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Enhancing Extreme Weather Resilience for Rail Systems: Multi-Capability Performance Monitoring Approach & Sustainability Integration

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16. Abstract
Resilience for rail systems may be defined by the set of system capabilities that enable the continued or improved functionality of rail systems exposed to multiple types of hazards, including extreme weather events. Assessing the resilience of rail systems and making appropriate investments may reduce the impacts of threats to system users and infrastructure. However, no studies found by the authors to date have proposed a comprehensive set of metrics that address all the commonly cited resilience capabilities: robustness, flexibility, preparedness, survivability, recoverability, adaptive capacity, and transformative capacity. Based on a review of studies across freight, intercity passenger, and urban transit rail systems, metrics for resilience are identified, categorized, and analyzed along the disruption and recovery timeline (from before disruption occurrence to long after system recovery). The intent of reviewing such a diverse set of rail system studies is to find appropriate metrics across different agencies, types of systems, and levels of maturity of the agencies' resilience-building practices. Building upon the review of rail resilience assessment metrics, this first thrust of this research proposes a rail-specific set of metrics to quantify resilience capabilities along the disruption and recovery timeline. These metrics can highlight what interventions can enhance each resilience capability for improved disruption response. The second thrust of this research applies the multi-capability resilience assessment approach to MARTA. Additionally, although resilience and sustainability assessments may provide advantageous information to decision makers in the rail industry, there is no formalized framework for integrating such assessments in rail practices in the US. The third thrust of this research presents a framework to integrate resilience and sustainability into rail planning and resource allocation decision making. This element supports investments in rail to prepare for extreme events, protect the natural environment, enhance economic competitiveness, and improve quality of life. The study could be useful for agencies looking to assess the sustainability or quantify the resilience of a rail network. More broadly, this study may be of interest to transportation practitioners, policy makers, and other stakeholders looking to better characterize transportation resilience by considering physical and organizational capabilities.

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Enhancing Extreme Weather Resilience for Rail Systems: Multi-Capability Performance Monitoring Approach & Sustainability Integration

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Enhancing Extreme Weather Resilience for Rail Systems: Multi-Capability Assessment & Sustainability Integration

Executive Summary

Resilience for rail systems may be defined by the set of system capabilities that enables the continued or improved functionality of rail systems exposed to hazards. Rail assets—defined here as trains, stations, track, signaling equipment, electricity lines, and structural elements supporting these components—may be located within forests vulnerable to wildfires, on soil foundations affected by weather patterns, near bodies of water that can flood during heavy precipitation, or in other locations vulnerable to hazards. Investing in resilience building may reduce the impacts of threats to system users and infrastructure, but these measures alone do not address social and environmental concerns. This research explores and addresses the challenges rail entities may face when attempting to enhance and monitor resilience and sustainability outcomes.

This research has multiple objectives. The first objective is to examine how to quantify or measure all commonly cited resilience capabilities: robustness, flexibility, preparedness, survivability, recoverability, adaptive capacity, and transformative capacity. Based on a review of studies across freight, intercity passenger, and urban transit rail systems, metrics for resilience are identified, categorized, and analyzed along the disruption and recovery timeline (from before disruptions occur to long after system recovery). The intent of reviewing such a diverse set of rail system studies is to find appropriate metrics across different types of agencies and systems. Building upon the review of rail resilience assessment metrics, this study proposes a rail-specific set of metrics to quantify resilience capabilities along the disruption and recovery timeline. These metrics can highlight what interventions can enhance each resilience capability for improved disruption response and prevention. This study further discusses how the proposed metrics can be phased into practice. The contributions may be useful to rail agencies looking to quantify the resilience of a rail network and could inform transportation practice more broadly with an approach to consider system resilience even when the disruption threshold is not exceeded (Chapter 2). This approach is applied to the Metropolitan Atlanta Rapid Transit Authority (MARTA) rail system as a case study and proof of concept (Chapter 3). The results of the case study application indicate that MARTA's rail system has areas for improvement across different resilience capabilities, including *robustness, flexibility,* and others.

The second objective of this research is to propose and describe a framework for incorporating resilience and sustainability considerations into rail systems management. To develop this framework, a literature review is conducted on rail resilience conceptual

frameworks, planning approaches, specific impacts of hazards, and example adaptation options. The proposed framework has five steps: general vulnerability assessment (identifying threats and relevant information), sustainability assessment (considering environment, quality of life, and economic factors), impacts analysis (examining specific vulnerability, risk, and criticality), alternatives analysis (reviewing organization- and asset-based alternatives to respond to identified needs), and implementation and monitoring (preparing plans, adaptation strategies, and performance metrics). Each step is described with potential resources to inform rail asset management practices. Resources discussed include tools to quantify hazard impacts, platforms to access downscaled projection data for temperature, wind, and other weather-related events, and example adaptations. This research offers a framework including strategies for agencies operating, maintaining, or regulating rail to enhance resilience while considering inter- and intragenerational sustainability outcomes (Chapter 4). This report concludes with recommendations for the private sector, public sector, and academia, followed by a discussion on future research directions.

Chapter 1: Introduction

Rail agencies, faced with various predictable and unpredictable challenges, have a growing need to build resilience and enhance adaptive capacity (1, 2) to futureproof rail system performance. In this study, rail agencies include both passenger (intercity, high-speed, transit, etc.) and freight (designated as Class I, II, and III railroads by the Surface Transportation Board) agencies. Rail assets are defined here as trains, stations, track, signaling equipment, electricity lines, and structural elements supporting these components. Rail systems are defined as the combination of all rail assets that enable people and goods to be moved along rail corridors (3). Figure 1 shows the general trend in movement of people on passenger rail systems and the employee hours worked on passenger rail systems in the United States between 1975 and 2021 (data accessed from 4). The trends indicate that passenger rail was steadily increasing between the mid-1990s up to the COVID-19 pandemic while passenger rail employee hours worked decreased. The Figure 1 also shows that freight rail carloads remained consistent between the late 1980s and 2008 but experienced drops following the 2008 recession and the 2020 pandemic.

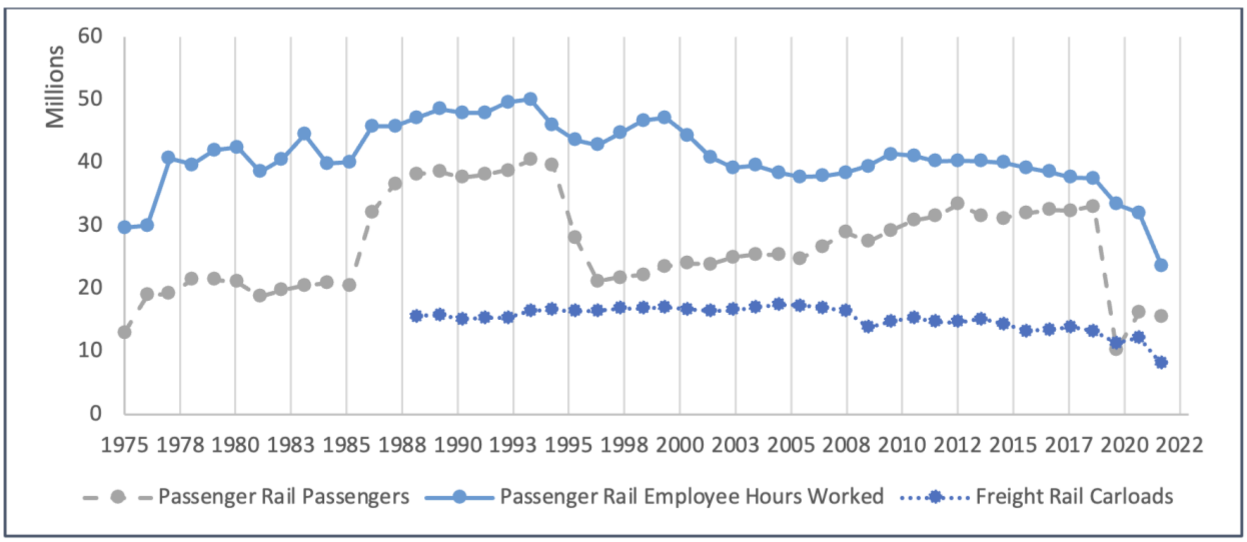

Figure 1. Number of Passenger Rail Passengers and Employee Hours Worked, 1975 – 2021; Freight Carloads Transported in US, 1988 – 2021 (data from 4).

There are six Class I freight railroad companies (BNSF Railway, Canadian National Railway, Canadian Pacific Kansas City, CSX Transportation, Norfolk Southern Railway, and Union Pacific Railroad) and one Class I passenger railroad company (Amtrak) operating in the United States as of September 2024. Amtrak was launched as a quasi-public enterprise in 1971 by the US government following the passage of the Rail Passenger Service Act or RPSA in 1970 (5). Following the Amtrak Improvement and Regional Rail Reorganization Acts, Congress transferred the operation of the Northeast Corridor to Amtrak (5). Amtrak's station density as of September 2024 is shown in Figure 2, where the yellow areas indicate a high density of stations, and the purple areas indicate low density (data accessed from 6). Figure 3 shows the areas with high ridership, indicating that the Northeast Corridor, Chicago, and Southern California are the areas with the most significant ridership (a small proportion of Amtrak's national system) (data accessed from 6).

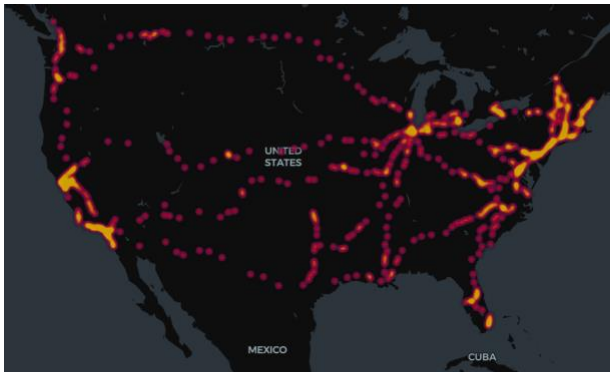

Figure 2. Amtrak Station Density, US (data from 6).

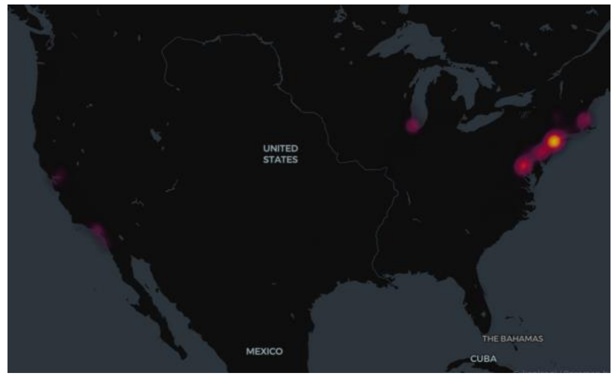

Figure 3. Amtrak Ridership Density, US (data from 6).

Passenger rail entities like Amtrak are impacted by extreme weather events and other unexpected disruptions. Figure 4 shows the CPI-adjusted weather-related damages reported by Amtrak and its partners to the Federal Railroad Administration (FRA) Office of Safety Analysis (7) and the Amtrak-caused hours of delay from the Bureau of Transportation Statistics (8). This figure indicates that Amtrak service delay has increased compared to the 1990s. Following reduced service during the COVID-19 pandemic, delay hours decreased, but as Amtrak service returned to pre-pandemic levels, so did hours of delay. Figure 4 also shows that weather-related damages (to the systems of Amtrak and its partners) can reach nearly $25 million in a single year. These numbers include damages reported by "host" railroads, which are freight or commuter railroads that allow Amtrak to use their tracks to operate passenger trains as part of the RPSA (9). However, there has been ongoing debate within the rail sector about Amtrak's access to these externally owned tracks, particularly around whether Amtrak should be given priority over other train operators (10, 11).

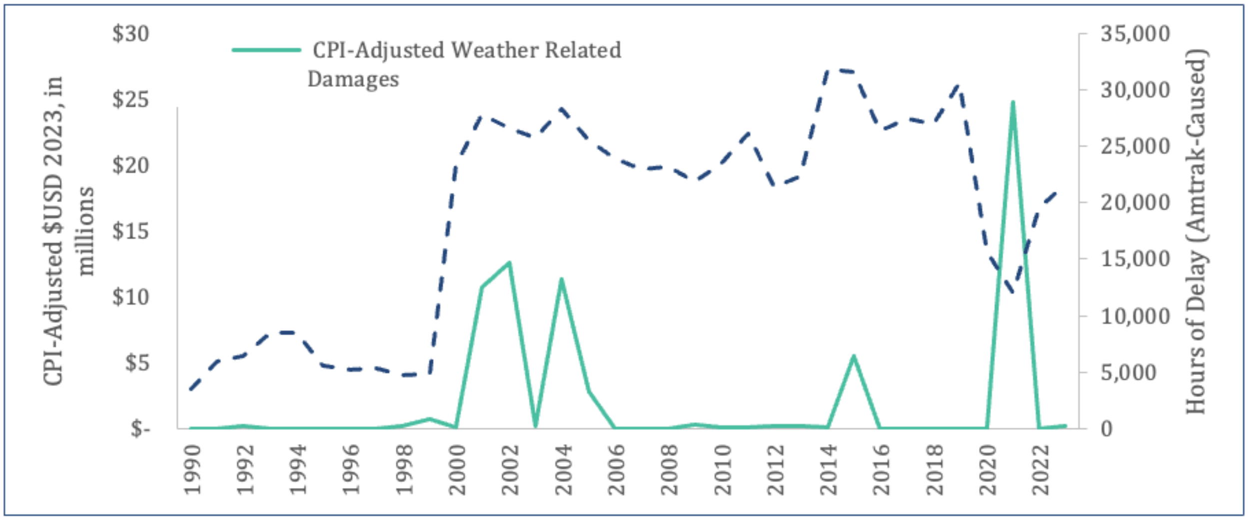

Figure 4. Amtrak Delays and Weather-Related Damages, 1990 – 2023 (data from 7, 8).

Performance monitoring is an important component of infrastructure management. Rail operators, like the Class 1 railroads, currently track a variety of metrics, including organizational performance (e.g., track velocity or number of cars for freight rail organizations), safety performance (e.g., accidents, fatalities, and injuries), asset performance (e.g., health and condition indices, track roughness), and other aspects of rail system efficiency (12). As weather-related events can cost millions in damages (Figure 4), monitoring resilience and vulnerability is increasingly important for rail agencies. The FRA has declared sustainability and building resilience as a priority area for research with an emphasis on enhancing the use of clean energy and examining how rail systems can adapt to reduce the impacts of weather-related failures (13). This study seeks to explore these emerging priorities.

Considering the importance of measuring the impact of investments in resilience and adaptation, the second chapter of this study proposes a multi-capability approach to assess rail system resilience for improved performance monitoring (1). The third chapter provides a limited demonstration as a proof of concept depicting how a rail agency may apply the multi-capability approach to resilience assessment (2). This chapter uses MARTA rail system as a case study rail agency. The fourth chapter provides an integrated resilience-sustainability framework for rail agencies looking to advance these two goals simultaneously (3). The fourth chapter also discusses the recommendations based on this research for public sector, private sector, and academia. The final chapter then presents the contributions of this research to rail asset management practice, policy, and the body of knowledge and concludes with future research directions. This research defines a set of resilience metrics to enhance the analytical capabilities of rail agencies—which may be critical when defining return on investment. This study examines the opportunities for enhanced resilience and sustainability considerations within the asset management principles and practices that guide rail agency action.

Chapter 2: Multi-Capability Approach to Monitoring Rail System Resilience

Introduction

Background

Transportation resilience has been defined in various ways across fields. Consistently, *capabilities* of resilience have been utilized to help conceptualize and formalize resilience across sectors (14). Table 1 highlights capabilities included some definitions of resilience found in studies of transportation, rail, or multimodal freight systems (14, 15, 16, 17, 18).

Table 1. Definitions of Resilience in Studies of Rail and Multimodal Freight Systems (1).

Type of Resilience	Definition of Resilience
Resilience (15, referenced by 16)	The ability of a "system, community or society exposed to hazards to **resist**, **absorb**, **accommodate** and **recover** from the effects of a hazard in a timely and efficient manner, including through the preservation and restoration of its essential basic structure and functions."
Engineering Resilience (14)	Resistance to disturbance and speed of return to equilibrium.
Freight Transportation System Resilience from the User Perspective (17)	The ability of users to "**prepare** for unforeseen network disruptions in such a way that they continue moving goods through alternative routes or modes (**redundancy**), maintain profitability by adapting variations in supply, and bounce back quickly from operational losses (**rapidity**)."
Freight Transportation System Resilience from the Organization Perspective (17)	The ability of organizations to "**anticipate** internal or external threats, disseminate information to users, **prepare** in advance for adverse situations, identify suitable recovery strategies, respond quickly with adequate resources, and **adapt** to operational changes in time to strive for continuing freight movements under the effect of network disruptions."
Infrastructure Resilience (17)	The ability of infrastructure to "be less degradable to disruptive events through available routes for moving goods (**survive**), quickly **adapt** to the situation, and return to normal operations in less time (**rapidity**)."
Rail transit system resilience (18)	The ability of the rail transit system to "perform effectively under normal conditions, as well as to **resist**, **absorb**, **accommodate** and **recover** quickly from disruptions or disasters."

The definition of *rail system resilience* in this study is: "*the ability of rail systems to provide effective services in various conditions through robustness or flexibility, as well as to prepare, survive, recover quickly, adapt, and transform in the context of disruptions while minimizing vulnerability to uncertain futures and damage to society, economy, and the environment*" (1). This definition references seven commonly cited capabilities that appear in work on resilience, uncertainty, and sustainability. Table 2 defines each of these seven capabilities (1).

Table 2. Capabilities, Definitions, and Related Concepts (1).

Capability	Definition	Related Concepts
Robustness	A capability describing the options enabled by the physical system design that may contribute to improved functionality.	*Topology, redundancy*
Flexibility	The ability of agencies to respond to predictable or unpredictable changes in an effective way – in terms of performance, cost, and time.	*Resource availability and allocation, interagency collaboration, flexible pathways, roadmapping*
Preparedness	A capability indicating the extent to which an agency has conducted emergency planning efforts and is able to communicate with relevant stakeholders before and during disruptive conditions.	*Stakeholder engagement, communication, emergency management*
Survivability	The ability of the system to absorb or degrade safely under disruptive conditions.	*Resistance, accommodation, absorption, withstanding*
Recoverability	The ability of the system to quickly return to normal operations after the system has stopped degrading.	*Responsiveness, agility*
Adaptive Capacity	The capacity to adjust to change, related to functional, organizational, financial, or other system characteristics.	*Dynamic adaptive planning, vulnerability, adaptation implementation, adaptability*
Transformative Capacity	The capacity of an agency or system to 'bounce back', fundamentally and deliberately change, and potentially improve through feasible interventions considering multiple future scenarios.	*Uncertainty, scenario planning, simulation, real options analysis (ROA), system evolution, safe-to-fail design*

Outline

This research examines the prevalence of the quantification of resilience capabilities in rail system studies and proposes an approach to quantify resilience considering these commonly cited capabilities. The remainder of the chapter is as follows. First, the methodology for collecting metrics is summarized. Then, the insights from the review of rail resilience metrics are introduced as described in detail in Garrett et al. (1). The metrics reviewed are grouped by approach to resilience quantification and example metrics are discussed. To encourage the use of the proposed metrics in practice, a phased implementation approach considering relative availability of resources is presented. Finally, the chapter concludes with a brief discussion of the contributions.

Methodology

To assess the current approach to quantifying rail system resilience, a review of metrics was conducted. The terms “rail AND resilience AND assessment” were searched in Scopus to collect book chapters, conference papers, and peer-reviewed journal articles that may include a metric or set of metrics for rail system resilience between date of first publication and December 2024 (n = 158). Once these articles were collected, the abstracts, titles, and article content were screened to ensure relevancy (n = 71). Studies that examined the resilience of individual rail components – such as signaling equipment or track – or not applied to a case study system were removed (n = 30). To complement this search, the same search terms were used for Google Scholar and the Transportation Research International Documentation (TRID) databases were searched to find any additional articles, conference papers, or book chapters that were relevant (n = 44). A detailed breakdown of the studies reviewed by publication type, year, and journal is available in Garrett et al. (1).

Review: Resilience Metrics

Research Questions

The main research questions in this study are: “What are the metrics used in the literature to quantify resilience across types of rail systems?” and “How well do these metrics quantify resilience capabilities?” The resilience capabilities explored in this study are *robustness*, *flexibility*, *preparedness*, *survivability*, *recoverability*, *adaptive capacity*, and *transformative capacity*. In addition, as efforts to enhance resilience seek to protect and improve quality of life for the current generation by reducing the impact of disruptions, efforts to enhance sustainability seek to protect and improve quality of life for present and future generations (19). This research further attempts to answer the question: “To what extent do these resilience assessment approaches consider sustainability?” To do so, this study examines if rail system resilience assessments consider sustainability *explicitly* (by incorporating sustainability factors into the assessment) or *implicitly* (by referencing all or at least one element of the Triple Bottom Line (TBL) model of sustainability: environment, economy, or quality of life).

Overview

Many studies have emerged examining quantification of resilience and vulnerability in recent years. Figure 5 shows the relationship between the papers related to resilience reviewed for this research, organized horizontally by year of publication. For simplicity, the papers are referred to by the first author's last name and year of publication. The lines indicate that papers are 'connected' through citations (e.g., a line between Chen 2012 and Jin 2014 indicates that the latter cited the former in the article) and the papers along the bottom of the Figure 5 were not cited by other articles found in the literature. The diameter represents the number of total citations as of July 2024. The papers with the most interconnectivity were Chen and Miller-Hooks (19) (labeled as "Chen 2012" in Figure 5), Jin et al. (20) (labeled as "Jin 2014" in Figure 5), and Zhang et al. 2018 (21). The Figure 5 shows that many studies are highly interconnected and may have similarities in approach while other studies built upon different research to quantify rail system resilience.

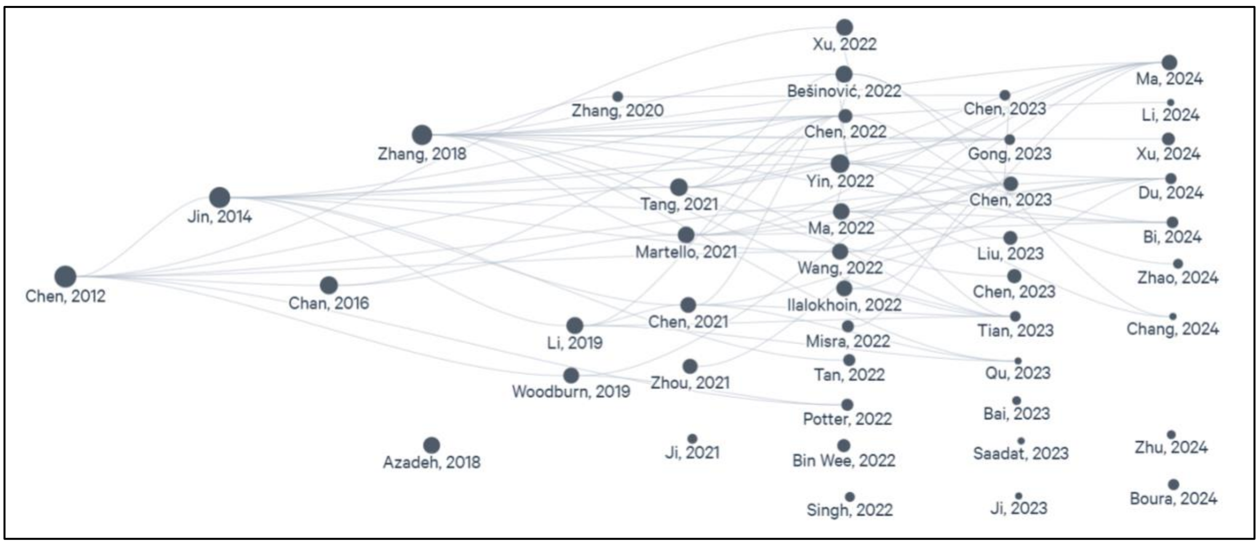

Figure 5. Rail resilience assessment literature interconnectedness (April 2025).

Review Insights

The review is described in detail in (1). From the 44 studies reviewed, metrics are explored and similarities drawn. Although many studies examined how to quantify resilience, most studies do not include organizational capabilities that contribute to resilience, such as *preparedness*. *Adaptive capacity*, or the concept of being adaptive, is repeated in resilience definitions across studies (Table 1), but the capability is not quantified in any of the studies reviewed. Although many capabilities are commonly mentioned when describing the definition of resilience, studies tend to only measure *survivability* and *recoverability* when quantifying resilience. In the next section, a metric for *adaptive* *capacity* that uses available data is described and, in the next chapter, an example of quantifying adaptive capacity is explored.

