VULNERABILITY AND RESILIENCY FRAMEWORK FOR THE ATLANTA REGION

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Introduction

Transportation network resilience is becoming an increasingly important concern to transportation agencies throughout the nation, in large part due to the impacts of extreme weather events (and over time long-term climate change) on system performance. In recent years, we have seen a multitude of extreme weather events nationally that have disrupted transportation systems and that have understandably led to the desire among transportation officials to raise the bar in their ability to identify and manage risks and to enhance their capacity to recover from possible system disruptions in their region. However, it is not only extreme weather that can disrupt the transportation system.

In the Atlanta region, the I-85 bridge collapse (March 30, 2017) caused widespread disruption to the region's transportation system. In addition, just in 2017, the Atlanta region faced a tropical storm, tornados, flooding, and an ice/snow storm. And only three years ago, January 2014, the region faced one of the worst ice storms in the region's history, "Snowmageddon," that not only paralyzed the region's transportation system (over 10,000 motor vehicles were abandoned on the region's roads) and economy, but also placed Atlanta in the national news as a region that did not know how to handle such large-scale disruptions.

Each of these events placed stress on the transportation and emergency management agencies preparing for, and responding to, the disruption.

The purpose of this study was to develop a vulnerability and resiliency framework for the Atlanta region that can be used as part of a system vulnerability assessment. Because not all risks and potential impacts occur suddenly and without much advanced warning, such a framework would want to demonstrate that predictable, long-term threats (such as increasing extreme temperatures) are being planned for in a strategic sense and from the perspective of eliminating, or at least minimizing potential adverse impacts through judicious long-term planning, design, deployment and operational management of transportation facilities. The work statement for this study stated that the FHWA Vulnerability Assessment Framework should serve as the backbone of this effort. Experience in applying this framework in other parts of the country suggests that it needs to be modified and extended to be more relevant to a particular jurisdiction's needs. For example, the framework does not really provide guidance on how the vulnerability analysis would extend to beyond just transportation system assets. In Atlanta, the vulnerability assessment should include at least public health, safety, and economic development impacts as well.

A proposed framework should also emphasize the linkage between the results of a vulnerability assessment to the decision-making processes that ultimately define the transportation system through investments and operational changes. This means that to be meaningful in a planning sense, the vulnerability assessment should lead to, 1) planning goals, objectives and performance measures that are more sensitive to system resiliency, 2) elements of the region's and other modal and comprehensive plans that examine resiliency as an important system characteristic, 3) project criteria that provide additional weight to projects that enhance system resiliency, and 4) ultimately projects and strategies that enhance resilient system performance.

Definition of Resilience

There are many definitions of "resilience." A review of such definitions for this study found 35 such definitions alone in transportation or similar fields of study. Many others are found in fields such as ecology, psychology, management, and materials science. For purposes of this study, the following definition of resilience from the American Association of State Highway and Transportation Officials (AASHTO) will be used as the working definition.[1]

> "The ability to prepare and plan for, absorb, recover from, or more successfully adapt to adverse events."

This definition contains some key phrases that are inherent to a good resilience framework. "Prepare and plan" by its very definition implies a structured approach, or framework, that allows officials to anticipate possible disruptions and then identify potentially successful strategies for minimizing the consequences. "Absorb, recover from, or more successfully adapt" suggests different types of strategies that can be considered by those responsible for the transportation system. Absorbing the impact(s) suggests that a facility or system has been designed with the capacity to handle disruptions, that there is perhaps redundancy in the network to allow traffic flows to bypass the disruptions, albeit with reduced performance (such as the I-85 bridge deck collapse).

Recovering from a disruption implies that resources are in place to remove the disruption as quickly as possible for the facility to continue to function as designed as part of a transportation system. From the bridge deck collapse example, the response of the Georgia Department of Transportation (GDOT) in expediting the building of the replacement bridge deck is a good illustration of a recovery strategy.

Adapting from a disruption suggests that lessons learned from a disruption are incorporated into the standard operating procedures of the responsible agencies. For example, Superstorm Irene (2011) in Vermont resulted in more than 2,400 roads, 800 homes and businesses, 300 bridges, and a half dozen railroad lines destroyed or damaged. In response, the Vermont Agency of Transportation (VTrans) has redefined its design approaches for bridges and culverts such that heavy water flows that are anticipated with expected future climate conditions can be handled more efficiently. In other words, the standard operating procedures for providing transportation capacity in the state have been redesigned to provide a better adaptability of the physical infrastructure to future weather-related stresses.

Adopting a resilience perspective in transportation planning and decision making does more than simply keeping operations in place during disruptive events. It points to the interrelationships among the many different agencies and organizations that must collaborate to promote system resilience; it shows a linkage to other policy goals that rely on a functional transportation system;

[1] AASHTO, "Resilient and Sustainable Transportation Systems Technical Assistance Program," https://environment.transportation.org/center/rsts/

and increasingly in many communities it is a prerequisite for obtaining good bond ratings. As noted by Lenny Jones, a managing director at Moody's, one of the nation's leading bond agencies,

> "What we want people to realize is: If you're exposed, we know that. We're going to ask questions about what you're doing to mitigate that exposure …. That's taken into your credit ratings."[2]

There are thus many reasons why emphasizing resilience when considering improvements to the transportation system makes sense.

Institutional relationships are one of the key characteristics of a resilience-focused transportation decision-making process. In almost every case where a transportation agency has adopted a resilience focus on the planning and operations of its transportation system, this has required collaboration with functional units within its own organization, as well as strategic alliances with other agencies that are critical in managing disruptions (e.g., emergency responders, police, and hospitals). Figure 1 shows the complexity of the institutional relationships that could be part of a resilience strategy. In many ways, even Figure 1 is too simplistic given that transportation system resilience can affect so many other policy areas. However, it does provide a sense of the interrelationships that might have to be managed to focus on system resilience.

What a System Resilience Focus Provides to the Transportation Planning Process

- Places greater emphasis on a reliable and efficient transportation system
- Given projected future weather conditions, it begins the process of putting in place safeguards to protect the transportation system and its users
- Places emphasis on the importance of physical "connections" (cascading effects, dependencies, etc.)
- Places emphasis on institutional "connections"
- Promotes a consideration of the broader implications of transportation system resilience to other policy areas
- Provides evidence for local government bonding requirements that infrastructure risk has been considered as part of the "due process" requirement
- Helps satisfy federal requirements

[2] Moody's Warns Cities to Address Climate Risks or Face Downgrades, Nov. 29, 2017. https://www.bloomberg.com/news/articles/2018-01-14/japan-s-renewable-energy-goals-lag-world-foreign-minister-says

Figure 1: Possible Institutional Relationships in a Resilience-oriented Perspective

Changes in Climate and Future Consequences to the Transportation System

Although many of the climate-related vulnerability assessments conducted by state DOTs and MPOs have occurred in coastal regions (due to obvious threats from sea level rise and storm surge), in reality all parts of the country are likely to see changes in weather patterns that will affect many different aspects of daily life as we know it today. The Third National Climate Assessment, for example, made the following statements about the southeastern United States:

- Temperatures across the Southeast are expected to increase during this century, with shorter-term (year-to-year and decade-to-decade) fluctuations over time due to natural climate variability
- Major consequences of warming include significant increases in the number of hot days (95°F or above) and decreases in freezing events.
- Projected increases for interior states of the region are larger than coastal regions by 1°F to 2°F. Regional average increases are in the range of 4°F to 8°F, depending on the emissions scenario analyzed.
- In general, annual average decreases in precipitation are likely to be spread across the entire region.

- Substantial increases in high intensity storms are projected as this century progresses, thus increasing the potential for more severe flooding.[3]

Although not yet in final form, the Fourth National Climate Assessment concluded the following, reinforcing the above statements:

- “The frequency and intensity of heavy precipitation and extreme heat events are increasing in most regions of the world. These trends are consistent with expected physical responses to a warming climate and with climate model studies, although models tend to underestimate the observed trends. The frequency and intensity of such extreme events will very likely continue to rise in the future. Trends for some other types of extreme events, such as floods, droughts, and severe storms, have more regional characteristics. (Very high confidence)
- Global climate is projected to continue to change over this century and beyond. The magnitude of climate change beyond the next few decades depends primarily on the amount of greenhouse (heat trapping) gases emitted globally and the sensitivity of Earth’s climate to those emissions. (Very high confidence)
- Accompanying the rise in average temperatures, there have been—as is to be expected—increases in extreme temperature events in most parts of the United States. Since the early 1900s, the temperature of extremely cold days has increased throughout the contiguous United States, and the temperature of extremely warm days has increased across much of the West. In recent decades, intense cold waves have become less common while intense heat waves have become more common. (Extremely likely, Very high confidence)
- The average annual temperature of the contiguous United States is projected to rise throughout the century. Increases of at least 2.5°F (1.4°C) are projected over the next few decades, meaning that recent record-setting years will be relatively “common” in the near future. Increases of 5.0°-7.5°F (2.8°-4.8°C) are projected by late century depending upon the level of future emissions. (Extremely likely, Very high confidence)
- Extreme temperatures are projected to increase even more than average temperatures. The temperatures of extremely cold days and extremely warm days are both projected to increase. Cold waves are projected to become less intense while heat waves will become more intense. (Extremely likely, Very high confidence)
- Future decreases in surface soil moisture over most of the United States are likely as the climate warms. (High confidence)
- Surface temperatures are often higher in urban areas than in surrounding rural areas, for a number of reasons including the concentrated release of heat from buildings, vehicles, and industry. In the United States, this urban heat island (UHI) effect results in daytime temperatures 0.9°-7.2°F (0.5°-4.0°C) higher and nighttime temperatures 1.8°- 4.5°F (1.0°-

[3] National Climate Assessment, http://nca2014.globalchange.gov/report/regions/southeast

> 2.5°C) higher in urban areas, with larger temperature differences in humid regions (primarily the eastern United States) and in cities with larger populations. The UHI effect will strengthen in the future as the spatial extent and population of urban areas grow. (High confidence)"

The Atlanta region, given its size and the connectivity of the transportation system, is likely to be much more vulnerable to the effects of a changing climate, and it is not only the transportation system that could be affected. Changing climatic conditions will have impacts on public health, water availability, economic growth, work conditions and air quality, to name a few.

Points of Departure for a Vulnerability Assessment Framework

Conducting successful climate vulnerability assessments can be a challenge, requiring experience and knowledge across a range of disciplines. From our experience, a successful vulnerability assessment incorporates an appreciation of the following:

Climate change and extreme weather events present a wide range of environmental stresses on the transportation system.

The National Cooperative Highway Research Program (NCHRP) Report 750, vol. 2 on climate adaptation planning for highways identified a large number of climate-related stresses and resulting impacts that could affect the nation's road network in the future.[4] One of the first tasks of any climate change vulnerability assessment is an understanding of the types of stresses and impacts that are of most concern to the transportation system managers. For Atlanta, these impacts include primarily changing precipitation patterns that could result in floods and higher temperatures with particular concern for heat waves.

Vulnerability assessments of transportation assets require several areas of expertise, but most importantly engineering.

Experience in conducting vulnerability assessment and adaptation studies has shown the need for understanding the design of a variety of assets and of how these assets will respond to different types of environmental stresses. If an asset is designed to withstand high levels of precipitation and/or high temperatures, then the vulnerability of that asset to such stresses is much lower than that for assets not designed with such factors in mind. Depending on the level of analysis, such analysis requires engineering expertise across a wide range of engineering disciplines. For example, vulnerability assessments of flood impacts benefit tremendously from expertise in hydrology and hydraulics; and geotechnical knowledge is indispensable for slope vulnerability assessments. We have found that a combination of planning and engineering expertise, connected to climate science, is a necessary foundation of effective adaptation planning.

[4] Meyer, M., M. Flood, C. Dorney, J. Keller, G. McVoy, K. Leonard, and J. Smith. 2014. "Climate Change, Extreme Weather Events and the Highway System: Impacts and Adaptation Approaches." NCHRP Report 750, Vol. 2, Transportation Research Board, Washington DC.

Risk is a key concept in vulnerability assessments.

A recent review of climate adaptation methodologies used world-wide concluded that "much of the transportation and infrastructure sector's approach to climate change impact analysis and adaptation planning is based on risk management practices."[5] It is important to note that vulnerability assessments that lead to a prioritized list of targeted assets include two major components of risk—vulnerability and criticality. In other words, if an asset is highly vulnerable to climate change-induced disruption, but the asset does not have a very important role in the state's transportation system, one could conclude that the asset is not a high-risk asset. However, an asset that is highly critical to the transportation network, but having a low likelihood of being disrupted raises the question of how willing decision-makers are to accept the risk of asset failure. Risk tolerances may very well need to be set differently for different asset types, addressing the question, how acceptable is disruption to major facilities as compared to lower value facilities?

Different climate change stressors use different analysis methodologies.

How one analyzes the impact of extreme precipitation events and flooding is very different than how one would analyze higher temperatures/drought. Many of the studies that have been supported by the Federal Highway Administration (FHWA) and used in adaptation studies have very different data needs, benefits, and limitations. Figure 2 provides an example of this observation (using a level of detail that is most likely beyond use in this study). This approach was used for the Minnesota DOT adaptation study in two of its districts.[6] Note that an asset vulnerability score was proposed consisting of three parameters---asset sensitivity, exposure and adaptive capacity. Much of the data for the approach came from the DOT databases, such as pavement type, previous flooding records, AADT, etc. In order to make the analysis as simple as possible, existing databases were used to determine the capacity to handle higher flows and stream velocity, both of which are important factors in determining whether an asset can withstand more intense flows. An approach using scores for each of the three dimensions shown in Figure 2 could also be used for the assessment.

Data availability and quality is a critical foundation for adaptation analysis.

Every adaptation study depends on data that not only reflects actual conditions, but is readily available. This was noted in a meeting of all the FHWA adaptation pilot study grantees where data availability was universally recognized as the limiting factor in conducting the pilot studies as envisioned. Much of the data that will be used in the vulnerability assessment will be available from either ARC or GDOT, either from existing asset management systems or from ARC databases. Other data, such as that relating to weather and climatic conditions, will come from efforts ARC has already undertaken, augmented with our own efforts at identifying likely future climatic conditions.

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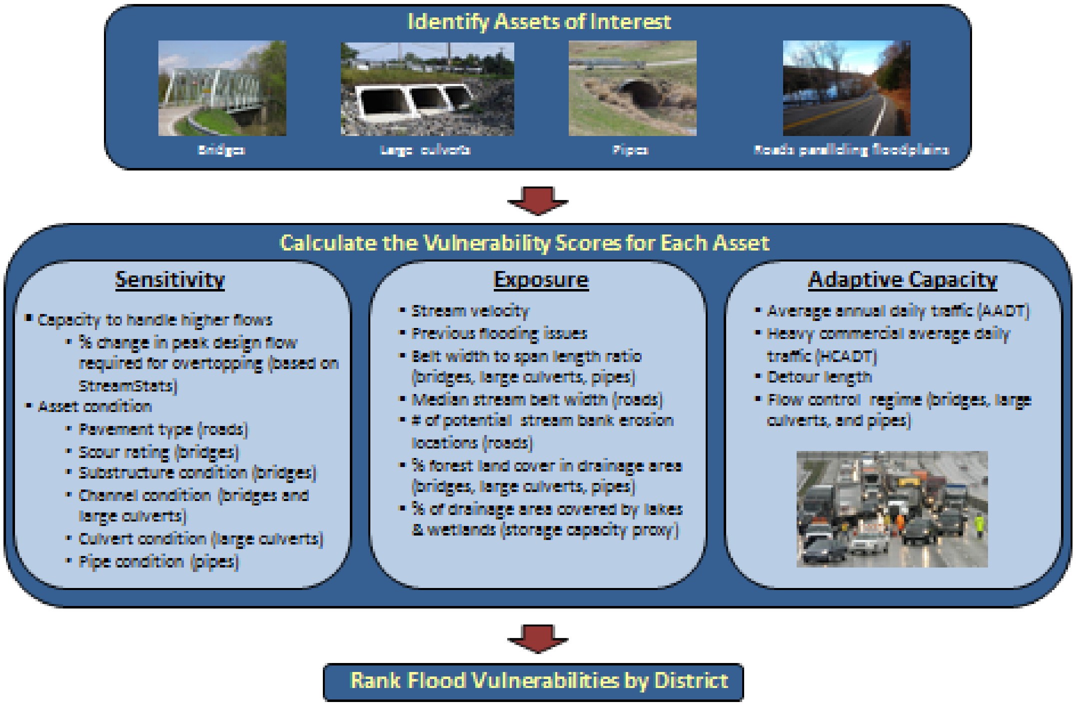
[5] Wall, T. and M, Meyer. 2013. "Risk-Based Adaptation Frameworks for Climate Change Planning in the Transportation Sector: A Synthesis of Practice," TRB Transportation Research Circular Number E-C181.

