A performance-based approach to developing capabilities for building resilience to climate hazards in transportation systems

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Abstract

Purpose – This paper discusses a multifaceted approach to developing specific and general climate resilience in a state transportation system that focuses on organizations and physical infrastructure. The paper focuses on resilience building to the dynamically evolving climate-related threats and extreme events in a transportation agency. This paper aims to enable agencies to understand better how their systems are exposed to different hazards and provide the information necessary for prioritizing their assets and systems for resilience improvement.

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Design/methodology/approach – This paper leverages long-term climate hazard databases, spatial and statistical analyses and nonprobabilistic approaches for specific and general climate resilience improvement. Spatial and temporal variability assessments were conducted on granular historical records of exposure obtained from Spatial Hazards Events and Losses Database for the United States data set to identify emerging hot spots of exposure. These were then assessed in combination with various asset specific vulnerability parameters, presented with examples of pavements and bridges. Specific metrics were obtained for the various aspects of vulnerability in the context of a given asset to estimate the overall vulnerability. A criticality-vulnerability matrix was then developed to provide a prioritization model for transportation systems.

Findings – This paper provides insights into the evolving nature of exposure, vulnerability and risk assessments and an approach to systematically account for climate change and the uncertainties associated with it in resilience planning. The Multi-Hazards Exposure, Vulnerability and Risk Assessment tool presented in this paper conducts climate hazard exposure, vulnerability and risk analysis on pavements, bridges and culverts and can be applied by any transportation agency.

Research limitations/implications – This study does not address operational aspects of the transportation system nor include future climate scenario data, but uses the historical records available at hand for resilience planning. With better climate projection data available in the future, the approach should be enhanced by leveraging scenario-based planning.

Practical implications – This paper is of potential value to practitioners and researchers interested in developing resilience building capabilities to manage the effects of climate-related hazards and extreme events as well as unknown threats on infrastructure and organizational performance.

Originality/value – This paper bridges an important gap in infrastructure resilience approaches by systematically accounting for the dynamic nature of climate change and the system level context of vulnerability beyond the physical condition of assets.

Keywords Transportation, Resilience, Infrastructure, Vulnerability, Exposure, Climate hazards

Paper type Research paper

Introduction
Civil infrastructure performance is the degree to which a facility or system serves its users and fulfills the purposes for which it was built or acquired (Uddin et al., 2013). The factors that determine performance are not static. They may evolve over time for various reasons including changes in stakeholder priorities, technology advances and disruptions, changes in the external environment, efforts to redress inequities in infrastructure provision and other factors that may be within or beyond the control or influence of infrastructure agencies and the communities they serve.

The changing climate is one such external factor that now demands the evolution of infrastructure performance measures. Analysis of the Spatial Hazards Events and Losses Database for the United States (SHELDUS) shows increased frequency in several climate hazards in the USA over the past six decades (Center for Emergency Management and Homeland Security (CEMHS), 2022), in a nonlinear geospatial pattern. Such changes, evident in growing costs of billion-dollar extreme events in the USA, are bound to affect the performance of transportation and other infrastructure systems (NOAA 2023).

How do these increases in climate hazard occurrences, those that are predictable or unexpected like the COVID pandemic, individually and collectively, affect infrastructure system performance and the quality of life (QOL) of system users in various localities and regions? How should infrastructure agencies adapt to these changes to preserve and continue to enhance system performance and community QOL? This paper addresses these questions by providing approaches of building resilience to known and unknown threats.
While resilience is defined in a myriad of ways in the transportation and other infrastructure literature, superior definitions of resilience for any entity to prevailing and unknown disruptions will support its development of effective capabilities to reduce organizational or system vulnerability to preserve or enhance performance, with resulting disaster cost reduction (American Association of State Highway and Transportation Officials (AASHTO), 2017, Amekudzi-et al. In Press). In the context of the changing climate, resilience building entails understanding the nature and evolution of key climate hazards in a region. It also entails identifying their past impacts, projecting their future impacts on the system and its users, and identifying, prioritizing and implementing resilience improvements to futureproof the system against future disruptions. While agencies build these capabilities, it will also be important to acknowledge the difficulty of predicting all future disruptions with high levels of confidence. This introduces increased challenges for agencies attempting to build general adaptive and transformative capabilities as well. Adaptive capabilities enable agencies and other entities to continue to adapt effectively when faced with unknown and unpredicted threats and transformative capabilities enable agencies to engage in more fundamental change that addresses the causes of these disruptions—not only their effects—for longer-term sustainability.

