based tool to track hospital bed count daily					
Trigger points and evacuation timeline					
Management					
Web EOC, E-team					

Annual county inventory of medical special needs/fragile populations and available ambulances					
Annual inventory of resources in counties not at risk					
Clearly defined roles and responsibilities for all agencies participating in the evacuation					
Gap analysis (between number of vehicles available and number needed for evacuation)					
List of vehicles in county available for evacuation					
Private Assets and Logistics Management System (PALMS)—Tool to manage private-sector assets that can be accessed during an evacuation					
Standard Operating Guidelines (SOG), updated every 2 years					
Statewide mutual aid agreements for ambulances					
Web-based EOC					

Resources	Number	Emergency/ Disaster	Planned Event	Does Not Apply	Comments/ Contact Information
Personnel					
ICS training					
NIMS compliance					
First responder standard ID					
Contacts in other agencies for real-time information					
Emergency medical personnel in EOC with decision-making authority					
State incident management team available to help counties with evacuation					
Logistics staff to coordinate resources and resource requests					
Personnel to update registry information					
Vehicles					
Ambulances (basic life support, advanced life support, bariatric), private and public					
Paratransit vehicles					
Emergency medical vehicles					
Fire department vehicles					
School buses (areas without mass transit)					

Resources	Number	Emergency/ Disaster	Planned Event	Does Not Apply	Comments/ Contact Information
Metropolitan Planning Organization/ Council of Governments (MPO/COG)					
Situational Awareness/Data					
511 service operated by state to provide updates on state and Interstate highways					
211/311 non-emergency numbers					
Digital warehouse (demographic, land use, traffic data)					
GIS maps					
Mapping tool to provide information to evaluate placement of law enforcement and equipment					
Weather information					
Hurricane tracking					
Traffic flow information, including contra flow map					
Modeling capabilities					
Evacuation models by zip code, traffic analysis zone/ neighborhood, city, county, or state					
Hurricane models					

Resources	Number	Emergency/ Disaster	Planned Event	Does Not Apply	Comments/ Contact Information
Monitoring of blue tooth numbers/other probe data to monitor traffic flow					
Reliable data from traffic cameras					
Management					
Centralized Traffic Operations Center (TOC)					
Convening leaders of different agencies to discuss evacuation plans					
Funding coordination					
Study to help public information officers reach populations with access and functional needs					
Personnel					
Staff support to committees for planning and after-action reviews					
GIS staff					
Transit Agency and Other Transportation Providers					
Equipment and Assets					
Evacuation route signage					
Generators at transit facilities					
GPS on buses					

Resources	Number	Emergency/ Disaster	Planned Event	Does Not Apply	Comments/ Contact Information
Meters in stations to count number of people allowed into stations					
Parking lots where stalled vehicles can be towed					
Queue ropes					
Radios on buses					
Subway stations (both non-accessible and ADA accessible)					
Situational Awareness					
Assessment to identify number of people who need assistance to evacuate from special facilities, their physical characteristics (e.g., ambulatory, able to transfer from wheelchair to bus seat, needs wheelchair, needs stretcher) and the type of vehicle they need					
Estimates of time required to load and unload buses, drive to destination, and return					
Hyper-alert application for mobile phones to alert staff and operators					
Drivers/operators as real-time view of roadway status, people's status and needs					

Resources	Number	Emergency/ Disaster	Planned Event	Does Not Apply	Comments/ Contact Information
Joint Rail Control Center					
Maps for drivers (e.g., to off-site bus storage areas, pickup, transfer, and drop off points)					
Management					
3-1-1 system to coordinate requests for evacuation transportation					
Communication – Internal, interagency, and external – Employee preparedness letters – Social media – Subscription service – Website					
Credentials/ identification for all personnel					
Designated pickup and transfer points					
Documents to track assets and operators' hours					
Off-site vehicle storage					
Registry (2-1-1, access and functional needs, medical needs, special needs)					
Shelter for transit facility personnel					
Signal systems					
Software that integrates resource requests with reimbursement					