[6] Minnesota DOT, 2014. "MnDOT Flash Flood Vulnerability and Adaptation Assessment Pilot Project," http://www.dot.state.mn.us/climate/pdf/MnDOTFldVulnPilotFinalRpt_v4.pdf



Source: Minnesota DOT, op cit.

Figure 2: Minnesota DOT's Vulnerability Assessment Framework for Flood Hazards

The FHWA Climate Change and Extreme Weather Vulnerability Assessment Framework serves as an important point of departure for vulnerability assessments, but it often needs to be modified for local circumstances.

This observation was made earlier, but bears repeating. The work statement notes that the FHWA framework should be used as a basis for an Atlanta-focused vulnerability assessment, but that the framework can be adjusted to meet the needs of this study. Many of the adaptation studies being conducted in the U.S. today are based on the FHWA Assessment Framework, which was developed and tested in a large part through work on the FHWA Gulf Coast 2 project.[7]

Although this framework provides a general construct for the types of factors that should be considered in a vulnerability assessment (and some of these factors will be used in the ARC effort), it does not provide much guidance on how the assessment should link to decision

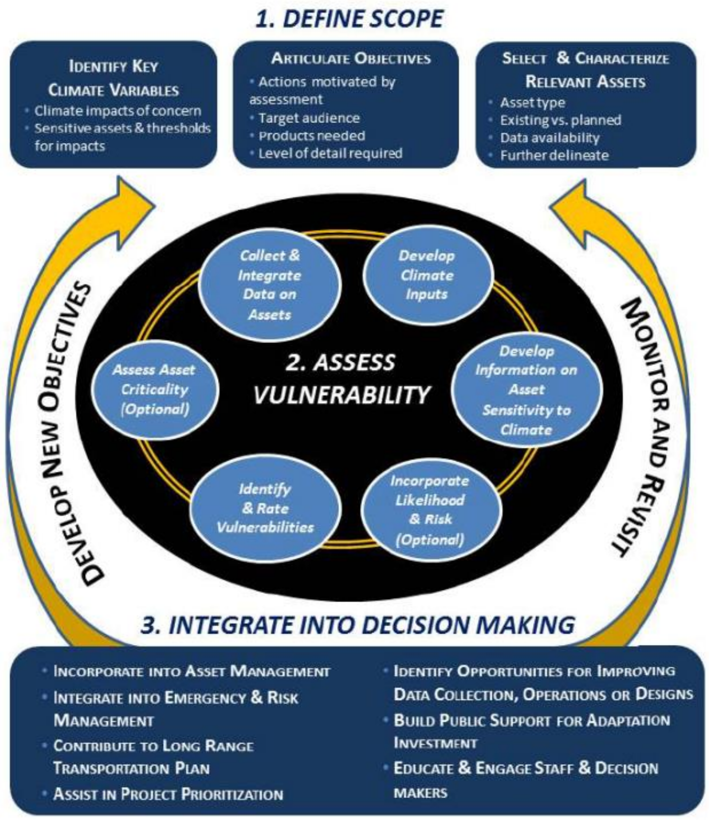
[7] Federal Highway Administration. "Gulf Coast Study," Website, https://www.fhwa.dot.gov/environment/sustainability/resilience/ongoing_and_current_research/gulf_coast_study/index.cfm

making and to some of the other important public policy concerns of interest to the ARC region. However, it does serve as a starting point for ARC's own vulnerability assessment framework, and thus is described in further detail in the following section.

FHWA's Climate Change and Extreme Weather Vulnerability Assessment Framework

FHWA's Climate Change and Extreme Weather Vulnerability Assessment Framework consists of three parts (see Figure 3). Part 1 of the framework involves defining the scope of the analysis in three steps which include: 1) identifying key climate variables to study, 2) articulating objectives for the assessment, and 3) selecting and characterizing relevant assets to study. Selecting relevant assets for a study is one of the most important steps. Often considered under a "criticality" rubric, this task in essence says that a transportation agency most often does not have the resources to protect all of its assets against extreme weather stresses, and thus the agency should identify which assets or facilities are most critical, most often relating this to some agency goal. The ARC's Regional Priority Freight Highway Network would be an example of a specified network of importance that should be included in the targeted network (in this case a network specified for a goal relating to economic activity). For transit, the MARTA rail network might be another such example. In the FHWA Gulf Coast 2 study, the identification of critical networks in the Mobile, AL metropolitan area considered: 1) a facility's linkages to socio-economic factors in the community (e.g., connection to key industrial sites), 2) the operational characteristics of the facility (e.g., volume of traffic), and 3) health and safety provisions (e.g., access to medical centers). Other studies have included such factors as connections to major employment centers, government buildings, environmental justice communities and a facility serving as an evacuation route.

Part 2 of the framework considers three factors of a facility's vulnerability to the identified stressors: a facility's sensitivity to a stressor, the exposure to the stressor, and the adaptive capacity of the facility (or asset) to handle the stress. The usual approach in developing this information is to overlay areas of a study area or a transportation network where the climate stressors could affect transportation system performance. Such an approach will clearly relate to the spatial nature of the stressor under consideration. For example, flooding will logically occur in low-lying areas and where culverts and drainage facilities exist to handle water flow. With respect to extreme temperatures, the extent of the impact will be spread over a much larger area. A temperature analysis is usually conducted at a subarea or regional basis in terms of potential impacts on certain types of infrastructure (such as rail track or pavement), on command and control equipment (such as signals and communications systems) and/or on users of the system.



Source: FHWA, op cit.

Figure 3: FHWA's Climate Change and Extreme Weather Vulnerability Assessment Framework

The sections below describe each of the factors in the FHWA Framework.

Sensitivity

One of the first steps in a vulnerability assessment will be identifying how an asset fares when faced with a climate stressor, with this sensitivity varying by different classes of assets. It will be important for such a determination that engineering expertise and previous work enumerating the impact of climate stressors on different types of assets be part of the analysis. Other studies in the country have worked closely with facility owners to determine key thresholds of impact significance for varying levels of stress. Asset condition and design characteristics are often determining factors. For example, the minimum elevation of the critical elements of a facility or asset such as low points of approach roadways or deck or low chord elevations of the bridge, are often important inputs into a sensitivity determination. The sensitivity of rails and pavements to extreme heat often requires close coordination with asset owners to ascertain critical thresholds. These critical thresholds are often recorded as fields in the GIS files for each facility type (as part of a critical network inventory).

Exposure

Exposure of the asset to the climate changes projected for the region given the scenarios chosen for the project is the next factor considered in the assessment. As noted earlier, for most climate stressors, this is done through a GIS analysis overlaying the transportation network onto the climate projection information. An entry is made into each facility's GIS record indicating whether a facility is exposed to a climate stressor for which it is sensitive (i.e. the projected value of the climate variable is beyond the sensitivity threshold). The degree to which it is exposed is also noted. This might consist of the maximum depth of flooding or for temperature how high over the facility's sensitivity threshold the projected future value is. Whether the facility was affected by any recent extreme weather events is often also flagged.

When considering exposure to riverine flooding inundation, special care must be taken to ensure that inundation could realistically occur at each facility and that false positives (e.g. bridges and roadways that are elevated) are rooted out. We have found this to be a challenge in other studies where the use of LIDAR data and GIS files often require a manual visual assessment of the GIS datasets.

Adaptive Capacity

Adaptive capacity, the ability of the transportation facility and network to cope with the consequences of exposure, is another key factor in a vulnerability assessment. An important concept when assessing adaptive capacity is the redundancy of the transportation network---the greater the network redundancies, the greater the ability of the transportation system to absorb the loss of use of a given facility affected by climate stressors (i.e., the higher its adaptive capacity). For the highway network, redundancies may take the form of alternate routes that can be used as detours around facilities compromised by climate stressors. For transit, it might mean alternative services put in place to serve the demand now not serviced due to disruption (e.g., bus service between subway stations to replicate disrupted subway service).

The usual approach to investigating the redundancy aspect of adaptive capacity is estimating the daily cost of the additional travel time required by different types of facility users (e.g. drivers, bus and rail passengers, freight movements) when taking an alternative mode or detour route. This is often assessed with the aid of the regional travel demand model. By removing potentially compromised links in a model, one can ascertain the optimal detour routes for travelers and the implications of those detoured trips on congestion. This will highlight routes that, if affected, might have significant ripple effects throughout the network. Once detour routes have been identified and the additional increment of travel time required to use them, the time-value of travel by different system users is used to estimate the cost of losing the use of a given facility. Facilities that are more heavily used and/or have longer detour routes (i.e., less redundancy) would tend to have lower adaptive capacity (and higher vulnerability). Note that the redundancy effort inherently incorporates the criticality of each facility into the vulnerability assessment.

Another component of adaptive capacity is how long it takes to restore service to the facility once it has been compromised---the longer the restoration time the lower the adaptive capacity and the higher is that facility's vulnerability. Restoration time (measured in days) can be considered a multiplier to the additional user costs associated with detours. In other words, each day of expected downtime can be multiplied by the user costs to arrive at a better representation of user costs if there is a failure. Restoration times might be as little as a day or two for temporary flooding where permanent damage is not expected or weeks or months as shown in the recent bridge deck fire on I-85 that required major reconstruction efforts. Assumed reconstruction or restoration times are developed for different types of facilities based on previous experiences and close consultation with the asset owners. The estimates will also make use of the degree of exposure information so that a high-level assessment of the degree of damage can be made (i.e., are only repairs needed or might full replacement be required?).

Replacement costs are the final component of adaptive capacity that will be considered in the vulnerability analysis. The costs to replace or repair a compromised asset are an important component of the adaptive capacity from an asset owner's perspective and, since federal money is typically involved, of interest to the federal government as well. Thus, all else being equal, larger transportation investments with higher replacement/repair costs can be considered to have a higher vulnerability worthy of greater prioritization for adaptive action.

Once vulnerability scores have been calculated for each facility for each climate scenario, the facilities are then ranked to determine priorities. The rankings can be done across all facilities analyzed in the entire region, by geographic subarea, by mode, by asset type or asset owner. Of particular interest as potential candidates for adaptive action are facilities that are impacted and rank highly under multiple climate scenarios. Climate scenarios that are slated to happen sooner are often given more weight in this calculation. The information gleaned from the overall rankings can then be used in Part 3 of the FHWA Framework---integration into decision making. An example would be using the vulnerability scores to prioritize site-level adaptation assessments for individual facilities or groups of facilities.

In sum, the FHWA Framework provides some important guidance on the factors that should be considered as part of a vulnerability assessment. Indeed, this framework has been used in many adaptation studies around the country. However, the framework has some limitations. As found in the southern Florida MPO Climate Adaptation Pilot Study,

> "The study found the overall framework to be quite useful in directing the study team to the types of data and analysis efforts that had to be undertaken. The framework, perhaps necessarily, is defined at a very high level, with little guidance on how the planning effort leads to actual actions. This study found that considerable effort was expended in defining the three factors in ways that were meaningful to the context of the study. Thus, for example, it was not enough to say that a facility or asset was in a 100-year flood plain to say it was vulnerable. More information on the asset design and characteristics such as elevation and drainage mitigation measures had to be part of the study process to understand fully the potentials risks associated with that facility.
>
> In addition, the three factors were used in the vulnerability scoring system with weights attached to each that could be changed by the user. This approach found that the exposure variable was being "overwhelmed" by the contribution to the score of the other two variables. One possible way of modifying the approach in the future might be to first rank the network segments by level

of exposure, and once this ranking is established consider a prioritization by sensitivity and adaptive capacity."[8]

The vulnerability assessment framework for the Atlanta region will take into account those aspects of the FHWA Framework that serve as a good foundation for such an assessment, and modify it as appropriate for the specifics of the Atlanta study area.

Proposed Vulnerability Assessment Framework for the ARC Region and Recommendations

A proposed vulnerability assessment framework for the ARC region is shown in Figure 4. Each of the steps is described in the following paragraphs.

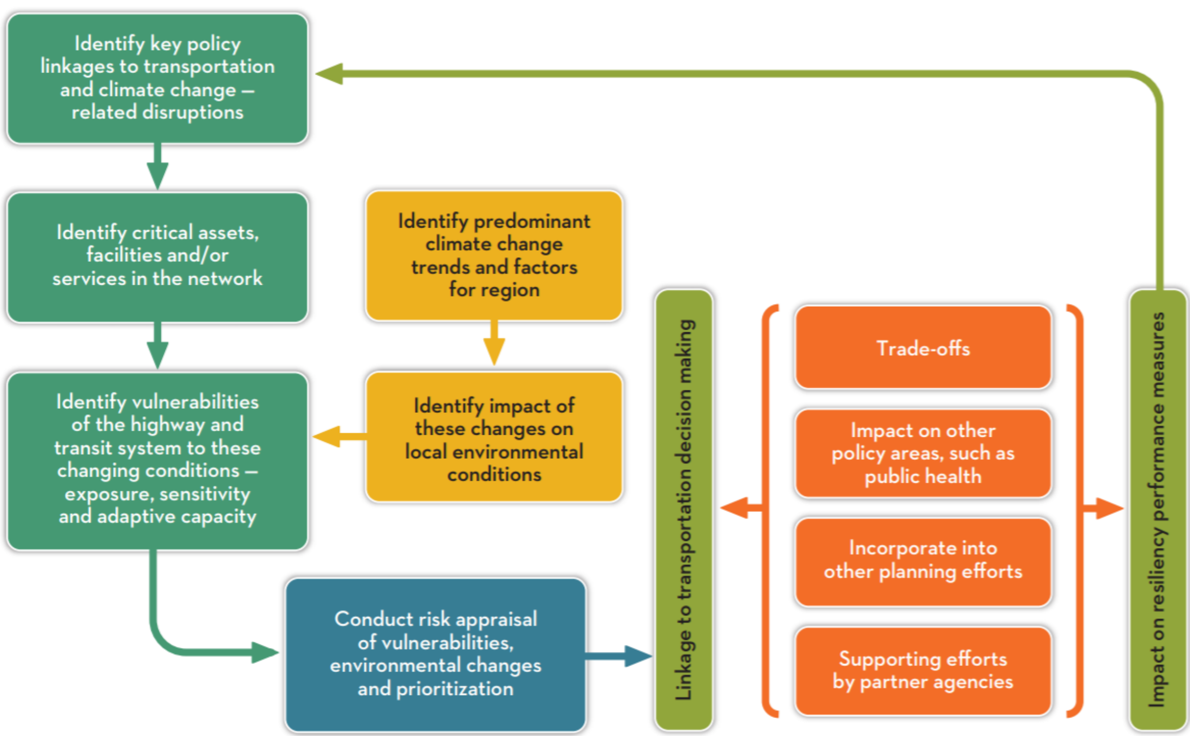


Figure 4: Proposed Vulnerability Assessment for the ARC Region

[8] http://www.browardmpo.org/images/WhatWeDo/SouthFloridaClimatePilotFinalRpt.pdf

Step 1: Identify key policy linkages to transportation and climate change-related disruptions

This step includes two major efforts, 1) define the importance of resilience to transportation planning and decision making, and 2) identify the linkages with other policy areas.