This paper discusses a multifaceted approach to developing specific and general climate resilience in a state transportation system that focuses on organizations and physical infrastructure. The research was conducted as part of a three-year study commissioned by the Georgia Department of Transportation to develop capabilities for incorporating climate resilience considerations in long-range transportation planning, transportation systems management and operations (TSMO) and Transportation Asset Management (TAM). In what follows, we present a short review of resilience building frameworks to characterize emerging effective practice for climate resilience building in transportation systems and offer definitions of climate and general resilience appropriate for the study context. We then present the development of the dynamic risk and vulnerability assessment approach. Subsequently, we present examples of climate vulnerability assessment results using this approach. Based on these outputs, we discuss how to use the results in prioritization to select appropriate resilience improvement strategies for a system. The paper is of potential value to practitioners interested in developing capabilities for resilience building to address both known and unknown climate-related threats and their impacts on infrastructure and organizational performance. It is also of potential value to researchers working with practitioners to develop capabilities to build resilience to both known and unknown threats. We conclude by identifying limitations of the proposed approach and by outlining future work.

**Methodology**

*Literature review highlights: effective practices emerging from conceptual frameworks for climate vulnerability assessment in transportation*

The American Association of State Highway and Transportation Officials (AASHTO), the Federal Highway Administration (FHWA), and the Transportation Research Board of the National Academies (TRB) have all published conceptual frameworks for climate vulnerability assessment and adaptation in recent years (Federal Highway Administration (FHWA), 2017, National Academies of Sciences, Engineering, and Medicine (NASEM with AASHTO), 2021, Transportation Research Board (TRB) Committee on Transportation Resilience Metrics Investing in Transportation Resilience, 2021).

Common and core elements of the three frameworks suggest a climate vulnerability assessment for transportation will do the following:
support the identification of the climate hazards to which the system under study is exposed;

- shed light on how these hazards are likely to affect the system in the future and on the consequences of these hazards on lives, QOL, infrastructure and economy of the system users;
- enable prioritization of the assets or system components for resilience (and other types of) improvement; and
- support identification and prioritization of appropriate resilience improvement strategies to future proof the system in an efficient manner.

We use these review highlights to inform the development of a multihazard’s vulnerability and risk assessment approach for pavements, bridges and culverts.

**Multihazard’s vulnerability and risk assessment approach**

In a three-year resilience study sponsored by Georgia Department of Transportation, the research team developed an approach and analytical tool to assess the dynamically evolving vulnerability and risk of the system to multiple climate hazards. The Multi-Hazards Exposure, Vulnerability and Risk Assessment (MHEVRA) tool conducts climate hazard exposure, vulnerability and risk analysis on pavements, bridges and culverts (Yang and Amekudzi-Kennedy, 2023) and can be applied by any transportation agency. The GIS-based tool takes input data from the SHELDUS – a long-term data set collected over the past 60 plus years at the county level for a range of climate hazards including tornadoes, thunderstorms, hurricanes, floods, heavy rainfall, extreme heat, wildfire, wind, drought, landslides and other hazards.

**Estimating asset exposure.** General exposure is a prerequisite for vulnerability [Federal Highway Administration (FHWA), 2017]. It is the presence of infrastructure in places and settings where it could be affected by hazards and threats – for example, a road in a floodplain is exposed to floods (National Academies of Sciences, Engineering, and Medicine (NASEM with AASHTO), 2021). The paper determines the exposure of an asset by the extent to which the area in which the asset is located experiences one or more type of hazards, and whether the asset’s performance is impacted by the occurrence of the hazard.