Resources	Number	Emergency/ Disaster	Planned Event	Does Not Apply	Comments/ Contact Information
Transportation resources database to track vehicle status					
Web-based EOC					
Personnel					
ICS training					
NIMS compliance					
First responder standard ID					
Dispatcher					
Drivers					
Law Enforcement					
Transit personnel assigned to EOC					
Transit personnel to track vehicles and number of evacuees (if an evacuation event)					
Key Infrastructure					
Arterial roads					
Freeways					
Highways-Interstate, federal, state, and county					
Bridges					
Tunnels					
Rail lines					
Waterways					
Vehicles					
Buses – Numbers – Sizes – Capacities (in passenger seats; in wheelchairs) – Lift-equipped – Axle height (for flooding)					

Resources	Number	Emergency/ Disaster	Planned Event	Does Not Apply	Comments/ Contact Information
Buses, *continued* – Turning radius (for suitability in neighbor-hoods) – Fuel type (e.g., natural gas buses will have limited range outside normal fueling radius)					
Paratransit vehicles – Number, – Capacity (in wheelchairs) – Capacity (in passenger seats)					
Rail vehicles – Subway (capacity, constraints, e.g., cannot operate if power is out) – Street cars (capacity, constraints, similar to subways) – Commuter rail (capacity, constraints, similar to subways and street cars) – Dual power?					
Private-Sector Partners: Business, Utilities, Communications, Owners, and Operators of Critical Infrastructure					
Equipment and Assets					
Situational Awareness/ Intelligence					

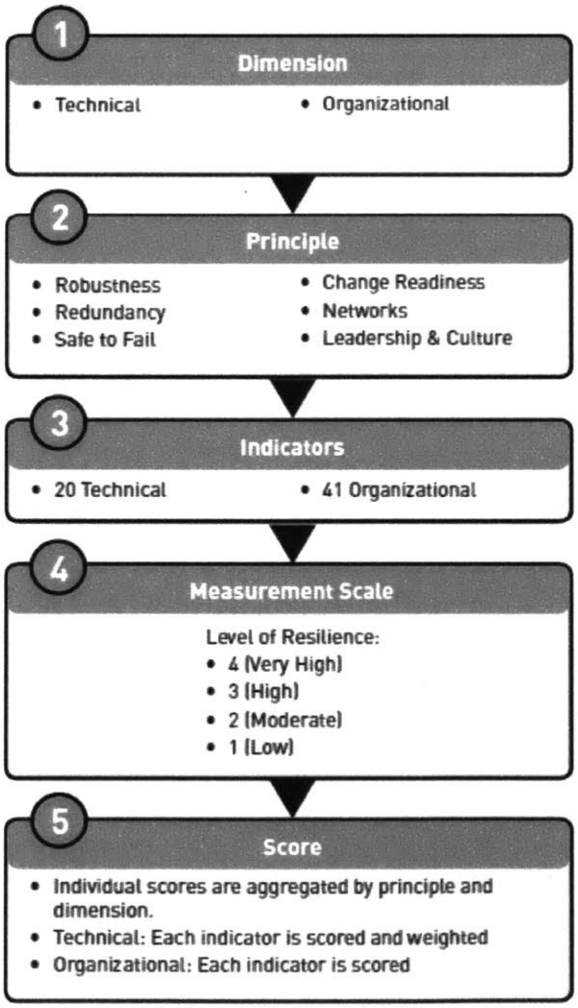
Resources	Number	Emergency/ Disaster	Planned Event	Does Not Apply	Comments/ Contact Information
Management					
Personnel					
Routes					
Community-Based/Faith-Based Organizations (CBOs/FBOs)					
Equipment and Assets					
Situational Awareness/ Intelligence					
Management					
Personnel					
Routes					

Appendix 3: Resiliency Indicator Framework

LA Metro identified and developed the following resiliency indicators, grouped by refined technical and organizational dimension. MassDOT should determine its current resiliency before establishing targets within an overarching resiliency framework strategy.