Importance of Resilience as a Transportation Planning Factor: The first step in promoting resilience as part of the transportation planning process is to articulate clearly that it should be explicitly considered when planning is undertaken. The Puget Sound Regional Commission (PSRC), for example, has identified “Resilience and Sustainability” as a major planning consideration for its planning program. In Nashville, TN, the MPO has sponsored a study that focused explicitly on resilience and what it means to the region. As noted in the report, success in implementing the report findings would mean, “that regional and community leaders across all sectors and jurisdictions prioritize and sustain collaborative action for climate resilience.”[9] The goals of the study included,

> Goal 1: The region implements preemptive adaptation measures and responses to extreme weather events that are planned, coordinated, and timely.
>
> Goal 2: The leaders and residents of the region value and protect water resources and prioritize improved water quality and conservation for the benefit of human and natural systems.
>
> Goal 3: The region’s growth and development promote equitable prosperity and is sustainable for people and natural resources.
>
> Goal 4: The region’s leaders and organizations work collaboratively and effectively in all resilience actions.

As an example of the types of actions that could result from this study, the following suggested steps and responsible parties were recommended for Goal 1 by the Nashville MPO.

1. Conduct detailed transportation infrastructure vulnerability assessment to extreme weather within the MPO planning area. MPO, Tennessee DOT, FHWA, Vanderbilt University (VU)
2. Map service gaps of storm shelters throughout the region. MPO, Offices of Emergency Management (OEMs), Red Cross, Tennessee State University (TSU)
3. Ensure that all emergency response and hazard mitigation plans consider the impacts of climate change to the region and are including this information in their plans. MPO, OEMs
4. Participate in decision making process for flood wall for downtown Nashville. Tennessee Visitor and Hospitality Association

[9] Nashville Area Metropolitan Planning Organization, “ Building Resilience: A Climate Adaptation Plan,” http://www.nashvillempo.org/docs/BuildingResilience_DRAFT.pdf

5. Conduct heat mapping for urban areas. MPO, Trust for Public Land
6. Conduct workshops for vulnerable populations on emergency preparedness and access to services. SEARS, OEMs
7. Ensure that all emergency response and hazard mitigation plans consider the impacts of climate change to the region and are including this information in their plans. MPO, OEMs
8. Develop climate metrics for MPO evaluation of proposed transportation projects. MPO, TDOT, FHWA
9. Ensure adequate maintenance of existing transportation infrastructure.

Importance of Resilience in Cross Cutting Policy Areas: As noted earlier, climate change is likely to have a significant impact in many of the policy areas for which ARC has a role. Step 1 in the framework also identifies the different sectors that could possibly be affected by changing climatic conditions, although the focus will still be on the potential impacts on the transportation system (broadly defined to include infrastructure, services and users). For example, a report by the US Environmental Protection Agency (EPA) entitled, *Climate Change in the United States, Benefits of Global Action*,[10] identified the following policy linkages to climate change that might be relevant to the ARC region:

Health: Air quality, extreme temperature, labor and water quality

Infrastructure: Bridges, roads, urban drainage, and coastal development

Electricity: Electricity demand, electricity supply, hydropower and thermoelectric cooling

Water Resources: Inland flooding, drought and supply and demand

Agriculture and Forestry: Crop and timber yields and market impacts

Ecosystems: Freshwater fish, wildfire and carbon storage

Step 1 should determine which of these areas are of most interest to ARC, identify work that has been done by ARC staff for each area and describe a work effort that would be necessary to address the potential implications of climate change-induced impacts for that particular policy area. This determination would occur via interviews with ARC staff working in each of the areas. The current Atlanta Region's Plan provides a good starting point for the different areas that might be most relevant (see Figure 5). However, a review of ARC documents and plans suggest that the two most important policy linkages would likely be public health and water resources.

[10]US Environmental Protection Agency (EPA), 2015. "Climate Change in the United States, Benefits of Global Action," https://www.epa.gov/sites/production/files/2015-06/documents/frontmatter.pdf

Source: http://documents.atlantaregional.com/The-Atlanta-Region-s-Plan/rtp/introduction.pdf

Figure 5: Interconnected Policy Area's in the Atlanta Region's Plan

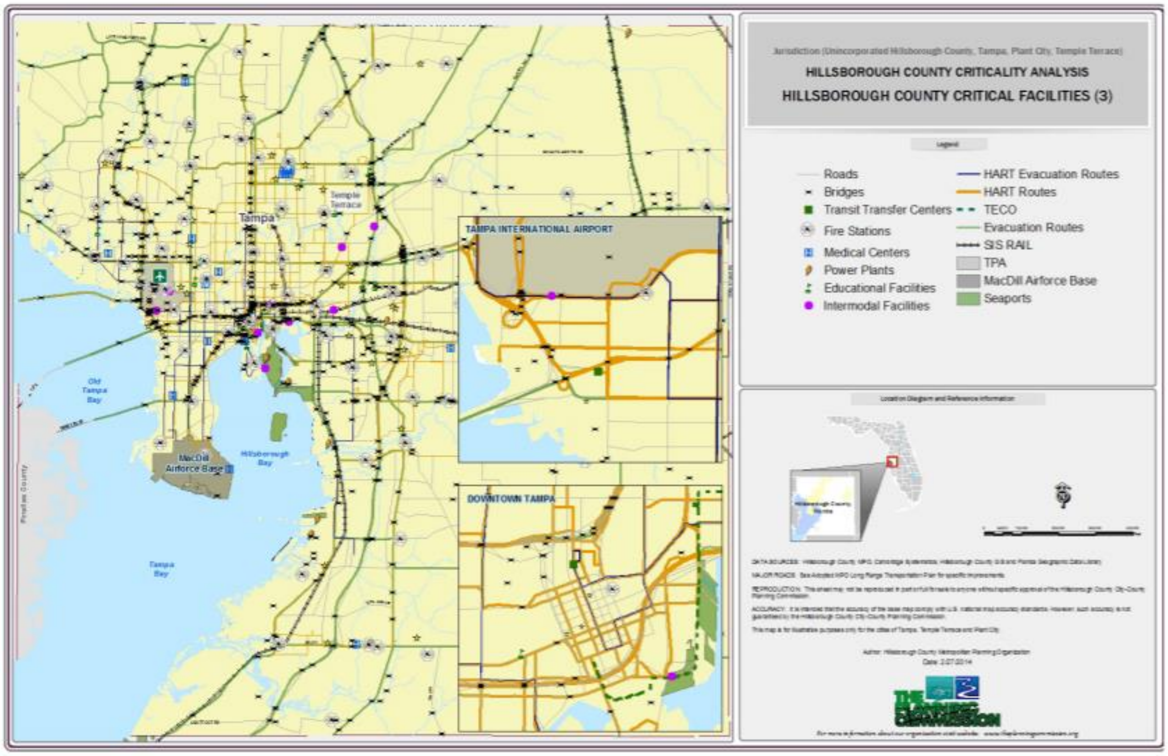
ARC Recommendation 1: Resilience as a system characteristic and as a planning factor needs to be reinforced in planning guidance and adopted policies and goals. For example, the current transportation plan talks about resilience as a federally required planning factor, but it does not include examples of how disruptions to the transportation system can impact mobility or accessibility. The illustration on page 11 of the transportation plan, which shows "how a robust and diverse transportation system helps seven hypothetical residents of the Atlanta region win their own individual futures," should include in a plan update an illustration of how a resilient system fosters efficient mobility. The goal "Improve Reliability" should be redefined as "Improve Reliability and Resilience."

Step 2: Identify critical assets, facilities and/or services in the network

Step 2 identifies the assets, facilities or services that will be the focus of the assessment. Very few, if any, transportation agency will have the resources to examine and protect every asset in its system against possible disruptions. Certainly, a transportation system the size of the Atlanta region's would require extensive resources to identify every possible vulnerability in the network. Thus, risk appraisals for climate change-related assessments rely on a determination of how important a facility, asset or service is to the targeted system of the study, in this case, the transportation system. An entire methodology has been developed for determining which facilities or assets are most critical.[11] For example, the roads designated as part of the National Highway System (NHS) is a usual designation of a critical network (which would include most of the roads that constitute the regionally significant freight network described earlier). Importantly, most approaches for determining the criticality of individual assets have been broadened to include socio-economic considerations and the importance of individual land sites to fostering community resilience. Thus, for example, evacuation routes into and out of communities that might not have the resources themselves to move large portions of their populations have received attention. Or, access routes to and from medical facilities or emergency operations centers, even though the routes might not be on a defined strategic network, become important assets to protect.

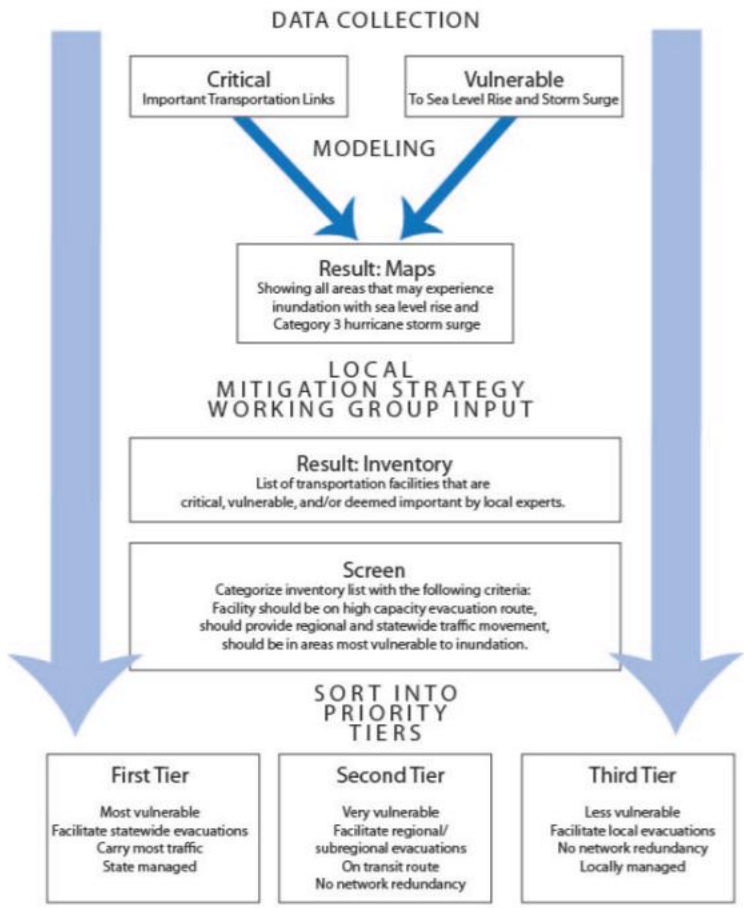
An example from Tampa, FL illustrates a typical approach to defining critical assets or areas. As shown in Figure 6, critical locations such as hospitals, power plants, educational facilities, and fire stations are located on the map. Evacuation roads and key transit routes are also identified. The critical transportation assets for providing access to these facilities or for keeping the routes functioning were then identified as part of the analysis. Figure 7 shows how the MPO proceeded to screen all of the assets and critical road links to define three tiers of assets based on their importance to the region and the level of vulnerability each is facing.

[11] FHWA, Impacts of Climate Change and Variability on Transportation Systems and Infrastructure: Gulf Coast Study, https://www.fhwa.dot.gov/environment/sustainability/resilience/ongoing_and_current_research/gulf_coast_study/phase2_task1/gulf00.cfm



Source: http://www.planhillsborough.org/wp-content/uploads/2013/10/Appendix-B_2040-LRTP-Technical-Memo.pdf

Figure 6: Tampa, FL Identification of Critical Assets



Source: http://www.planhillsborough.org/wp-content/uploads/2013/10/Appendix-B_2040-LRTP-Technical-Memo.pdf

Figure 7: Tampa, FL Screening Process for Identifying Critical Investment Assets

The Atlanta region has identified key or strategic networks as part of the transportation system, such as the strategic thoroughfare network and the Atlanta Strategic Truck Route network. There are thus well-defined roads that can be targets for vulnerability assessment. However, there is little attention (except in the freight study) given to the relationship between access to key community facilities and the road network.

For MARTA, a climate assessment as part of a Federal Transit Administration (FTA) study conducted in 2012 focused on its key assets (primarily the rail network). In addition to the rail network, however, one possible focus for a vulnerability assessment might be on the MARTA "lifeline" bus routes, which serve critically important destinations such as hospitals, government centers, etc. The major focus of such an effort would be on bus routes on local streets that might flood. In addition, a vulnerability assessment for MARTA services should focus on the impact of extreme temperatures on the users of the system …. the impacts on air conditioning, shelters from the sun and other appurtenances that provide a comfortable and safe trip for MARTA users.

The pedestrian and bicycle networks are less well defined in terms of asset location and condition. It is not clear, and would have to be a decision on part of the ARC, to what extent the actual pedestrian and bicycle networks would be a focus of a vulnerability assessment. The sidewalk and (most) bicycle networks are on local roads and thus most likely not included in the scope of a high-level vulnerability assessment as it relates to physical disruption to facility. Some of the more significant bicycle facilities (the Atlanta Beltline, for example) might be of interest, however. In most cases, an analysis would likely focus on the effects of extreme temperatures on such travelers.

It is assumed that the identification of critical assets does not include infrastructure or services owned and operated by private firms, such as rail track.

ARC Recommendation 2: Key community facilities that would likely become even more important in an emergency should be analyzed from the perspective of road access, and the impacts of that access being disrupted. Regional facilities and assets should be identified based on the following criteria: usage (e.g., AADT, truck trips or ridership), economic importance (access to key industrial, business or educational areas (e.g., Fulton Industrial Park or Buckhead), lifeline importance (e.g., access to medical centers), and availability of detour routes. A map of critical facilities and assets would then be developed that could form the basis of a vulnerability assessment.

Step 3: Identify predominant climate change trends and factors for region

Step 3 identifies future likely characteristics of the region's climate and weather. This has largely been done by ARC already, which has been presented in tabular form.[12] ARC-developed tabular climate data were based on four grid cells in the center of the region, and by analyzing two time periods---mid-century (2040-2070) and end-century (2070-2099). The analysis examined different emissions concentration scenarios as follows:

- Baseline: 1950-1999
- Representative Concentration Path (RCP) 2.6: Assumes substantial and sustained emissions reductions to an average 475 CO_2 equivalent parts per million (ppm) by 2100
- RCP 4.5: Assumes stabilization of emissions concentrations at 630 CO_2 equivalent ppm by 2100
- RCP 6.0: Assumes stabilization of emissions concentrations at 800 CO_2 equivalent ppm by 2100 and represents the emissions pathway associated with the Paris Climate Agreement

[12] ARC, "Downscaling Climate Model Data for the Atlanta Region," Presentation, undated.

- RCP 8.5: Assumes higher emission trends continue reaching 1,313 CO_2 equivalent ppm by 2100

Table 1 shows the projected temperature characteristics for the Atlanta region (as represented by the four grid cells), and Table 2 shows similarly generated data for precipitation projections.