Many existing exposure assessment tools use aggregate information on the history of hazard occurrence as the parameter, where a region with the highest count of events in the past 50 years (or another significant span of time) is considered exposed to the highest level. With the increasing variability and uncertainty in climate parameters, we need to further augment the approach to account for the spatial-temporal patterns in exposure assessment. The MHEVRA tool, an emerging hot-spot analysis tool, was used to identify spatial and temporal trends in the historical disaster data set. The emerging hot-spot analysis identifies regions that are consistently statistically significant hot spots and are increasing in intensity; those that have been persistent; newly emerging hot spots; and those that were significant for the majority of the past but have recently seen a decrease. These differentiations help identify the type of resilience effort needed, as the approach used for intensifying vs diminishing hot spots will be different, even if the sum of events in the past has been the same. Similarly, in a traditional approach to exposure assessment, due to the low overall count of events in the past, the new emerging hot pot might get underestimated. Using the approach presented here, policymakers can take proactive measures or set up monitoring to prevent the region from getting negatively affected in the future. We have assigned weights to the different categories of hot spots emerging from the analysis, with the higher weight assigned to the type of hot spot that needs the most urgent attention.
Table 1 shows the different hot spots resulting from an emerging hot spot analysis, along with the weights assigned to each hot spot category. We have highlighted the four categories within which a region falls; they might need to be prioritized in climate action plans.

The emerging hot-spot analysis of hazard events at the county level identifies the exposure to a given region. To further identify exposure to specific transport assets, we identify the hazard-asset pairs where a hazard can have a significant impact on the asset performance. For example, even though a region might have high exposure to high winds, the pavement as an asset would not be significantly impacted, but a bridge can get impacted by heavy winds. We provide a score to the hazard-asset combination (that is, hazard-asset pairs with known failure mechanisms) and then use the two criteria in a multi-criteria decision making (MCDM) approach to calculate the specific hazard exposure score for each asset. Figure 1 shows the hazard-asset pairs (with corresponding failure mechanisms) that are used in assigning asset-hazard impact weights in the MCDM analysis. The hazard list is one of the 14 hazards listed in the SHELDUS database. The default assignment is equal weights to all hazards present that can reduce the performance of a particular asset (i.e. if out of 14, 10 hazards impact the performance of pavements, each of the 10 hazards gets a weight of 0.1, and 0 for the 4 hazards that do not impact performance of pavements). The weights may be modified based on local practitioner knowledge and input on the relative importance of specific hazards in asset and system performance. The general climate hazard exposure for a particular asset, e.g. pavement, in a particular county is calculated by amalgamating the normalized scores (using Table 1) and weights (using Figure 1) based on all the asset-hazard combinations that result in performance loss for the asset.

For a particular asset, multihazard or general exposure score is estimated as a sum of the hazard specific exposure score [equation (1)]:

$$E_p = \sum_{i=1}^{n} W_i \times e_{ip}$$

where:
- $E_p$ = general exposure score for pavements (capturing pavement exposure to all climate hazards that affect pavement performance, and factoring in the relative importance of those hazards to pavement performance);
- $W_i$ = emerging hot-spot category weight for hazard $i$;
- $e_{ip}$ = asset-hazard impact weight for pavement;
- $i$ = each hazard type; and
- $n$ = total number of hazards relevant for the system.

The general exposure score of bridges, culverts and other assets can be calculated similarly, by replacing the values of $e_{ix}$, where $x$ represents the specific asset.

Table 2 below illustrates the estimation of pavement exposure (general) in three different counties. This exposure has a dynamic element captured by the results of the emerging hotspot analysis and, thus, may be referred to as dynamic pavement exposure. This dynamic exposure score captures the historical dynamics of the hazard in the county, based on 30 years of data.

**Asset sensitivity.** Asset sensitivity refers to the extent to which the asset may be damaged or disrupted by the stressor (Transportation Research Board (TRB) Committee on Transportation Resilience Metrics Investing in Transportation Resilience, 2021, Federal Highway Administration, 2015a). Two assets may be exposed to the same natural hazards but may have different sensitivities to these hazards. Hazard sensitivity can be directly
Table 1. Climate hazard exposure – score categories based on hot spot analysis results