Dimension	Principle and Definition
Technical Ability of the physical system(s) to perform to an acceptable/ desired level when subject to a hazard event	**Robustness** Strength, or the ability of elements, systems and other units of analysis, to withstand a given level of stress or demand without suffering degradation or loss of function (Bruneau et al 2003). *Summary Version: Strength of system that can withstand stress and not suffer degradation or loss of function.*
	Redundancy Extent to which elements, systems, or infrastructure exists that can be substituted to satisfy functional requirements and provide business continuity. This can be achieved through either: a) providing multiple (back-up) or reserve capacity within a system, to fill in for the compromised system until it can be replaced or repaired (i.e. redundancy) (Bruneau et al 2003); or b) providing a range of types, methods or modes of service provision or operation in order to reduce the potential negative impact to a whole network (or city) of the failure of any one particular system (i.e. diversity). For example, Metro, diversity is provided by the combination of a bus and rail system. *Summary Version: Extent to which elements, systems, or infrastructure exist that can be substituted to satisfy functional requirements and provide business continuity.*
	Safe-to-fail Design approach that allows for failure (where relevant) in a controlled and planned manner that facilitates rapid recovery. Importantly, this recognizes that the possibility of failure can never be eliminated. This may be achieved through innovative design methods [to complement traditional, incremental risk-based design (Park et al 2013)], or through specific 'modularity'. This modularity can be characterized by; a) system components having enough independence so that damage or failure of one part or component of a system has a low probability of inducing failure, or b) system components being constructed in a 'modular' manner that facilitates rapid rebuild / restoration following failure. *Summary Version: Design approach that allows for failure in a safe and controlled manner, and facilitates rapid recovery.*
Organizational Capacity of an organization to make decisions and take actions to plan, manage and respond to a hazard event	**Change Readiness** Ability of an organization to anticipate hazards and failures. Involves ability to be flexible, to be able to change, evolve or adopt alternative strategies (either in the short or long term) in response to changing conditions (Da Silva, et al, 2012), and learn from success and failure (adapted from Bruneau et al 2003 and Park et al 2013). The ability to sense and anticipate hazards, identify problems and failures, and to develop a forewarning of disruption threats and their effects through sourcing a diversity of views, increasing alertness, and understanding social vulnerability (Resilient Organisations 2012). Also involves the ability to adapt (either via redesign or planning) and learn from the success or failure of previous adaptive strategies (Park et al 2013). This also includes resourcefulness - that can be conceptualized as: a) the capacity to mobilize resources when conditions exist that threaten to disrupt some asset or system (adapted from Da Silva et al, 2012); b) the ability to skillfully prepare for, respond to, and manage a crisis or disruption as it unfolds (NIAC, 2009), and; c) the ability to apply material (i.e. monetary, physical, technological, and informational) and human resources to meet established priorities and achieve goals (Bruneau et al 2003). *Summary Version: Ability to anticipate hazards and failures. Involves ability to adapt, be flexible and resourceful, and learn from success and failure.*

	Networks The ability to establish relationships, mutual aid arrangements and partnerships, understand interconnectedness and vulnerabilities across all aspects of supply chains and distribution networks, and; promote open communication and mitigation of internal/external silos (Resilient Organisations 2012). *Summary Version: Ability to establish internal/external relationships, mutual aid arrangements, and regulatory partnerships.*
	Leadership and Culture The ability to develop an organizational mind-set/culture of enthusiasm for challenges, agility, flexibility, adaptive capacity, innovation and taking advantage of opportunity (Resilient Organisations 2012). *Summary Version: Ability as an organization to embrace challenges, agility, flexibility, adaptive capacity, innovation, and opportunity*



Technical
ROBUSTNESS
R-01. Maintenance - Day to Day
R-02. Maintenance - Post Incident
R-03. Renewal/Upgrade (Long Range Plans)
R-04. Design - Compliance with Current Codes
R-05. Design - Condition of Asset
R-06. Design - Vulnerability Assessment
R-07. Design - Resilience Design Criteria
R-08. Design - Overheating Standards
R-09. Extreme Weather Repair Costs
R-10. Supplier Utility Robustness - Awareness
R-11. Supplier Utility Robustness - Improvement
REDUNDANCY
RE-01. Alternate Route/Mode Availability
RE-02. Alternate Route/Mode Capacity
RE-03. Spare Capacity
RE-04. Back Up Parts and Equipment
RE-05. Re-routing and Communication Plans
RE-06. Supplier Utility Redundancy - Awareness
RE-07. Supplier Utility Redundancy - Improvements
SAFE-TO-FAIL
S-01. Safe-to-Fail - Design Approach
S-02. Safe-to-Fail - Design Guidelines