Table 1: Projected Future Temperature Characteristics, Different Emission Scenarios

		Average Annual Mean Temp.	Days Above 92°F (Very Hot)	Days Above 96.3°F (Extremely Hot)	Consecutive Days Above Very Hot	Consecutive Days Above Extremely Hot	Summer Days Above 95°F
Mid-Century (2040-2070)	**Baseline**	**60.3**	**18.3**	**3.7**	**7.0**	**1.8**	**5.8**
	RCP2.6	63.5	54.9	22.8	18.5	7.3	16.9
	RCP4.5	64.3	65.0	3.9	2.4	10.6	24.0
	RCP6.0	**64.0**	**63.6**	**31.4**	**24.6**	**10.7**	**23.2**
	RCP 8.5	65.6	81.7	48.1	34.8	16.4	35.7
End Century (2070-2099)	RCP2.6	63.4	53.2	22.2	18.7	7.4	16.6
	RCP4.5	65.1	73.1	38.7	27.2	12.6	29.1
	RCP6.0	**65.8**	**84.0**	**49.7**	**36.3**	**17.2**	**36.7**
	RCP 8.5	68.7	114.5	84.6	63.0	37.5	62.9

RCP 6.0 chosen for comparison because of its use in Paris Climate Accord

Table 2: Projected Future Precipitation Characteristics, Different Emission Scenarios

		Average Total Precip. (inches)	Largest 3-Day Winter Precip. Event (inches)	Very Heavy Precip. Events	Extreme Precip. Events
Mid-Century (2040-2070)	**Baseline**	**51.9**	**2.9**	**10.6**	**2.1**
	RCP2.6	55.1	3.6	12.3	2.9
	RCP4.5	54.3	3.3	12.1	3.1
	RCP6.0	**54.0**	**4.1**	**11.9**	**2.9**
	RCP 8.5	55	3.3	12.5	3.2
End Century (2070-2099)	RCP2.6	55.6	3.6	12.7	3.1
	RCP4.5	55.3	3.4	12.7	3.2
	RCP6.0	**54.1**	**4.2**	**12.1**	**3.1**
	RCP 8.5	55.2	3.4	12.9	3.6

RCP 6.0 chosen for comparison because of its use in Paris Climate Accord

Several observations that are critical to a vulnerability assessment arise from these two tables. First, and perhaps most importantly, the number of "extreme" events increases dramatically. Thus, for example, the average number of days of extremely hot temperatures (96.3° F) increases from about four in the baseline to between 22.8 and 48.1 days in the mid-century period depending on the emission scenario; from about four in the baseline to between 22.2 and 84.6

days in the end-century period depending on the emission scenario. These data correspond to a study conducted at the Georgia Institute of Technology that found,

> "In the 2080s, the average summer high will probably be 96 degrees in Atlanta, with extreme temperatures reaching 115 degrees. Conditions seen in the 1998 southern heat wave and drought – damages in excess of $6 billion and at least 200 deaths – would become commonplace. Human health concerns are greatest for lower income households that lack sufficient resources to improve insulation and install and operate air conditioning systems. With a warming of only 2 degrees (which is likely over the next few decades), heat related deaths in Atlanta are expected to increase from 78 annually now to anywhere from 96 to 247 people per year, with major heat waves associated with even greater loss of life."[13]

The number of consecutive days of extremely hot temperatures shows a similar dramatic increase. Second, increases in average precipitation show similar increases in future years no matter the emissions scenario. Third, the average number of very heavy or extreme precipitation events does not increase that dramatically from the baseline, on average an increase from 1 to 1.5 days for extreme precipitation events, depending on the emissions scenario. One of the major conclusions in examining these projections is that although severe precipitation events and the resulting flooding will likely be an important concern in the future, the implications and consequences of extreme temperatures---the most important hazard facing the Atlanta metropolitan area in the future—will be of greatest concern.

The data used by ARC in projecting future temperatures and precipitation came from the Coupled Model Intercomparison Project (CMIP5) database. However, another database can be used to present similar information in map form. The Localized Constructed Analogs (LOCA) data set, the data used in the latest National Climate Assessment effort, present maps for one historical and three future scenarios:[14]

- "Historical Climate" product — Averages from 32 model simulations of the 1976–2005 climate.
- "Lower Emissions" product — Averages from 32 model simulations under the Representative Concentration Pathway (RCP) 4.5 scenario.
- "Higher Emissions" product — Averages from 32 model simulations under the RCP8.5 scenario.
- "Upper Bound" product, temperature-derived variables — Averages from the warmest three models (for the continental United States and adjacent portions of Canada and Mexico) at the end of the 21st century under the RCP8.5 scenario. The three models are

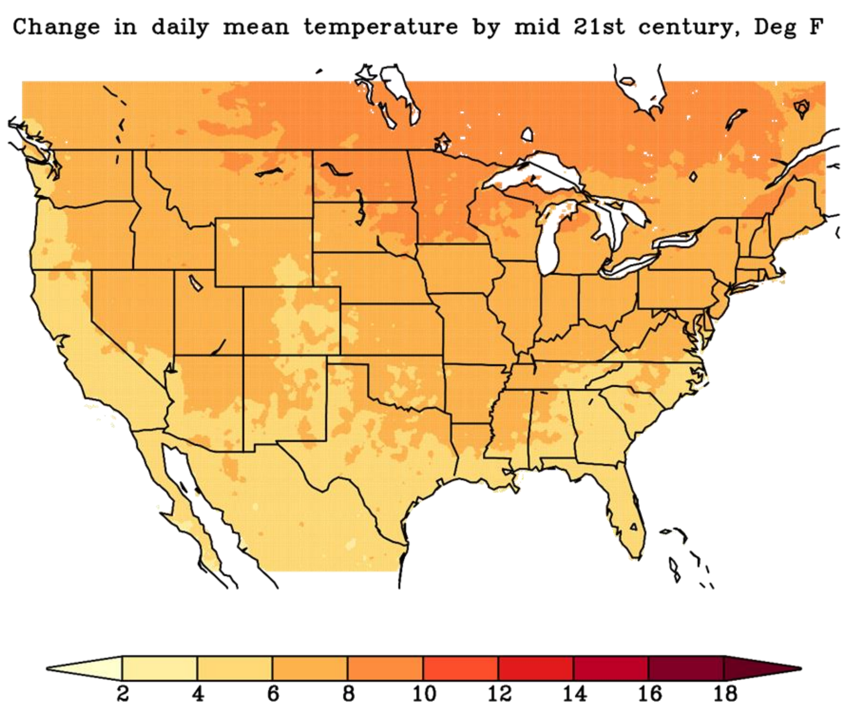
[13] Curry, J. "Local Warming: Consequences of Climate Change for Atlanta," http://curry.eas.gatech.edu/climate/pdf/atlanta_rev.pdf

[14] https://scenarios.globalchange.gov/loca-viewer/

consistent across all variables and were determined as those producing the largest daily average temperature increase for 2070–2099 compared to 1976–2005.

- “Upper Bound” product, precipitation-derived variables — Averages from the wettest three models (for the continental United States and adjacent portions of Canada and Mexico) at the end of the 21st century under the RCP8.5 scenario. The three models are consistent across all variables and were determined as those producing the highest single day precipitation increase for 2070–2099 compared to 1976–2005

Using the LOCA database, maps such as that shown in Figure 8 can be generated showing changes in Georgia and such change relative to other states. Maps such as these are often much easier to understand than data shown in tabular form, and ARC should consider using such illustrations when presenting climate change data. In addition, many states and regions are switching from CMIP5 to LOCA as a database for climate projections, and it is recommended that ARC do the same.



Source: https://scenarios.globalchange.gov/loca-viewer/

Figure 8: LOCA-generated Climate Change Map

ARC Recommendation 3: Presentation of climate change projected data can have an important effect on people's understanding of the challenges facing a particular region. The ways are often used to present such data, either in tables or maps. ARC should, when possible, use maps to show likely changes in temperature and precipitation as such a depiction are much easier to comprehend.

Step 4: Identify impact of these changes on local environmental conditions

Many of the climate projection models provide very high-level representations of likely changes in temperature and precipitation. This is mainly due to the large grid size used by these models in representing the atmospheric conditions that result in changing conditions. However, to be useful to transportation planners, some efforts must be made to downscale the larger forecasts to smaller areas in order to determine what impact, if any, these changed conditions might have on transportation system performance. Methods have been developed to provide a more "localized" projection of climatic conditions, and databases exist where such downscaled data can be obtained, including the CMIP data used by ARC.[15,16] The focus of such an analysis is to identify what impact changed climatic conditions will have on the local environmental conditions faced by the transportation system. There are several examples nationally of how this has been done.

Austin, TX: Table 3 shows another way that planning agencies relate changing climatic conditions to transportation system performance.[17] In essence, the approach identifies the threshold level at which some impact might occur on the condition or performance of the transportation system. In this manner, once the future climate conditions are projected, one can determine if any impacts will likely occur. The next step is then to determine where they might occur.

[15] Worldclim. "Downscaling future and past climate data." Website. http://www.worldclim.org/downscaling

[16] National Oceanic and Atmospheric Administration. Website, https://toolkit.climate.gov/tool/cmip-climate-data-processing-tool

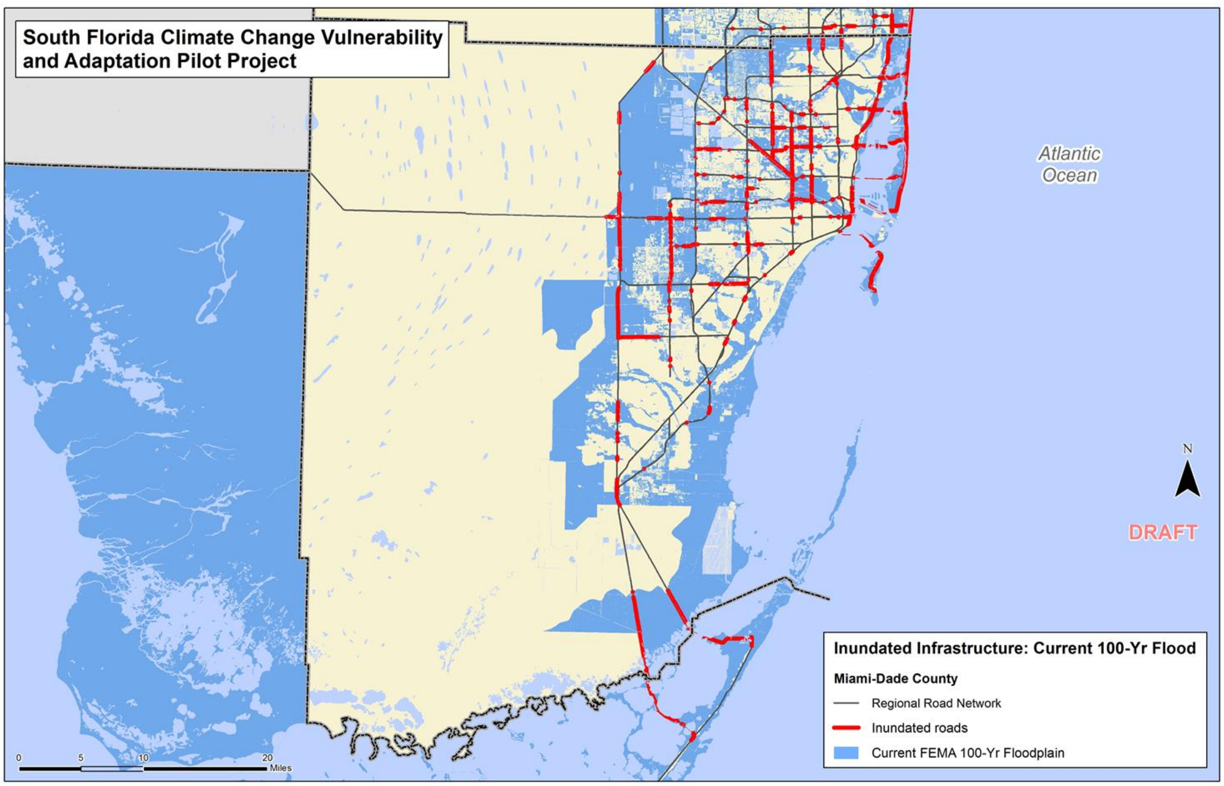
[17] Capital Area Metropolitan Planning Organization, https://austintexas.gov/sites/default/files/files/CAMPO_Extreme_Weather_Vulnerability_Assessment_FINAL.pdf

Table 3: Climate-related Thresholds for Potential Impacts on the Transportation System, Austin, TX

Impact	Modes Affected	Threshold
Flooding	Highways, Rail, Transit	General flood risk increases when >2” in less than 12 hours; Rural roads >3.44” in 24 hours; principal arterials >7.64” in 24 hours; Major highways >10.2” in 24 hours
Pavement cracking or other deterioration	Highways, Aviation	Extended temps. >100 °F; average 7-day max. temp>108°F; drought lasting longer than 14 days; alternating wet and dry weather patterns; extremely wet conditions for >1 month; temps. < 50 °F
Thermal misalignment	Rail	Risk increases when surface temps. >100 - 115 °F
Air conditioning stress and failures	Rail, Transit, Aviation	Temps. >100 °F
Limited ability for maintenance and construction work	Highways, Rail, Transit	Temps. >100 °F
Icy, unsafe road conditions	Highways	Surface temps < 32 °F and precipitation (any)
Damage to switches	Rail	Surface temps < 32 °F and (precipitation > 3/16” of ice)
Wildfire	Highways, Rail, Transit	Drought index > 575; relative humidity <20%; winds > 15-20 mph; La Nina conditions favoring wildfire outbreaks

Source: https://austintexas.gov/sites/default/files/files/CAMPO_Extreme_Weather_Vulnerability_Assessment_FINAL.pdf

South Florida MPOs: The three MPOs in southern Florida—Broward County, Dade County, Palm Beach County—and the county planning agency for the Florida Keys—Monroe County—jointly sponsored a vulnerability study of the region's transportation system to a variety of climate stressors.[18] Primarily concerned with sea level rise and storm surge, the region is also subject to intensive flooding during high intensity storms. Thus, part of the study was to determine where in the study area flooding will likely occur in the future given more intense storms. The approach taken in this study is similar to that found in other studies around the nation. The first method was to use the Federal Emergency Management Agency (FEMA) updated flood maps, which were to reflect the new circumstances regarding more intense storms. Figure 9 shows the estimated extent in flooding (shown in blue). Note that this approach requires updated FEMA maps (which are not available for all counties in the Atlanta region). This will be discussed later in the recommendations section below.

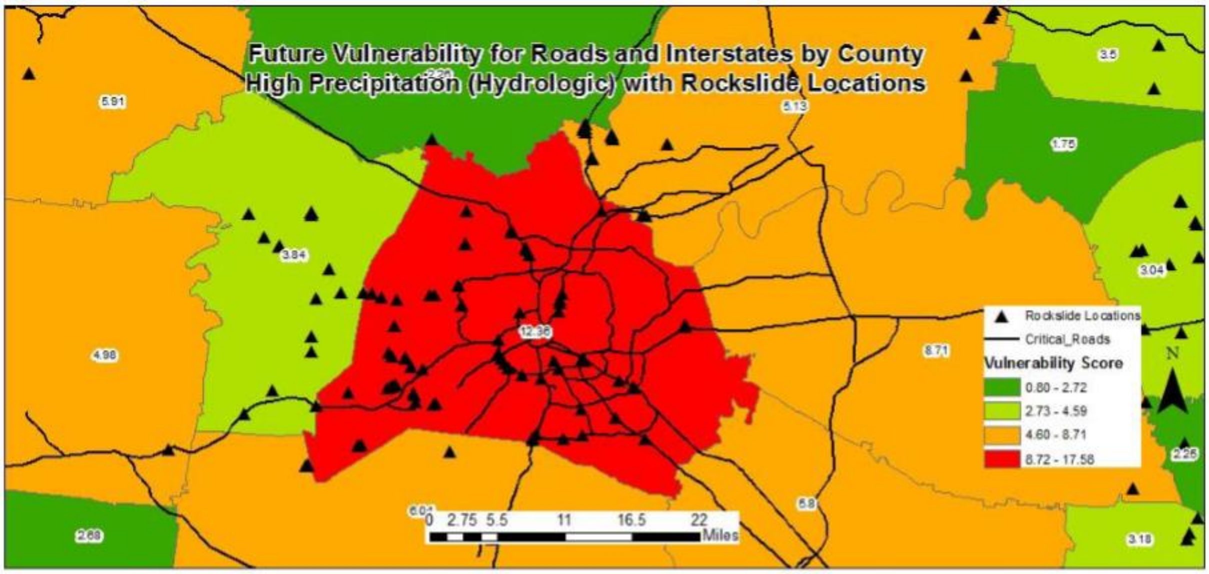


Source: http://www.browardmpo.org/images/WhatWeDo/SouthFloridaClimatePilotFinalRpt.pdf

Figure 9: Estimating Extent of Future Flooding, South Florida

[18] Broward Metropolitan Planning Organization Miami-Dade Metropolitan Planning Organization Monroe County Planning and Environmental Resources Department Palm Beach Metropolitan Planning Organization, 2015. "South Florida Climate Change Vulnerability Assessment and Adaptation Pilot Project," http://www.browardmpo.org/images/WhatWeDo/SouthFloridaClimatePilotFinalRpt.pdf

Nashville MPO: Figure 10 illustrates how the Nashville MPO identified, at a very high level, the areas in its study area where roads might be vulnerable to landslides due to extreme precipitation events. Vulnerability scores were estimated based on expected hydrologic conditions and where landslide potential exists. This is a very high-level assessment that simple states that every road in the "highly vulnerable" area is susceptible to landslides and thus one should consider such factors when designing or reconstructing roads in this area.