Singh et al. (23) refer to an improving disruption threshold. As agencies build resilience capabilities over time, the system threshold for experiencing a disruption to performance should increase – even as disruptions intensify (Figure 6). The disruption threshold may be quantified based on previous hazard conditions that the system was able to withstand. Many resilience assessment approaches discussed above only consider resilience once the disruption threshold has been reached; however, a resilient system may not show any change in performance during a potentially disruptive event because the system is more robust, flexible, and prepared than ever. This research proposes a multi-capability approach to monitoring resilience to more accurately reflect the resilience of a system with an improving threshold to disruptions.

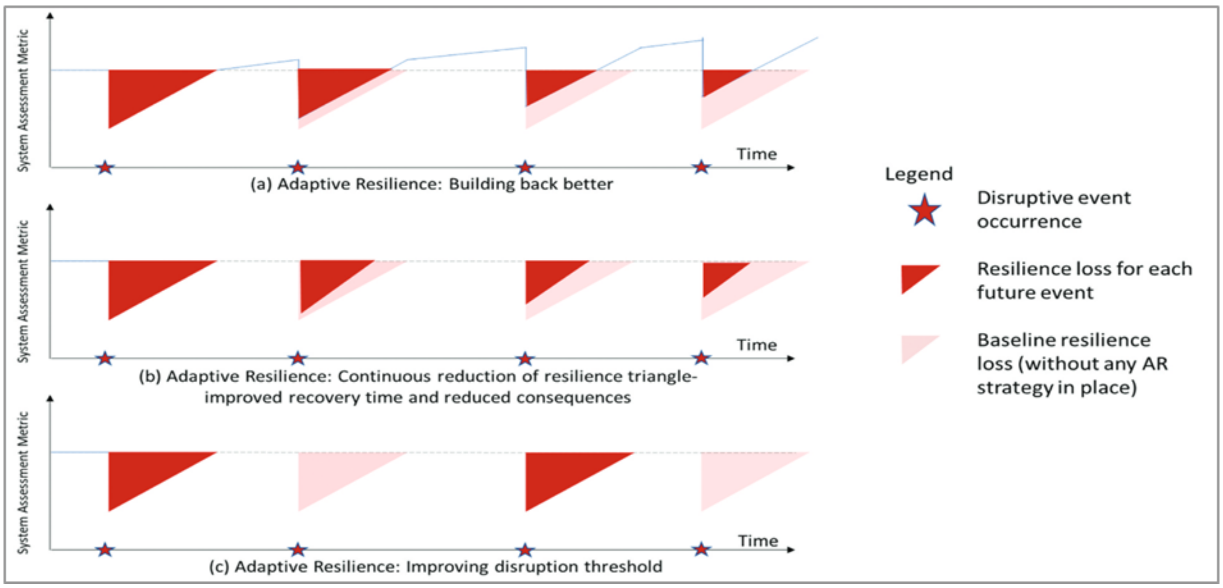

Figure 6. Modified Resilience Triangle Approach with concept of improving disruption threshold demonstrated (reprinted with permission from 23).

Rail Resilience Metrics

Resilience Capabilities Along Disruption-Recovery Cycle

Ultimately, metrics reflecting resilience must reflect the status of the rail resilience system across multiple phases of a disruption (1, 15, 23, 24). The discussion of commonly quantified capabilities in (1) demonstrates that most studies quantify only two capabilities of resilience when considering the resilience of rail systems (Figure 7). Figure 8 shows the seven resilience capabilities along the disruption-recovery cycle (1).

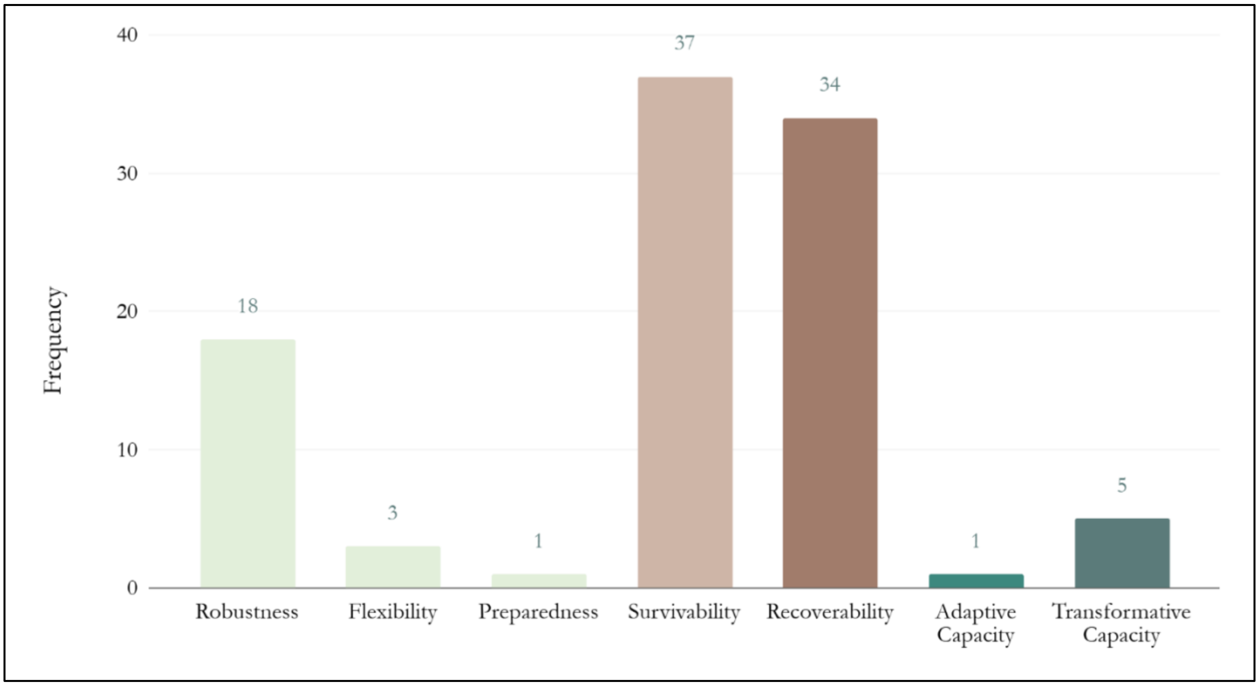

Figure 7. Frequency of capability quantification in reviewed studies (1).

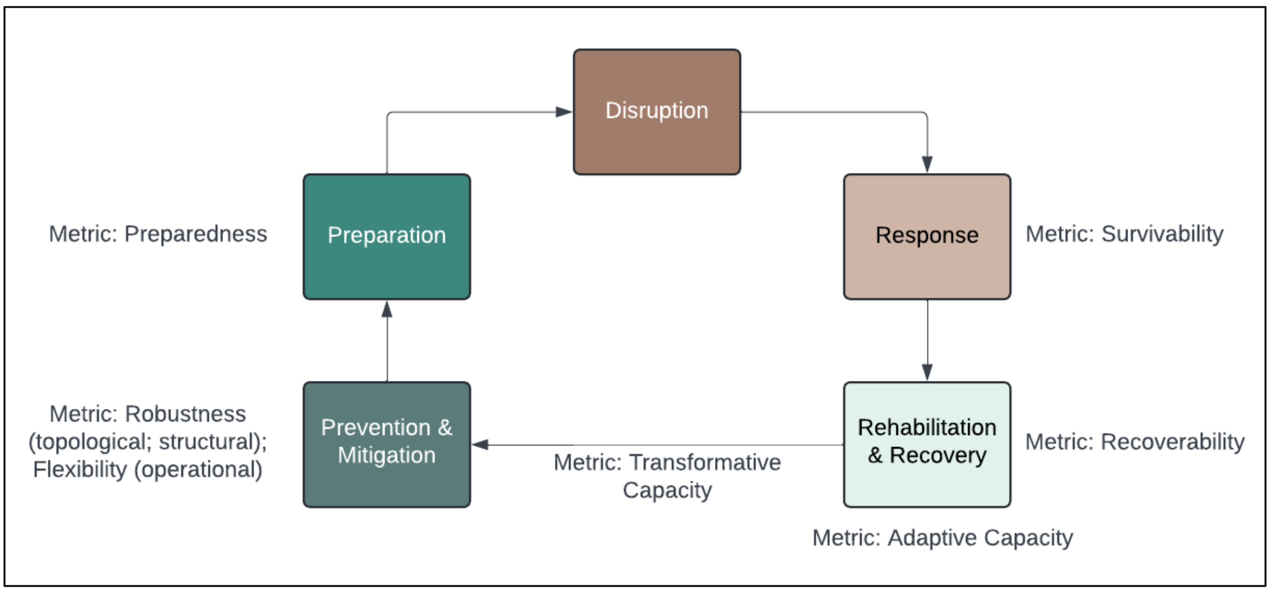

Figure 8. Metrics for resilience capabilities along the disruption-recovery cycle (1).

Capabilities

"Measures of performance" will vary by agency type and agency goals. Additionally, some capabilities such as preparedness, robustness, and flexibility can be measured regardless of the selected measure of performance. These capabilities relate to the agency's activities or system characteristics. Adaptive capacity was not quantified in any of the studies reviewed, although the capability is explicitly considered in some system vulnerability assessments conducted by rail entities (see, for example, Amtrak's vulnerability assessment of the Northeast Corridor, 25). Transformative capacity relates to the potential of the system to fundamentally shift or deliberately change to increase its resilience (26). In previous work, transformative capacity has been quantified using potential future interventions and the predicted performance of the adapted system in a set of future scenarios (23).

Table 3 summarizes considerations for resilience metric development. In the Table 3, *mitigation-based* indicates that the approach relates to preventative strategies that occur before a disruption takes place. *Preparation-based* approaches place the emphasis on equipping agencies with the tools needed to effectively handle disruptions. *Outcome-based* approaches emphasize the system's performance and ability to return to a desired level of functionality during and after a disruption. *Process-based* approaches highlight continuous improvement and adaptation through system change to increase resilience over time.

Table 3. Considerations for Resilience Metric Development (adapted from 1 and 27).

Goal	Related Capabilities	Disruption Timeline	Approach
Infrastructure Components to Enhance Response	Robustness	Pre-Disruption	Mitigation-Based
Organizational Components to Enhance Response	Flexibility	Pre-Disruption	Mitigation-Based
Strategies and Plans to Withstand Disruptions	Preparedness	Pre-Disruption	Preparation-Based
Graceful Degradation or Failure	Survivability	During/Immediately Post-Disruption	Outcome-Based
Recovery to Desired Function in Set Time	Recoverability	During/Immediately Post-Disruption	Outcome-Based
Reduced Impact from Similar or Intensifying Events	Adaptive Capacity	Post-Disruption	Process-Based
Potential for Increased Resilience	Transformative Capacity	Post-Disruption	Process-Based

Reflecting upon the goals outlined in Table 3, there are seven related resilience capabilities that can be measured along different points of the disruption timeline (as demonstrated in Figure 9). *Robustness, flexibility,* and *preparedness* can be measured before the disruption occurs and thus are strong capabilities to monitor for agencies that have realized a high disruption threshold.

Robustness

For *robustness*, agencies may consider a single topological metric or a set of topological metrics. For simple networks, agencies could consider the number of alternative routes available for each OD pair in their network. For more complex networks, there are a variety of metrics presented in the literature (29, 30, 31). Example *robustness* metrics include average degree, network density, degree centrality, global efficiency, and several others.

Flexibility

For *flexibility*, organizations can consider their ability to make operational changes to improve response during disruptions. This may be measured through scorecards, as explored in other transportation studies on enhancing flexibility in long-range transportation planning (32). Flexibility relates to planning actions that an agency can take to increase resilience; example actions include scenario planning, increasing modularity, and collaborating. Table 4 shows the dimensions used to assess the flexibility in Garrett (32).

Table 4. Description for Dimensions Presented for Evaluating Flexibility (adapted from 32; 33; 39; 40; and others).

Dimension	Definition
Identifying Values and Vision (IVV)	Agencies can examine informal and formal institutions by explicitly calling out shared values and working to define a vision. *Vision identification* enables agencies to begin the process of roadmapping in an effective way.
Roadmapping (R)	*Roadmapping* enables organizations to weave flexibility into planning practices, programs, and policies long before disruptions occur. *Roadmapping* is defined as "managing short-term demands and urgencies along with an intentional long-term perspective toward developing structures that cope with rapid evolution of systems and deep uncertainty" (33).
Defining Resilience (DR)	Agencies that develop an agency-wide definition of resilience build a deeper understanding of the impact of various resilience-building alternatives.

Dimension	Definition
Assessing Vulnerability (AV)	Vulnerability assessments enable transportation agencies to identify which assets and communities are most likely to be negatively impacted by extreme conditions. Vulnerability assessments often include exposure, sensitivity, and adaptive capacity of assets. Participating in a vulnerability assessment enables an agency to take information from uncertainty planning and apply it in a way that enables more effective project prioritization.
Uncertainty or Scenario Planning (USP)	In plans, processes, and programs, uncertainty or scenario planning can be used as a tool to understand where to best invest funding to protect assets. Different funding pathways, technological implementations, or scenarios may be considered in an uncertainty or scenario planning process.
Reallocating Resources (*modularity*) (RR)	Reallocation of resources relates to modularity, defined as "the ability to readily add, remove, or modify individual organizational components without significantly disrupting or affecting other components and in turn, the overall system" (32, 33, 39). An agency with high modularity is able to manage, access, and utilize resources effectively, regardless of internal or external conditions.
Exploring Flexible Alternatives, Pathways, and Prioritization (EFAPP)	In plans, programs, and policies, agencies may consider how flexibility can be incorporated into alternatives and prioritization. Once an alternative is selected, agencies can reflect on additional pathways with a range of intermediate steps to incorporate additional flexibility in the decision-making process and, later on, in project implementation.
Collaborating (C)	Collaboration can be enhanced through inter- and intra-agency partnerships. There have been references to the benefits of collaboration in the context of disaster resilience and reducing infrastructure failure (39) as well as in the context of improving organizational dynamics, minimizing repeated work between agencies, and increasing effectiveness of resource allocation (40).

Preparedness

Preparedness is related to various planning factors that enable agencies or system users to withstand disruptions. This can be measured through Capability Maturity Models (CMMs), as demonstrated by various applications of CMMs within transportation planning beyond the rail sector (33, 34, 35, 36, 37). The selection of measurement tool or model will vary by agency, but once an agency selects a model, the agency may benefit from using the same measurement instrument over time for comparability – as long as it remains viable relative to the agency's objectives.

An example of such a tool is the Negotiated Resilience-Capability Maturity Model (34). This tool examines the intersection of emergency preparedness and stakeholder engagement.

Figure 9 shows an example of a capability from the NR-CMM centering on the quality of relationships and interactions with different types of stakeholders before, during, and after a disaster (34). This enables agencies to understand more elements related to rail system user capabilities.

Stakeholder Communication - Disaster Context

The quality of relationships and interactions with stakeholders before, during, and after a disaster.

Theme	Level 1 (initial)	Level 2 (repeatable)	Level 3 (defined)	Level 4 (managed)	Level 5 (optimizing)
Strategic	During a disaster, my agency struggles to communicate with stakeholders.	Communication efforts are reactive; no formal networks of communication with stakeholders.	Communication networks are established. After disasters, stakeholders can reach out to the agency to share thoughts or feedback.	Stakeholders are invited to make decisions about how to return the system to acceptable performance levels post-disaster. The agency documents what occurs during a disaster but may not use that information to inform future practices.	Communication efforts post-disaster are monitored and evaluated. The agency uses lessons learned to inform future emergency management efforts. The agency works with stakeholders to establish new goals for the system post-emergency and to return the system to acceptable performance levels.

Figure 9. NR-CMM Stakeholder Communication - Disaster Context (34).

Survivability & Recoverability

Survivability and *recoverability* relate to the performance degradation and recovery of the system (38). *Survivability* (*S*) is considered as the ratio of actual performance ($P(t)$) to normal performance ($NP(t)$) between time *t* (the start of the disruption) and time t_{min} (the time at which the minimum performance occurs). *Recoverability* (*R*) is considered as the ratio of the actual performance ($P(t)$) to normal performance ($NP(t)$) between time t_{min} and t_{end} (the time at which the system is considered 'recovered' from the disruption). These equations capture the extent to which performance degrades during a disruption and also the amount of time that passes during the degradation and recovery phases. These two capabilities represent a change in performance that may be measured through automatic systems (e.g., ridership counters, sensors) and quantified by the agency immediately following a disruption. Common metrics used to measure *S* and *R* are shown in Equations 1 and 2, respectively.

$$S = \frac{\int_{t_i}^{t_{min}} P(t)dt}{\int_{t_i}^{t_{min}} NP(t)dt} \quad (1)$$

$$R = \frac{\int_{t_{min}}^{t_{end}} P(t)dt}{\int_{t_{min}}^{t_{end}} NP(t)dt} \quad (2)$$

Adaptive Capacity

Adaptive capacity and adaptability are related concepts, but the two terms have distinct meanings. Adaptability refers to the ability of a system to adjust to shocks and stressors based on implemented adaptations, meaning that this is a backward-looking concept. Adaptive capacity, on the other hand, relates to the capacity (i.e., resources) of a system or agency to manage or respond to changes over time and is a present and forward-looking concept. 33 Economic resources, technology, information and skills, and other conditions combine to determine the capacity of systems to adapt (41, 42). From these determinants, it is clear that adaptive capacity may be defined differently depending on the spatiotemporal scale of analysis. A review from early 2025 indicates that the majority of studies evaluating adaptive capacity occur at the community scale and that studies are increasingly considering assets and resource availability when measuring adaptive capacity (43). This review further indicates that researchers increasingly consider institutions and governance as crucial determinants of adaptive capacity (43).

No consistent way to quantify adaptive capacity has been found across studies and, in most resilience assessments for rail systems, adaptive capacity is not quantified at all (1). Thus, this study proposes a simple approach to quantify adaptive capacity but also acknowledges that further research needs to be conducted to advance quantification approaches and broader understanding of adaptive capacity. For example, the Amtrak vulnerability assessment methodology considers adaptive capacity as the ability to adjust to an extreme weather event or stressor (25). The Sound Transit vulnerability assessment similarly proposes rating adaptive capacity (limited, moderate, or high) considering the extent to which the system utilizes both preemptive adaptation strategies (e.g., not siting tracks in landslide-prone areas, using expansion joints on rail tracks) and reactive adaptation strategies (e.g., slow orders during heat days) (45). In a vulnerability assessment of the Santa Clara Valley Transportation Authority's system, adaptive capacity ratings are determined by the answers to the questions 1) is there an alternative for this asset if it stops functioning and 2) can the asset or operation recover quickly once the hazard event ends? This approach to rating adaptive capacity relies on surveys and workshop responses from transportation authority practitioners (46).

Other studies consider adaptive capacity as related to strategic, programmatic, and tactical capabilities within an agency (33). Climate-ADAPT, part of the European Environment Agency, describes GDP, education statistics, availability of impact data, appropriate emergency response, and existence of business continuity schemes as indicators that can be used to assess adaptive capacity – but states that appropriate indicators vary depending on the scale of analysis (47). Araya-Munoz et al. (48) propose measuring urban adaptive capacity as a function of seven indicators derived from openly available census statistical data, including tertiary qualification, capacity to undertake research, transport, and municipal budget. Hu and He (49) also use a combination of indicators (based on the Driver-Pressure-State-Impact-Response or DPSIR framework) to evaluate urban adaptive capacity. The authors use indicators such as rate of GDP growth, built-up area, green area coverage rate in developed area, rate of unemployment, public budget expenditure, and many others to determine an urban area's adaptive capacity (see Table 5).

Table 5. Index System for Assessing Urban Adaptive Capacity (49).

Dimension	Index
Driver	Rate of population growth (%) Rate of urbanization (%) Rate of GDP growth (%)
Pressure	Energy consumption per unit of GDP (ton of SCE/10,000 yuan) Electricity consumption per unit of GDP (Kwh/10,000 yuan) Volume of industrial wastewater discharged per unit of GDP (ton/10,000 yuan) Volume of industrial waste emission of unit GDP (m^3/10,000 yuan) x_7 Built-up area (sq.km) Urban construction land-use area (sq.km) Population density (person/sq.km)
State	Percent of air quality days (%) Per capita water resource (m^3/person) Green area coverage rate in developed area (%) Proportion of the added value of tertiary industry in GDP (%) Per capita green park land (m^2/person) Customer price index Area of natural reserves (10,000 hectare) Per capita cultivated area (mu/person)
Impact	Income of urban households (yuan) Per capita total retail sales of consumer goods (yuan/person) Rate of unemployment (%) Household saving deposits (100 million yuan) Total floor space of dilapidated buildings at year-end (10,000 sq.m) Per capita floor space of residential buildings (sq.m/person) Output of grain (ton)
Response	Number of students in higher education (person) Environmental protection expenditure (10,000 yuan) Public budget expenditure (10,000 yuan) Ratio of wastewater treatment by sewage disposal (%) Percentage of solid wastes utilized (%) Number of beds per 10^4 persons (bed) Number of mobile telephone users at the year-end (10,000 subscribers) Number of internet users (10,000 subscribers)

Vajjarapu and Verma (50) use the Analytical Hierarchy Process (AHP) to determine the weights of indicators for a composite adaptability index to assess an urban transportation system's susceptibility to flooding. The FTA Transit Resilience Guidebook describes two approaches to assess adaptive capacity: a qualitative approach that involves interviews, surveys, or workshops; and a quantitative approach that utilizes indicators, with example indicators being ability to reroute service, cost of replacement, or the existence of protective features (51). These two approaches provide distinct results, with the former providing a more present-and-forward-looking, decision-based view of adaptive capacity and the latter providing a backward-looking, infrastructure-based value. The latter approach aligns more with the definition of *adaptability* presented above. This approach can also be seen in vulnerability assessments conducted by transit agencies such as Sound Transit and LA Metro (45, 51). For example, siting of infrastructure to reduce hazards or selecting a material that is more resistant to a specific threat can enhance a system's *adaptability*.

Adaptive capacity for transit and rail agencies may be related to financial and other resources, organizational values and culture, and governance; example sub-criteria could include: 1) Resource Availability (multiple funding sources, emergency resources, technological resources), 2) Organizational Values and Culture (support for innovation and technology transfer, knowledge and awareness, learning orientation), and 3) Governance (political and institutional support, transparency, continuity). Multiple approaches could be appropriate for combining these indicators, including qualitative assessments, Multi-Criteria Decision Analysis, or other methods (50).

More research is necessary to propose a broadly defensible, replicable and practical approach to measure rail system adaptive capacity. In this study, adaptive capacity is measured as a composite function of criteria across resource availability, organizational values and culture, and governance. This preliminary approach is described in detail in the pilot application of the multi-capability resilience assessment approach to MARTA, presented in Chapter 3.

Transformative Capacity

Transformative capacity refers to the post-disruption potential of the system to increase resilience based on a variety of scenarios and interventions considering *resilience loss* (*RL*) involving some fundamental change. RL is considered in the table below as the total difference over time between normal and actual performance during a disruption (23). For transformative capacity, the approach described in Singh et al. (23) offers a way for agencies to estimate the potential benefit of various resilience strategies. Singh et al. (23) present the Modified Resilience Triangles (MRT) approach to assess the long-term benefits of adaptive resilience investments for infrastructure agencies looking to prepare for uncertain conditions. As mentioned above, the MRT Approach involves four key steps: (1) define infrastructure and socio-technical system characteristics; (2) identify disruption characteristics and potential future scenarios; (3) explore future adaptations and determine the impact of potential interventions; and (4) calculate the expected resilience loss and net present value for each resilience strategy and each scenario. The last step requires a context-specific performance metric that represents success to the agency.

This approach can provide insight into what mitigative or adaptive measures would be most beneficial economically.

Practical Implementation

There are potential practical limitations for transportation agencies when initiating resilience assessments. In practical application, it may be unrealistic for an agency to implement metrics for all capabilities within performance monitoring practices in the short term. For example, there may be challenges such as lack of data availability, institutional constraints, or methodological barriers. Assessing resilience across the lifecycle of infrastructure requires coordination between planning, operations, and finance departments.