Organizational
CHANGE READINESS
C-01. Warnings - General Public
C-02. Communication Systems - Staff
C-03. External - Public Awareness
C-04. Sensors
C-05. Current Weather Data
C-06. Backup
C-07. Coverage
C-08. Information
C-09. Roles & Responsibilities - Key People Identified
C-10. Roles & Responsibilities - Succession Planning
C-11. Internal Coordination - Event Response
C-12. Remote Response Ability
C-13. Staffing Responder Roles
C-14. Sufficient Staffing
C-15. Risk Assessment and Scenario Planning
C-16. Emergency Management Plans - Existence
C-17. Tracking Climate-related Injuries
C-18. Joint Planning
C-19. Priority Routes/Structures to Manage First
C-20. Lessons Learned and Thinking Ahead
C-21. Training /Drills - Curriculum
C-22. Training /Drills - Offered
C-23. Training /Drills - Completed
C-24. Training /Drills Practice - Testing & Public Eng.
C-25. Capital Availability
C-26. Operational Funding for Resilience Initiatives
C-27. Integration with Resilience
C-28. Contingency Funding
C-29. Modelling
NETWORKS
N-01. Internal Relationships
N-02. Information Sharing - Internal
N-03. Inter-agency Compatibility
N-04. Business Continuity/Awareness
N-05. Information Sharing - External
N-06. Inter-agency Compatibility and Cooperation
LEADERSHIP AND CULTURE
L-01. Roles and Responsibilities
L-02. Staff Engagement
L-03. Leveraging Knowledge
L-04. Crisis Decision Making
L-05. Advance Agreements
L-06. Approach to Projects

Resiliency Score and Weighting

The assessor selects a score for each indicator, based on a measurement scale from 1 (least resilient) to 4 (most resilient) that has been tailored for each indicator. In addition, each technical indicator is automatically weighted on a 4-tier scale (low, medium, high, highest). See example, Figure 2-3.

The weighting is predetermined and based on Metro's core values of safety, service reliability, and fiscal responsibility and priorities outlined in Metro's policy and plans. See appendix A for summary of weighting methodology. *Note: at this time only the technical indicators have been weighted.*

All of the indicator scores are aggregated into one overall weighted resiliency score on a 10 point scale (1 least resilient, and 10 most resilient) and is based on the total percentage of points achieved for that assessment.

A graphic is also automatically generated to provide a snap-shot of a technical assessment (see example, figure 2-2). The number in the center of the graphic is the overall resiliency score. Each segment represents an indicator, grouped by principle. Each principle is noted on the graphic by a color (purple for robustness, yellow for redundancy, and blue for safe-to-fail). The size of each segment of the graphic illustrates the weighting (the bigger the segment, the greater the weighting) and the color of each segment illustrates the score (the darker the green, the higher the score). The assessment scorecard also provides a score for each principle.

The purpose of the scoring and weighting system is to ensure Metro prioritizes certain resiliency indicators. This will help focus limited funding on improving areas of resilience that are in line with the agency's other key priorities. The graphic will also provide a side-by-side comparison of assessments.

Figure 2-2: Example Technical Resiliency Summary Score

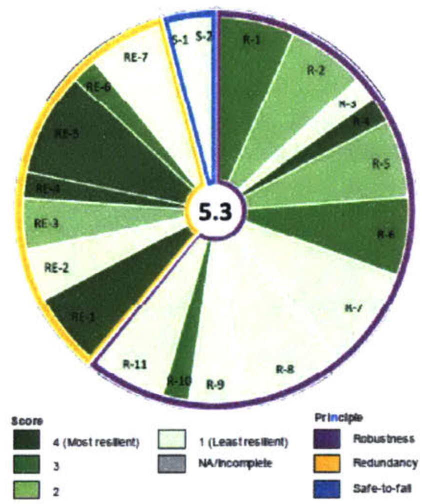


Figure 2-3: Example Indicator

Indicator	Measurement Scale	Lead Department/ Source of Information	Score *1 = Least Resilient 4 = Most Resilient*	Weighting *Lowest - Highest*	Assessment Notes/ Score Justification
ROBUSTNESS					
<u>Maintenance- Day to day</u> Standard Operating Procedures (SOP's) exist to maintain asset(s) and ensure safe and reliable operation - as per operations manual, asset management plans (e.g. - stormwater systems are not blocked).	4 - Audited inspection of Standard Operating Procedures (SOP's) and corrective maintenance completed within a specified timeframe. 3 - Partially audited inspection of SOP's and corrective maintenance completed when required. 2 - Ad hoc inspections and corrective maintenance completed, but with possible delays/backlog. 1 - No inspections or corrective maintenance completed.	<u>Lead Department(s)</u> Operations - Maintenance Equipment Maintenance, Facility Maintenance, RFM - Rail Facilities Maintenance, Rail Communications, Contract Management <u>Source of Information</u> Maintenance plans and procedures	*Completed by assessor*	High	*Completed by assessor*