Source: http://www.nashvillempo.org/docs/BuildingResilience_DRAFT.pdf

Figure 10: Location of Roads in Nashville, TN Vulnerable to Landslides

Atlanta Region: Estimating the extent of flooding, although challenging, is fairly straight-forward. When examining the broader implications of such flooding and in particular the impacts of higher temperatures, one often sees generalized statements such as that below from a Georgia Tech study.

> "While the prospect of heavier rainfalls from thunderstorms and landfalling hurricanes seems like blessed relief during this period of severe drought, the associated flooding can cause substantial property damage, loss of life, ecosystem damage, and environmental damage. Atlanta's storm sewer system is inadequate to handle the rainfall from severe thunderstorms and tropical cyclones. Besides the threat to property, floodwater can be tainted with raw sewage, pesticides, petroleum products, animal waste, and dead animals. The far more serious issue for the region is drought. The economic impact in North Georgia of the current drought has been estimated at $1.3 billion. Such droughts with greater severity are expected to become more commonplace. Compounding the issue of drought is rapidly growing population: water demand in the greater metropolitan Atlanta

region in 2020 is expected to increase by approximately 60%. We are currently in the midst of a water crisis; we are facing the prospect of future water catastrophes. A first step in adapting to drought should be the adoption of the Georgia statewide water management plan, Georgia's Water Resources: A Blueprint for the Future. The projected increase in Atlantic hurricane activity is a two-edged sword for Atlanta: while heavy rains and tornadoes from Gulf landfalling hurricanes can cause substantial damage in Georgia, these same heavy rains provide critical replenishment of our reservoirs and relief from drought."[19]

The easiest way of estimating extent of flooding would be to use the FEMA floodplain data, which is available for the ARC region (see https://msc.fema.gov/portal/advanceSearch). However, many of the ARC counties have not had the maps updated in some time, thus they do not reflect the latest data and information on flooding as it might occur with higher intensity storms.

The dates for the most recent FEMA map update of ARC's 10 county regional commission area are:

- Cherokee County – 9/6/06
- Clayton County – 6/7/17
- Cobb County– 3/4/13
- DeKalb County– 12/8/16
- Douglas County– 3/4/13
- Fayette County– 9/26/08
- Fulton County– 9/1/13
- Gwinnett County– 3/4/13
- Henry County– 10/6/16
- Rockdale County– 12/8/16

One could use the most recent maps for Clayton, DeKalb, Henry and Rockdale Counties as a reflection of the latest thinking in those areas of likely flooding. However, that leaves the other six counties with out-of-date maps. Based on experience from other studies in the country, it is not desirable to use one, more rigorous methodology for identifying vulnerable areas in some parts of a study area, and use a different approach for others. Inconsistent approaches often lead to questions concerning the validity of the overall results

[19] Curry, J. "Local Warming: Consequences of Climate Change for Atlanta," http://curry.eas.gatech.edu/climate/pdf/atlanta_rev.pdf

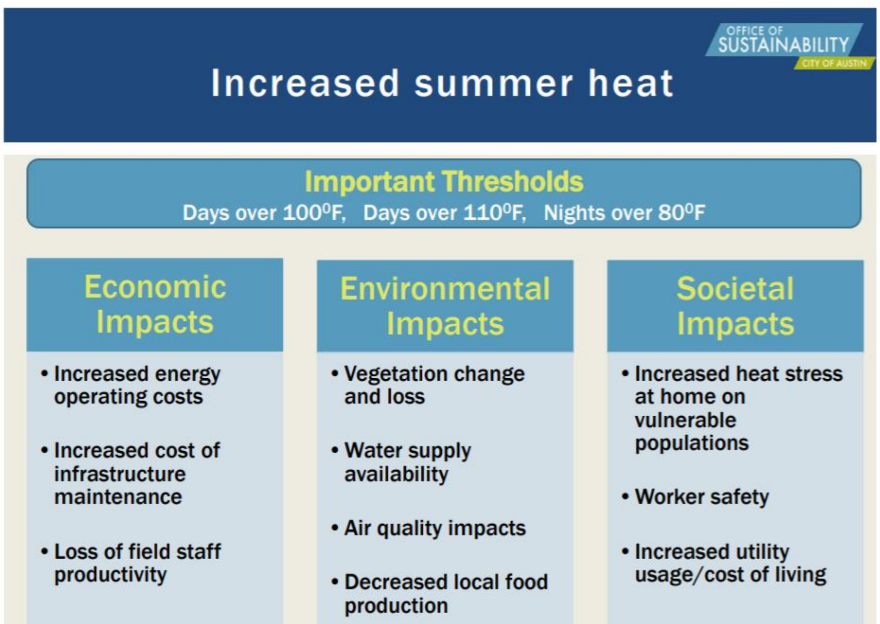
ARC Recommendation 4: Higher temperatures, and prolonged consecutive days of high temperatures, are likely to be one of the most important future climate stressors facing the Atlanta region. Not only might this have an impact on transportation system performance (e.g., lower train speeds to prevent rail buckling), but such temperature conditions could have a significant consequence to users of the system and those working outside (such as highway construction workers). Similar to the approach in Austin (and elsewhere), an ARC resilience study should identify the threshold temperature ranges that will likely affect transportation system condition and performance, compare them to what is likely going to occur, and identify strategies to mitigate these impacts. Particular attention should be given to the impact of higher temperatures on transit riders, pedestrians and bicyclists. Public health input should be sought in determining what temperature levels constitute unhealthy conditions whereby physical activity outdoors should be discouraged.

ARC Recommendation 5: ARC should obtain a license for ArcHydro and link its input to computer models that project future precipitation levels. The two need to go together. ArcHydro simply estimates the spatial extent of flooding given the amount and intensity of rainfall. Thus, the need for projections of future precipitation levels. More is said about this in a companion report on methods and tools.

ARC Recommendation 6: ARC should consider a pilot study in the counties with the most up-to-date FEMA maps given that these maps provide a valuable tool for identifying potential flood zones near transportation facilities. The intent of the pilot study would be to illustrate how FEMA maps could be used in such an assessment and provide guidance to individual counties on how they can conduct their own resilience study.

Step 5: Identify vulnerabilities of the highway and transit system to these changing conditions

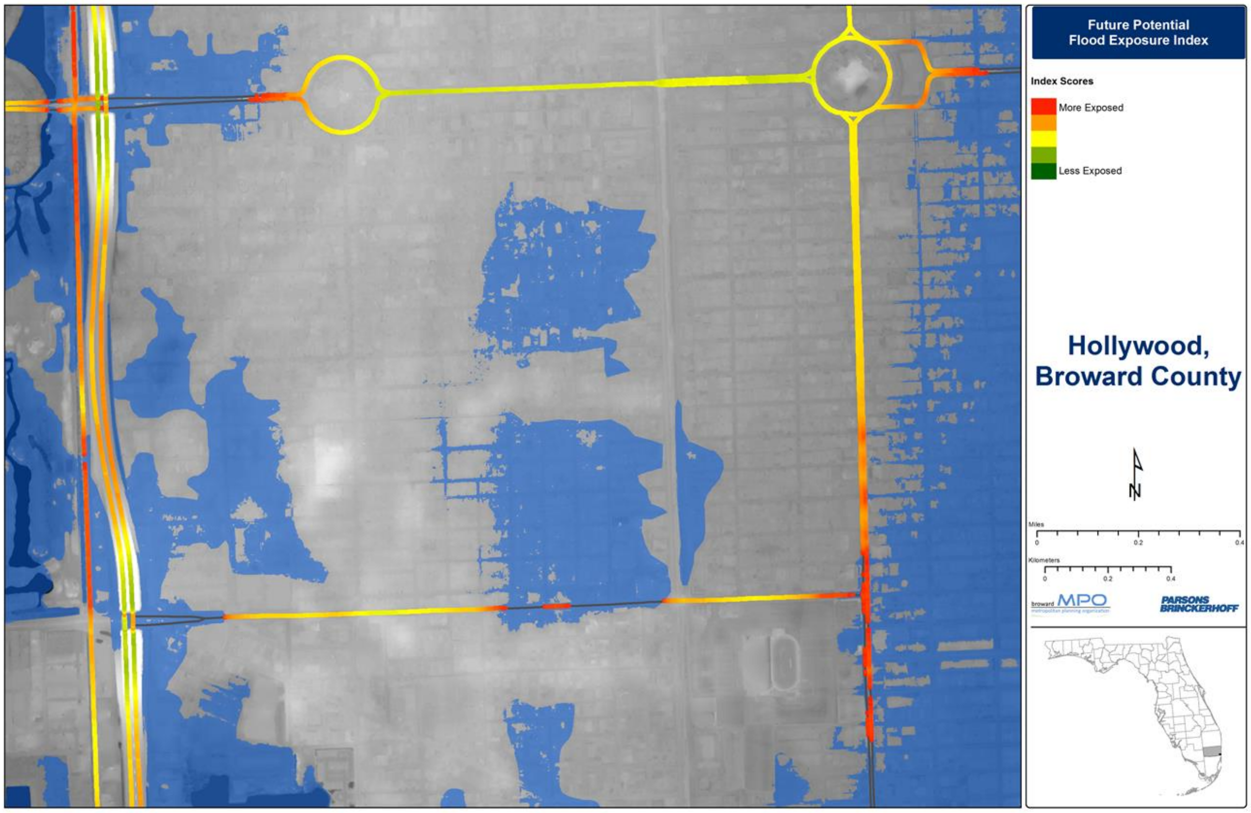
Once the extent of a hazard is estimated, Step 5 determines to what extent a particular asset, facility or system might be vulnerable. As with step 4, this determination can be very qualitative in which potential vulnerabilities are only stated at a very high level, or they can be based on modeling and engineering assessments of the likelihood that a particular asset might be disrupted. Figure 11 provides an example from Austin of the first type of determination, in this case for heat-related impacts. As shown, the threshold values that were established in step 4 were related to the types of impacts likely to be seen in the region. For example, the consequences of more days over 110°F included higher energy use, lower productivity of personnel who work outside, increased cost of maintenance, and increased heat stress for vulnerable populations. This qualitative analysis is useful in that it brings into consideration many potential impacts that often fall outside of transportation, but for which transportation plays a supporting or enabling role.



Source: http://austintexas.gov/sites/default/files/files/Toward_a_Climate_Resilient_Austin.pdf

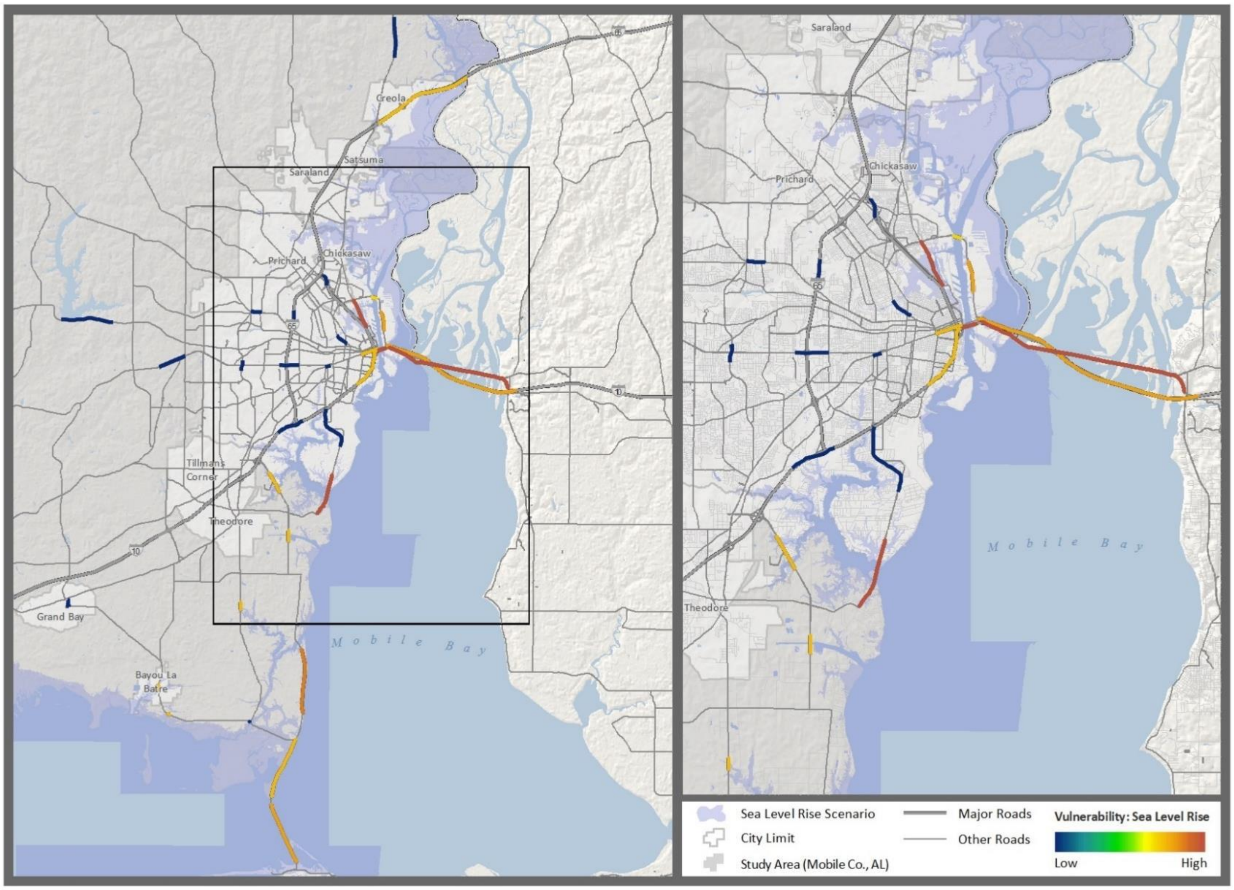
Figure 11: Heat-related Vulnerabilities in Austin, TX

A more rigorous approach to identifying vulnerabilities would likely entail overlaying different databases that include such things as bridge and road elevations, condition data, traffic volume, population density, economic activity data and socio-economic data with the data layer representing the extent of the hazard. For example, Figure 12 shows some roads that were considered vulnerable in the South Florida study to flooding. In this case, the roads were rated to flood exposure, although the ultimate vulnerability scores also represented the level to which alternative routes existed and the importance of the road to the network (denoted with different colors). Figure 13 shows the results of a similar analysis in Mobile, AL.



Source: http://www.browardmpo.org/images/WhatWeDo/SouthFloridaClimatePilotFinalRpt.pdf

Figure 12: Vulnerability of Roads to Future Flooding, Broward County, Florida



Source: ICF International, 2013. Task 2: Climate Variability and Change in Mobile, Alabama. Report No.: FHWA-HEP-12-053.
http://www.fhwa.dot.gov/environment/climate_change/adaptation/ongoing_and_current_research/gulf_coast_study/phase2_task2/mobile_variability/task2_main.pdf

Figure 13: Vulnerability of Roads to Future Storm Surge and Flooding, Mobile, AL

For precipitation-based hazards, the key data for identifying vulnerability are: 1) asset location, 2) asset elevation, 3) asset condition and 4) flood elevation.