An additional challenge may arise when considering the resilience of rail systems in conjunction with other transportation systems. Rail systems depend on other transportation systems and thus failures in one system may cause cascading failures on other systems. Priorities, regulations, funding mechanisms, and other system differences may complicate coordination between modal agencies. Agencies may benefit from establishing cross-agency collaborations to access data that may be infeasible for an agency to collect on its own. For metrics often measured using modeling or simulation, such as transformative capacity, agencies may partner with university research groups or use proxy indicators that enable them to explore potential futures and disruption impacts based on context-specific values, objectives, plans and proposed activities, and constraints.

As budgets and resources are limited at many transportation agencies – including rail agencies – a phased approach to incorporating the resilience capability metrics into performance monitoring is proposed. The approach described below has three phases: baseline, baseline & performance, and multi-capability monitoring.

Phase I: Baseline Monitoring

Agencies with very few resources to devote to resilience assessment may easily measure baseline capabilities based on organizational information. Phase I includes the following capabilities: f*lexibility*, *preparedness*, and *adaptive capacity*. Agencies may refer to existing scorecards and Capability Maturity Models (CMMs) (see for 32, 33, 34, and other references for examples). Additionally, agencies may work with their financial departments to establish an agency-specific measure for adaptive capacity that captures funding and resource availability.

Phase II: Baseline & Performance Monitoring

Agencies that have some resources to devote to resilience assessment and granular deviations from normal performance can measure all Phase I metrics as well as *survivability* and *recoverability*. At the beginning of this phase, agencies select a performance metric for their system (e.g., on-time performance, number of people moved per hour, percent of stations operating). The measured values for this performance metric become the inputs for *survivability* and *recoverability* (see 38 for an example).

Phase III: Multi-Capability Monitoring

Agencies with ample resources or partnerships can leverage resource networks to monitor all seven resilience capabilities. Agencies with in-house modeling resources can monitor *robustness* and *transformative capacity* over time. Agencies without these resources may partner with research institutions to support this monitoring effort, or use proxy measures to monitor these capabilities without relying upon modeling. Measures of *robustness* will vary significantly depending on the complexity of the network (see 29, 30, and 31 for examples). Additionally, measuring *transformative capacity* varies by network, resilience strategy considered or implemented, and economic factors (see 23).

Discussion

Acute Shocks versus Chronic Stressors

In the context of rail system resilience, it is essential to differentiate between disruptions and degradations in service, as well as between acute and chronic stressors. A disruption is generally understood as a sudden, often unexpected event that causes significant interruptions in service (such as a power outage that halts rail operations). In contrast, degradation refers to a reduction in service quality without a total shutdown. For instance, during extreme heat events, utilities may choose to operate below full capacity to avoid grid failure. In such cases, large electricity consumers like MARTA may be asked to reduce train frequency, resulting in partial service impacts.

This distinction is especially relevant in resilience assessment, as degradation is often more difficult to detect and quantify than disruption. Degraded service may not trigger emergency response protocols or be captured in binary operational performance metrics. Still, degraded service can have cumulative effects on ridership satisfaction and system efficiency. Furthermore, chronic stressors (such as sea level rise) can drive recurring degradation that can undermine service reliability in the long term, even if acute disruptions are avoided in the short term. Integrating both acute and chronic stressors, and their associated outcomes, into assessments allows for a more nuanced understanding of system resilience and sustainability.

Thus, resilience frameworks should include indicators that capture both the severity and duration of service impacts across a spectrum of operational conditions. Performance monitoring approaches should consider frequency reductions or reduced accessibility as meaningful indicators of degradation, not just total shutdowns or unexpected disruptions. Doing so enables agencies to assess the full range of vulnerabilities while targeting interventions that improve robustness and adaptability during emergencies, under sustained stress, and as assets generally degrade over time. Recognizing this continuum strengthens the case for resilience-building actions that maintain service reliability and customer satisfaction in both disruptive and degrading conditions.

Resilience and Sustainability Relationship

Understanding rail network resilience at different stages along the disruption cycle can enable rail agencies to identify the most vulnerable assets or governing processes of the rail system. Environmental, economic, and social impacts of rail system investments, and failures, can inform prioritization decisions. Investing to develop a highly resilient rail network has the potential to decrease the energy footprint for freight shipments, increase the efficiency of each dollar of governmental infrastructure investment, and achieve social goals. This study also examined to what extent the studies reviewed include a metric or mention of sustainability; the results presented in Garrett et al. (1) show that only one of the studies considered sustainability explicitly (44). This indicates that although resilience and sustainability outcomes are intrinsically related, they are considered separately during assessment and thus during project prioritization and capital, maintenance, repair, and rehabilitation investments – most likely. Future studies on resilience assessment approaches for highway, sea, air, and active transportation infrastructure can indicate if this pattern occurs across studies of other transportation modes.

Summary

This study demonstrates that a singular resilience metric based on performance is not sufficient to reflect the resilience of a system as complex as rail systems. This study thus proposes a phased approach for implementing a resilience measurement approach considering seven capabilities to be measured at different points along the disruption timeline. This study further posits that adaptive capacity can be measured as a function of standardized quantified damages to the system and event intensity. Practitioners at rail agencies like transit agencies with rail infrastructure may find the proposed approach to measuring rail system resilience helpful or informative, and may apply this approach to strengthen the resilience and enhance the sustainability of their respective systems.

Chapter 3: Application of Multi-Capability Resilience Assessment: Metropolitan Atlanta Rapid Transit Authority Rail System Case Study

Introduction

Chapter 2 argues that a multi-capability resilience assessment approach reflects evolving system dynamics and leverages mixed-methods techniques more effectively than an aggregated metric approach. This study seeks to be intentional about having a multiple level and multiple scale approach for complex systems analysis. This study further seeks to extend the previous chapter by assessing the resilience of real transit systems in the context of real disruptions. This study demonstrates a pilot application of the proposed multi-capability approach to rail system resilience assessment as proof of concept. The case study selected is the Metropolitan Atlanta Rapid Transit Authority (MARTA) rail system. Although MARTA is in the process of preparing a Vulnerability Study and a plan to build their system's resilience, the transit agency currently does not include resilience-related metrics in its performance monitoring practices (as of November 2024). Figure 10 shows the four lines (Red, Green, Blue, and Gold) of the MARTA rail system.

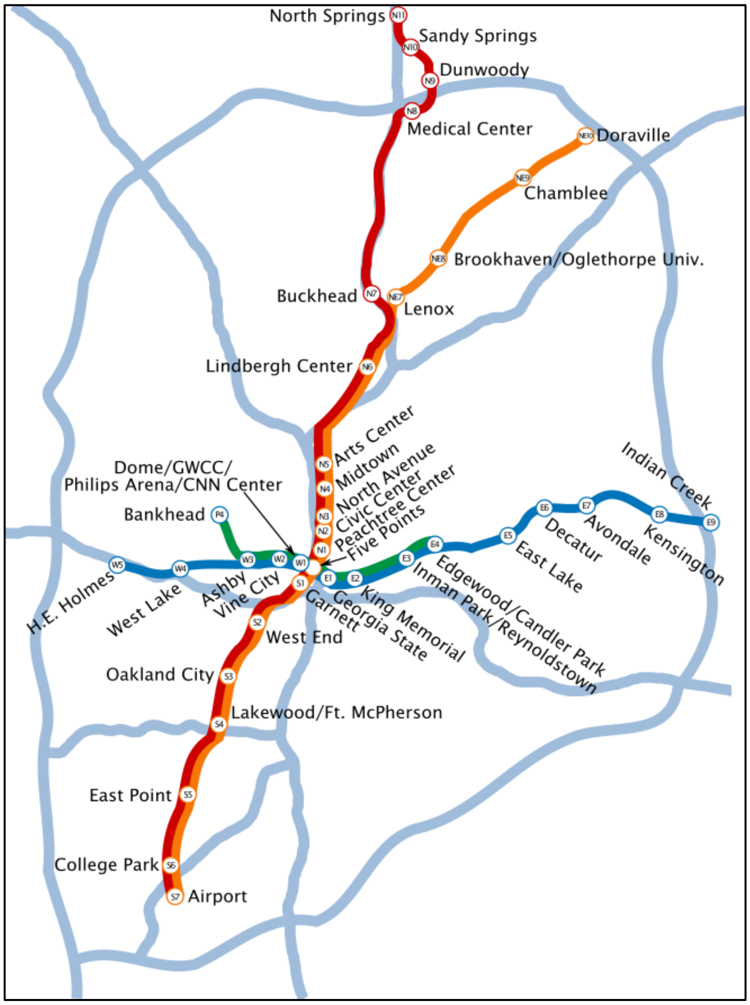

Figure 10. MARTA Rail System on a Map of Metro Atlanta.

This study uses MARTA as a case study to demonstrate how the proposed metrics can be implemented by a transit agency and the kinds of value this effort can add to an agency's operations. Some metrics will include examples from two other sprawling cities with metro systems: Los Angeles (LA Metro) and Washington, D.C. (Washington Metropolitan Area Transit Authority, or WMATA).

Figure 11 shows the monthly ridership of MARTA's rail system (unlinked passenger trips) between January 2002 and March 2024 (data retrieved from 52). The trend shows a significant decrease following the introduction of the COVID-19 pandemic regulations. Figure 12 shows the Vehicle Revenue Miles, the number of miles a transit vehicle travels when it is available to the general public, that is, when the vehicle is in revenue service. The figure Figure 12shows a decrease in the early 2010s and a decrease in revenue miles following the COVID-19 pandemic (data retrieved from 52).

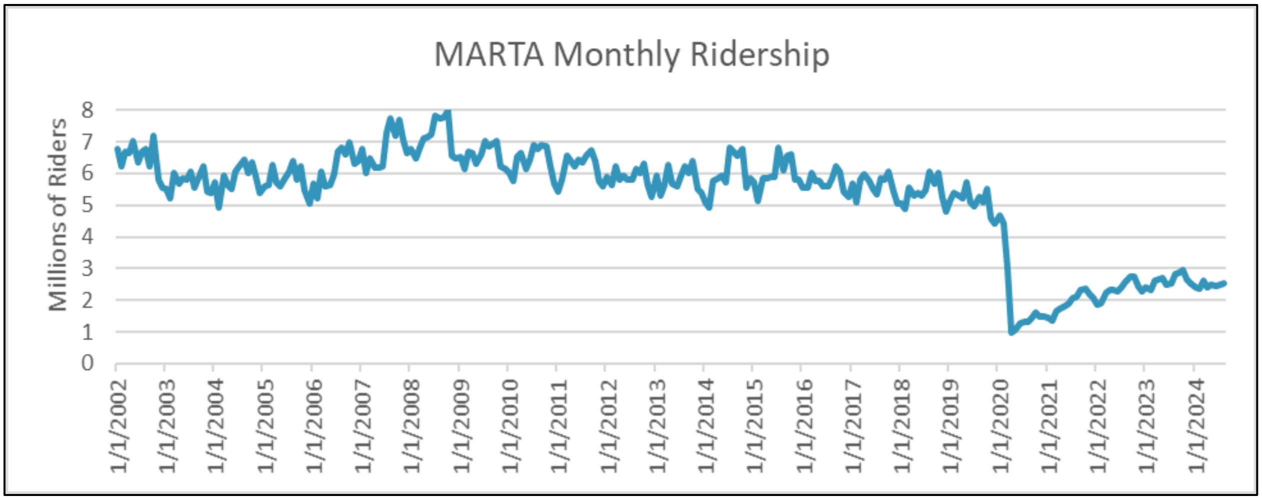

Figure 11. MARTA Monthly Ridership (data from 52).

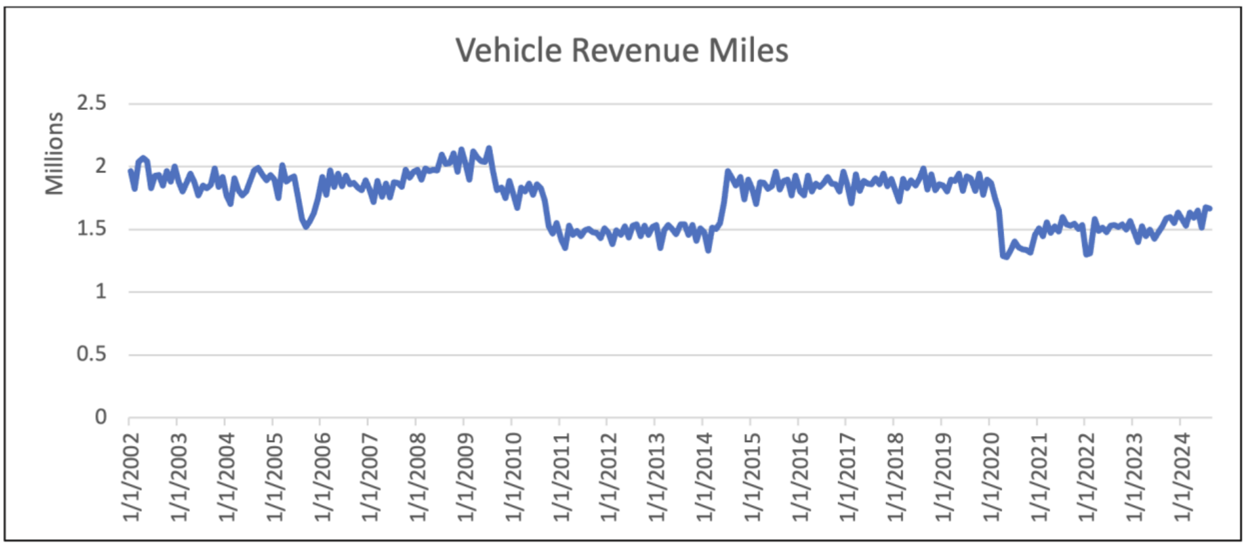

Figure 12. MARTA Vehicle Revenue Miles (data from 52).

Background

Overview of the Atlanta MARTA

Atlanta's first public transit company, the Atlanta Streetcar Company, began operating its first rail line in 1871. This line involved horses and mules pulling transit cars along steel tracks (53). A century later, voters in the City of Atlanta, Fulton County, and DeKalb County approved a referendum to have a bus and heavy rail system constructed, and the first heavy rail system in the South began operating in 1979 (54, 55). Given MARTA's role in moving commuters between the city's downtown and suburbs, the northern stations on the Red and Gold lines (including North Springs, Sand Springs, Doraville, Chamblee, and others) provide ample parking. MARTA now operates and maintains 48 miles of rail in the Metropolitan Atlanta area (56).

In 2013, researchers at Georgia Tech conducted a vulnerability assessment of MARTA using historic and projected weather data combined with insights from practitioner interviews (58). Crane (58) identified the following as potential impacts of various patterns of extreme weather events on MARTA's assets and operations:

1. Higher extreme temperature for longer periods of time, with potential impacts on key electrical instrumentation, worker and passenger comfort, track integrity, and rail vehicle maintenance needs, and
2. Higher-intensity precipitation and storm events, with potential impacts on some assets and facilities like drains, pipes, and older roofs.

This study shows that MARTA's system is vulnerable to extreme temperature and storm events, indicating that MARTA system may benefit from resilience-building initiatives. MARTA's Office of Sustainability, founded in 2022, has an objective to provide "safe, accessible, and inclusive transit options through proactive community engagement and sustainable initiatives" and defines resilience as the "ability to anticipate, adapt to, and recover from service disruptions caused by natural hazards and extreme weather events, prioritizing issues related to absorptive capacity, adaptive capacity, and recoverability, which decreases its vulnerability" (57). In 2023, MARTA conducted a Vulnerability Assessment Study to review vulnerabilities from multiple perspectives, including assessing risks and internal MARTA sustainability culture (57). The vulnerability study finds that MARTA needs to invest in robust drainage and flood management systems and enhance the agency's emergency response strategies. This assessment also finds that MARTA needs to participate in **long-term monitoring to assess the effectiveness of implemented strategies**.

Multi-Capability Assessment Approach

This research proposes measuring resilience as a set of capabilities at different phases of the disruption process. The previous chapter discusses considerations for resilience metric development. The following sections provide a pilot application of example capabilities across the disruption-recovery cycle to the MARTA heavy rail system.

Overview of Capabilities & Data Preparation

Robustness

To understand variables representing the robustness of the system, this study examines the Clustering Coefficient and Network Density. This study uses network analysis software (Snoman, accessible at 59) to represent the network as a series of nodes and edges and calculates Network Density, Network Diameter Average Degree, and Average Distance. The network, latitude, and longitude data are compiled using Google Earth and ArcGIS. For a subway network, nodes represent stations and edges represent the links between stations.

Flexibility

For flexibility, organizations can consider their ability to make operational changes to improve response during disruptions. This may be measured through scorecards. An example of an approach to develop a scorecard to measure the flexibility and agility of an agency as enabled by long-range plans is presented in Garrett (32).

To measure flexibility using the *flexibility and agility evaluation tool*, a recent long-range plan is needed. Because MARTA does not regularly publish a long-range transportation plan, the plans selected for analysis are the Sustainability Report from 2022 (60) and the an adaptation assessment/asset management pilot for MARTA from 2013 (61). The adaptation assessment (61) was a joint research effort by Dr. Amekudzi-Kennedy and Matthew Crane at Georgia Institute of Technology, David Springstead from MARTA, and Dr. David Rose and Tiffany Batac from Parsons Brinckerhoff, Inc.

Additionally, as of the writing of this report (November 2024), MARTA is developing a Vulnerability Assessment and resilience plan. These documents are not yet available to the public. The Sustainability Report (59) and Asset Management Plan (61) will thus be used as the available documents indicating the flexibility enabled by the transportation agency's planning practices.

Preparedness

Preparedness is related to various planning factors that enable agencies or system users to withstand disruptions. This can be measured through Capability Maturity Models (CMMs). The selection of measurement tool or model will vary by agency, but once an agency selects a model, the agency should use the same measurement instrument over time for comparability. To measure the preparedness of the agency, the Negotiated Resilience-Capability Maturity Model (NR-CMM) is used (34). Emails with specific questions regarding emergency preparedness have been sent to six practitioners at MARTA working in emergency preparedness and/or stakeholder engagement. Although these practitioners from MARTA have been emailed with questions to inform the preparedness score, they are yet to respond. Crane (58) provides notes from interviews with MARTA in the context of resilience.

Additionally, MARTA created a Riders' Advisory Council (RAC) in 2020 to increase the role that neighborhood members and other stakeholders have in MARTA's decisions. The RAC meets the first Wednesday of every month to discuss MARTA's finance, transit planning, major bus and rail projects, arts and cultural initiatives, transit-oriented development (TOD), and other initiatives (62). Additionally, MARTA live streams MARTA Board committee and work session meetings on YouTube (63). MARTA also provides reports and publications on their website to increase transparency (64). These resources have been reviewed to provide preliminary results for the preparedness capability.

Survivability & Recoverability

Survivability

This study applies survivability and recoverability metrics to quantify how the system performed during a major service disruption. Survivability, in this context, refers to the proportion of normal system performance maintained during the period between the onset of disruption and the implementation of recovery actions. Recoverability measures the extent to which service was restored before full operations resumed. These metrics provide a structured way to evaluate system capacity to absorb and respond to sudden shocks, moving beyond static whole-day ridership figures. Considering the formula for *survivability* where the performance is given as discrete data for the time of degraded performance, t_S (Equation 3):

$$\text{Survivability} = \frac{\text{disrupted performance}}{\text{normal performance}} = \frac{disrupted\ ridership\ for\ time\ period\ t_S}{normal\ ridership\ for\ time\ period\ t_S} \quad (3)$$

To understand the impact of a weather event on MARTA's operations and infrastructure, the December 2015 heavy rain and flooding event was examined. On December 24, 2015, Atlanta's transportation system was impacted by heavy precipitation and flooding. According to the National Weather Service, the Atlanta Intrenchment Creek reached 13.33 feet at 12:45pm that day, the highest crest recorded at that point since 2003 (65, 66, 67). MARTA experienced delays on all rail lines due to weather that day, and rail service between the Five Points and Oakland City stations were cancelled (68). Figure 14 and Figure 15 show how water moves through the Atlanta Intrenchment Creek and the affected stations (69, 70). In Figure 16, the affected rail stations – Oakland City, West End, Garnett, and Five Points stations – are circled.

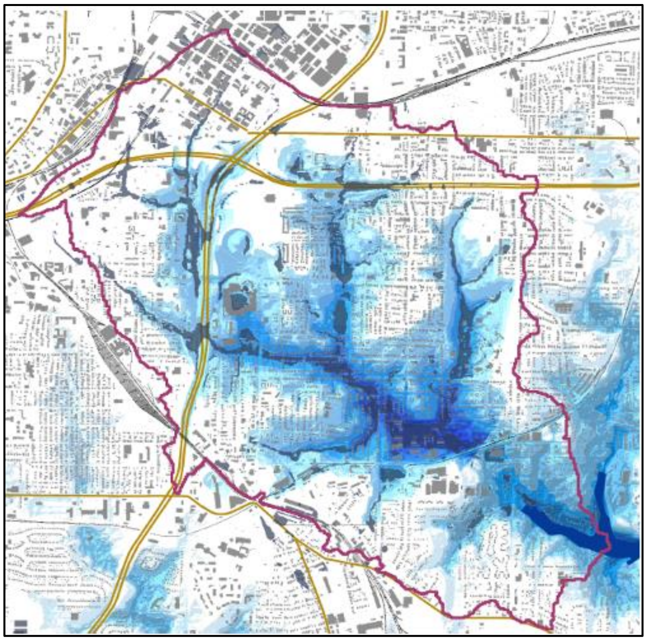

Figure 13. Atlanta Intrenchment Creek Water Flow (69).

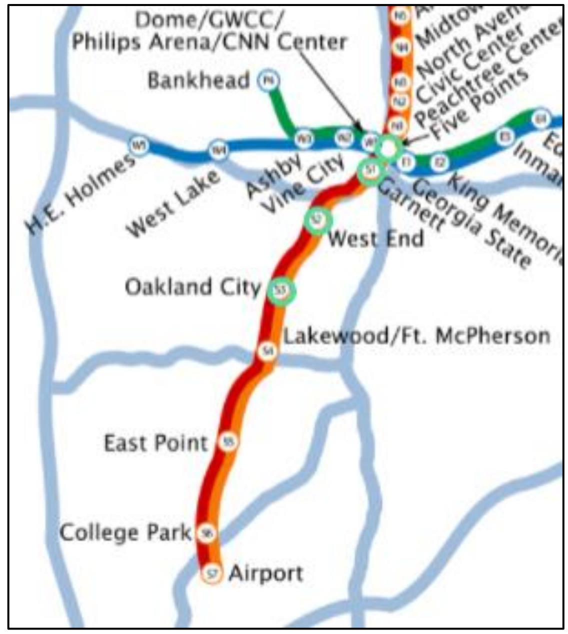

Figure 14. Rail Stations Affected by 2015 December Floods.

MARTA's services were impacted by the floods, and this problem added between 30 minutes to an hour for riders using the transit service that day (71). MARTA rail had 5,820,177 riders in December 2015 (72). Assuming that approximately the same number of riders use the service per day, MARTA rail provided service to between 185,000 and 190,000 riders per day at this time. This study assumes that the weekday average in December 2015 as 187,748.

Based on 2013 station-level entry data, approximately 67% of systemwide boardings occurred on the Red and Gold lines, equating to 100,633 Red/Gold line riders and 49,565 Blue/Green line riders on a weekday in December 2015. The survivability window is defined as the two-hour period from 11:00 a.m. to 1:00 p.m., during which the system experienced severe flooding and station closures, but the bus bridge had not yet been activated. Assuming continuous service on the unaffected Blue and Green lines, and that approximately 9.88% of daily Red/Gold ridership would have been expected during this two-hour period, the number of riders served is estimated at 59,509.

Recoverability

Recoverability is calculated once recovery efforts are initiated until the system returns to normal during time period t_R (Equation 4):

$$\text{Recoverability} = \frac{disrupted\ ridership\ for\ time\ period\ t_R}{normal\ ridership\ for\ time\ period\ t_R} \quad (4)$$

The recoverability window spanned from 1:00 p.m. to 12:40 a.m., or approximately 59.26% of the agency's daily service period. During this period, MARTA deployed a bus bridge to temporarily substitute rail service in the affected segment. Assuming that 70% of the Red/Gold line ridership expected during this recovery window was successfully served by this adaptive operation, an estimated 41,765 riders were recovered.