<table>
<thead>
<tr>
<th>Hot spot</th>
<th>Definition</th>
<th>Score</th>
<th>Normalized score</th>
</tr>
</thead>
<tbody>
<tr>
<td>Intensifying (I)</td>
<td>A location that has been a statistically significant hot spot for more than 90% time steps, including the final time step. In addition, the intensity of clustering of high counts in each time step is increasing</td>
<td>8</td>
<td>1.00</td>
</tr>
<tr>
<td>Persistent (P)</td>
<td>A location that has been a statistically significant hot spot for more than 90%, with no discernible trend indicating an increase or decrease in the intensity of clustering over time</td>
<td>7</td>
<td>0.875</td>
</tr>
<tr>
<td>Diminishing (D)</td>
<td>A location that has been a statistically significant hot spot for more than 90% time steps. In addition, the intensity of clustering of high counts in each time step is decreasing, or the most recent time step is not hot</td>
<td>6</td>
<td>0.75</td>
</tr>
<tr>
<td>New (N)</td>
<td>A location that is a statistically significant hot spot only for the last time steps of the time series</td>
<td>5</td>
<td>0.675</td>
</tr>
<tr>
<td>Consecutive (C)</td>
<td>A location with a single uninterrupted run of statistically significant hot spot bins in the final time-step intervals. The location has never been a statistically significant hot spot before the final hot spot run and less than 90% of time steps are statistically significant hot spots</td>
<td>4</td>
<td>0.5</td>
</tr>
<tr>
<td>Sporadic (S)</td>
<td>A location that is an on-again then off-again hot spot. Less than 90% time steps have been statistically significant hot spots</td>
<td>3</td>
<td>0.375</td>
</tr>
<tr>
<td>Oscillating (Os)</td>
<td>A statistically significant hot spot for the final time-step that has a history of also being a statistically significant cold spot during a prior time step. Less than 90% of the time-step intervals have been statistically significant hot spots</td>
<td>2</td>
<td>0.25</td>
</tr>
<tr>
<td>Historical (H)</td>
<td>The most recent time period is not hot, but at least 90% of the time step intervals have been statistically significant</td>
<td>1</td>
<td>0.125</td>
</tr>
<tr>
<td>Others (Ot)</td>
<td>All cold spots and other nonsignificant hot-spot categories</td>
<td>0</td>
<td>0.00</td>
</tr>
</tbody>
</table>

Source: Table created by authors

Figure 1. Climate hazard exposure – indicator from hazard-asset categories with failure mechanisms

Source: Figure created by authors
linked to the condition of the asset. In this study, we estimated general sensitivity for pavements, bridges and culverts using network-level condition measures: the pavement condition index (PCI), the bridge sufficiency rating and the culvert condition index. We applied the inverse of these values to capture the general sensitivity of the asset to the particular hazards to which it is exposed, as a pavement in poor condition will generally lead to higher damage to the services due to a disaster as compared to a new pavement or one in good condition. Data for the PCI came from the Georgia Department of Transportation, and data for the Bridge Sufficiency Rating and Culvert Condition Index came from the National Bridge Inventory.

**Adaptive capacity.** Adaptive capacity refers to the ability of a system to adjust, repair and respond to damage or disruption (Transportation Research Board (TRB) Committee on Transportation Resilience Metrics Investing in Transportation Resilience, 2021, Federal Highway Administration, 2015b). Adaptive capacity may be measured in a variety of ways. In this study, we proposed the application of one or more capability maturity models measuring the agency’s capability for resilience building, including but not limited to vulnerability reduction. These models include the Resilience Rating Tool and Scorecard – which measures an entity’s capabilities for vulnerability reduction, investing equitably, enhancing the redundancy of important routes and other capabilities – modeled after the World Bank’s Resilience Rating System; the Adaptive Resilience Capability Maturity Model which measures the agency’s capability to adapt to changing conditions to build resilience (Singh, 2021, Singh et al., 2022); and Flexibility/Agility Score Cards, which help the agency measure and enhance flexibility and agility in its long-range transportation plan and other plans (e.g. TSMO and TAM); flexibility and agility are both precursors to adaptive capacity (Chester and Allenby, 2019, Garrett, 2023).