The Georgia DOT has several asset management systems that would be highly relevant to a resilience assessment of the region's state highway network as it considers asset-based data. The most important systems include:[20]

- Highway Maintenance Management System (HMMS) tracks the daily work of maintenance crews throughout the state, allowing the department to develop a work program for tracking costs.
- The Computerized Pavement Condition Evaluation System (COPACES) is an assessment survey that rates every mile of every road each year.
- The Pipe Inventory (PI) is a module of the HMMS and provides condition assessments of pipes.
- The Highway Performance Monitoring System (HPMS) is a subset of the Federated Road Enhancement Database collected for the Federal Highway Administration (FHWA).
- The Life-Cycle Cost Analysis (LCCA) tool provides comparisons of the lifecycle costs for different pavement types.
- The Bridge Information Management System (BIMS) holds input data from bridge inspections and generally holds more data than the federally required National Bridge Inventory (NBI).
- The Georgia Pavement Management System (GPAMS) provides forecast data for COPACES each year and helps with analysis and prioritization, giving GDOT the ability to better predict current and future needs.

Several components of this asset management system hold some promise in conducting a resilience analysis of the Atlanta region's transportation system:

Maintenance Work: As indicated above, the Highway Maintenance Management System (HMMS) tracks the daily work of maintenance crews. Such data could help identify where flooding currently occurs on the road network (even though future storms will be more intense, the logic of using this data is that "if it floods today, it will flood with more intense storms").

Bridges: The Georgia DOT bridge information management system, which reports on bridge condition, is the most complete and most important database for a resilience assessment in that it assesses the overall condition of the bridge deck, substructure and superstructure. A bridge prioritization formula places additional weight on bridges with timber components, reduced weight limits, repairs, substandard vertical or horizontal clearance, fracture, critical and unknown

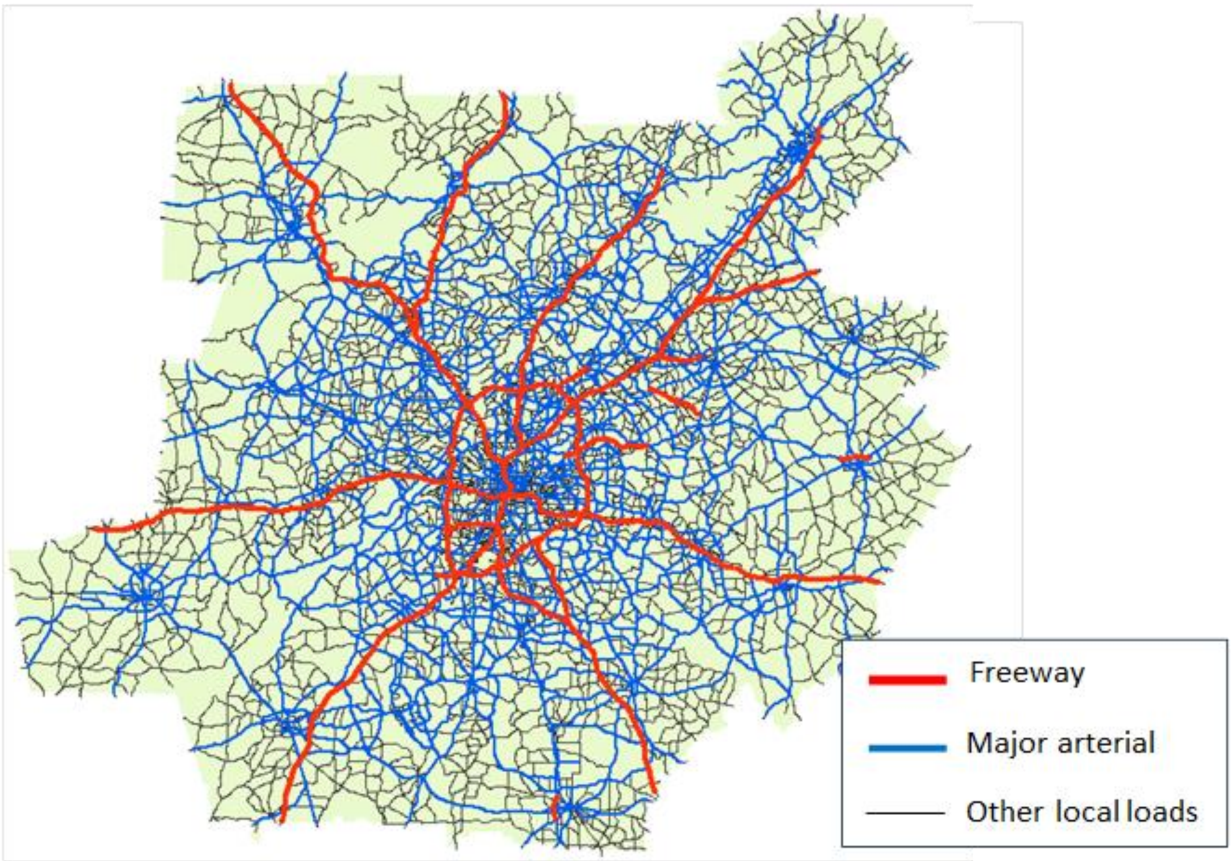
[20] Georgia DOT, 2014-2018 Transportation Asset Management Plan, http://www.dot.ga.gov/BuildSmart/Programs/Documents/AssetMgmt/TAMPlan.pdf

or scour critical foundations. Thus, at least for bridges, adequate data exists on the physical characteristics and condition of bridges that could be linked to future flood-related stresses.

Culverts: Similar to other states, the Georgia DOT has very little data on culverts in terms of location and capacity (as defined on a GIS layer) although there is condition data on pipes. This has been a challenging aspect of many other resilience studies in that culverts are one of the weak links in the highway network in that if they wash away they often take the road with them. This was the case in Vermont where many of the roads damaged by Superstorm Irene were the result of washed-out culverts. As a simplified approach, ARC could intersect the NAVTEQ streets with the GDOT stream database to identify crossings then remove those that have bridge points given that they are already included in the bridge database. As noted by the ARC GIS staff, it might be possible to separate streams by Perennial/Intermittent and Major/Minor streams, which would be a useful distinction in determining the likelihood of flood occurrence.

Elevation Data: A typical database that is used often in determining asset elevation comes from the use of Light Detection and Ranging (LiDAR) technologies (often flights over a study area, although ground-based LiDAR data have also been used). LiDAR provides good accuracy (anywhere from 10 centimeters to one meter depending on the survey parameters) and has been used in vulnerability studies around the nation to identify the elevation of key assets in relation to expected heights of floods. However, LiDAR data for the Atlanta region is sparse, with only a few counties having such data. As is typical for other regions, ARC does have access to the National Elevation Dataset for the entire region, which is basically an improved Digital Elevation Model (DEM) with 10-meter resolution (not very useful for estimating overtopping of bridges, for example). However, one could potentially use the DEM to derive contours and then interpolate elevations for roads and streets located between the contours.

Another approach for estimating elevation would require a project with Georgia Tech. Over the past several years, a research team headed by Dr. Randy Guensler in the School of Civil and Environmental Engineering has developed a streamlined method to extract and process roadway elevation profile from the United States Geological Survey (USGS) Digital Elevation Model (DEM) database (the digital cartographic/geographic dataset of elevations) and generate road grade at high resolution. The primary source of data is the 3-Dimensional Elevation Program (3DEP) LIDAR and interferometric synthetic aperture radar data. Terrain elevations are sampled at regularly spaced horizontal grid intervals. The DEM contains multiple resolution data sets, providing elevation values at grid resolutions of 1×1 meter (1/27 arc-second, the highest resolution), 3×3 meter (1/9 arc-second), 10×10 meter (1/3 arc-second), and 30×30 meter (1 arc-second). Elevations are pixel-centered in raster datasets representing the value at the center. Considering its wide coverage and spatial resolution, the DEM has been used to estimate road grade, and append road grade information into test vehicle GPS trajectories that were the primary data-gathering method for a study on vehicle emissions. Based on the road grade validation compared with field measurement, the proposed method generates highly accurate road grade, with root mean-square error (RMSE) of grade at 0.20% - 0.23% for highways and 0.50 - 0.60% for local roads. The terrain elevations for ground positions are sampled at 20-30 ft. spaced horizontal intervals along the roads, and road grade data was interpolated in 10-ft interval, which was matched with vehicle second-by-second GPS data. The team has generated road grade for the Metro Atlanta Area (20 counties, see Figure 14), including 1,435 miles of freeways, 7,493 miles of major arterial, and 11,935 miles of minor arterial or local roads.



Source: Communication with Dr. Randy Guensler, Georgia Tech

Figure 14: Road Elevations Covered by Georgia Tech Vehicle-based Emissions Data Collection

Step 5 results in a list of assets/facilities that will be vulnerable to flooding. This list is then used as an input into Step 6, which prioritizes the different locations for investment.

ARC Recommendation 7: A resilience study for the Atlanta region transportation system should begin with an examination of GDOT maintenance records to determine which locations on the road network currently flood most often. Interview with maintenance personnel should also accompany this examination.

ARC Recommendation 8: In the absence of accurate and precise elevation data, a resilience study will have to rely on interpolated estimates generated from the DEM for the region. This is not very accurate but should provide at least a +/- estimate of within one foot of true elevation, which could be accurate enough to determine whether flood levels would overtop the asset. A more accurate approach would be to engage the Georgia Tech research team on its approach to estimating road elevations.

ARC Recommendation 9: In the longer term, ARC should consider buying LiDAR coverage for its region. Not only does such data provide important elevation and locational information for transportation assets, it can also be used for a wide range of planning purposes.

ARC Recommendation 10: The GDOT asset management system provides useful data on bridge condition and other performance characteristics. This data base should be heavily used for the bridge component of the resilience study.

Step 6: Conduct risk appraisal of vulnerabilities and environmental changes, and prioritize resilience strategies/actions

This step combines steps 2 and 5 to determine which assets are at the highest risk to climate change-based disruption. Risk, in this case, refers to the, 1) level of vulnerability a particular asset faces relating to a particular hazard, 2) the likelihood that given the hazard the asset will fail, and 3) the costs to the owner of the asset and to the users (or society, in general) if failure occurs (and for how long the asset is disrupted). For example, two identical facilities might face the same vulnerability to heavy rains (and thus flooding), but one facility carries 200,000 average annual daily traffic (AADT) while the other carries 50,000 AADT. All things being equal, the facility carrying the 200,000 AADT would represent a higher risk to the DOT given the level of disruption. Similarly, let’s assume two facilities that carry similar traffic volumes, but one has an easy-to-implement detour around a likely disruption point (e.g., a bridge) while the other has a lengthy and circuitous detour route. In this case, the road without the easy detour is a higher risk. As another example, assume one facility carries 100,000 AADT while another carries 125,000 AADT. The likelihood of disruption is the same for both, but the 100,000 AADT road provides direct access to a major regional medical center (e.g., the Northside hospital complex). The decision here involves a trade-off between the costs to 25,000 additional drivers/passengers over whatever period of time the disruption occurs on one hand and the costs to society of having direct access to the medical center on the other.

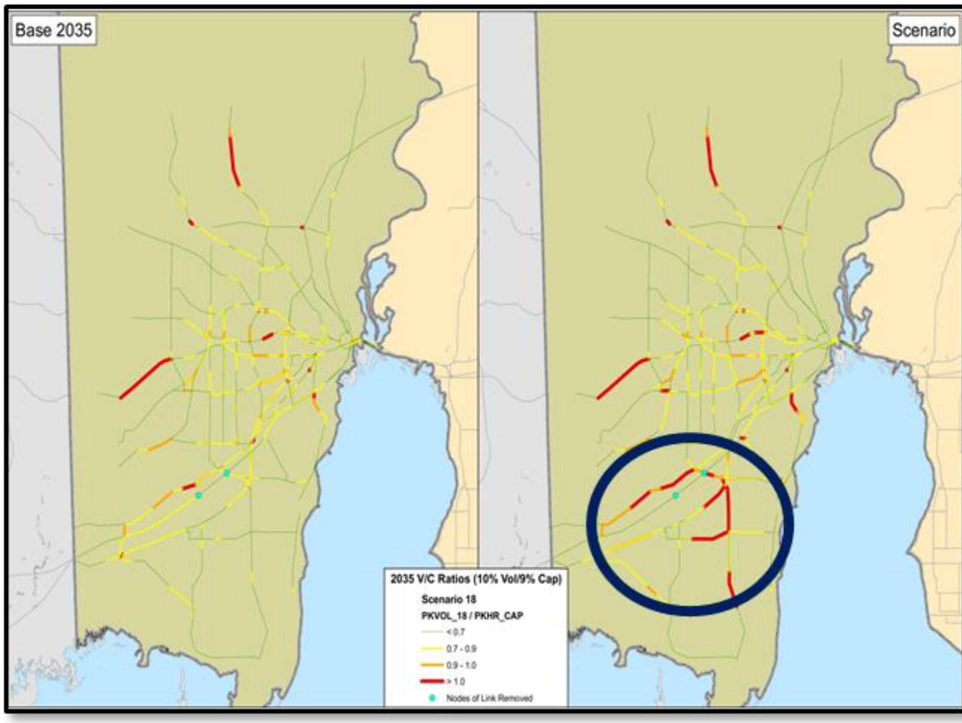
A good example of a risk-based prioritization scheme currently in use at Georgia DOT for prioritizing bridge projects includes the following inputs:[21]

- Inventory Rating - an indicator of the bridge's load carrying capacity. In essence, this answers the question "How strong is this bridge?"
- Average Daily Traffic - the number of vehicles, on average per day, that use the bridge each year
- Bypass -the distance, in miles, that a vehicle must travel if the bridge is posted or closed
- Bridge Condition – a factor that indicates the overall condition of the bridge deck, substructure and superstructure
- Risk Factor - used to weigh the risk associated with the various classifications of roadway systems for which the bridge is a part.

Note in this methodology that the condition of the asset, the use of the facility, the availability of a reasonable bypass (referred to as adaptive capacity), and some sense of the importance of the asset (the risk factor) are all included in the prioritization effort. Some examples of how metropolitan areas have approached vulnerability assessment follow.

Mobile: An example from the climate assessment in Mobile, AL provides an illustration of how a regional traffic demand model can be used as input into identifying risk by estimating the impacts of different climate scenarios on the highway network. In this case, the key parameter was network redundancy, in other words, were reasonable alternative routes available in the event that a particular road failed? The regional travel forecasting model was used to test the loss of 18 selected links in highway network; the “reasonableness” of alternative routes was determined by the volume/capacity ratios on nearby roads during the peak hour (see Figure 15). The ultimate result was a determination of whether the remainder of the road network could accommodate travel patterns (note: there was very little capacity in the system for transit to handle the diverted demand, which might not be the case in the Atlanta region).

[21] Georgia DOT, op cit.



Source: ICF, op cit.

Figure 15: Use of Travel Demand Model to Determine Network Redundancy, Mobile AL

South Florida: In most cases, the risk assessment process applies risk criteria to the candidate projects and then weights the different categories based on decision maker preferences. For example, in the South Florida MPO climate assessment, the risk criteria and ultimate scoring related to the bridge condition index (sensitivity measure), percent of the road segment inundated at the 1-foot, 2-feet and 3-feet inundation levels as well as a present and future flood exposure index (exposure measures), and AADT and detour length (adaptive capacity measures). For transit facilities, the exposure measures were used and the adaptive capacity metric was level of transit ridership.