Appendix 4: TAMP Standalone Template

Introduction

1. **Explain how your agency assets have been affected by extreme weather related events such as flooding, tornadoes, mud slides, hurricanes, straight line winds, etc. in the last three decades. Describe expected trends on how extreme weather events might change in the future?**
2. **Have forecasts been made on how extreme weather events might change in the future? (e.g., more heavy precipitation for longer durations, warmer winters, etc.)?**

Inventory and Condition

1. **Provide a narrative and visual (e.g. table) describing the frequency, type of extreme weather, and impact of event by asset type in the last three decades. If available, discuss typical replacement costs such as labor, equipment, and materials for different types of assets.**
2. **What are the possible impacts of future extreme weather events on the agency's assets, both in terms of the possible greater intensity of such events or the likelihood of increased asset failures with deteriorating asset conditions in light extreme weather events?**
3. **Are certain types of assets more vulnerable to extreme weather events than others (e.g., culverts)?**

Objectives and Measures

1. **Which objectives are most susceptible to extreme weather-related risks? Has consideration been given to reducing extreme weather risks in achieving these objectives?**
2. **Have you considered performance measures that relate to asset risks and potential damage related to extreme weather events?**
3. **Does the agency have a risk tolerance policy (e.g., some facilities or assets are too important to fail?**

Performance Assessment

1. **Which performance measures will be most affected by the influence of extreme weather?**
2. **Which other performance measures will be most affected by the influence of extreme weather?**
3. **How are these performance measures linked to other sections of the TAMP, and thus possibly cause a cascading effect of extreme weather impacts on the success of the TAMP?**

Exhibit 2: Extreme Weather/Climate Change Incorporated into the Stand-alone Template

Lifecycle Management

1. **How have extreme weather-related impacts been considered in the lifecycle management of the agency's assets? For example, have maintenance programs been adjusted to account for extreme weather considerations, e.g., are drainage cleaning activities conducted in anticipation of severe weather events or with greater frequency during storm seasons? Do designs for asset rehabilitation or reconstruction consider extreme weather and provide improved resiliency?**
2. **How have extreme weather-related risks to assets been identified and included in the agency's strategy to minimize damage due to extreme weather events?**

Risk Management

1. **How are extreme weather-related impacts considered in the agency-wide risk management strategy?**
2. **How has the risk of recurring damage and cost of future repair due to extreme weather events been considered in the risk management strategy?**
3. **How do risk-based asset inspections and monitoring take into account potential extreme weather impacts?**
4. Does your agency have a risk tolerance policy, that is, some assets should have a lower risk tolerance than others? This can help drive decisions on priorities.
5. How are extreme weather-related risks taken into account in maintenance planning and practices?
6. Have emergency response plans for extreme weather events available and have they been developed collaboratively with emergency response agencies?
7. What monitoring strategies and reporting processes related to extreme weather risks are in place to inform the agency's risk management strategy? Are extreme weather risk monitoring and response strategies captured in the agency's risk register?

Exhibit 2: Extreme Weather/Climate Change Incorporated into the Stand-alone Template

Financial Plan

1. **How have agency funds been spent in responding to extreme weather events and their aftermath?**
2. **Which assets have had the greatest amount of funding allocated to reconstruction for recovery from extreme weather events?**
3. **To what extent is priority given to extreme weather-related adaptation projects?**
4. Are funds allocated to extreme weather risk monitoring/mitigation and/or programs to improve asset resiliency?

Investment Strategies

1. **What are the short- and long-term financial needs associated with recovery from extreme weather events? How have these needs been reflected in the investment scenarios? And in the budget?**
2. What types of strategies for mitigating the potential impact of extreme weather events have been considered as part of the investment strategies?

Process Improvements

1. **Have changes been made in the TAM process to incorporate consideration for extreme weather events?**
2. **What data or information is needed to improve the consideration of extreme weather/climate change factors in the TAMP?** For example, should failure points be calculated for each high priority asset to determine which assets have the smallest margin of error before failure occurs? Have economic loss calculations been estimated for high priority assets to guide decisions based on the amount of network and economic disruption?

Source: Meyer and Flood 2015

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