Assuming that all the transportation districts in the study area were in the initial stages of building adaptive capacity during the study period, we ascribed a unit score to all seven districts in the state DOT for this measure. This assumption was verified by professionals at GDOT. From the TSMO and emergency operations perspectives, route redundancy is a measure of adaptive capacity. From a TAM perspective, building better is a measure of adaptive capacity to build resilience to identified vulnerabilities. What gets measured gets managed: agencies generally have the basis for managing what is being measured because

\[
E_{i,C} = \text{Normalized exposure score for pavement in County C for hazard i, based on the host-spot category weight identified from Table 1}
\]

<table>
<thead>
<tr>
<th>County Hazard</th>
<th>Weight ( (e_{i,p}) )</th>
<th>County 1</th>
<th>County 2</th>
<th>County 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tornadoes</td>
<td>0.1</td>
<td>1.00</td>
<td>1.00</td>
<td>0.86</td>
</tr>
<tr>
<td>Inland flooding</td>
<td>0.1</td>
<td>0.00</td>
<td>1.00</td>
<td>0.86</td>
</tr>
<tr>
<td>Hurricane wind</td>
<td>0.1</td>
<td>0.43</td>
<td>1.00</td>
<td>0.86</td>
</tr>
<tr>
<td>Severe storm</td>
<td>0.1</td>
<td>0.29</td>
<td>1.00</td>
<td>0.86</td>
</tr>
<tr>
<td>Coastal flooding</td>
<td>0.1</td>
<td>0.00</td>
<td>1.00</td>
<td>0.86</td>
</tr>
<tr>
<td>Drought</td>
<td>0.1</td>
<td>0.57</td>
<td>1.00</td>
<td>0.14</td>
</tr>
<tr>
<td>Severe winter weather</td>
<td>0.1</td>
<td>0.57</td>
<td>1.00</td>
<td>0.14</td>
</tr>
<tr>
<td>Wildfire</td>
<td>0.1</td>
<td>0.86</td>
<td>1.00</td>
<td>0.14</td>
</tr>
<tr>
<td>Extreme heat</td>
<td>0.1</td>
<td>0.43</td>
<td>1.00</td>
<td>0.14</td>
</tr>
<tr>
<td>Landslide</td>
<td>0.1</td>
<td>0.37</td>
<td>1.00</td>
<td>0.50</td>
</tr>
</tbody>
</table>

**Table 2. General pavement exposure estimation using MCDM**
they have the data to justify investments to enhance these measures. Thus, the agencies may decide on and prioritize various measures of adaptive capacity for implementation that best address their climate vulnerabilities.

*Asset criticality.* Criticality refers to the importance or value of an infrastructure asset, in terms of the cost to users, owners and society from a loss in function (Transportation Research Board (TRB) Committee on Transportation Resilience Metrics Investing in Transportation Resilience, 2021). A critical asset is an asset that is so important to a study area that its removal or disruption would result in significant losses (Federal Highway Administration, 2011). Our vulnerability assessment approach makes use of the Georgia State Department of Transportation State Route Prioritization Criteria as shown in Figure 2 below (weighted at 80%) and combined with the social vulnerability index (weighted at 20%) to capture social equity. The social vulnerability index (SVI) refers to the potential negative effects on communities caused by external stresses on human health, including natural or human-caused disasters or disease outbreaks [CDC/ASTDR (Center for Diseases Control and Prevention/Agency for Toxics and Diseases Registry), 2023].

Social equity is a key element of asset criticality, but it is not explicitly captured in most criticality metrics (Litman, 2023). Resilience for historically underserved communities may not be properly captured in climate vulnerability assessments unless there is intent to characterize the vulnerabilities of these populations and address them explicitly with appropriate investments to reduce vulnerability and enhance resilience. In particular, resilience tends to be defined not by the strongest elements of the system but by the weakest elements, which may cause the system to fail with consequences that may extend beyond the particular locality. While the SVI was included in the asset criticality metrics to begin to address transportation equity, we acknowledge that the SVI does not capture all context-specific community strengths and needs. An ongoing research project, sponsored by the US Department of Transportation Center for Transportation, Equity, Decisions and Dollars, is refining the methodology for addressing social equity in climate vulnerability assessment and adaptation planning (Amekudzi-Kennedy et al., 2022).