Adaptive Capacity

Adaptive capacity has been defined in a variety of ways in the literature and in transit agency vulnerability assessment reports (43, 44, 45, 46, 48, 49, 50, 51). Many of these sources consistently apply an indicator-based approach to represent different elements of an agency's capacity to adjust to change. This study considers adaptive capacity as related to three criteria: resource availability, organizational values and culture, and governance. Combining sub-criteria may help characterize an agency's adaptive capacity. Farebox Recovery, for example, may be one example of an indicator that can shed light on an agency's financial resource availability. Farebox Recovery is defined with the following equation (Equation 5):

$$\text{Farebox Recovery} = \frac{\text{Fare Revenue}}{\text{Operation Expenses}} \tag{5}$$

Investment in emergency management programs and technology may further indicate what resources an agency or system may have available during disruptions. For organizational values and culture, understanding an agency's relative investment in learning and development or technology transfer/adoption (if an agency is leveraging new technologies or research for implementation), per employee training or professional development budget, and number of research projects can indicate if the agency devotes resources to adapting to change regularly. Governance relates to political support (represented below as operations and maintenance annual funding by source), transparency of expenses and decisions, and the relative stability or continuity of the agency's workforce (represented by the agency's annual turnover rate). Each of these indicators is just one example of what an agency may use to determine a value for adaptive capacity. Larger organizations may have specific research that do not involve universities but still represent that agency's research orientation. Other agencies may have a standard method for determining transparency; in this study, MARTA's budget document availability and planned capital project progress tool are considered to represent the relative transparency of the agency.

Table 6 summarizes some example indicators and data sources for understanding MARTA's adaptive capacity. An [H] indicates a high value is preferred and an [L] indicates a low value is preferred.

Table 6. Transit-Specific Adaptive Capacity Criteria, Sub-Criteria, Example Indicators, and Example Data Sources.

Criteria	Sub-Criteria	Example Indicators	Example Data Source
Resource Availability (RA)	Financial Resources	Farebox Recovery (Percentage) [H]	National Transit Database
	Emergency Resources	Emergency Management Program Investment [H]	Press Releases; Plans Available Online
	Technological	Investment in Technology [H]	Proposed FIP Budget
Organizational Values and Culture (OVC)	Innovation Culture	Office of Learning & Development Expenses/Total Annual Expenses [H]	Operating & Capital Budget
	Knowledge & Awareness	Training or Professional Development Budget per Employee [H]	FY2024 Operating & Capital Budget
	Research Orientation	Number of Research Projects with Universities, per *n* Years [H]	Press Releases; Grant Databases
Governance (G)	Political Support	O&M Funding Source – Local (Percentage) [H]	National Transit Database
		O&M Funding Source – State (Percentage) [H]	National Transit Database
	Transparency	Existence of Resources Promoting Transparency of Expenses and Decisions [H]	Press Releases; Published Budget Documents
	Continuity	Turnover Rate [L]	Employee Retention Reports

Transformative Capacity

As mentioned above, the MRT Approach involves four key steps: (1) define infrastructure and socio-technical system characteristics; (2) identify disruption characteristics and potential future scenarios; (3) explore future adaptations and determine the impact of potential interventions; and (4) calculate the expected resilience loss and net present value for each resilience strategy and each scenario.

Define System Characteristics

Infrastructure & Operations: The MARTA rail system includes four lines and 38 stations (73). Assets include track infrastructure, tunnels, platforms, signals, and other facilities. MARTA's rail system includes 296 rail cars, operates 48 route miles (124 total track miles), 3 rail yards (Avondale, South Yard, and Armour), 24,354 parking spaces, and 77,059,623 Kilowatt Hours of propulsion Power (FY2023 data from 74). MARTA has charged $2.50 for the full base fare on the rail system since October 2011 (74). Figure 15 shows the Atlanta Beltline, divided into regions.

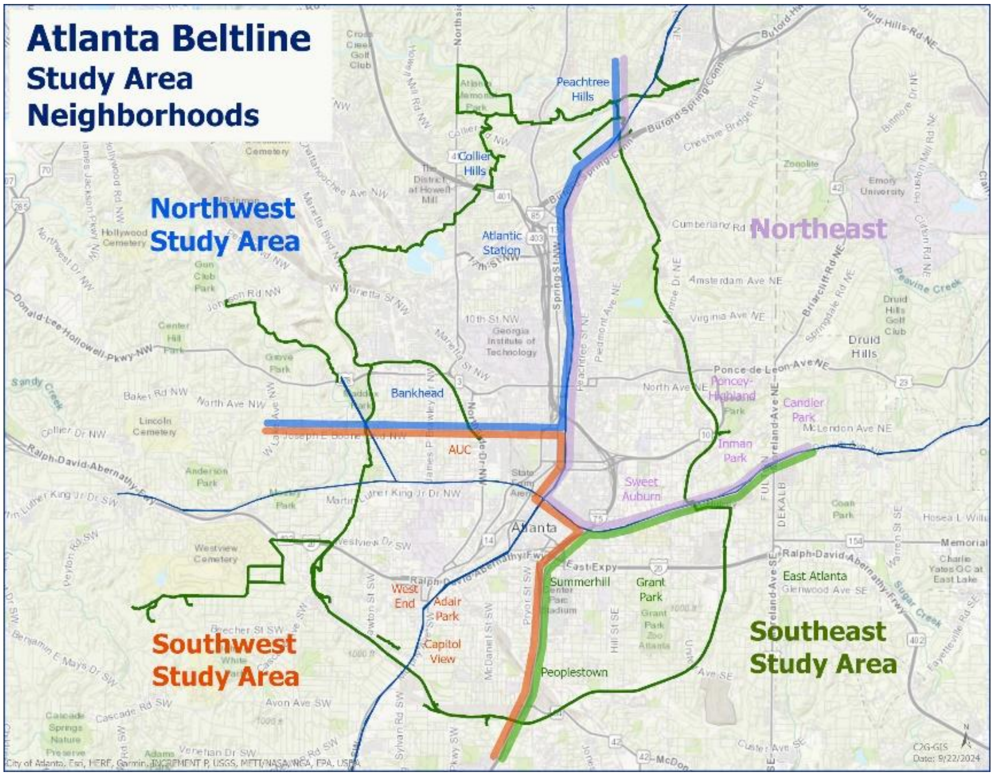

Figure 15. Atlanta Beltline Study Area Neighborhoods (75).

MARTA rail runs on electricity, meaning that the system also relies on energy infrastructure to run. The five busiest rail stations are (73):

- Five Points
- College Park
- Airport
- Peachtree Center
- Lindbergh Center

Users: In FY2023, MARTA's rail system carried 30,385,534 unlinked passenger trips (74). MARTA carries over 2.3 million riders a month, as shown in Figure 16 showing rail ridership for MARTA between June 2023 and June 2024 (73).

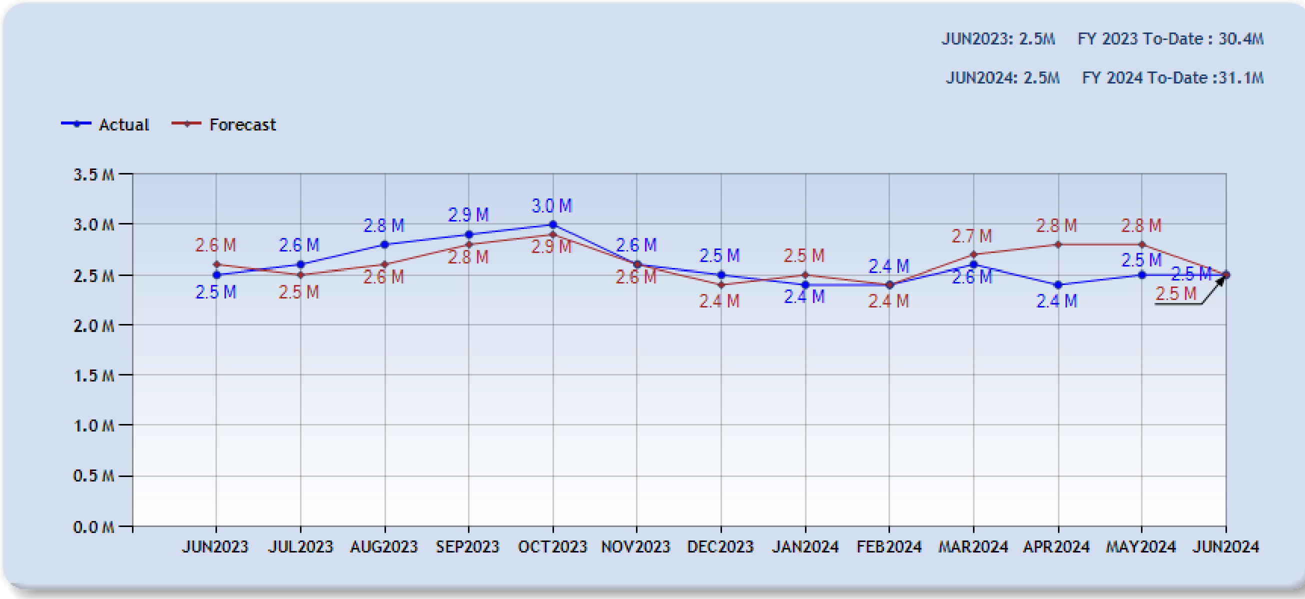

Figure 16. Rail Ridership (73).

Employees: MARTA employs over 4,000 people, including operators, administrators, professionals, police, and other personnel (74).

Identify Disruption Characteristics

Extreme weather-related disruptions to MARTA include major temperature variations, extreme precipitation, and flooding. **Extreme heat** can stress energy infrastructure, leading to power outages and delays. **Precipitation** and **flooding** can also damage or inundate tracks, stations, or critical energy infrastructure. Any single hazard can cause rail cars to break down or for links between stations to close, meaning that MARTA must also be prepared for handling, evacuating, or re-routing passengers during emergencies.

Explore Adaptive Resilience Strategies

This section introduces an adaptive resilience strategy that examines opportunities to enhance MARTA's system redundancy.

Disruption Mitigation: Enhancing Rail System Redundancy

The proposed infill stations are shown in the two figures below. The Figure 17 on the left shows the proposed streetcar extension, with infill locations highlighted as stars in circles. The Figure 18 on the right shows the infill locations as stars on the MARTA rail map, indicating that there are proposed infill locations between Arts Center and Lindbergh stations (Armour Yards); King Memorial and Inman Park/Reynoldstown stations (Krog Street/Hulsey Yard); West End and Oakland City stations (Murphy Crossing); and Ashby and Bankhead stations (Joseph E. Boone Boulevard) (76).

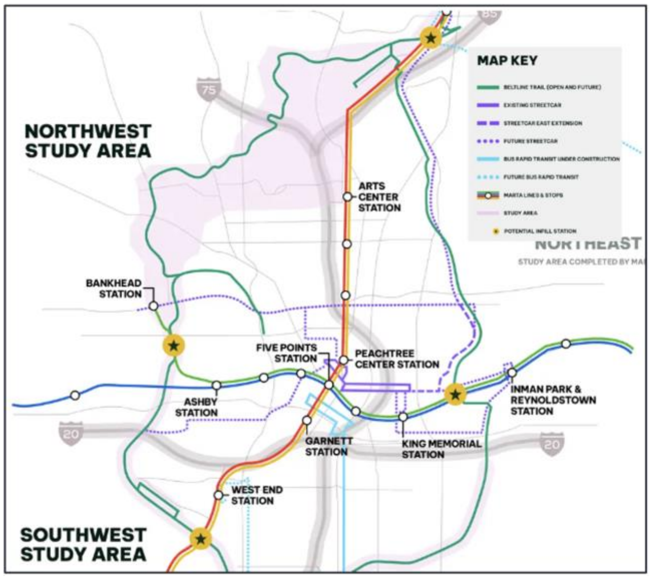

Figure 17. Atlanta Beltline with Proposed Eastside Streetcar Extension (75).

Figure 18. Approximation of MARTA Infill Stations (76).

From 2005 to 2017, the Atlanta Beltline Tax Allocation District (TAD; a program where a government entity forgoes increased property tax revenues to fund infrastructure projects in the area) generated $325 million. Table 7 shows how the Atlanta Beltline is funded, costing approximately $4.8 billion (77).

Table 7. Project Profile Costs for the Atlanta Beltline (77).

Source	**Funding (2017$)**
Bonds	$143 million
City of Atlanta	$85 million
Private Philanthropic Grants	$43 million
Other Governmental Grants	$43 million
City of Atlanta (TAD)	$48 million
Atlanta Public Schools (TAD, net)	$80 million
Fulton County (TAD, net)	$51 million
Other Income	$8 million

Light rail would likely be funded by the Federal Transit Administration (78). Potential grants include the Capital Investment Grants (CIG) and the Reconnecting Communities and Neighborhoods Grant Program. The Atlanta Streetcar East Expansion is projected to cost $230 million in total (79). The Figure 19 below shows the proposed station stops, with a goal of having the streetcar open and operational in 2028 (79).

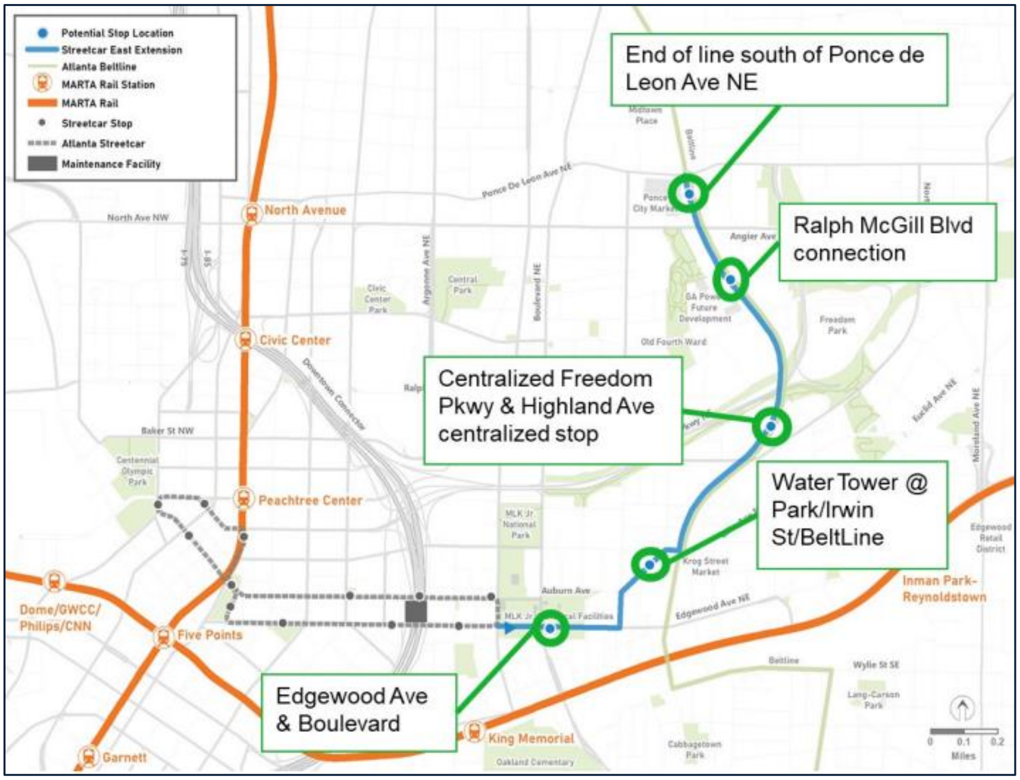

Figure 19. Eastside Beltline Streetcar Extension/Downtown East Extension (79).

Calculate Resilience Loss and Net Present Value

Enhancing MARTA Rail System Redundancy: Beltline Streetcar Extension

The performance metric is rail system functionality. The time period is 50 years. The three cases considered:

1. Only heavy rail (current case)
2. Eastside Beltline streetcar extension (or "Downtown East Extension") construction including proposed infill stations (includes Atlanta Streetcar)
3. Full proposed Beltline rail construction and all four infill MARTA stations (includes Atlanta Streetcar)

The local cost share (capital budget) of the Eastside Beltline streetcar extension, full proposed Beltline Light Rail Transit (LRT) local construction cost, and infill station costs are summarized in Table 8 (80). These costs are calculated assuming that LRT projects are split 50% local and 50% federal except for the Downtown East Extension, which is funded locally. The infill stations are also assumed to be funded locally. The final column assumes an inflation rate of 28.78% between 2017 and 2024 (81).

Table 8. Costs of Beltline Rail and Infill Stations (80).

Project (approx. number of miles)	Notes	Local Cost (2017$)	Local Cost (2024$)
Beltline Loop – Downtown East Extension (2 miles)	LRT service from Downtown Streetcar to Ponce City Market along Atlanta Beltline - Northeast	$125,400,000	$161,490,120
Beltline Loop – Downtown West Extension (3 miles)	LRT service from Downtown Streetcar to Atlanta Beltline - Southwest	$84,800,000	$109,205,440
Beltline Loop – Northeast (3 miles)	LRT from Ponce City Market to Lindbergh Station along Atlanta Beltline - Northeast	$85,800,000	$110,493,240
Beltline Loop – Northeast – Southeast Connector (2 miles)	LRT along Atlanta Beltline corridor	$64,100,000	$82,547,980
Beltline Loop – Northwest (6 miles)	LRT along Atlanta Beltline corridor	$151,800,000	$195,488,040
Beltline Loop – Southeast (4 miles)	LRT along Atlanta Beltline corridor	$54,800,000	$70,571,440
Beltline Loop – Southwest (4 miles)	LRT along Atlanta Beltline – Southeast to Oakland City Station	$96,800,000	$124,659,040
Beltline Loop – Southwest – Northwest Connector (2 miles)	LRT along Atlanta Beltline corridor	$52,300,000	$67,351,940
Infill Station: Armour	Infill station between Arts Center and Lindbergh stations	$102,000,000	$131,355,600
Infill Station: Boone	Infill station between Ashby and Bankhead stations	$42,700,000	$54,989,060
Infill Station: Hulsey/Krog	Infill station between King Memorial and Inman Park/Reynoldstown stations	$103,500,000	$133,287,300
Infill Station: Murphy Crossing	Infill station between West End and Oakland City stations	$103,500,000	$133,287,300
Total – Case 2	**Case 2 – Downtown East Extension and Four Infill Stations**	**$477,100,000**	**$614,409,380**
Total – Case 3	**Case 3 – All Projects**	**$1,067,500,000**	**$1,374,726,500**

The scenario considered in this research is an outage at one station (Five Points). Five Points is currently the only station in the network that connects to all four lines. In Spring 2024, MARTA was prepared to close down street access to Five Points for four years so the agency could implement renovations (82), but the public backlash was so strong that MARTA first paused the renovation (83) and then decided to continue with the renovation with at least one station entrance open at all times to allow pedestrian access (84).

Preliminary Results

Robustness

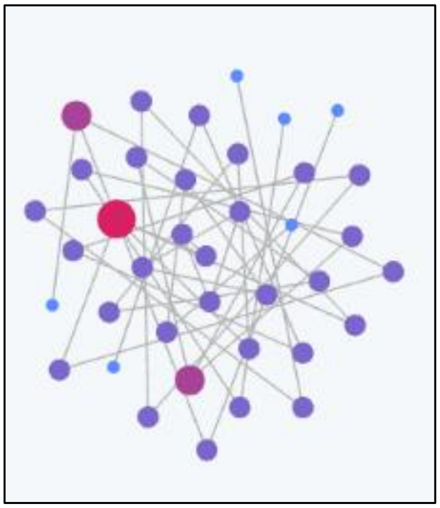

Figure 20. Network Representation of MARTA Rail Stations and Links.

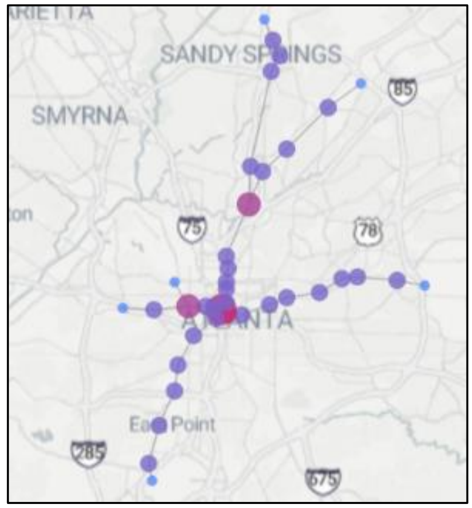

Figure 21. Map Representation of MARTA Rail Stations and Links.

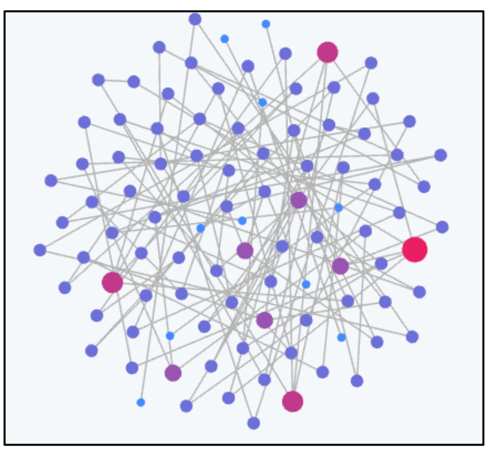

Figure 22. Network Representation of WMATA Rail Stations and Links.

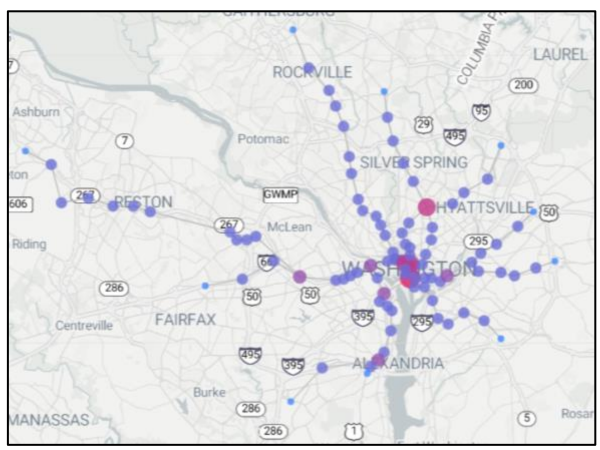

Figure 23. Map Representation of WMATA Rail Stations and Links.

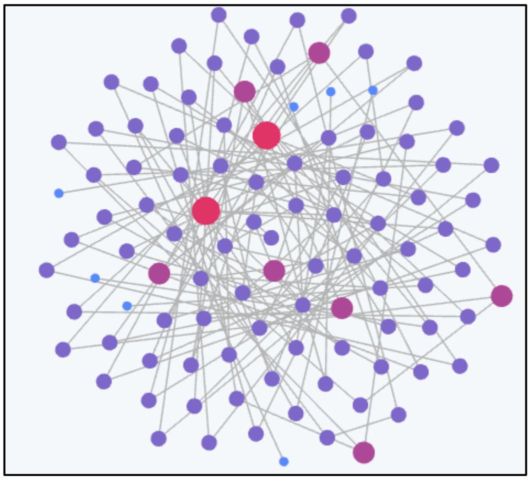

Figure 24. Network Representation of LA Metro Rail Stations and Links.

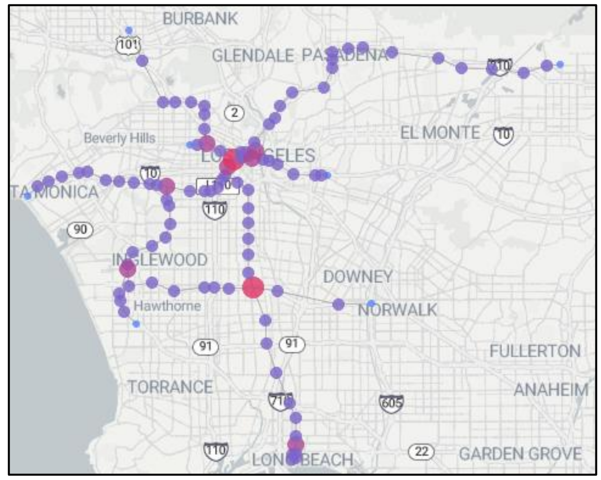

Figure 25. Map Representation of LA Metro Rail Stations and Links.

Figure 20 and Figure 21 demonstrate the robustness of the MARTA network as a network and on a map. The most robust nodes (greatest number of connections) are Five Points, Lindbergh, and Ashby. For comparison, Figure 22 and Figure 23 show the WMATA Network and Map Representations and Figure 24 and Figure 25 show the same for LA Metro.

Network Density is calculated by dividing the total number of edges in the network by the maximum number of edges. Network Density values range from 0 to 1, and a higher network density indicates higher connectivity and potential redundancy within the network. For the MARTA network, Network Density was calculated as 0.053. This value is higher than the Network Density values calculated for LA Metro and WMATA.

Network Diameter is the length of the longest shortest path between two nodes in a network. A lower value for network diameter indicates a more compact network. MARTA's value for Network Diameter is 11 kilometers, which is lower than the Network Diameter values calculated for LA Metro (52) and WMATA (27). This indicates that MARTA's network is more compact and may thus not provide as much coverage as the networks used for comparison. Furthermore, MARTA has only 38 stations while LA Metro and WMATA have 103 and 98 stations, respectively.