The vulnerability scores were organized into five tiers applying the Jenks natural breaks methodology for classifying data. Classifying the scores facilitated the identification of differing policy treatments for each tier, and also addresses error margin between the scores. It was important to note that just because a segment was shown as Tier 4 or Tier 5, it did not mean it had no vulnerability to the stressors evaluated; it is just an indicator that, relative to the other segments, its vulnerability was lower.

Tampa: In the Tampa climate assessment, change in travel time delay, vehicle miles traveled (VMT), and lost trip outputs due to disruption estimated from a travel demand model were input into a Regional Economic Models, Inc. (REMI) model. The daily VMT and vehicle hours of delay results were scaled to weeklong periods. REMI captured direct, indirect, and induced impacts of the transportation disruption, parameterized with regionally specific data, estimated the state and regional economic impacts of storm-related disruption. These economic costs were then incorporated into an evaluation matrix to provide decision makers with a sense of which package of resilience investments would provide the greatest benefit.

Hampton Roads, VA: A decision model was developed to prioritize elements of the region's long range strategic plan.[22] Four types of priority setting were addressed: 1) future transportation projects; 2) existing transportation assets; 3) long-term multimodal transportation policies; and 4) transportation analysis zones (TAZs). The study used scenario-based, multi-criteria decision analysis (MCDA) as the analysis approach to provide the information needed to establish priorities for the different types of priority setting. The use of scenarios recognized the high levels of future uncertainty with respect to climate change and the role of such uncertainty in estimating the long-term impacts of current decisions. Importantly, the prioritization process was developed to include all benefits and costs associated with transportation investment. Thus, the climate change-related factors were integrated into the entire prioritization process for the transportation planning process.

The MCDA approach consisted of the following steps.

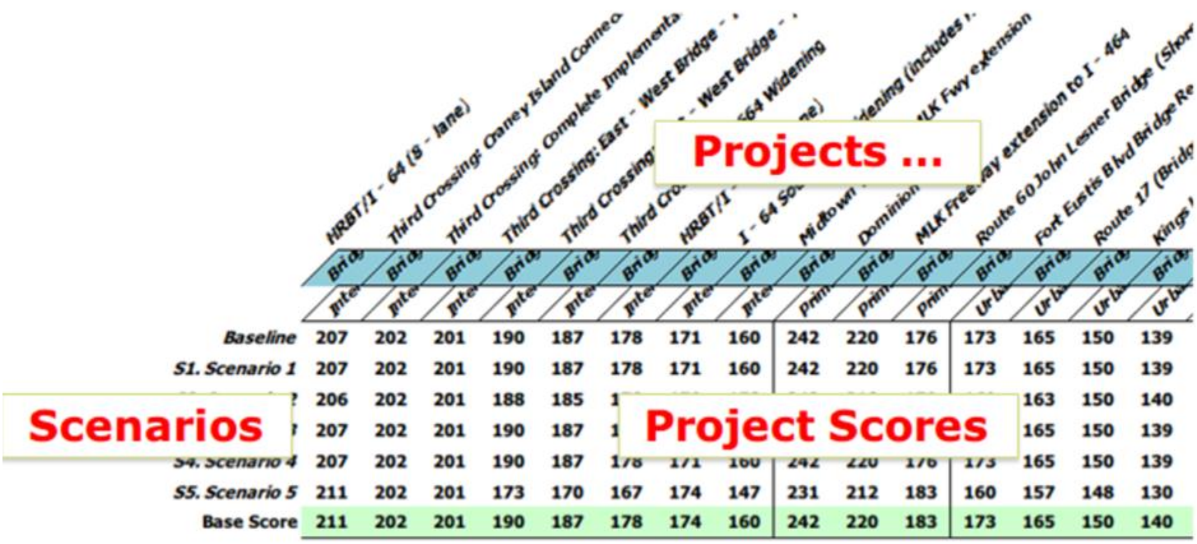
1. Define the criteria and assign max score (indicating relative importance) for each criterion. For example, prioritization criteria might include congestion levels, cost effectiveness index, user benefits, system continuity, etc.
2. Identify the projects to be prioritized.
3. Give baseline ratings to projects (staff provided).
4. Based on the criteria and scores developed in steps 1 to 3, calculate the aggregate score of each project via a multi-criteria value function that is simply a weighted additive function incorporating assigned values for each variable.
5. Define default climate and non-climate scenario conditions. For example, climate scenarios included in the study were sea level rise, increased storm water, increased storm surges, increased precipitation, increased days below freezing, and increased number of consecutive extreme temperature days. Some of the non-climate change scenarios included economic recession, energy shortage, increased tourism, increased wear-and-tear on the region's infrastructure, population growth and advances in personal technology use.
6. Record expert opinions on the changes of criteria relative importance across the scenarios. These opinions were summarized in general categories such as: major and minor increase, and major and minor decrease. The tool incorporated the magnitude of changes likely to occur for each criterion that reflected the assessment of likely change.

[22] Virginia DOT and Hampton Roads Transportation Planning Organization (HRTPO). 2014. Assessing Vulnerability and Risk of Climate Change Effects on Transportation Infrastructure, Hampton Roads, Virginia Pilot Study. http://www.virginia.edu/crmes/fhwa_climate/files/finalReport.pdf

7. Produce adjusted project scores based on likely changes to weighted variables in the MCDA tool.

8. Quantify and show the influence of each individual scenario in terms of the changes on rankings comparing to the baseline rankings.

A spreadsheet was developed to display the scores of the projects across the scenarios as well as the baseline score of each project. The tool included another table that showed the ranking of each project against other projects for each scenario. X-Y graphs with sensitivity bars accompany both tables in the spreadsheet. The displays of project scores make it possible for transportation planners to become acquainted with the effects of strategic transportation projects in climate and climate-inclusive scenarios. Figure 16 shows the results of the projects scoring across the scenarios climate only. Figures were also shown in the original report for project baseline scores and the range in scoring given different climate scenarios; and results for targeted transportation assets.



Source: Virginia DOT and HPTPO, op. cit.

Figure 16: Scores of Selected Transportation Projects Across Baseline and Climate Change Scenarios, Hampton Roads, VA

A proposed risk assessment/prioritization methodology for an ARC resilience study should be based on data (or forecasts) that are available. The following four principles were used to help define an appropriate method for prioritizing risk to regional transportation assets.

1. The criteria should reflect ARC's goals and policies to the extent possible, and indeed should be incorporated into these policies and procedures. Thus, for example, the ARC emphasis on supporting the strategic freight network could be an item

incorporated into the methodology. The lack of availability of data is one of the most serious gaps in conducting a transportation resilience study in the Atlanta region.

2. The risk prioritization method should utilize the data and/or forecasts readily available or obtainable in defining asset vulnerability.
3. The variable(s) used in the methodology should be easily understood and relatable to perceived impacts of network disruptions due to extreme weather events.
4. The method should be easily implemented within the current capabilities of ARC staff.

The proposed risk methodology is based on scoring; in some cases, the scores reflect actual numbers (e.g., AADT) and in others the score might be based on subjective opinion of experts (e.g., expected number of days of disruption). The methodology is based on obtaining a maximum of 10 points for the following criteria. These criteria can be modified by the ARC as desired, and weights assigned to each category.

Two approaches are proposed below: one for intense precipitation events (and flooding) and a second for high (and prolonged) temperature events. The reason for this is that the types of strategies associated with both types of hazards are very different, and thus difficult to compare.

Risk Assessment for High Intensity Precipitation Events for Assets/Facilities Deemed Vulnerable

Table 4: Climate Change Exposure Risk Scoring

Expected Number of Days of Disruption	High AADT (> 200,000)	Medium/High AADT (200,000 – 130,000)	Medium/Low AADT (130,000 – 75,000)	Low AADT (< 75,000)
High (>60 days)	10	7	5	3
Medium (30 to 60 days)	5	3	2	1
Low (<30 days)	3	2	1	0
Not in Exposure Zone	0	0	0	0

Table 5: Magnitude of Impact Scoring: AADT

Average Daily Traffic	Score
>200,000	10
200,000>ADT>130,000	7
130,000>ADT>75,000	5
75,000>ADT>35,000	3
ADT<35,000	1

Table 6: Magnitude of Impact Scoring: Truck Volume

Average Daily Truck Volume	Score
>40,000	10
40,000>ADTT>20,000	7
20,000>ADTT>10,000	5
10,000>ADTT>5,000	3
<5000	1

Table 7: Inter-regional Trips

Average Daily Truck Volume	Score
Large numbers of inter-regional trip-making	10
Small number of inter-regional trip-making	5
Very few inter-regional trips	1

Table 8: Transportation Connectivity

Does facility connect to intermodal transfer point?	Score
Yes, more than one	10
Yes, one major transfer point	5
None	0

Table 9: Adaptive Capacity: Alternative Routes/Services

Alternative Routes Available	Score
None	10
Network of local streets	7
Alternate routes nearby	5
Alternate routes but far away	3

Table 10: Community Impact: Access to Key Community Facilities

Characteristic	Score
Sole access	10
One of several access routes	5
Many access routes	2

Table 11: Community Impact: Access to Key Industrial/Business Areas

Characteristic	Score
Sole access	10
One of several access routes	5
Many access routes	2

Table 12: Cascading Effects

System Impact Factor	Score
Potentially long-lasting impacts on other public policy goals, such as public health, economic development, environmental quality, etc.	10
Potentially short-term impacts on other public policy goals, such as public health, economic development, environmental quality, etc.	5
Low potential for impacting other public policy areas	1

Table 13: Multiple Benefits

Could Improvements Provide Not Only Resilience Benefits, But Also Other Benefits?	Score
Yes, multiple benefits possible	10
Yes, one or two other benefits could be obtained	5
Possibly, but not obvious	1

The following example illustrates how it could work (note: this illustration is provided before the factors for heat simply to show how one can use the method).

Assume there are two assets on the highway network that have been identified as having some exposure to future climatic conditions. The following characteristics relate to the criteria in Tables 4 to 13 (scores for each criterion are shown in parentheses)

Asset 1:
- AADT: 250,000 (10)
- Expected disruption days: 3 months (10)
- Truck volume: 35,000 trucks per day (7)
- Major handler of inter-regional trips (10)
- Connects to many intermodal transfer locations (10)
- Alternate routes would most likely be a local street network (7)
- One of several access options to major community facilities (5)
- Many access routes exist to key industrial/business areas (2)
- Cascading effects are minimal (1)
- Mitigation at this location would provide benefits for two other goals (5)

Asset 2:
- AADT: 210,000 (10)
- Expected disruption days: 2 months (10)
- Truck volume: 45,000 trucks per day (10)
- Small number of inter-regional trips (5)
- Connects to one major intermodal transfer locations (5)
- No alternate routes would most likely be a local street network (10)
- One of several access options to major community facilities (5)
- Sole access to key industrial/business areas (10)
- Cascading effects are minimal (1)
- Mitigation at this location would provide multiple benefits (10)

Assuming that each criterion is equally weighted, the risk scores for the two assets are as follows:

Asset 1: 10 + 10 + 7 +10 +10 + 7 +5 + 2 + 1 + 5 = 67

Asset 2: 10 + 10 + 10 + 5 + 5 + 10 + 5 + 10 + 1 + 10 = 76

From a scoring perspective, investment in asset 2 is more favorable over investment in asset 1. Such scoring could be very different if weights were assigned to each criterion. For example, from a resilience perspective the expected number of days of disruption by AADT category might be weighted more importantly than providing multiple benefits for investing at this location.

Cost estimates are not incorporated into the scoring criteria because doing so would require cost estimation for every asset under consideration. If a cost estimation guide was developed for different types of mitigation strategies, cost estimates and some sense of cost effectiveness (e.g., dollar spent per AADT per expected days of delay) could be incorporated into the methodology.

The criteria for heat-related hazards are necessarily more general in that the spatial extent of the exposure is not site-specific, but rather occurs over large spaces. Thus, a temperature of 110°F over extended periods could affect a wide range of assets and users of the transportation system, and thus the use of threshold values as described earlier. Note that for heat, criteria are established for both system users and equipment.

Risk Assessment for High Temperature Events for System Users

Table 14: Climate Change Exposure Risk Scoring

Expected Number of Days of High Heat	Score
High (>30 days)	10
Medium (15 to 30 days)	5
Low (<15 days)	3

Table 15: Heat Exposure Reduction, by Number of People

Degree to Which Action Reduces Heat Exposure	Many Transportation Users Affected	Few Transportation Users Affected
Estimated Major Reduction	10	5
Estimated Low Reduction	7	1

Table 16: Strategy Can Be Replicated Throughout System

Can the Action/Strategy by Replicated Cost Effectively Throughout Region?	Many Transportation Users Affected
Yes	10
Not easily done	3

Table 17: Cascading Effects

System Impact Factor	Score
Potentially long-lasting impacts on other public policy goals, such as public health, economic development, environmental quality, etc.	10
Potentially short-term impacts on other public policy goals, such as public health, economic development, environmental quality, etc.	5
Low potential for impacting other public policy areas	1

Table 18: Multiple Benefits

Could Improvements Provide Not Only Resilience Benefits, But Also Other Benefits?	Score
Yes, multiple benefits possible	10
Yes, one or two other benefits could be obtained	5
Possibly, but not obvious	1

Risk Assessment for High Temperature Events for System Equipment

All of the above in addition to the following.

Table 19: Thresholds

Is Heat Exceeding Threshold Specifications?	Score
Yes	10
Will likely do so intermittently	5
No	0

ARC Recommendation 11: A risk-based project prioritization methodology should be used by ARC to prioritize the project locations where investment can occur to enhance transportation system resilience. One such method has been suggested in this section. ARC might want to modify or define a different set of criteria for prioritization, but the lack of data on location and condition of many of the key assets (e.g., culverts) severely limits a modeling or more quantitative approach.

Step 7: Establish linkage to transportation planning and decision making

Linking system resilience to transportation planning and decision making can occur in many different ways. Step 7 of the framework examines how this can be done, and focuses on key components of planning where resilience should be considered.

Impact on transportation planning and other planning efforts

Step 1 in the resilience framework noted that resilience as a system characteristic and as a planning factor needs to be reinforced in planning guidance and adopted policies and goals. In the subsequent discussion, it was suggested that transportation planning goals (and illustrations in the region's plan) reflect the importance of resilience. Integrating resilience into transportation planning should include more than just making sure the goals set includes resilience in its statements. The south Florida MPO study on climate adaptation, for example, wanted recommendations on how adaptation could be integrated into decision making as one of its products. The suggested ways of doing so included:

Transportation Planning and Prioritization

- Plan goals statement
- Prioritization criteria
- Performance measures
- Analysis tools

Rehabilitation or Reconstruction of Existing Facilities in High Risk Area

- Road and transit design approaches and standards
- Assume sea level rise as a "given" when planning and designing new infrastructure
- Drainage systems
- Asset and maintenance management systems

New Facility on New ROW in High Risk Areas

- List above plus, realignments or relocation

Operations and Maintenance

- Detour routes
- Emergency response strategies
- Harden assets
- Maintain drainage systems
- Effective communication to users

Note in this list that "decision making" was broadly defined, including design, operations and maintenance decisions that could also affect system resilience.

With respect to the elements included under transportation planning and prioritization, plan goals statement and prioritization criteria were discussed earlier, and performance measures are discussed in the following section. Analysis tools are covered in a companion document.

One of the key aspects of system recovery is having in place a means of timely and effective communications with the public. As noted by the Georgia DOT Commissioner,

> "Social media has been particularly effective in times of crisis this past year – like safety videos released during Hurricane Irma; and telling important stories – like detour information during the I-85 rebuild. The department has seen exponential growth on Facebook and Twitter, where we not only quickly share crucial information, but also create two-way communication with our customers."[23]

Periodic examination of the effectiveness of conveying information to the users of the transportation system during periods of disruption is an important part of successful system resilience. This is a task that ARC might coordinate with other transportation agencies in the region.