*Estimating asset vulnerability and risk to the changing climate.* Vulnerability is the degree to which a system is susceptible to, or unable to cope with the adverse effects of climate change or extreme weather events. In the transportation context, climate change vulnerability is a function of the transportation system’s exposure to the effects of extreme events, its sensitivity

<table>
<thead>
<tr>
<th>Criteria</th>
<th>Criticality Score</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1 Low Impact</td>
</tr>
<tr>
<td></td>
<td>2 Moderate Impact</td>
</tr>
<tr>
<td></td>
<td>3 High Impact</td>
</tr>
<tr>
<td></td>
<td>4 Very High Impact</td>
</tr>
<tr>
<td>AADT Low</td>
<td>Low</td>
</tr>
<tr>
<td>Number of Lanes &lt;4</td>
<td>&gt;= 4</td>
</tr>
<tr>
<td>Governor’s Road Improvement Program</td>
<td>Yes</td>
</tr>
<tr>
<td>Evacuation Route</td>
<td>Yes</td>
</tr>
<tr>
<td>STRAHNET/ STRAHNET Connectors</td>
<td>Yes</td>
</tr>
<tr>
<td>State Freight Corridors</td>
<td>Yes</td>
</tr>
</tbody>
</table>

**Source:** Figure created by authors
to climate effects and its adaptive capacity (Federal Highway Administration (FHWA), 2017). The transportation resilience literature considers asset vulnerability to be a function of threat exposure, asset sensitivity and adaptive capacity [Federal Highway Administration (FHWA), 2017, National Academies of Sciences, Engineering, and Medicine (NASEM with AASHTO), 2021, Transportation Research Board (TRB) Committee on Transportation Resilience Metrics Investing in Transportation Resilience, 2021]. This study estimates asset vulnerability to the changing climate or extreme events as the product of climate hazard exposure, asset sensitivity and adaptive capacity [equations (2.1) and (2.2)]:

\[
\text{Vulnerability} = f(\text{Climate Hazard Exposure}, \text{Asset Sensitivity} \times \text{Adaptive Capacity})
\] (2.1)

\[
\text{Vulnerability} = \text{Climate Hazard Exposure} \times 1/\text{Asset Condition} \times 1/\text{Adaptive Capacity}
\] (2.2)

Asset risk (to the changing climate) is estimated as the product of asset vulnerability and asset criticality, with criticality used as a surrogate for the consequences of hazard exposure (that is, the impact of damage or disruption) [Transportation Research Board (TRB) Committee on Transportation Resilience Metrics Investing in Transportation Resilience, 2021, National Academies of Sciences, Engineering, and Medicine (NASEM with AASHTO), 2021, Federal Highway Administration (FHWA), 2017]. Equations (3.1) and (3.2) explain the relationships between risk, vulnerability, sensitivity and climate exposure:

\[
\text{Risk} = f(\text{Climate Vulnerability}, \text{Asset Criticality})
\] (3.1)

\[
\text{Risk} = \text{Climate Hazard Exposure} \times 1/\text{Asset Condition} \times 1/\text{Adaptive Capacity} \times \text{Asset Criticality}
\] (3.2)

Asset prioritization. A four-by-four asset prioritization is used to rank the assets based on the relative urgency for more detailed examination to address the general vulnerability of the assets to the changing climate (Figure 2). The vulnerability/criticality matrix is also proposed by the TRB’s Committee on Resilience Metrics in their consensus report on a framework for informed choices for investing in transportation resilience (Transportation Research Board (TRB) Committee on Transportation Resilience Metrics Investing in Transportation Resilience, 2021). In Figure 3, the color gradient signifies the dynamic risk, which is the product of criticality and dynamic vulnerability. Projects within the same color box (i.e. prioritization category) can be further prioritized based on the gradient (dynamic risk).

Specific exposure, sensitivity and adaptive capacity
While the treatment above focuses on general exposure and general sensitivity (i.e. exposure and sensitivity to multiple hazards), the methodology can be applied to characterize the exposure of assets to specific hazards, e.g. flooding or heat. In the latter case, asset sensitivity would be based on the asset-hazard failure mechanism for that specific hazard, e.g. bridge scour index or heat index, respectively, and adaptive capacity would involve specific structural and nonstructural treatments to enhance resilience to the particular failure mechanism, e.g. riprap and installation of gabions at the bridge abutments and stone pitching upstream from the foundation for bridge scour. The specific vulnerability function will also include specific exposure, calculated with the normalized score from the results of the hot spot analysis for the particular hazard (see Table 1), and a weight of 100% for the particular hazard under
consideration. The specific condition relative to the specific hazard will be used in estimating asset sensitivity, and adaptive capacity will be tailored to address the particular hazard. As Figure 3 shows, the high-criticality, high-vulnerability assets fall into the highest priority category; these are also the highest-risk assets. Generally, low-vulnerability assets have lower priority than high-vulnerability assets. In several agency systems, the low-criticality, high-vulnerability assets may include critical assets for underserved populations. A closer examination of these assets is necessary to determine which assets or portions of the network require resilience treatments. High-criticality, low-vulnerability assets or portions of the network may have low vulnerability either because they are in lower exposure areas or because they have low sensitivity. Monitoring both climate exposure and asset condition is therefore important to determine in a timely manner when a closer examination is necessary for particular assets or portions of the network. Low-criticality, low-vulnerability assets or portions of the network also have the lowest risk and are therefore ranked as the lowest priority.