The Average Degree is the average number of connections (edges) a node in the network has with other nodes. This value indicates how well stations are connected to other stations within the network. MARTA's value for Average Degree is 1.947, which is lower than the values calculated for LA Metro and WMATA.

The Average Distance is the mean of the shortest distances between all pairs of nodes in the network (regardless of whether they are connected by a link). Lower values for Average Distance indicate that most nodes are close to each other. MARTA's value is 2.00, which is higher than the Average Distance value for the LA Metro (1.69) and comparable to the Average Distance value for the WMATA (1.98).

Table 9 shows examples from other cities in the United States for benchmarking. Data for MARTA were collected using Google Earth (85), data for LA Metro were collected from the LA County ArcGIS Hub (86), and data for the WMATA were collected from Open Data DC (87).

Table 9. Robustness Values for Atlanta MARTA, LA Metro, and WMATA.

City Network (State)	City Area	Network Density	Network Diameter (km)	Average Degree	Average Distance (km)	Number of Nodes (Stations)	Number of Edges (Links)
Atlanta MARTA (Georgia)	132.4 square miles	0.053	11	1.947	2.00	38	37
LA Metro (California)	469 square miles	0.020	52	2.039	1.69	103	105
WMATA (Washington, D.C.)	68.3 square miles	0.021	27	2.041	1.98	98	100

Flexibility

Using the flexibility scorecard developed for transportation plans by Garrett (32) to develop scores for the flexibility enabled by the adaptation assessment/asset management pilot for MARTA (58) and MARTA's 2022 Sustainability Report, a score of **19 out of 24** was determined. For each dimension, both plans were reviewed since MARTA does not create a Long-Range Transportation Plan like some other transportation agencies do (including state DOTs and MPOs) or a Transit Plan like other transit entities (including the Atlanta Transit Link) do. Table 10 summarizes the results of the application of the flexibility dimensions to the two documents. These results are demonstrative and will be revised upon the release of the agency's resilience plan and Vulnerability Assessment.

Table 10. MARTA Flexibility Score: Preliminary Results.

Dimension	Score	Justification
Identifying Values and Vision (IVV)	2/3	In the Sustainability Report, MARTA outlines the vision forward for sustainability and resilience actions, including the intention to develop a sustainability management plan and a resilience plan. The vision section enables roadmapping. The agency's values are not explicitly stated in the 2022 Sustainability Report.

Dimension	Score	Justification
Roadmapping (R)	3/3	The 2022 Sustainability Report outlines specific actions that can increase the agency's awareness of potential hazards. The Asset Management Pilot document also specifically highlights opportunities to integrate adaptation into policy, asset management, financial requirements, and other practices. The Office of Sustainability is charged with handling some of these actions.
Defining Resilience (DR)	3/3	The Asset Management Pilot document clearly defines Resilience and references multiple capabilities that support resilience systems before, during, and after disruptions occurs: "Resilience represents the ability of a system to react to stresses that challenge its performance. A resilient system can adjust its functioning prior to, during, or following changes and disturbances, so that it can continue to perform as required after a disruption or a major mishap, and in the presence of continuous stresses. Resilient systems can recover from sudden and severe stresses in a dynamic environment." The plan goes beyond resilience to define other relevant terms like *vulnerability assessment*, *risk assessment*, and *criticality*.
Assessing Vulnerability (AV)	3/3	During the plan development process, a hazard exposure assessment was conducted. The Asset Management Pilot document identified how the exposure assessment should be incorporated into preventative maintenance strategies and addressed by various adaptation strategies. MARTA conducted another vulnerability assessment in 2024 which is not yet available for the public.
Uncertainty or Scenario Planning (USP)	3/3	The Asset Management Pilot document considers how future extreme temperatures and high-intensity precipitation will impact the network. The plan looked at temperature and precipitation forecasts through 2100 and explored how this may impact planning and asset management. The plan has adaptations for potential hazards, which can prepare the agency for multiple future scenarios.
Reallocating Resources (RR)	1/3	Although the plans are both forward looking, these two plans do not specify actions to increase the flexibility of the usage of existing resources or identify how funding or resources can be reallocated during emergencies or disruptions.

Dimension	Score	Justification
Exploring Flexible Alternatives, Pathways, and Prioritization (EFAPP)	2/3	The Asset Management Pilot document examines hazards and various adaptations for MARTA's system and defines a template that incorporates 'Risk Mitigation Strategies into Lifecycle Management Planning'. Still, these two documents do not define pathways of actions for multiple futures.
Collaborating (C)	2/3	Within the 'Governance' section of the 2022 Sustainability Report, MARTA describes collaborating with partner agencies such as the Atlanta Regional Commission and Atlanta Transit Link. The plans do not describe task forces or other groups developed to support the agency's flexibility or resilience goals.
Total	19/24	

An updated application based on the to-be-released MARTA resilience plan and Vulnerability Assessment will be conducted and validated with MARTA practitioners. The results of the updated application will be included in future deliverables.

Preparedness

This study uses Version 1.3 of the NR-CMM Self-Assessment Tool to calculate the preparedness scores for MARTA, available online. For any question that cannot be answered without additional input from MARTA practitioners, the question is answered as "N/A" or "Neither True Nor False". Any prompt beginning with "I think" is given a "N/A" score because those questions must be answered by an internal practitioner. Because of this, many scores calculated below may change significantly when practitioner input is acquired. The other questions are answered on a four-point scale ranging from "Strongly Disagree" to "Strongly Agree".

Table 11 summarizes the scores along all capabilities included in the NR-CMM based on the resources available for review. These scores will evolve as additional practitioners provide feedback on the agency's capabilities across the four themes.

Table 11. Preparedness Preliminary Scores (various sources).

Theme	Capability	Score (out of 5)
Strategic	Community Engagement	3
	Community Collaboration Monitoring and Adjustment	3
	Information Dissemination to Communities	4
	Community Communication – Disaster Context	3
Institutional	Culture of Change	3
	Resilience Strategy	3
	Program Connectivity within Organization	3
	Continuity and Talent Development	3
Programmatic	Vulnerability and Criticality Assessments	4
	Roadmapping	4
Tactical	Stakeholder and Community Data Management	1
	Technology and Implementation Approaches	2
	Resilience Data Management	2
	Total	38/65

These scores indicate that while MARTA is successfully disseminating information to communities by leveraging multiple social media platforms, performing vulnerability assessments, roadmapping, the agency has opportunities to improve. Specifically, the agency could advance practices related to data management, technology and implementation approaches, and resilience data management. MARTA can refer to the specific resources for improvement associated with each of these capabilities using the *Suggestions for Improvement in NR-CMM* (accessible at 89). Although two practitioners provided some feedback throughout the development of this case study (90, 91), a research effort involving multiple practitioners across departments within the agency would yield more representative results.

Survivability & Recoverability

Survivability

Using the estimated values described earlier in this chapter, the value for survivability may be calculated as:

$$Survivability = \frac{disrupted\ ridership\ for\ time\ period\ t_S}{normal\ ridership\ for\ time\ period\ t_S} = \frac{59{,}509}{150{,}198} = 39.6\%$$

This yields a survivability rate of 39.6%, reflecting the significant disruption to MARTA's north-south corridor prior to operational recovery. With an estimated survivability of 39.6%, the network was able to maintain a portion of its daily functionality despite major service interruptions before recovery efforts began, underscoring the vulnerability of the Red and Gold lines to localized hazards.

Recoverability

The deployment of a bus bridge led to a recoverability rate of 70.0% during the remainder of the day until full service was restored, as shown in the equation below:

$$Recoverability = \frac{disrupted\ ridership\ for\ time\ period\ t_R}{normal\ ridership\ for\ time\ period\ t_R} = \frac{41{,}765}{(100{,}633 * 0.5962)} = 70\%$$

This results in a recoverability rate of 70.0%, indicating that the majority of disrupted service was restored through temporary means before full rail operations resumed. Although centralized infrastructure vulnerability contributed to a relatively low survivability rate, the agency's rapid implementation of a recovery strategy allowed it to recapture most disrupted trips in a few hours.

Adaptive Capacity

This study proposes using a set of indicators based on the resource availability, organizational, and governance sub-criteria to quantify the adaptive capacity of a rail system. Table 12 summarizes adaptive capacity criteria for MARTA. These values are not final but are rather intended to show examples of how the sub-criteria may be measured for an agency. Context-specific indicators, discussed with agency practitioners, will better reflect the resource availability, organizational values and culture, and governance capabilities of an agency in a manner that is more contextually relevant. Future efforts may also expand the criteria and sub-criteria to capture additional factors that may support adaptive capacity.

Table 12. Adaptive Capacity Criteria Values for MARTA (Examples) (data from 92 - 99).

Sub-Criteria	Example Indicators	Value	Data Source
Financial Resources	Farebox Recovery	$72,271,100/ $594,097,547 = 0.122	National Transit Database 2023 Annual Agency Profile
Emergency Resources	Emergency Management Program Investment (High, Medium, or Low)	Medium	Press Release: MARTA Police Department Receives APTA Rail Emergency Management Gold Award
Technological Resources	Investment in Technology (High, Medium, or Low)	Medium	FY2025 Proposed Budget
Innovation Culture	Investment in Learning and Development (High, Medium, or Low)	Medium	FY2024 Operating & Capital Budget; FY2025 Proposed Budget

Sub-Criteria	Example Indicators	Value	Data Source
Knowledge & Awareness	Training and Leadership Development Budget/Total Non-Operations Employees*	$200,000/1,426 = $140	FY2025 Proposed Budget
Research Orientation	Number of Research Projects with Universities, per 5 Years (2020 – 2025)	1	Press Release: MARTA, Georgia Tech Awarded Grant to Pilot On-Demand Multimodal Transit System
Political Support	O&M Funding Source – Local	4.5%	National Transit Database 2023 Annual Agency Profile
	O&M Funding Source – State	0%	National Transit Database 2023 Annual Agency Profile
Transparency	Transparency of Expenses and Decisions (High, Medium, or Low)	High	Press Release: MARTA Releases Interactive Online Tool to Track Capital Program Progress
Continuity	Annual Turnover Rate	23%	MARTA Employee Retention Efforts (FY22)

*MARTA's Division of Operations uses other training programs beyond the Training and Leadership Development Program (e.g., bus operator training, rail conductor training) and has an additional 3,434 employees.

As each indicator has a value along a different scale, normalization is used to bring all values to a common scale. The formula used for min-max normalization is (Equation 6):

$$\text{Normalized Value} = \frac{\text{Actual} - \text{Min}}{\text{Max} - \text{Min}} \tag{6}$$

Table 13 shows how each criterion is normalized, with justification. "High" values are given a 1; "Medium" values are given a 0.5; and "Low" values are given a 0.

Table 13. Normalization of MARTA Adaptive Capacity Criteria, with Justification.

Criteria	Example Indicators	Value	Normalized	Justification
RA	Farebox Recovery (Percentage) [H]	12.2	0.203	Assuming a 0% minimum and a 60% maximum Farebox Recovery (100).
	Emergency Management Program Investment (High, Medium, or Low) [H]	Medium	0.5	MARTA won an award for the emergency management program but does not have publicly available emergency management plans.
	Investment in Technology (High, Medium, or Low) [H]	Medium	0.5	Although MARTA has hired additional employees in the Department of Technology, the department's budget allocation shrunk by 18% between FY24 and FY25 (93).
OVC	Investment in Learning and Development (High, Medium, or Low) [H]	Medium	0.5	MARTA allocated $2,136,562 to the Office of Learning & Development in FY24, but the Dept of Research and Analytics is shrinking (93).
	Training and Leadership Development Budget/Total Non-Operations Employees [H]	$140	0.13	Assuming a minimum of $0 and a maximum of $1,075 for a state or local government to spend on training per employee (101).
	Number of Research Projects with Universities, per 5 Years (2020 – 2025) [H]	1	0.2	Assuming a minimum of 0 and a maximum of 5 research projects per 5 years.

Criteria	Example Indicators	Value	Normalized	Justification
G	O&M Funding Source – Local (Percentage) [H]	4.5	0.173	Assuming a minimum of 0% and a maximum of 26% (100).
	O&M Funding Source – State (Percentage) [H]	0	0	MARTA does not receive any state funding for its O&M expenses (92).
	Transparency of Expenses and Decisions (High, Medium, or Low) [H]	High	1	MARTA publishes its financial accounts each year and the agency has created an online tool to track capital program progress (93, 95, 97).
	Annual Turnover Rate (Percentage) [L]	23	0.563	Assuming a minimum of 14% (based upon MARTA annual turnover rates between 2019 and 2023) and a maximum of 30% (100).

Various methods have been used to determine the appropriate weighting of criterion for adaptive capacity (50). To determine the weights of justification for the purposes of this pilot application, equal weighting across all indicators is assumed. Future efforts can include surveys and workshops with practitioners to have a more context-specific weighting approach for determining the adaptive capacity of MARTA. Table 14 shows the applied weights for each of the criterion.

Table 14. Scores for Each Criterion.

Criteria	Example Indicators	Normalized Value	Weight	Score
RA	Farebox Recovery (Percentage) [H]	0.203	0.1	0.0203
	Emergency Management Program (High, Medium, or Low) [H]	0.5	0.1	0.05
	Investment in Technological Training and Equipment (High, Medium, or Low) [H]	0.5	0.1	0.05
OVC	Investment in Learning and Development (High, Medium, or Low) [H]	0.5	0.1	0.05
	Training and Leadership Development Budget/Total Number of Employees [H]	0.13	0.1	0.013
	Number of Research Projects with Universities, per 5 Years (2020 – 2025) [H]	0.2	0.1	0.02
G	O&M Funding Source – Local (Percentage) [H]	0.173	0.1	0.0173
	O&M Funding Source – State (Percentage) [H]	0	0.1	0
	Transparency of Expenses and Decisions (High, Medium, or Low) [H]	1	0.1	0.1
	Annual Turnover Rate (Percentage) [L]	0.563	0.1	0.0563
			Total	0.3769

This example analysis shows that, given these assumptions, MARTA's adaptive capacity would be given a relatively low score. Future efforts working directly with multiple practitioners and departments will enable more exact indicators (e.g., a value for investment in technology relative to other agencies) to be used for a more detailed comparison. The estimations shown here are intended to reflect a forward-looking metric, based on resource availability, organizational values and culture, and governance that may reflect an agency's ability to adjust to new changes or opportunities.

Transformative Capacity

Three Cases: Robustness Results for Building Beltline Rail

Table 15 indicates the changes to robustness values for the three cases considered, assuming all stations are functioning. Case 1 only includes the heavy rail system. Case 2 includes the Atlanta Streetcar, infill stations, and Downtown Streetcar Extension. Case 3 includes all of Case 2 and the full proposed rail coverage that would be provided by the Beltline Rail loop.

Table 15. Robustness Comparison for Three Cases (IS = Infill Stations, DSE = Downtown Streetcar Extension, BR = Beltline Rail (Full Corridor)).

Case	Network Density	Network Diameter	Average Degree	Average Distance (km)	Stations	Links	Capital Cost
Case 1: No Build	0.053	11	1.947	2.00	38	37	$0
Case 2: IS + DSE	0.035	22	2.000	1.39	58	58	$614,409,380
Case 3: IS + BR	0.028	29	2.122	1.25	82	87	$1,374,726,500

The robustness results for the expansions indicate that, if MARTA were to build the full Beltline Rail and all proposed infill stations, the Average Degree would exceed that of WMATA and LA Metro. This increase in Average Degree indicates that the stations within the MARTA rail system would be more heavily connected and have more transfer points, which is consistent with the arguments supporting the implementation of the Beltline Rail and construction of the Infill Stations. Additionally, the Average Distance between stations would also be lower than WMATA and LA Metro, indicating that Atlanta's MARTA rail stations would be closer together, providing a more robust network.

Figure 26 and Figure 27 show the streetcar extension and the four infill stations.

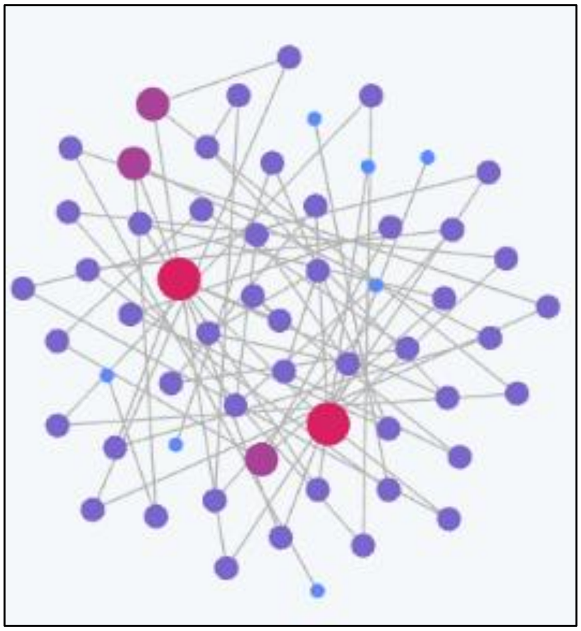

Figure 26. MARTA with Streetcar Extension and Proposed Infill Station as a Network.

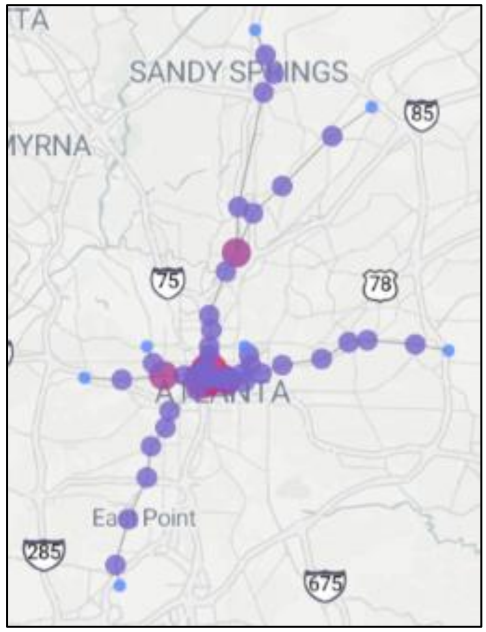

Figure 27. MARTA with Streetcar East Extension and Four Proposed Infill Stations.

Figure 28 and Figure 29 below show the network after all Beltline Rail stations are added. Comparing Figure 26 and Figure 27 to Figure 28 and Figure 29, the Beltline Rail construction would increase the connectivity of most nodes in the network, especially the four proposed infill stations.

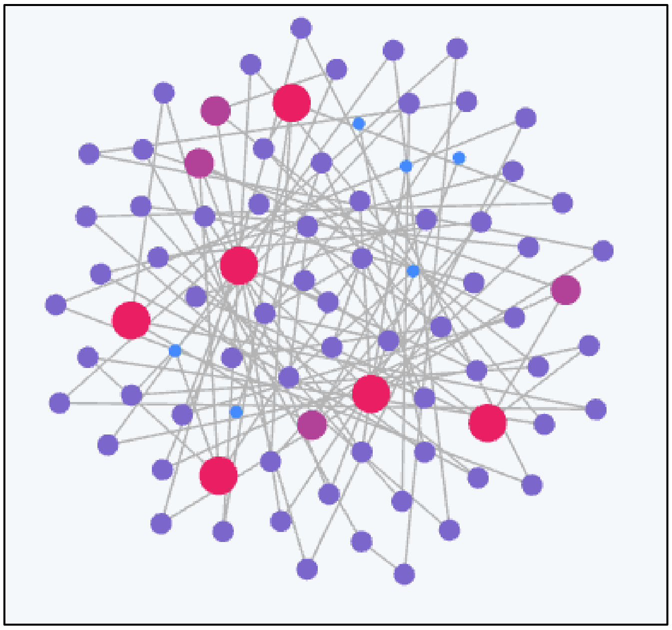

Figure 28. MARTA with Beltline Rail and Proposed Infill Station as a Network.

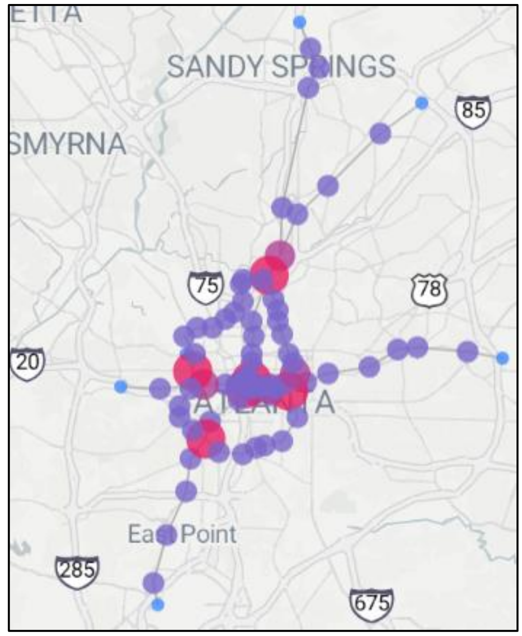

Figure 29. MARTA with Beltline Rail and Four Proposed Infill Stations.

Figure 29 demonstrates that, post-Beltline Rail construction, the stations with the highest connectivity are Five Points station, Civic Center station (connecting to the Atlanta Streetcar, and the proposed infill stations.

Table 16 indicates the changes to robustness values for the three cases considered, assuming Five Points is not functioning.

Table 16. Robustness Comparison for Atlanta MARTA (without Five Points).

Case	Network Density	Network Diameter	Average Degree	Average Distance (km)	Stations	Links	Capital Cost
Case 1: No Build	0.050	10	1.784	2.17	37	33	$0
Case 2: IS + DSE	0.034	22	1.895	1.45	57	54	$614,409,380
Case 3: IS + BR	0.026	29	2.049	1.28	81	83	$1,374,726,500

Comparing Table 15 and Table 16 shows exactly what concerned stakeholders, who were against the shut-down of the MARTA Five Points station, would expect. The Average Degree decreases for all cases in the scenario that Five Points is removed from the network, which is exactly what MARTA should expect given that Average Degree increases as transfer points within a transit network increase. As expected, the Average Distance between nodes also increases once Five Points is removed from the network. Between the cases, Case 3 (the construction of all Infill Stations and Beltline Rail) still shows the highest Average Degree and lowest Average Distance for stations, indicating that across both scenarios, this case may provide the most desirable robustness values.

Resilience & Sustainability Intersection

MARTA's resilience efforts are led by the agency's Office of Sustainability, founded in 2022. MARTA uses the Environmental, Social and Governance (ESG) framework to determine specific criteria for guiding sustainability efforts. Table 17 shows select environmental sustainability criteria across and MARTA's 2012 and 2022 values per Vehicle Revenue Mile (VRM) (60).

Table 17. Select MARTA Environmental Sustainability Criteria and Values (60).

Criteria	2012	2022	Percent Change
Water (gallons per VRM)	0.71	0.48	-32%
Waste (lbs per VRM)	0.12	0.11	-12%
Energy (kBtu per VRM)	27.73	23.69	-15%
Criteria Air Pollutants (tons)	325	321	-1%

MARTA utilizes the criteria in Table 17 when benchmarking sustainability and ESG efforts and further follows the United Nations Sustainable Development Goals (SDGs) as a framework for building sustainability and resilience (57). MARTA is increasingly embedding resilience considerations into its sustainability efforts as the agency seeks to address environmental impacts on and of its transit system. For instance, MARTA's transition to more efficient railcars helps to support the agency's environmental sustainability and operational resilience goals simultaneously. Additionally, MARTA's station rehabilitation program further promotes robust infrastructure, reduces the likelihood of station-related disruptions, and improves rider experience. MARTA's resilience plan identifies gaps in the agency's past, current, and planned resilience initiatives. This plan includes 13 mitigation actions and 17 adaptation actions, which were prioritized using the Action Selection and Prioritization (ASAP) Tool (57). Furthermore, data availability challenges – including lack of data, barriers to gathering data, data granularity, and sensitivity concerns – are identified as challenges to understand MARTA's resilience and sustainability.

To evaluate the effectiveness of its sustainability and resilience metrics, MARTA can integrate resilience metrics (such as those proposed and demonstrated in this chapter) within its sustainability performance monitoring efforts. Environmentally, MARTA already tracks criteria related to water, waste, and energy usage (as shown in Table 17). Economically, metrics like avoided service disruptions due to adaptive infrastructure help demonstrate the financial value of building rail system resilience. Metrics like service coverage, reliability, or customer satisfaction – during normal and disruptive conditions – can reflect the broader social impact of the system. These indicators collectively reflect how resilience and sustainability capabilities can be complementary for short- and long-term functionality and image. Additional discussion on integrating resilience and sustainability across agency programs is provided in Chapter 4.