Results – illustrative
In this section, we present examples of results showing the dynamic hazard exposure, sensitivity, criticality, vulnerability and risk of pavements, bridges and culverts in the state of Georgia. We also present examples of results ranking the respective pavement, bridge and culvert asset portfolios using the four-by-four ranking matrix. We follow these results with a discussion of their significance – in particular, how they may be used in determining and prioritizing resilience improvement strategies and in monitoring the performance of the entire system.

Figures 4 and 5 depict the cumulative count (1960–2020) and emerging hot spots (1990–2020) for thunderstorms, as illustrated by the SHELDUS data for a specific
Figure 4. Cumulative thunderstorm events (1960–2020) [SHELDUS]

Figure 5. Thunderstorm hot spots (1990–2020) [SHELDUS]
hazard. The hot spot data is used in the development of the dynamic hazard exposure index, as described in the sections above.

*Figures 6 to 10* depict pavement exposure, sensitivity, criticality, vulnerability and risk. The methodology generates similar results for bridges and culverts and may be extended to other assets using appropriate data sets. Pavement vulnerability is the product of pavement exposure, sensitivity and adaptive capacity; adaptive capacity is estimated at the district level and assigned a unit value for all seven transportation districts. Pavement risk is the product of pavement vulnerability and criticality. The availability of vulnerability and risk data at the district level also provides insights into equitable treatments from the standpoint of urban and rural districts, as well as on a district-by-district basis, as the nature and extent of critical hazards may differ from district to district.

*Figures 11 to 14* show the prioritization recommendations for pavements and bridges, mapped and in tabular form, using the four-by-four vulnerability-criticality matrix. These results align with the risk results but provide more nuanced information as the analyst can determine assets that fall into various categories of vulnerability-criticality. Within these categories, the analysts may then take a deeper dive to determine whether hazard exposure, asset sensitivity or both are driving the vulnerability results.

*Performance monitoring at the system level*

Time-based monitoring of asset exposure to climate hazards, asset sensitivity, vulnerability and risk will inform practitioners of whether the system is becoming more or less resilient. Vulnerability and risk reduction over time will reflect that the system is becoming more resilient. As they invest in resilience building, practitioners would expect vulnerability distributions and risk distributions (as shown in *Figures 15 and 16* as examples) to shift to the left – reflecting a reduction of climate vulnerability and risk in the system.

![Figure 6. Pavement exposure](image_url)

*Source:* Figure elaborated by authors
Climate hazards in transportation systems

Figure 7. Pavement sensitivity

Source: Figure elaborated by authors

Figure 8. Pavement criticality

Source: Figure elaborated by authors
Figure 9. Pavement vulnerability

Source: Figure elaborated by authors

Figure 10. Pavement risk

Source: Figure elaborated by authors
methodology provides vulnerability and risk distributions for all the assets included in the climate vulnerability/risk assessment. Furthermore, agencies that link their carbon reduction strategies with their climate resilience strategies create opportunities to integrate shorter-term and longer-term initiatives better. This integration is more likely to facilitate achieving resilience in the long-term by addressing both the drivers and impacts of the changing climate. Such an approach is more likely to lead to sustainable resilience.

**Notes:** 1) Unit in Centerline Miles; 2) This analysis was conducted using SHELDUS data from 1990-2020

**Source:** Figure elaborated by authors
Conclusions
The Infrastructure Investment and Jobs Act in the USA prioritizes infrastructure resiliency, makes funds available for resilience building in transportation and other infrastructure agencies, and incentivizes the development of resilience improvement plans (The White House, 2022). This paper presents an approach to building climate resilience through climate vulnerability and risk reduction and the development and application of adaptive and transformative capacity.
The results of the vulnerability assessment and risk analysis enable the analyst to determine the highest-risk assets (i.e., high vulnerability and high criticality) and prioritize them for closer examination, leading to resilience improvement. In the more detailed examination phase, a closer look will be taken at the specific hazards that are most likely to cause damage.