Recommendations for MARTA

Short-Term

The *preparedness* analysis in this pilot application indicates that MARTA could improve in the tactical category, especially in Stakeholder and Community Data Management. Determining clear standards and systems for collecting stakeholder and community input, as well as any other relevant information, can help improve this score.

In terms of data collection for improved resilience assessments, MARTA may implement real-time train or station-level monitoring to determine how disruptive events (like floods, extreme heat waves, or even sudden ridership increases due to concerts or sports events) impact hour-by-hour and station-by-station on-time performance. Sharing this data publicly – potentially through a resilience dashboard – can improve transparency and provide a valuable source of data for researchers in this area. This would further support longitudinal tracking of resilience capabilities, potentially helping to communicate the return-on-investment of resilience-building efforts. Furthermore, understanding how both positive and negative disruptions impact on-time performance can inform MARTA's operational planning to reduce disruption-related costs, improve reliability, and boost customer satisfaction.

Long-Term

The preliminary results of this analysis further highlight the potential benefits that may result from expanding Atlanta's rail system and adding the proposed four infill stations. The simulated network scenarios demonstrate that building the Beltline light rail system and the four proposed infill stations would increase the average degree of the network while reducing the average distance between stations. This improvement in robustness would also enhance redundancy and connectivity, allowing for alternative routes during disruptions. For example, in the case that Five Points station is removed, the light rail network helps to connect the four main heavy rail lines to provide alternative routes for passengers to get to their destinations.

Discussion

Limitations

This analysis is based on publicly available data, informed assumptions, and media reports. Ridership is assumed to be evenly distributed over the day, though actual demand likely fluctuates by hour. The 67% share of Red/Gold line usage is derived from 2013 data and may not precisely reflect 2015 patterns. A more precise survivability metric would require access to hourly ridership data, automatic passenger counts, and MARTA's internal service logs from the day of the event. Additionally, the adaptive capacity metric relies upon many assumptions about hypothetical maximum and minimum values for each example indicator. Involving more practitioners can provide practice-based input on maximum and minimum values for each indicator. Throughout the development of this case study, eight practitioners at MARTA were contacted but only two practitioners responded to provide insight and feedback (90, 91). Further ground-truthing is necessary to validate and align results with the most current information and data available for the seven metrics explored in this study.

Summary

This case study provides a preliminary demonstration of an application of the multi-capability resilience assessment approach for rail systems. The data included in this study is collected from a variety of open-access sources, including MARTA's budget documents, meeting minutes, GIS files, and others. The preliminary results presented in this chapter indicate that MARTA's *robustness* values increase with the addition of the infill stations and the Beltline Rail. The preliminary results also indicate that MARTA has opportunities to improve across *flexibility* and *preparedness by* advancing some resilience-building practices, such as reallocating resources, data management, and technology and implementation approaches. Considering the disruption of the COVID-19 pandemic, MARTA's calculated value for *survivability* was within the range of values calculated for peer agencies, while the agency's value for long-term *recoverability* was slightly lower when compared to peer agencies. Initial pilot results indicate that MARTA's *adaptive capacity* may be improved through some increasing investments in research, technology, and training. Furthermore, MARTA's *transformative capacity* may be advanced through an expansion to its network.

Chapter 4: Integrated Resilience-Sustainability Framework for Rail Systems

Introduction

As extreme weather events exacerbate rail asset management challenges, rail agencies look to enhance system resilience while optimizing sustainable outcomes. Rail networks provide redundancy within the overall transportation system by providing an additional mode to transport people and goods beyond road, sea, and air transport (3). Additionally, rail networks provide an energy- and space-efficient alternative to transport by highway or air (102). Rail agencies may seek to simultaneously enhance sustainability, thus reducing the impact of systems on external environments, and promote resilience, to better prepare a system for potential threats or uncertain futures.

Understanding the rail assets that have high exposure, high sensitivity, and low adaptive capacity can help identify the most vulnerable components of the rail system. In addition, environmental, economic, and social impacts of rail system investments, and failures, can inform prioritization decisions. The combination of vulnerability and sustainability assessments may facilitate clearer identification and prioritization of the most critical facilities for resilience and sustainability interventions. Based on the specific hazards and conditions at these critical facilities, appropriate adaptation activities may be designed to enhance the performance of railway infrastructure for a variety of future scenarios – introducing more robustness into the system. Furthermore, these analyses can highlight what changes must be made at the organizational level to enhance flexibility in disruption response and operations. Rail infrastructure faces the challenges of hazard exposure, aging assets, and dynamically evolving social demands, but there is no formalized framework (found by the authors to date) for incorporating resilience and Triple Bottom Line sustainability assessments into planning and decision making (3).

Literature Review

Numerous studies and governmental documents were reviewed to build the integrated resilience-sustainability framework. In a paper exploring the vulnerability of railways to floods, mass movements, slope fires, and tree falls, Fabella and Szymczak (103) point out that rail has lower network density and fewer route alternatives, meaning that there is little redundancy in many rail networks. According to the paper, the steps of measuring resilience for rail infrastructure are as follows (103):

1. Determine the specific quantities of the asset to examine
2. Find daily usage and the approximate usage for each segment
3. Collect relevant weather data that may affect selected portions of track
4. Match traffic and disruptive event data

Although these steps include exposure data and traffic (criticality) data, the study does not include sensitivity or sustainability data when considering rail system resilience for present and future generations. Acknowledging that there are limited frameworks for incorporating the impacts of uncertainty into rail planning, Quinn et al. (104) present a potential pathway for enhancing rail network resilience. The pathway includes identifying existing factors (i.e., location, condition, and hazard exposure), exploring alternatives, and identifying relevant implementation strategies (104). This pathway indicates there are benefits associated with understanding the condition and location of the assets, as well as exposure to hazards, before creating alternatives and making plans, but also does not explicitly acknowledge sustainability considerations or related factors. This framework was also created for the railway systems of Europe and did not include input from US rail practitioners. Figure 30 shows the framework proposed by that study (figure simplified from 104). The square boxes with thick borders indicate the elements of the framework related to preparing the adaptation strategy and the rounded gray rectangles related to the implementation plan.

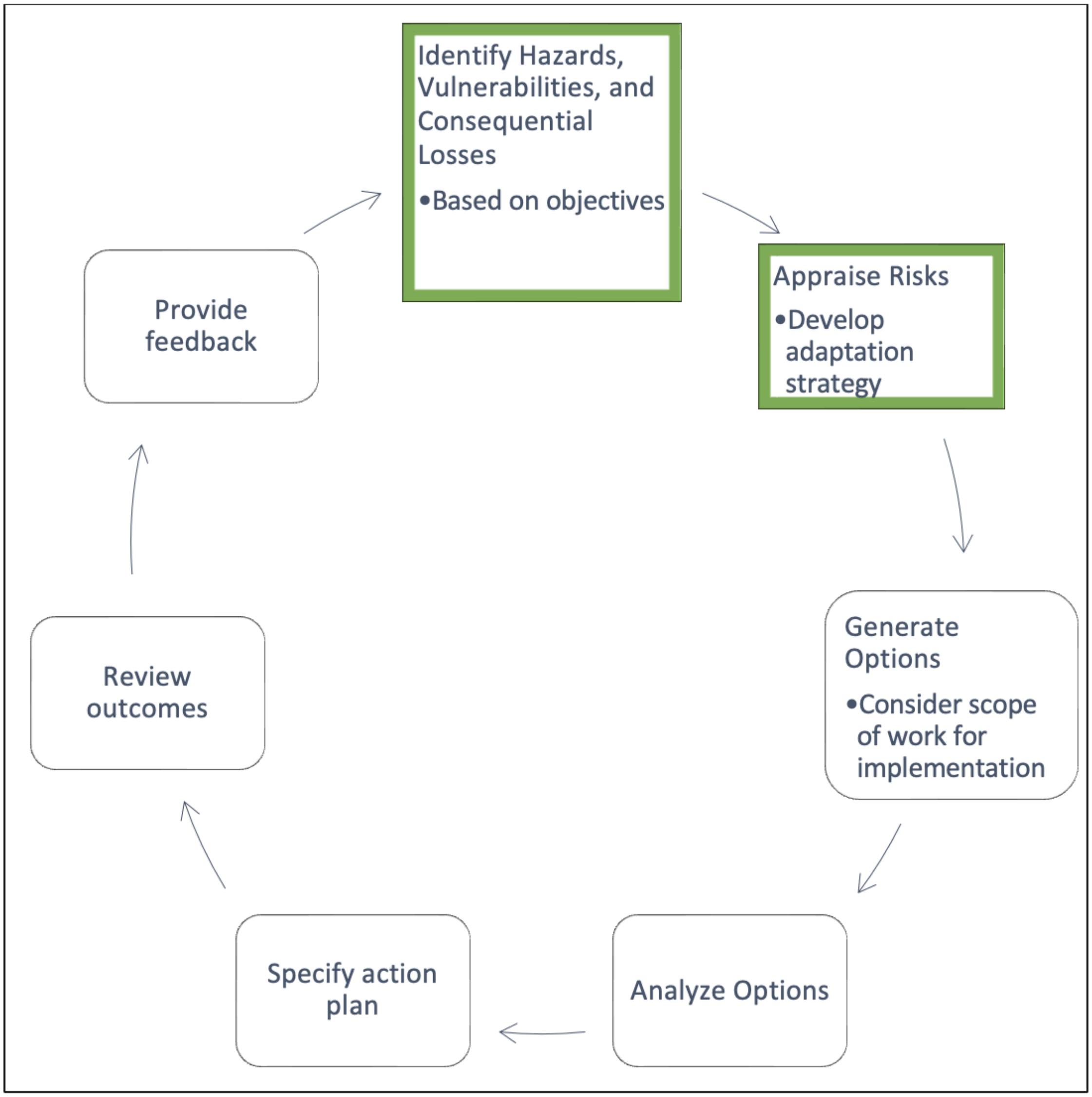

Figure 30. Rail Adaptation and Implementation Framework (adapted from 104).

The FHWA published another framework for incorporating extreme weather events into transportation systems operations in 2015 (105). This framework specifically outlines how to assess vulnerability and then integrate the information into decision making. The 2015 framework calls attention to the need for organizational change in business processes, culture, collaboration, performance management, and others. In the vulnerability assessment and resilience framework, published in 2017 (revised on their website in 2021), the FHWA includes identifying risk posed by certain hazards and criticality of hazards (106). The National Academies of Science, Engineering, and Medicine (2021) identified further opportunities for incorporating vulnerability/risk analysis into transportation system operations and capital improvements. The NASEM Framework for enhancing agency resilience to natural and anthropogenic hazards and threats (FEAR-NAHT) draws attention to the importance of developing programmatic measures and monitoring system performance over time (107). Figure 31presents a simplified FEAR-NAHT framework.

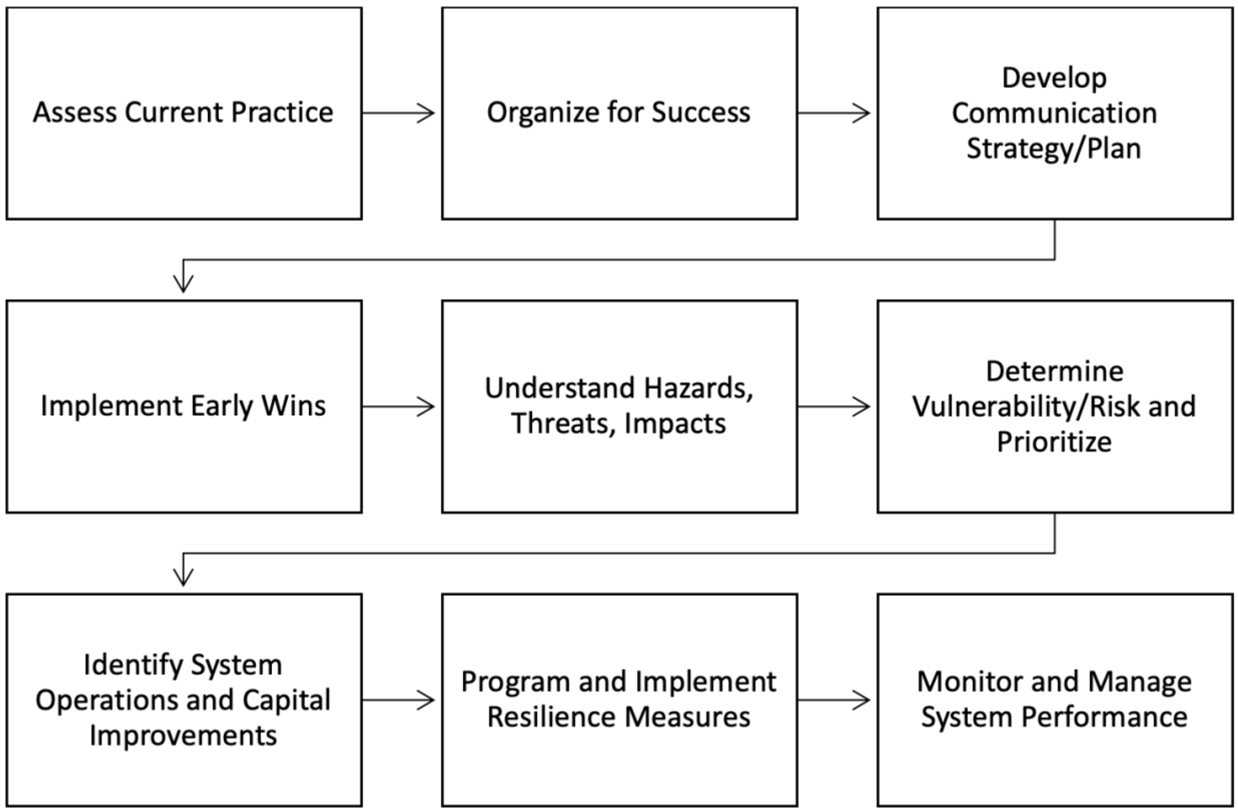

Figure 31. Simplified FEAR-NAHT framework (adapted from 107).

The Federal Transit Administration (FTA) released the Transit Resilience Guidebook in 2024, describing a process to implement resilience considerations into transit system planning and operations while considering the USDOT's guiding principles of adaptation and resilience (1). These principles include prioritizing vulnerable assets while preserving ecosystems and building community relationships (1). The guidebook highlights some relevant federal regulations and policies related to building transit resilience including 49 CFR Parts 602, 625, and 673 (Emergency Relief Program, Transit Asset Management, and Public Transportation Agency Safety Plan requirements, respectively); 23 U.S.C. 176 (Promoting Resilience Operations for Transformation, Efficient, and Cost-Saving Transportation program); and others. These policies indicate a commitment to reducing the impact of hazards on transit infrastructure and operations. This guidebook also does not specifically highlight the role of sustainability assessments or how to integrate sustainability factors into resilience-oriented work.

Faber et al. (108) highlight the importance of considering the socio-ecological-technical elements of systems at local and global, as well as short- and long-term, scales to build infrastructure system resilience. **Gudmundsson et al. (**109**) note that the principles of**

sustainable development—not just elements of the TBL model of sustainability—must guide sustainability assessment. These principles of sustainable development include preserving and restoring environmental and ecological systems, fostering neighborhood vitality, improving economic prosperity, and ensuring fairness between groups and over generations (109). This last principle relates back to **Faber et al.** (108), in which the authors **argue that, to achieve sustainability and resilience outcomes simultaneously, agencies must consider the trade-offs between consumption of materials, pollutants, enhanced robustness, and potential economic and social benefit.**

Thaduri et al. (110) review the impact of extreme weather events on railway operations in Sweden. Major hazards identified in this study include flooding, landslides, wind, heat, ice, and changes in precipitation patterns. After exploring the hazards that potentially threaten Sweden's rail network, the authors identify failure modes (i.e., short circuit, loss of power, obstructed track), related asset failures (i.e., breakdown of signals, catenary, track), and network effects of these failures (i.e., delays, increased maintenance, increased stress). Building on this study, Garmabaki et al. (112) present a method for conducting a weather hazard impact assessment in the context of railway maintenance in Sweden. The authors discuss the need for agencies to explore relevant adaptation measures but do not identify specific adaptations that address rail system vulnerability. Greenham et al. (113) review the impact of elevated temperatures on a major rail transit system in the United Kingdom. This study reviews the range of extreme heat impacts on rail assets and then uses projection data to predict heat-related delays for the system. Rossetti (114) summarizes the potential impacts of extreme weather events on railroads for the U.S. and performs an analysis of 10 years of Federal Railroad Administration data to find the trends of railroad accidents associated with different hazards. **Rossetti recommends that future studies develop strategies to address extreme weather events impacts on rail (referring to both organizational and infrastructure adaptations, as discussed by 115) and measures to address the effectiveness of these strategies.**

Ngamkhanong et al. (116) present a method to monitor railway track resilience. This study states that rail operators should identify critical asset locations, assess damaged rail assets, and adapt and enhance performance based on lessons learned from previous disruptions. Network Rail published a resilience and adaptation plan that summarizes some potential rail adaptations, including monitoring of assets using remote sensors, as proposed by Ngamkhanong et al. (116, 117). Beyond monitoring, the plan mentions interventions for specific hazard impacts on rail, similar to AAR documentation on extreme weather impacts on the US freight rail system (118). Blackwood et al. (115) summarize specific weather impacts on rail assets, current adaptation measures, and potential nature-based solutions as pathways to enhance rail adaptability for extreme temperatures, high and low precipitation levels, wind, lightning and electric storms, and flood events. Using nature-based solutions as adaptations for rail systems can also enhance system sustainability by reducing negative environmental impacts that may be associated with adaptation projects. In addition, Blackwood et al. (115) argue that proposed adaptations should not be country-specific but rather hazard-specific. **Quinn et**

al. (104) present a similar sentiment and further **imply that context-specific factors should influence adaptation strategies**. These studies begin to address some of the challenges with enhancing rail system resilience but do not discuss how mitigation efforts and adaptations can impact sustainable outcomes.

Other studies approach rail network adaptability differently, focusing less on physical adaptations and more on rail users (i.e., passengers being transported on passenger rail or the owners of goods on freight rail) adaptability. **Vodopivec and Miller-Hooks (**111**) argue that coupling a transit network with other technical systems supports user adaptability**. Vodopivec and Miller-Hooks found that individual rail users may respond to the same disruption differently (111), indicating that social factors inherently impact resilience to disruptions. For multimodal or intermodal systems, responses to disruptions may vary even more. Chen and Miller-Hooks (19) describe a method to measure resilience in an intermodal system. **This study highlights the importance of planning for recovery activities before a disruption occurs (**116**), which would take place after the agency conducts a vulnerability assessment and identifies impacts**. The approach presented by Chen and Miller-Hooks also requires active engagement of stakeholders relying upon rail infrastructure to ensure recovery activities will be implemented successfully.

Motivated by the increasing rate and frequency of hazards, Kortazar et al. (123) investigate if a new high-speed rail line between Madrid and Basque Country could be environmentally justified considering the full transportation infrastructure lifecycle. The authors find that this rail project is not justified environmentally considering factors like energy consumption and freight traffic volume. Considering the importance of robust, multimodal transportation networks as critical infrastructure in the context of extreme weather event occurrence may have led this study to a different result. **As Carvalho et al. (**124**) describe, when conducting sustainability assessments, researchers should "not exclusively focus on environmental monitoring but also deal with other uncertainties and provide guidelines to analyse governance and processes of action"** (pg. 10). **This study found that an appraisal of sustainability of a potential high-speed rail project in the UK included environmental, social, and economic factors as well as climatic factors and adaptability. Another study by Xu et al. (**125**) further supported the importance of considering the resilience of urban spaces when striving for sustainable development.** <u>**These studies indicate that there is a potential benefit to having a standardized approach for considering both factors in rail planning and decision-making.**</u> Table 18 summarizes the contribution of the articles and documents from the literature review to the proposed framework (content adapted from 3).

Table 18. Contributions of review to proposed framework (adapted from 3).

Contribution	**Relevant Literature**	**Part(s) of Proposed Framework**
Framework Design	Fabella and Szymczak (103), Quinn et al. (104), FHWA Frameworks (105, 105), NASEM FEAR-NAHT (107), FTA Resilience Guidebook (1), Gudmundsson et al. (108)	Vulnerability Assessment, Sustainability Assessment, Impacts Analysis, Alternatives Analysis, Implementation and Monitoring
Short- and long-term extreme weather threats; existing conditions	FHWA Frameworks (105, 105), Fabella and Szymczak (103), NASEM FEAR-NAHT (107)	Vulnerability Assessment
Risk and criticality information	FHWA Frameworks (105, 105), Fabella and Szymczak (103), NASEM FEAR-NAHT (107), Vodopivec and Miller-Hooks (111)	Impacts Analysis
Sustainability assessment	FTA Resilience Guidebook (1), Faber et al. (108), Gudmundsson et al. (109)	Sustainability Assessment
Specific hazard-asset impacts	Thaduri et al. (110), Garmabaki et al. (112), Greenham et al. (113), Rosetti (114), Blackwood et al. (114)	Impacts Analysis
Organizational and asset-based alternatives analysis	Quinn et al. (104), Vodopivec and Miller-Hooks (111)	Alternatives Analysis
Adaptation strategies	American Association of Railroads Freight Rail and Climate Resiliency (118), Greenham et al. (113), Rosetti (114), Blackwood et al. (114), Ngamkhanong et al. (116), Network Rail's resilience and adaptation plan (117), and others	Alternatives Analysis, Implementation and Monitoring
Measures, targets, and indicators	Gudmundsson et al. (108), Chen and Miller-Hooks (19), Bešinović (16); Fang et al. (119), Tang et al. (120), Gong et al. (18), Ma et al. (121), Xu et al. (122)	Implementation and Monitoring
Performance monitoring; iterative process	Quinn et al. (104), FHWA Frameworks (105, 105), NASEM FEAR-NAHT (107), Garmabaki et al. (112)	Implementation and Monitoring

Proposed Framework

Fabella and Szymczak (103), Quinn et al. (104), and the Federal Transit Administration (1) propose resilience-building frameworks for rail and related systems. Other authoritative bodies have proposed vulnerability or risk assessment approaches for transportation more broadly (105, 105, 107). These studies provide the foundation for reducing vulnerability to hazards but do not provide guidance for building resilience while enhancing sustainability. This study provides a framework that builds upon traditional vulnerability and sustainability assessments and incorporates emerging resources and approaches to build adaptive capacity (3). Figure 32 shows the proposed framework, which includes steps to address resilience and sustainability concerns through infrastructure and organizational interventions (3).

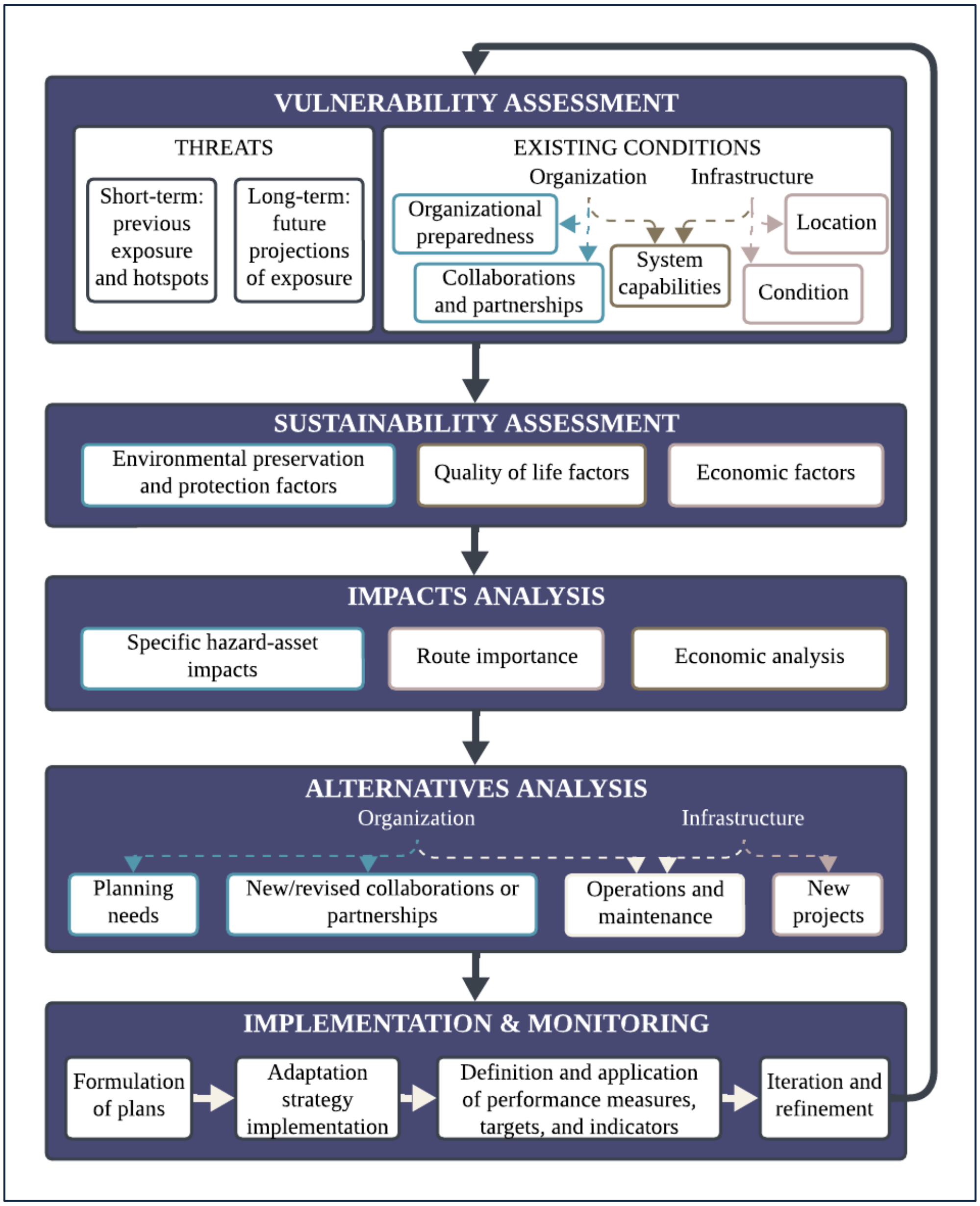

Figure 32. Assessment, Analysis, and Implementation Plan for Rail Resilience and Sustainability (3).

This framework describes an approach for rail agencies to incorporate vulnerability assessments, projections, and adaptations into planning. Each step presented in the Figure 32 is discussed in detail in the following sections. First, background on vulnerability assessments and necessary data acquisition is discussed in the 'Vulnerability Assessment' section. Categories of data at this step include asset, organization, and exposure data. Then, the 'Impacts Analysis' section explores specific vulnerability and criticality by discussing hazards and impacts on each component of rail infrastructure, economic analysis, and route importance. Organizational and asset-based approaches to addressing impacts are presented in the 'Alternatives Analysis' section. Finally, the

‘Implementation and Monitoring’ section discusses developing and redefining performance measures to track the effectiveness of the implemented actions over time.

Vulnerability Assessment

To improve long-term resilience, rail agencies can conduct vulnerability assessments that incorporate exposure, asset usage, condition, and other asset characteristics into prioritization and decision-making processes. Vulnerability of a railway transport system is related to the rail system's susceptibility to failure and can be defined as a function of the hazard characteristics and the location, condition, and adaptive capacity of assets (10). Vulnerability assessments can highlight which aspects of a transportation system are most exposed to extreme weather and other hazards and which are most sensitive to inform decisions regarding prioritization for maintenance or further action.

Before a vulnerability assessment can be completed, railway infrastructure managers must understand the existing conditions of their physical and organizational assets. Railway managers regularly monitor the condition of the components of their railway track geometry. Rail operators also monitor the locations of their assets, key corridors, intermodal facilities, and areas where there are competing priorities (e.g., shared passenger-freight corridors). These location, condition, connectivity, and importance data inform criticality and risk calculations later. Understanding organizational preparedness (i.e., plans and strategies in place to respond to shocks) and collaborations with other modal agencies and emergency management entities can also be key to enhancing rapidity and flexibility during and after a disruption.

Identifying potential weather-related hazards can be as simple as monitoring weather events in an area and noting impacts on railway infrastructure over time. As weather events intensify, however, there may be value in improving understanding of potential future extreme weather scenarios to inform rail planning and adaptation. For the US, temperature, wind, and other weather-related data is available at a spatial resolution of 12 kilometers from Argonne National Laboratory’s ClimRR portal (126). Using information from the Weather Research and Forecasting (WRF) model developed by the National Center for Atmospheric Research, ClimRR provides projection data for maximum and minimum temperatures, heating and cooling degree days, wildfire index, precipitation, and other weather variations. The data is available for mid-century and end-century projections for two Representative Concentration Pathways, RCP4.5 and RCP8.5 (126). Incorporating projected exposure to these stressors can inform long-range planning and reduce some of the uncertainty associated with adaptation investments. Specifically, utilizing dynamically downscaled projections for multiple scenarios can enable rail agencies to identify areas where hazards are increasing in frequency (i.e., hazard hotspots) to prioritize projects, adaptation strategies, and maintenance. Figure 33, Figure 34, Figure 35, and Figure 36 show examples of projection data from the ClimRR data portal (126).

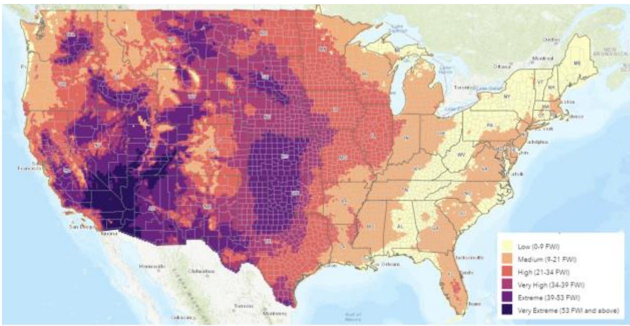

Figure 33. Mid-Century Fire Weather Index Classes for RCP8.5 (126).

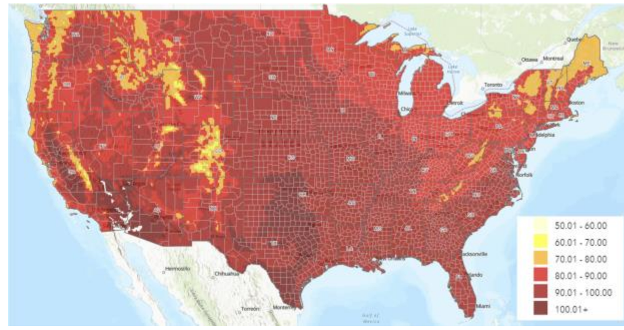

Figure 34. End-Century Summer Seasonal Temperature Averages for RCP8.5 (126).

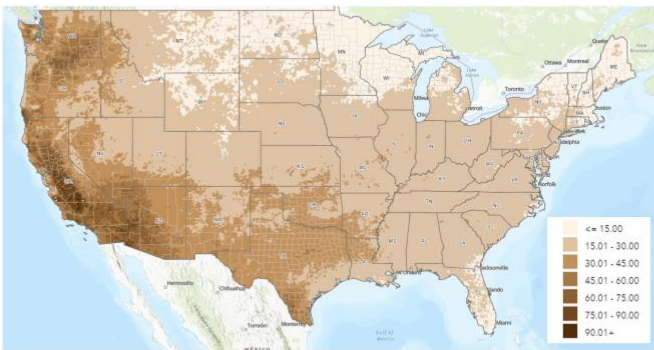

Figure 35. End-Century Consecutive Days with No Precipitation (Decadal Maximum) for RCP8.5 (126).

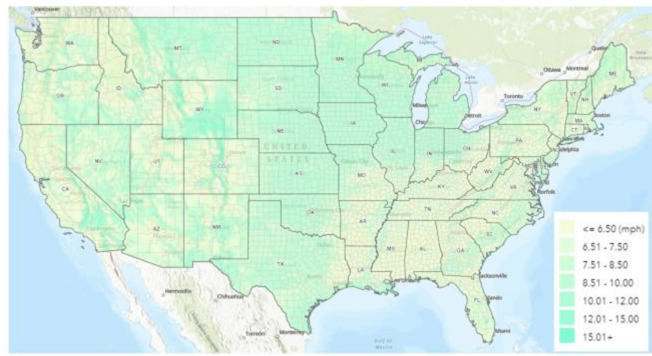

Figure 36. End-Century Wind Speed for RCP8.5 (126).

Sustainability Assessment

Gudmundsson et al. (109) i**ndicate that if future generations are considered well during the sustainability assessment process, investments enhancing resilience will also enhance sustainability**. Faber et al. (108) present an approach to quantify sustainability leveraging the Planetary Boundaries model. The authors describe Life Quality Index (LQI) as a function of gross domestic product per capita (an economic factor), life expectancy (a factor that relates to quality of life and environmental factors like air quality), and the fraction of life spent to earn a living (another quality-of-life factor) (108). Agencies may select a combination of factors for each dimension of sustainability to conduct their assessment and assign weights to the dimensions in line with their beliefs, values, and goals. **Acknowledging the relationship between resilient and sustainable outcomes, Xu et al. (**29**) recommend including three stages (disaster prevention, damage propagation, and recovery) and five dimensions (society, economy, infrastructure, environment, and physics) when conducting comprehensive resilience assessments in the context of advancing sustainable development goals.** The authors further highlight community resilience dimensions as playing a role in both resilience and sustainability outcomes. Table 19 shows some examples of metrics used in studies examining rail sustainability.

Table 19. Sustainability Dimension Sample Metrics.

Sustainability Dimension	Sample Metrics
Environment	**Energy**: Energy efficiency (kilowatt-hour/passenger-kilometer), total usage, energy (MJ) used per passenger-kilometer **Land Use**: Railway network length, station's service area, land use diversity, density of rail network (line kilometers per 10000 square kilometers)
Economy	**Lifecycle Costs**: cost per pass-km, discounted present value LCC, total rail infrastructure funding per segment **Market Costs**: Tobin's q, market share of passenger movement, revenue from passenger trains **Operational Costs and Profits**: Operating margin, average operation cost, total expenditure on infra/pass-km **Mobility**: Average velocity, speed of trains **Productivity**: Volume of passengers, daily ridership
Quality of Life	**Employment Statistics**: Number of employees/new capital project **Safety**: Total number of fatalities, accident rate or number of accidents, organizational efforts to measure safety **Public Accessibility**: Accessibility of stations **Feedback and Satisfaction**: Presence of feedback mechanisms, ability for public comment, customer satisfaction rate **Local Resilience:** Neighborhood connectedness, risk and vulnerability, procedures, and available resources

Agencies can also use sustainability assessments to quantify the impact that new projects or design changes may have on environmental conditions, economic outcomes, and quality of life. Integrating sustainability considerations into resilience planning can also provide long-term cost savings through energy efficiency and use of sustainable resources while facilitating infrastructure robustness and emergency preparedness (which reduce potential recovery costs). **If a corridor or asset is identified as vulnerable during vulnerability assessment (next section), sustainability assessments can highlight if the surrounding area is in further need of environmental remediation or jobs creation – elements for an agency to consider when designing adaptations.**

Impacts Analysis

Identifying Specific Impacts of Hazards on Rail

Rail operators may also benefit from reviewing previous and current causes of asset failures to identify potential correlations with impacts (3, 113). Analyzing historical weather event records and future weather condition modeling can inform how natural hazard trends are developing and increasing exposure in vulnerability assessments (114). Further analysis of the relationship between extreme weather events and railroad infrastructure is also important for long term railroad resilience and sustainability (114).

Precipitation: Rossetti (114) explored the impacts of weather on railroad operations, including that precipitation and fog can lead to reduced visibility for rail conductors. In addition, storm events can cause flooding which can cause washout of tracks, derailment, track blockages, or overhead system failures (127; 128). Drainage systems may also overflow or fail during extreme precipitation events (127). Long-term extreme rainfall can also cause bridge scour (36; 117; 128) which can lead to high maintenance costs or the need for bridge replacement.

Extreme heat: In the summer, rail tracks may be warped or may buckle due to thermal expansion (114; 127; 128). There will also be issues with the environmental conditions surrounding tracks, including issues with the substructure of the track and changes to the growing systems of surrounding vegetation (127; 128). For systems with underground tunnels, there could also be increased ventilation issues or air conditioning needs (127), especially for systems that carry passengers. Summer heats also cause general delays, as reported by rail service providers across the country (including San Francisco's BART, North Texas's DART, Orlando's Sunrail, and Amtrak lines in the Northeast). For all projected scenarios, increased operational delays for rail service providers are predicted in a case study of the London Underground (113).

Drought: Some areas may experience drought during the summer months as well. Drought may have an impact on subgrade moisture conditions and cause an increased risk of earthworks failure (115). These conditions are related to necessary undercutting and railroad maintenance activities, indicating increased costs. Impacts of dry soils and subgrade conditions may also cause misalignment of assets, including rail tracks as well as poles supporting overhead lines (128). Damaged or destroyed assets increase maintenance needs, but drought and extreme heat conditions may also require revised maintenance schedules to protect crew well-being (127).

Wildfire: Rail assets and the associated electricity required have started wildfires (129). In conjunction with natural conditions increasingly enabling fire weather, rail assets may be faced with increased exposure to wildfires. Wildfires can cause trees to fall and obstruct the track (127), which can be highly dangerous for rail operators, freight, and passengers. Heat from wildfires can also cause the track or overhead lines to overheat or become damaged, leading to operational delays and increased maintenance needs (115). Wildfires also complicate maintenance working conditions as smoke reduces visibility and causes negative health impacts (127).

Extreme Winds: Extreme winds may cause objects to impact, damage, or block rail assets (128). Extreme winds may occur during severe storms or winter weather, which can amplify the damage to the rail assets. Railroad signals and electronic infrastructure may also fail due to outages (115), causing cascading failure for other rail assets and operations.

Winter Weather: Tracks may deform, break, or crack in extreme temperatures, including in extremely cold temperatures (115; 128). Snow may cause blockages of the rail track, disrupting operations and increasing maintenance costs (115; 117). Melting snow can interfere with the soil moisture content for the earthworks underneath rail tracks and later lead to earthworks failures (115; 128).

Economic Analysis

Understanding the consequential losses and appraising the risks of extreme weather threats is also important for communicating funding needs to stakeholders and decision makers. Incorporating economic analysis into rail system decision making to support resilience and sustainability involves evaluating short- and long-term costs and benefits of infrastructure investments, maintenance strategies, and operational changes. Costs to railway systems due to disruptions include rerouting and delaying trains, resending goods, increased labor due to development of new itineraries, repair, and missed opportunities (16). Benefits include reduced user costs, improved reliability, improved customer satisfaction, among others. Traditional Benefit-Cost Analysis (BCA) can be adapted to account for the avoided losses in infrastructure damage or service disruptions; Garmabaki et al. (112) recommend incorporating the cost effectiveness of adaptation solutions versus the "no build" for rail systems into BCA. Standard values for the individual losses related to disasters as presented by FEMA (130) include the value of lost time, traffic delays, residential displacement, and loss of services, including electric, wastewater, potable water, and communications. These values and other relevant information for costs related to disasters that may be used in BCA are shown in Table 20. These estimated costs identify consequential losses and appraise the risks associated with extreme weather events and adaptation investments (104).

Table 20. Standard Costs Associated with Disasters for BCA (3, adapted from 130).

Standard Economic Value	**Cost (2022)**	**Relevant Information**
Value of Lost Time	$38.07	Per one hour of an individual's time
Traffic Delays for Roads and Bridges	$35.60	Per vehicle per hour
Residential Displacement	$98	Per hotel room per night
Loss of Electric Services	$182	Per capita per day
Loss of Wastewater Services	$60	Per capita per day
Loss of Potable Water Services	$116	Per capita per day
Loss of Communications/ IT Services	$130	Per capita per day

There are other costs not included in Table 20 that may be reflected in full-scale benefit-cost analysis. The costs of non-residential displacement, such as commercial and industrial facilities, vary by location, facility type, and many other factors. Loss of essential services, such as emergency and health care services, are also included in the FEMA BCA framework but not included here. These costs also do not include the costs of traffic or transportation delays related to railroad infrastructure. Although the Benefit-Cost Ratio is a simple criterion for comparing the quantified or monetized benefits and costs of projects, the approach is subject to multiple limitations. These limitations include the inability to account for social values, hard-to-monetize factors, and subjectivity in defining benefits, disbenefits, and costs (131).

The Net Present Value (NPV) approach to conducting economic analysis may also be beneficial at this phase. The NPV is calculated as the difference between the present value of the benefits and the present value of the costs of a defined system (131). Equivalent Uniform Annual Worth (EUAW) analysis and Internal Rate of Return (IRR) may also be appropriate approaches for evaluating certain alternative sets. FEMA's National Risk Index mapping tool provides Expected Annual Loss (EAL) values for 18 weather-related hazards for each county in the country. EAL values are calculated as a function of hazard exposure, annualized frequency, and the historic loss ratio. Reports can be generated by location, or hazards can be viewed on the national level (132). This annual loss value may be more helpful for rail agencies looking to compare resilience and sustainability investments with other year-by-year expenditures and may be used as an input within EUAW analysis. During economic analysis, rail agencies must take care to consider values and other hard-to-monetize factors, whether using BCA, NPV, EUAW, or IRR.

Life-cycle cost analysis (LCCA) is particularly useful for comparing design alternatives by factoring in initial construction, maintenance, and rehabilitation costs incurred over an asset's lifespan; national agencies such as the FTA encourage the use of LCCA for analyzing all major infrastructure investment. The determination of system *life* may vary within LCCA. Rail agencies may choose to analyze over the infrastructure's *physical*, *functional*, *service*, *economic*, *design*, or *actual* lifespans (131). LCCA can be used as a tool to inform decisions of the use of standard or more resilience materials. Additionally, LCCA can help agencies evaluate various maintenance schedules or strategies under different potential climate scenarios.

Other economic analysis tools may further support decision-making under uncertainty. Real options analysis (ROA), on the other hand, is particularly useful in managing uncertainty and enabling flexibility in decision-making. ROA applies financial option theory to infrastructure investments and allows agencies to adapt decisions as new information becomes available. This approach gives agencies flexibility in making decisions in the context of changing conditions that may affect the financial viability of a project by enabling agencies to examine NPV profiles under different scenarios for projects. In ROA, decision trees are used to help an agency determine which option (e.g., to undertake or decline a project, to expand or contract, to defer or proceed right away) is most favorable (133). Although more time-consuming, this approach may enable agencies to have more flexibility when making decisions in the context of extreme weather or unpredictable events.

Route Importance

Agencies can approach criticality as a function of route importance. This may be considered as the presence or lack of redundancy, type of goods transported along that route, sensitivity of communities near the route, or other metrics. Rail asset management agencies can consider criticality measures separate from the benefit-cost analysis and vulnerability assessment to identify the risk that failure poses to the agency. In addition, criticality assessment also enables agencies to understand potential impacts to communities that surround transportation assets. Agencies interested in reducing disparities in user experience can also choose to include user experience as a criticality metric and further ensure that other activities are not exacerbating the needs of marginalized communities.

Alternatives Analysis

Identifying Actions and Alternatives

Utilizing Multiple-Criteria Decision Analysis (also called Multiple-Criteria Decision-Making or MCDM) can provide a systematic approach to clearly integrate sustainability and resilience considerations, with justifications for weights and normalization, into decision making (134). MCDM is particularly valuable because it enables decision-makers to compare alternatives using a range of qualitative and quantitative data collected during the vulnerability assessment, sustainability assessment, and impacts analysis phases. MCDM techniques vary widely in their complexity; simpler methods such as the Analytic Hierarchy Process are relatively easy to interpret and can help communicate infrastructure and operational decisions to impacted stakeholders (134). More advanced methods also may allow for more nuance by incorporating uncertainty but may require more technical expertise, thus becoming less intuitive for non-technical audiences. Agencies therefore can decide which approach to alternatives analysis is most appropriate for their needs based on the context of the decision, data availability, and importance of transparency.

Although specific adaptation plans will range for the hazards posed to the infrastructure and available resources, nature-based solutions are emerging as a potential option to increase rail system resilience (3). Blackwood et al. (115) give examples of such solutions, including vegetation management, establishment of tree-free zones, and natural drainage mechanisms. Development of strategies to address the impacts or provide adaptation options, including mitigation efforts, changes to operations and maintenance, and planning are also key (114). As rail assets are not flexible, can't be moved easily, and are expensive to duplicate, agencies may consider detour routes or multimodal alternatives to increase the redundancy of their network (103). Improving emergency communications can also further enhance the rapidity of adaptation to disruption, regardless of the specific hazard. As railways already have sensor technology detecting issues and triggering warnings for the operators, technology that can accelerate the speed at which this information is communicated to relevant stakeholders can enhance the system and community resilience in the case of a failing asset. Identifying interdependencies between rail assets and other infrastructure sectors, such as power, could also be key in increasing the general resilience of the network (113). Dynamically downscaled data can provide insight into the locations of hazards posed to each infrastructure sector. Downscaled data of this type facilitates prioritization of maintenance, rehabilitation, and resilience-building activities to ensure that adaptation measures are implemented in the most vulnerable locations.

Example Rail Adaptation Options for Specific Hazards

Combining emerging tools with research on specific asset-hazard adaptations, managers of transportation infrastructure can effectively adapt their assets to better withstand, absorb, and respond to extreme weather events and associated impacts (3).

Precipitation: As flooding and rates of precipitation increase, railways are vulnerable to the impacts of bridge scour, track flooding, and slope and embankment failure. Within design standards and plans moving forward, agencies can incorporate adaptations to address these specific impacts as new threats emerge and more information about adaptive practices arises. For example, foundation countermeasures can reduce the impacts of bridge scour (135). Regular maintenance and improvement of drainage systems can reduce track flooding during high precipitation events in the short term, and tracks can be elevated in the long term to reduce likelihood of flooding (110). High precipitation may also cause slope and embankment failure, the risk of which may be evaluated by the slope risk evaluation model developed by the Railway Technical Research Institute (135). Slope and embankment failures may also be mitigated through vegetation management near the tracks (103; 115).

Extreme heat: For both freight and passenger trains, implementing speed restrictions during extreme heat events is the first action to reduce the likelihood of a catastrophic failure (137). Although sensor technology is utilized approximately every 20 to 40 miles along a rail track, more frequent sensor technology can help monitor real-time heat issues (137). Furthermore, painting rails white in buckle-prone locations can reduce solar gain and thus reduce the likelihood of failures related to track geometry (128). Green corridors and vegetation shading may also alleviate some of the heat that tracks and overhead lines experience (115). Overhead lines may also be replaced with wiring systems that can withstand higher temperatures. Alternatively, rail infrastructure providers can consider using auto-tension systems that adjust the lines at different temperatures (137). For rail carrying passengers, increasing passenger cooling stations and ventilation inside stations may reduce the likelihood of heat-related passenger health issues (113).

Drought: Due to the increased risk of earthworks failure, utilizing green walls and embankments may decrease negative impacts of drought (115). Soil may be significantly cracked due to low moisture content during these periods. As a response, rail infrastructure managers can consider adding stone to support the tracks and tamping the track more frequency to realign the rails as needed (137). In addition, the decreased subgrade moisture may benefit from re-ballasting (117).

Wildfire: Vegetation management near rail tracks can reduce the risk of fallen trees causing damage to the tracks. As wildfires may also cause damage to the overhead lines, tree-free zones along the rail corridor may reduce the potential negative impacts of wildfires on rail (115). In addition, rail infrastructure can sometimes cause or contribute to wildfires due to electrical failures or overheating (129). As a result, ensuring that rails have a sufficient distance from trees, brush, and other fire-prone vegetation can reduce the risk of wildfire-rail interaction.

Extreme winds: Extreme winds can cause damage to a multitude of infrastructure assets. Ensuring that there are back-up generators for electricity can increase the agility of response to an outage. Vegetation management can also be key for rail assets located in zones likely to be exposed to this hazard (101). Shelterbelts, referring to a style of planting trees or shrubs, can break the wind-flow and reduce wind speeds (117). Additional efforts to consider adaptations that address multiple hazards may be necessary to ensure that adaptations to prevent wind impacts do not interfere with adaptations addressing other hazards.

Winter weather: To reduce the likelihood of track deformation, breaks, or cracks due to extremely cold temperatures, rail asset managers can use sun sheds (138) or consider insulation of embankments to regulate temperatures (115). The use of signal hoods and heating of conductor rails can also reduce the impact of snow on rail assets (117). To prevent earthworks failures, agencies may also consider the installation of geothermal piles or methods for rock slope stabilization (115). Specific adaptations for precipitation, extreme heat, drought, wildfire, extreme winds, and winter weather are discussed in this section and summarized in Table 21.

Table 21. Threats, Impacts, and Example Adaptation Options for Rail (from 3).