**Notes:**
1. Unit in Centerline Miles.
2. This analysis was conducted using SHELUSD data from 1990-2020.
3. The L/M/H categories in this analysis are based on the ranking of the pavement dynamic vulnerability index, with each category containing nearly the same centerline miles of pavements (differences may come from duplicated data at splitting thresholds).
4. The thresholds for splitting L/M/H are set at 2.286 and 4.714. (By observing the change of these thresholding values, it tracks GDOT's progress over time.)

**Source:** Figure elaborated by authors

The results of the vulnerability assessment and risk analysis enable the analyst to determine the highest-risk assets (i.e., high vulnerability and high criticality) and prioritize them for closer examination, leading to resilience improvement. In the more detailed examination phase, a closer look will be taken at the specific hazards that are most likely to cause damage.

**Notes:**
1. This analysis was conducted using SHELUSD data from 1990-2020.
2. The L/M/H categories in this analysis are based on the ranking of the bridges dynamic risk index, with each category containing nearly the same number of bridges (differences may come from duplicated data at splitting thresholds).
3. The thresholds for splitting L/M/H are set at 6.599 and 13.2. (By observing the change of these thresholding values, it tracks GDOT's progress over time.)

**Source:** Figure elaborated by authors
obstruct system performance or cause system failure, as well as the general vulnerability results, which capture the effects of all climate hazards to which the assets are exposed and sensitive. When particular assets are prioritized at the state and district levels, a broad multi-agency stakeholder effort will be helpful to identify resilience improvement strategies at the asset, corridor and system levels for consideration. Climate adaptation, or climate resilience improvement, has elements of both science and art. It involves creativity in thinking through multiple alternatives to determine combinations of strategies that have the most significant impact on resilience improvement while producing co-benefits to achieve other system goals. It also involves exploring and identifying gray-, green- and blue infrastructure and policy-based alternatives that may be combined in implementation. Third, it involves addressing system interdependencies. In some cases, the best project alternatives may not be infrastructure improvement alternatives. Cuadra et al. discuss climate adaptation of infrastructure recognizing systems and project and organizational interdependencies (In Press), and Tennakoon offers a climate adaptation guidebook that links contextual hazards to various adaptation strategies that have been implemented around the USA and internationally (2023). Case studies in this guidebook are organized into four categories: defend, accommodate, retreat and change policies and practice, indicating the broad range of pathways, including combined alternatives, that an agency may use in resilience building.

The study does not address operational aspects of the transportation system or include future climate projections. These will be addressed in the future as the approach is enhanced to support resilience building efforts in the state and other departments of transportation. Agencies that can reduce vulnerability while enhancing adaptive capacity in ways that are synergistic with other transportation goals, will strengthen the resilience of their infrastructure systems and organizations in an efficient manner.

References


Garrett, A. (2023), “Incorporating resilience capabilities into long-range transportation plans: flexibility and agility”, A Thesis Presented to the Academic Faculty in Partial Fulfilment of the Requirements for the Degree of Master of Science in the School of Civil and Environmental Engineering, Georgia Institute of Technology.


Transportation Research Board (TRB) Committee on Transportation Resilience Metrics Investing in Transportation Resilience (2021), A Framework for Informed Choices, a Consensus Report of the National Academies of Sciences, Engineering and Medicine (NRC), Transportation Research Board, Washington, DC.


Further reading


Popp, K. (2021), “Emerging frameworks for handling deep uncertainty with applications to Long-Term transportation planning”, *A Thesis presented to the Academic Faculty in Partial Fulfillment of the Requirements for the Degree of Master of Science in the School of Civil and Environmental Engineering, Georgia Institute of Technology*.

Tennakoon, M. (2023), “Harmonizing climate adaptation planning for transportation system resilience: Development of an adaptation guidebook for the state of Georgia”, *A Thesis Presented to the Academic Faculty in Partial Fulfillment of the Requirements for the Degree of Master of Science in the School of Civil and Environmental Engineering, Georgia Institute of Technology*.


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