Threat	Impact	Example Adaptation Options
Extreme heat	Track buckling (114; 115; 128)	More frequent placement of sensors to monitor real-time heat issues (137); paint rails white at buckle-prone locations to reduce solar gain (128); nature-based solutions: green corridors, vegetation shading, vegetation management (115)
	Extreme temperature impacts on structural integrity (127; 128)	Concrete mixes with lower drying shrinkage and reduced coefficient of thermal expansion (139); install and maintain concrete joints to accommodate potential expansion (139)
	Change in construction scheduling (127)	Create plans with alternate construction days; explore sensor technologies to monitor site conditions (140)
	Passenger health (127)	Increase ventilation inside stations (113)
	Sagging of overhead line equipment (115)	Replace wiring systems with newer systems that can withstand higher temperatures; use auto-tension systems that have springs to adjust the lines at different temperatures; implement speed restrictions during summer months and adjust schedules accordingly (137)
Winter weather	Track deformation, breaks, or cracks (115; 128)	Insulation of embankments and air ducts in embankments (115); sun sheds (138)
	Track blockages or signals (115; 117)	Use of signal hoods; heating of conductor rails (117)
	Earthworks failures (115; 128)	Installation of geothermal piles; rock slope stabilization (115)
High precipitation	Bridge scour (115; 117; 128)	Foundation countermeasures (135)
	Flooding of track (127; 128)	Maintenance and upgrade of drainage; elevation of track
	Slope or earthworks failure (115)	Slope risk evaluation model (135); vegetation management (115); natural drainage (115)
	Excessive moisture content decreases the resilient modulus of the subgrade (116)	Use of piezometers and tensiometers to track moisture (116)
Extreme winds	Damage to rail infrastructure, railroad signals, electronic infrastructure, track blockages (115; 117; 128)	Vegetation management (including tree-free zones); shelterbelts (115; 117)

Threat	Impact	Example Adaptation Options
Droughts	Decreased subgrade moisture; increased risk of earthworks failure (115); misalignment of assets, including poles supporting overhead lines and tracks (128)	Re-ballasting and tamping (117); green walls and embankments (115); if soil has significantly cracked, add more stone to support the tracks and machines realign the rails (137)
Wildfire	Falling trees causing obstructions; overheating of track; overhead line damage (115; 127)	Vegetation management along tracks; establishment of tree-free zones in rail corridor (115)
	Staff or maintenance working conditions (127)	Revised scheduling and maintenance plans

Implementation & Monitoring

Performance measurement is a vital component of the transportation planning process and can enable organizations when performing outcome review (as suggested by 104). Rail entities are currently tracking organizational performance (e.g., track velocity or number of cars for freight rail organizations; on-time performance or ridership for passenger rail organizations), safety performance (e.g., accidents, fatalities, and injuries), asset performance (e.g., health and condition indices, track roughness), and any federally defined standards. Future performance measures can be used to assess the efficiency and effectiveness of adaptations or resilience-building alternatives (112).

Example Applications

Example 1: Passenger Rail Agency Addressing Extreme Weather Impacts on Continuous Welded Rail

The proposed framework could be applied by a passenger rail agency looking to address the impacts of extreme weather on continuous welded rail (CWR). The agency will first conduct a vulnerability assessment to establish what hazards the rail is most exposed to, where the rail condition is low, and determine the adaptive capacity. The agency could then examine the sustainability dimensions (economic, environmental, and social) related to the rail system to provide more context for the potential adaptations and impacts assessed later. Then, the agency could analyze specific hazard impacts on the rail. Using this information, the agency then could prioritize which rail corridors should be addressed first considering criticality and cost-benefit analysis. To address the potential impacts, the agency then examines infrastructure interventions, organizational changes, or other alternatives to address the potential impacts – considering the long-term goal of sustainable development. Following this systematic approach to prioritizing and deciding which interventions to implement, the passenger rail agency could act on the plans and any promising adaptations. To measure the benefit of these interventions and provide support for future investments in building adaptations, the agency can select and monitor performance measures over time.

Example 2: Short Line Railroad Enhancing Resilience of Track and Signal Infrastructure

The proposed framework could be employed by an agency managing a short line railroad looking to understand and enhance the resilience of track and signal infrastructure. The vulnerability assessment highlights which hazards are most common and likely to impact the assets of interest. Agencies then assess the sustainability factors influenced by the presence and potential failure of the tracks and signaling equipment – which may involve working with stakeholders. From there, the agency could analyze specific hazard impacts on track and signal infrastructure, prioritize the assets considering criticality, and perform cost-benefit analysis to examine the cost of losing these assets (temporarily or permanently) factoring in the outputs of the sustainability assessment. The agency could then examine the alternatives to address the impacts – including proposing new projects that may be located away from exposed areas or built with adaptive materials. As an organization, there may need to be some new planning and collaborative activities to implement the potential alternatives. The alternatives may include revised operations and maintenance needs compared to original schedules. Finally, the agency would implement the plans and adaptation strategies selected and monitor the performance of these strategies over time.

Discussion

This research promotes a five-step approach to enhance rail system resilience and sustainability. During the proposed framework's implementation, agencies may face organizational resistance or lack of flexibility, funding constraints, and technical limitations. Agencies may be able to overcome some of these potential challenges by exploring ways to build a *culture of change*. Funding constraints may be addressed by allocating budget for research and pilot projects. For agencies with limited resources, they can begin by simply assessing system vulnerability and factoring the outputs of that assessment into prioritization and asset management plans. As agencies can allocate more resources to sustainability- and resilience-building practices, they can conduct sustainability, impacts, and alternatives analyses. To reduce the burden on any one department, collaboration across departments or agencies can distribute the workload while providing opportunities for more innovative approaches.

A key limitation in enhancing rail system resilience and sustainability is the extent to which the performance and stability of interdependent sectors influence outcomes. Rail systems, especially electrified transit networks, are heavily reliant on a continuous and reliable power supply for operations such as signaling, communication, and propulsion. Disruption in the energy sector, regardless of the cause, can directly compromise rail service reliability and further hinder recovery efforts following a disruption. Furthermore, dependence on energy providers can introduce sustainability challenges. Energy from renewable resources such as solar or wind may have a lower environmental impact but also face predictability issues, further complicating an agency's ability to meet sustainability and resilience goals simultaneously. As a result, enhancing rail system sustainability and resilience may require targeted collaborations with agencies managing interdependent infrastructure to align energy and transportation goals.

This study does not focus on community resilience in its exploration of rail infrastructure resilience and sustainability. Although community resilience and user adaptability have been explored for public transportation, community resilience impacts on overall system resilience have not yet been widely explored in large (i.e., regional, national) rail networks. This study provides a pathway for rail agencies to consider impacts on social mobility and economic productivity during resilience-building efforts for agencies to refer to if they wish to consider community resilience factors; context-specific case studies will provide additional insight.

Summary

This research provides a framework that seeks to facilitate the integration of vulnerability assessments into sustainability- and resilience-building activities. The framework is supported by various resources and example applications to help rail agencies integrate this research into future practice. This research could be of use to agencies looking to incorporate resilience and sustainability into existing practices.

Chapter 5: Recommendations, Contributions, & Conclusion

US Rail System Resilience and Sustainability Overview

Since Rosetti explored the potential impacts of extreme weather events on US rail infrastructure in 2003, there have been increasing delays and maintenance costs associated with hazards to rail systems such as Amtrak (141). This indicates that the state of the practice seems to be lagging relative to needs in the United States. The American Railway Engineering and Maintenance-of-Way Association (AREMA) hosted the first Resilience & Sustainability Symposium in February 2024. MxV, a subsidiary of the Association of American Railroads, conducts testing and research for member railroads, published the first resilience-focused technology digest publication in September 2023, later presented at the AREMA symposium (142). The research by MxV Rail and the event by AREMA indicate that the US rail industry is beginning to consider the importance of preparing for extreme weather events.

Following the Bipartisan Infrastructure Law in 2021, the Federal Railroad Administration established a program that promoted increased sustainability and resilience of the US rail network. This program published the first Resiliency Bulletin in summer of 2024 (143). The FRA has also established a variety of funding opportunities to help rail agencies take resilience-building actions; these opportunities include the Consolidated Rail Infrastructure and Safety Improvements (CRISI) grant, the Railroad Rehabilitation & Improvement Financing (RRIF) Express Pilot Program, the Promoting Resilient Operations for Transformative, Efficient, and Cost-Saving Transportation (PROTECT) discretionary grant program, and others. In 2023, the FRA issued a Notice of Safety Advisory 2023-07 which recommended railroads do the following (144):

- Evaluate communication and training programs, rules, policies, and procedures related to severe weather,
- Ensure weather-related action plans can be promptly implemented,
- Evaluate railroad weather forecasting policies and procedures and incorporate these into dispatch operations and positive train control systems, if applicable,
- Identify critical and geographical elements susceptible to severe weather events, and
- Collaborate to develop best practices for utilizing technologies and plans to mitigate potential consequences of severe weather.

Key Takeaways for Practice

Agencies with high organizational maturity and access to resources (e.g., Class I freight railroads, large urban transit authorities) should begin integrating standardized resilience metrics into asset management and planning practices. These organizations are well positioned to pilot advanced frameworks and share best practices to inform national standards. Small or mid-sized agencies may be more resource-constrained and thus benefit from simplified or phased assessment approaches, as well as collaborations with other agencies that may provide data and other support for resilience and sustainability assessments. Furthermore, the development of national guidance can support the alignment of resilience and sustainability goals across jurisdictions, agencies, and transportation modes. Finally, collaborations with research groups and universities can facilitate the translation of emerging adaptive strategies and options into practice and provide additional support for more complex systems analysis, as discussed in Chapter 2 and Chapter 4.

Recommendations for Practice

Private Sector

Depending on the availability of resources, private companies may be able to respond to system disruptions quickly to minimize delays. Private companies with ample resources have likely identified a variety of approaches to minimize extreme weather impacts to rail based on in-house research. As unpredictable events pose threats to critical transportation infrastructure that may be located near sensitive communities or wildlife preservations, rail managers nationally and internationally may benefit from the sharing of adaptations that have been successful during testing and implementation through conferences, publications, and other methods of dissemination. Additionally, for tracks that are owned by private companies but used by Amtrak, the private sector could share all relevant condition information to ensure that Amtrak is aware of the potential vulnerabilities in its national network. The federal government can work with Amtrak and the private sector companies to ensure this information is shared between the infrastructure owners and Amtrak without fear of negative impacts to business (considering that Amtrak is subject to the Freedom of Information Act). Public-private partnerships could be very useful to advancing objectives in both sectors by helping to improve response time to disruptions, broaden expertise, and enhance stakeholder engagement in decision making.

Private organizations can proactively manage interactions between rail operators and customers and can mitigate the negative consequences of disruptive events. These organizations can enhance resilience by supporting flexibility within resource allocation, ensuring that plans enhance the organization's ability to control the negative effects of disruptions, and consider strategies ahead of time to mitigate potential damages (17). Ensuring that operators, conductors, and other railroad personnel have received trainings on properly documenting incidents for FRA safety reporting can improve data quality that can then be used by the public and academic sectors (including how to correctly indicate if the accident occurred because of one of the ‘miscellaneous causes’ indicated by codes M101, M102, M103, M104, M105, M199, and T109) (145).

Public Sector

The FRA may benefit from creating a new category of “Types of Train Accidents” that focuses on Environmental and Extreme Weather Conditions within Form F6180.54 to improve reporting on weather-related incidents. Expanding the set of codes from codes M101, M102, M103, M104, M105, M199, and T109 to include distinctions for specific hazard impacts on rail operations can further improve the data quality reported to the FRA. To facilitate the implementation of these more nuanced codes into practice, the FRA can work with the private sector to disseminate this information to conductors, operators, and other relevant personnel.

Very few research projects coming out of the FRA Office of Research, Development, and Technology include any mention of resilience or environmental sustainability (146). Partnerships between the FRA and research entities (including universities) will ensure that research projects align with the needs identified by the FRA. Expanding partnerships with additional universities can also help to expand research and curriculum devoted to rail systems nationally.

The FRA could establish a mechanism to ensure compliance to resilience and sustainability-oriented outcomes. In addition to the resilience-building federal funding opportunities previously identified, the FRA could incentivize rail agencies to create resilience improvement plans (RIPs) as state DOTs and MPOs are incentivized to create RIPs through PROTECT (along with other incentive policies for increasing infrastructure resilience).

Establishing a consistent source of funding for passenger rail transportation at the state and national levels can also reduce the environmental impacts associated with the US transportation sector. Additionally, finding additional opportunities to use regulatory levers to support the movement of goods by rail can reduce the number of heavy trucks on the road and, thus, reduce the amount of taxpayer dollars required for maintaining US highway infrastructure. Supporting public-private-academic partnerships to share project costs and increase innovation can further support resilience. Releasing funding specifically for research and development can promote these partnerships; following state DOT-funded “Research Needs Statement” (RNS) programs, FRA and short line railroads can partner with academic institutions to lead and advance new projects in the rail sector.

The Federal Transit Administration may also wish to request that transit agencies report On-Time Performance for rail systems hourly during disruptions so that agencies can easily monitor survivability and recoverability. This data could be made available to the public via the National Transit Database (NTD). Additionally, the FTA could request that transit agencies report the elevation of various transit stations can help indicate the vulnerability of these facilities to hazards like flooding. This data could be made public with the NTD or through local GIS databases.

Agencies within the USDOT, including the FRA and FTA, could further collaborate to lead the development of standardized metrics and methods for assessing resilience and sustainability across freight and passenger rail systems. These standards should include guidance on how to define, measure, and monitor key resilience capabilities – such as robustness, flexibility, recoverability, and adaptive capacity – within the context of both routine and extreme weather-related disruptions. The lack of consistency in how resilience, vulnerability, and sustainability limits comparability between agencies and transparency. USDOT-developed standards could provide a foundation for more coherent national and local efforts to improve system resilience and sustainability.

Academia

A key objective of this research is to inform rail asset management curriculum development. Ensuring that railway engineering programs incorporate curriculum surrounding emerging data sources, hazard adaptation planning, environmental regulations and policy, and dealing with uncertainty can promote a more resilience-oriented culture within the rail industry. Expanding existing transportation engineering programs to include rail engineering curriculum will also help to prepare the next generation of railroad engineers. Figure 37 shows the distribution of universities with rail educations programs in the United States, highlighting the lack of programs in many states in the South and West (data from 147). The figure also shows a high concentration of programs in the Northeast and Chicago.

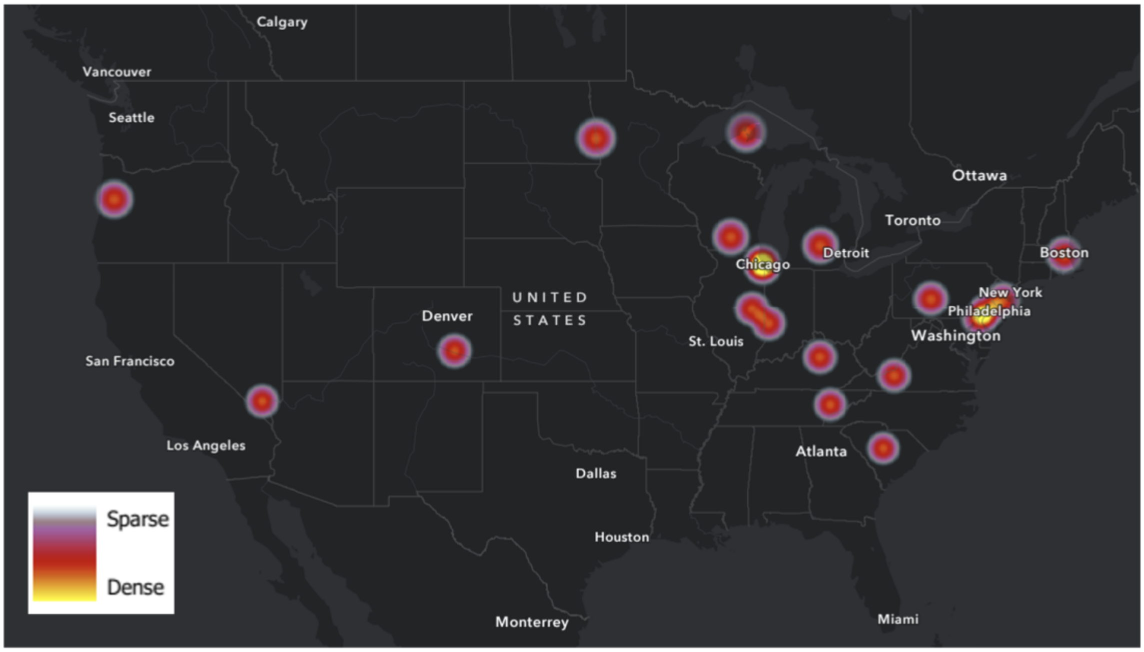

Figure 37. Distribution of Universities with Rail Education Programs in the United States (2015).

Additionally, collaborations between academia and the public and private sectors can facilitate the translation of adaptive strategies into operational practices. For example, these partnerships can facilitate the implementation of dynamic adaptive policy pathways (DAPP; 148) to rail systems (149), similar to the work done by Wall et al. (150) on implementing a DAPP in the San Francisco Bay Area.

Future Research

To examine the institutional factors impacting rail adaptive capacity, future work can examine the factors impacting rail adaptation strategies in countries with effective practices, such as the United States, Japan, and Australia. Future research can explore the success of adaptation implementation and the specific adaptation options implemented. Future work will expand upon Table 20 and ensure that impacts, vulnerabilities, and a wide variety of adaptation options and strategies can be shared with practitioners for reference. Future research will further reveal what adaptation options are most effective for addressing the impacts of various hazards to rail systems – and the cost and technical effectiveness of both physical and organizational adaptations.

Additionally, many of the assessments cited in this report focused on the rail system as a single system. Some studies acknowledge, however, that when rail systems degrade or fail, other transportation modes become burdened, and the entire network is affected (151). Rail passengers may have access to rideshare services, alternative bus routes, or nontraditional modes of transportation such as micromobility. Goods that must be delivered will likely be shifted to trucks that can travel efficiently on the redundant highway system. Future research can examine nuanced multimodal and intermodal transportation system disruption response in ways that more realistically reflect the impacts of disruptions on accessibility and mobility.

Contributions to Practice

This study offers a comprehensive set of metrics to enhance the analytical capabilities of rail agencies that seek to monitor the resilience of their systems across the disruption cycle – which may be critical when defining return on investment. This study further defines a framework for agencies to refer to when looking to integrate resilience and sustainability when defining, prioritizing, and building projects. More broadly, transportation practitioners, policy makers, and other stakeholders looking to better characterize transportation resilience – by considering physical and organizational capabilities – may refer to this work.

Contributions to Theory

This research contributes to the characterization of adaptive capacity to strengthen the vulnerability function. This study defines a novel approach for quantifying resilience, advancing resilience theory for rail and transportation systems applications. This novel approach highlights the importance of understanding resilience across the disruption-recovery cycle. The proposed framework also provides insight into the temporal relationship between resilience and sustainability to emphasize the interdependencies between the two concepts.

Conclusion

Moving beyond the understanding of vulnerability of rail systems, the rail industry needs to identify opportunities to incorporate resilience into activities across departments. Chapter 2 summarized commonly used metrics to quantify the resilience of rail systems and proposed a comprehensive set of metrics that can be utilized before, immediately after, or long after a disruption to reflect the resilience of a rail system. Chapter 3 applied the set of metrics described in Chapter 2 to a real rail system (MARTA) as a case study and proof of concept. Chapter 4 demonstrated that resilience and sustainability outcomes are related and proposed an approach to integrate the two concepts across the planning, design, construction, operations, maintenance, and monitoring phases. This study examines the importance of considering sustainability and resilience dimensions simultaneously to ensure infrastructure investments advance both objectives and maximize co-benefits. The three parts of this study can help rail managers prioritize maintenance and adaptive capacity-building activities and identify projects that achieve resilience, sustainability, safety, and other objectives simultaneously.

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Data Summary

Products of Research

During this research, the total costs associated with weather-related damages were examined using data from the Federal Railroad Administration Safety Reporting via Form 54: https://railroads.dot.gov/safety-data/accident-and-incident-reporting/accidentincident-dashboards-data-downloads. Data regarding Amtrak's weather-related incidents were extracted from the original datasets provided by the FRA. Additionally, damages and costs related to weather-related incidents were CPI-adjusted using data from the Federal Reserve. The Consumer Price Index (CPI) for All Urban Consumers between 1975 and 2023 was used to adjusted the FRA Safety data costs. The CPI data is available from: https://fred.stlouisfed.org/series/CPIAUCSL#. The Amtrak On-Time Performance Trends and Hours of Delay were pulled from the Bureau of Transportation Statistics: https://www.bts.gov/content/amtrak-time-performance-trends-and-hours-delay-cause. The CPI transformation was performed using a simple script in R. This data informed the motivation and background section of this study.

Additionally, data on Amtrak's routes and stations was pulled for additional insight into the nature of the network. This information was pulled from the Geospatial element of the United States Department of Transportation Bureau for Transportation Statistics (USDOT BTS): https://data-usdot.opendata.arcgis.com/. The data was transformed in ArcGIS Pro to include latitude and longitude to be more easily visualized in other spatial software (e.g., kepler.gl). This data informed the motivation and background section of this study.

The Monthly Transportation Statistics, provided by USDOT BTS, provided insight into the number of passengers moved by passenger rail between 1975 and 2021: https://data.bts.gov/stories/s/Monthly-Transportation-Statistics/m9eb-yevh. This data was aggregated by year to clearly visualize trends over the last five decades of Amtrak's passenger rail service provision. This data informed the motivation and background section of this study.

Data Format and Content

The **Amtrak Weather and Safety Data** is presented in a spreadsheet (.csv), which is uploaded to Zenodo, the repository suggested by the NCST. This file includes:

- All Amtrak Safety Reports, as reported to the FRA via Form 54
- Weather-Related Accidents, as reported to the FRA via Form 54 based on the Primary Accident Cause, Accident Cause, or Narrative.
- Amtrak CPI-Adjusted Weather-Related Damages between 1975 and 2023.
- Amtrak Hours of Delay and CPI-Adjusted Weather-Related Damages between 1990 and 2023.
- A grouping of weather-related damages by 5-year buckets (1975 – 2023).

Additionally, the **Amtrak Stations and Route** were converted from shapefiles to spreadsheets with latitude and longitude information to be brought into data visualization tools such as kepler.gl. The data is available as a .csv. This file can easily be brought into ArcGIS, QGIS, or another geospatial software.

The **Transportation Statistics for Rail from 1975 to 2021** file (available as a .csv) includes the following:

- By_year_date: Year (based on aggregated values for previous year, so 1/1/1976 shows the sum of all values for 1975 for the following variables).
- Freight Rail Carloads: Number of freight carloads moved by rail between 1988 and 2021.
- Transportation Employment – Rail Transportation: Number of employees in rail transportation between 2004 and 2021.
- Passenger Rail Passengers: Number of people transported by intercity passenger rail systems (not transit systems) between 1975 and 2021.
- Passenger Rail Passenger Miles: Number of miles passengers were transported by intercity passenger rail systems between 1975 and 2021.
- Passenger Rail Employee Hours Worked: Number of hours worked by passenger rail employees between 1975 and 2021.
- Note: Provides additional information on any element of the relevant row.

The **Locations of Universities with Rail Education Programs** was based on a document released by the Federal Railroad Administration (linked below). The document did not include addresses, so addresses were collected for visualization in ArcGIS.

The data for **MARTA, LA Metro,** and **WMATA** ridership came from the National Transit Database, county GIS databases, or Google Earth. Other data collected on the three systems are included as spreadsheets at the data repository linked below.

Data Access and Sharing

The public can access all data generated and used within this report at this link: https://doi.org/10.5281/zenodo.14278394.

The ArcGIS Online map showing the distribution of universities with rail education programs can be accessed from this link: https://gtmaps.maps.arcgis.com/apps/mapviewer/index.html?webmap=628f494528d34748abc7297d9388cc6a

Reuse and Redistribution

All data has been curated from open access sources. Please see the citation guidelines from the following open access sources:

- https://railroads.dot.gov/safety-data/accident-and-incident-reporting/accidentincident-dashboards-data-downloads
- https://fred.stlouisfed.org/series/CPIAUCSL#
- https://www.bts.gov/content/amtrak-time-performance-trends-and-hours-delay-cause
- https://data-usdot.opendata.arcgis.com/
- https://data.bts.gov/stories/s/Monthly-Transportation-Statistics/m9eb-yevh
- https://railroads.dot.gov/sites/fra.dot.gov/files/fra_net/15442/Railroad%20Education%20Resources%20-%20Universities%20Community%20Colleges%20and%20Assoc....pdf
- https://www.transit.dot.gov/ntd