As will be noted in the next section on performance measures, measuring system resilience in quantitative terms is very challenging. Often when faced with such difficulties, the evaluation process resorts to a series of questions that reflect the characteristics of the phenomenon being examined, in this case, system resilience. The three questions in Table 20 are suggested as the three major questions that plans and studies (that focus on projects) should address with respect to system resilience. A "resilience index" could also be developed based on how these questions are answered (e.g., a high index score if all the questions are answered in the affirmative; a low index score if the answers are mixed).

Table 20: Resilience Questions that Form Part of an Evaluation Process

Resilience Questions	Yes, No, Somewhat
Does the project reduce the vulnerability of the asset to all hazards?	
Does the project increase redundancy in the network?	
Does the project make system recovery easier and more effective?	
(If applicable) For system users exposed to the elements (such as high temperatures), does the project reduce the exposure of these users to the hazard?	

[23] Russell McMurray, "The year ahead in Georgia transportation," The Saporta Report, https://saportareport.com/year-ahead-georgia-transportation/?utm_source=Saporta+Report+List&utm_campaign=107fd7a90a-EMAIL_CAMPAIGN_2018_1_8&utm_medium=email&utm_term=0_bea7737106-107fd7a90a-232132213&mc_cid=107fd7a90a&mc_eid=a20cf7965b

ARC Recommendation 12: ARC should adopt a series of questions (similar to those shown in Table 20) for incorporating resilience into the evaluation process. These questions could be developed into a resilience index reflecting how the questions are answered. Once a more comprehensive resilience study is completed, these questions could be replaced with more quantitative information on the likely resilience benefits of individual projects.

Performance measures

Performance measures provide input into the decision-making process by informing decision makers on the performance of the transportation system over time. All things being equal, changing performance could be related to the level and types of investment that have been made in the transportation system. Of course, all things are not equal, and with increasing population, changing real price of fuel, the advent of newer and safer vehicle technologies, etc., travel behavior in reality responds to many different influences not under the control of transportation agencies. However, even with such a qualification, performance measures can still provide useful information to the planning and decision-making processes.

There is very little experience in transportation planning with system resilience performance measures.[24] Summaries of how resilience has been defined in the context of transportation planning indicate that very few applications for performance measurement are found in the field. The most extensive application occurred in New Zealand where resilience was defined as having two components: a technical, systems performance element, and an organizational element.[25] The technical element consisted of three components: robustness, redundancy and what was referred to as "safe to fail." Table 21 shows how these three components were defined.

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[24] California Department of Transportation, http://www.dot.ca.gov/newtech/researchreports/preliminary_investigations/docs/resiliency_metrics_preliminary_investigation.pdf

[25] New Zealand Transport Agency, http://www.nzta.govt.nz/assets/resources/research/reports/546/docs/546.pdf

Table 21: Resilience Performance Measurement, New Zealand

Principle	Measurement Category	Description
Robustness (National Infrastructure Pan (NIP) attributes: service delivery, adaptation, Interdependencies)	Procedural	Non-physical measures relating to existence, suitability and application of design codes, guidelines
	Structural	Physical measures relating to asset/network design, maintenance and renewal
	Interdependencies	This relates to upstream dependencies and their relative robustness in both a structural and procedural sense
Redundancy (NIP attribute: adaptation, Interdependencies)	Structural	Physical measures relating to network redundancy, alternate routes and modes and backup supplies/resources
	Procedural	Non-physical measures relating to existence of diversion and communication plans Interdependencies This relates to upstream dependencies and their relative redundancy in both a structural and procedural sense.
Safe-to-fail (NIP attribute: adaptation)	Structural	The extent to which innovative design approaches are implemented, allowing (where relevant) controlled failure during unpredicted conditions. This may complement traditional, incremental risk-based design.
	Procedural	The extent to which safe-to-fail designs are specified in design guidelines

Source: http://www.nzta.govt.nz/assets/resources/research/reports/546/docs/546.pdf

With respect to transportation system performance measures in the U.S., the closest most come to resilience are those relating to "reliability." In this case, reliability measures relate to the day-to-day performance of the highway system, and not so much to unexpected disruptions. The federally-required reliability performance measures include:

- Percent of the person-miles traveled on the interstate that are reliable
- Percent of the person-miles traveled on the non-interstate national highway system (NHS) that are reliable
- Truck Travel Time Reliability (TTTR) Index
- Annual hours of peak hour excessive delay per capita percent of non-SOV travel

Possible resilience-related performance measures that have been used in other regions include:

- Condition data (risk-based asset management)
- Number of designated detour routes
- Number of critical assets with high risk scores
- Number of "continuity of service" plan updates
- Incident response rates and associated average traffic delay

Performance measures for system resilience should focus on three elements of a potential disruption that would warrant periodic monitoring: 1) to what extent is the regional transportation system prepared to handle disruptions? 2) what is the record for reducing the vulnerability of the transportation system? 3) what is the performance of the system in recovering from a disruption?

Each of these questions are important to system resilience, although it is not clear whether all belong as part of a regional performance measure focus. The first question about preparation relates to such things as the number of updated "continuity of service" plans and the identification of detour routes. The second focuses on the reduction in the number of high risk scores or those with high vulnerability to all hazards (which would be measured after the risk analysis has been undertaken). The third question really reflects the level of coordination and collaboration that emergency response and related agencies have in responding to a disruption. The ARC could act as a forum for fostering such collaboration, but, in reality, it would likely have very little influence on how these relationships evolve. Outside of major, catastrophic events (such as the I-85 bridge deck collapse), however, a performance measure that monitors response to system disruptions such as major crashes and the associated delay to system users is a useful metric to assess how resilient the transportation system is.

ARC Recommendation 13: After a resilience study has been completed and a list of high risk locations/facilities/assets has been identified, ARC should monitor over time how the risk at these locations is being addressed through investments. This could simply be a metric that identifies the number of high risk locations on a biennial basis.

ARC Recommendation 14: In the short term, ARC should adopt a performance measure that monitors incident response times for major crashes on the highway network. This data could originate from the HERO system or possibly from police records for roads not covered by the HERO service.

Impact on other policy areas, such as public safety, health and economic development

Figure 5 showed the many different policy areas that are part of the Atlanta Region's Plan. The transportation system is one of the critical infrastructures supporting the economic health and quality of life of metropolitan areas. It is not surprising given this important role that other policy areas can be linked to the success of the transportation system in providing mobility and accessibility. When the system does not function as intended, serious problems can occur. Several of the policy areas that would be affected by a resilient transportation system are described below.

Public Safety and Health: From a public health perspective, the interrelationship between transportation system performance and health has been well established. Since the 1960s, transportation officials have been concerned with the more physical and obvious health-related impacts of transportation decisions. Motor vehicle safety, emissions, noise, community disruption, and motor vehicle-related water pollution impacts have been the focus of many studies and plan components, often in response to national and state legislation requiring such attention. Over the past decade, however, the public health nexus with transportation has broadened to include many other issues, such as the role of transportation system design on physical activity (and thus on the incidence of obesity and chronic disease), access to healthy food (in particular for underrepresented population groups), the lack of mobility and its effect on mental health and sense of isolation, transportation facilities serving as conduits for the spread of disease (especially in relation to climate change), and vulnerabilities of transportation systems to extreme weather events and the like. Climate change also influences the ambient conditions in which transportation systems operate such that the impact of motor vehicle emissions might be exacerbated (even with cleaner fuels) given changing atmospheric conditions.

At a broader level of potential public health consequences of climate change, the 2014 National Climate Assessment noted the following:[26]

- "Climate change is projected to harm human health by increasing ground-level ozone and/or particulate matter air pollution in some locations.
- Climate change, resulting in more frost-free days and warmer seasonal air temperatures, can contribute to shifts in flowering time and pollen initiation from allergenic plant species, and increased CO_2 by itself can elevate production of plant-based allergens.
- Climate change is projected to increase the frequency of wildfire in certain regions of the United States. Smoke exposure increases respiratory and cardiovascular hospitalizations, emergency department visits, and medication dispensations for asthma, bronchitis, chest pain, chronic obstructive pulmonary disease (commonly known by its acronym, COPD), respiratory infections, and medical visits for lung illnesses.
- Extreme summer heat is increasing in the U.S., and climate projections indicate that extreme heat events will be more frequent and intense in coming decades. Many cities have suffered dramatic increases in death rates during heat waves. Deaths result from heat stroke and related conditions, but also from cardiovascular disease, respiratory

[26] https://nca2014.globalchange.gov/report/sectors/human-health

disease, and cerebrovascular disease. Heat waves are also associated with increased hospital admissions for cardiovascular, kidney, and respiratory disorders.

- The frequency of heavy precipitation events has already increased for the nation as a whole, and is projected to increase in all U.S. regions. Increases in both extreme precipitation and total precipitation have contributed to increases in severe flooding events in certain regions. Floods are the second deadliest of all weather-related hazards in the U.S., accounting for approximately 98 deaths per year, most due to drowning.
- Drought also poses risks to public health and safety. Drought conditions may increase the environmental exposure to a broad set of health hazards including wildfires, dust storms, extreme heat events, flash flooding, degraded water quality, and reduced water quantity.
- Daily, seasonal, or year-to-year climate variability can sometimes result in vector/pathogen adaptation and shifts or expansions in their geographic ranges. Such shifts can alter disease incidence depending on vector-host interaction, host immunity, and pathogen evolution.
- Mental illness is one of the major causes of suffering in the United States, and extreme weather events can affect mental health in several ways. First, following disasters, mental health problems increase, both among people with no history of mental illness, and those at risk – a phenomenon known as "common reactions to abnormal events." Second, some patients with mental illness are especially susceptible to heat., Suicide rates vary with weather, rising with high temperatures."

As it relates to transportation system resilience, the linkage between public health and transportation system performance can be considered as follows:

- Public safety is clearly affected when catastrophic events occur. A bridge collapse, for example, could very well have fatalities associated with the actual collapse itself. Secondary crashes could occur in the traffic back-ups that will likely occur due to the collapse.
- Depending on the criticality of the facility or asset that was disrupted, emergency responders often respond to catastrophic events largely by using local streets (helicopter access, notwithstanding). Thus, providing potentially life-saving attention to those injured or moving the seriously injured to nearby medical facilities will rely on a transportation network that provides such an ability.
- The transportation system is the major means of evacuating areas that are subject to some form of hazard. This has been shown to be the case for areas vulnerable to hurricanes. However, other types of incidents also require a resilient transportation system. A study on the evacuation of the Georgia capitol area given the explosion of a "dirty bomb" suggested that the local streets would be inundated with people and cars trying to escape the area, and in essence creating gridlock. The 'Snowmageddon" experience where everyone leaving the city attempted to do so more or less at the same time, along with ice on the highways, caused regional gridlock.

- Changing atmospheric conditions could increase motor vehicle-caused ground ozone, although the magnitude of this impact is unclear given the changing motor vehicle and fuel technologies.
- Highway contractors might have to provide more water breaks, or change project hours to the evening to avoid work in extreme heat. Some state DOTs have already instituted such provisions in construction contracts.
- Air-conditioned vehicles, such as rail cars or buses, or providing shaded areas near stations could be an important strategy for lessening heat exposure to transit users.

Education/Arts and Culture/Workforce/Aging: The cultural, educational, workforce and aging services all depend on locational access. And the image of a city such as Atlanta as it reflects a cultural and educational center, or a good place to work, is largely influenced by how easy it is to get from one place to another. For many years, the Atlanta region has been trying to get rid of an image of "sprawl city" or being the "poster child for congestion." The benefits of a resilient transportation system to the aging population in terms of elderly mobility and for agencies who provide services to the elderly are clearly a concern to most people. Effective and efficient mobility in all forms is thus a prerequisite for a modern, sustainable metropolitan area. This explicitly means that the number of disruptions to the transportation system are minimal, and when they occur the response and recovery is fast.

The I-85 bridge deck collapse is an example of a very low likelihood/high impact event that caused major disruption to the regional transportation system. However, the monumental job the Georgia DOT did in reopening the bridge to traffic in six weeks was considered a national model on how to respond and recover quickly to major disruptions. Georgia DOT paid incentives to the contractor to provide such a fast turn-around, so the fast recovery cost money, but given the importance of the bridge and the Interstate to the economy, most would think this was money well spent.

Linking a resilient transportation system and the reliable transportation service that follows to education/arts and culture/workforce and aging policies places resilience in a context that is understandable to most people.

Economy:

The Atlanta region is known for investing in transportation infrastructure that enables and supports a strong economy. The region's road network, the MARTA system, Hartsfield-Jackson International Airport and the extensive freight facilities that serve and traverse the region reflect the important relationship between transportation system performance and the economy. The "just-in-time" supply chains that are now part of many industrial, manufacturing and service industries assumes that the transportation system is reliable, and that variability in trip times over the same route are known (with some variation) and can be incorporated into logistics schedules. Unreliable transportation, caused by a system that is not resilient, can have a serious impact on the economic reality and image of the region.

In addition, the direct economic costs of recovering from a major disruption can be significant for local businesses. For example, a study of the economic impact of the I-85 bridge deck collapse showed that 75 percent of the businesses in the affected area lost customers during the time it took to replace the deck. This was likely caused not only by the loss of a major highway serving the area, but also because of the significant levels of congestion on the local roads caused by diverted traffic that discouraged local customers from visiting local businesses. It might be an interesting exercise to run a REMI model for the Atlanta region to reflect the economic costs of a disruption in the transportation system (likely manifested as longer travel times).

Finally, as was mentioned earlier, bond rating firms are now expecting communities to undertake resilience studies as part of the risk assessment process for obtaining bond ratings. Presumably those that do not will incur less favorable ratings that will ultimately cost their residents more in the long term.

> ***ARC Recommendation 15:*** Given the focus of the Atlanta Region's Plan, the ARC should describe and portray system resilience as a critical characteristic of the system that enables and supports the achievement of other policy goals.

Supporting efforts by partner agencies

Key parts of a broad resilience systems perspective, e.g., critical infrastructure, infrastructure protection, all-hazards response, and system risk management, have their own set of operational characteristics. This suggests that agencies outside the purview of a DOT, e.g., emergency management, public safety agencies, local communities, medical and health agencies, transit agencies, and perhaps the Department of Homeland Security (DHS), Federal Emergency Management Agency (FEMA), FHWA and the like, will have critical roles in responding to catastrophic system disruptions. These roles will vary by type of disruption and how long the effects are likely to last.

In many ways, the concept of a multi-agency approach to resilience is the approach adopted by DHS in its operational concept for incorporating system resilience into its activities. The DHS broadens the perspective of system resilience from simply the actions of individual agencies, and notes that, "In the public and private sectors, the ability of critical systems and key functions to fully recover from a catastrophe depends on the pre-planned as well as ad hoc actions and reactions of staff, contractors, volunteers and ordinary individuals."[27] Depending on the type of disruption, DHS notes that the characteristics of resilience could include personal, organizational, community, infrastructure, state, national and global factors. Thus, system resilience must be viewed from beyond the agency boundaries and address such questions as how transportation system resilience can effectively support community resilience in the broadest sense.

[27] Department of Homeland Security. 2007. Transportation Systems Critical Infrastructure and Key Resources Sector-Specific Plan as input to the National Infrastructure Protection Plan. Washington DC. Accessed at https://www.dhs.gov/xlibrary/assets/Transportation_Base_Plan_5_21_07.pdf.

DOT officials in agencies that are advanced in their resilience culture are likely to become personally engaged in the process of building partnerships and establishing working relationships at all levels with other agencies in assessing risks, and in formulating and directing the implementation of recovery strategies. They are likely to have thought about the need for some degree of redundancy to compensate for partner agencies that may, for whatever reason, be unable to fulfill their roles in responding to system and service threats. They are also likely to be engaged in communicating their strategies and actions in terms of how they will minimize the adverse economic and social impacts of system and service disruptions. In addition, they can become advocates for inter-agency, table-top and field exercises to test how well their contingency plans translate into demonstrable, harmonized action.

The ARC has an important role to play in fostering a stronger perspective on a resilient transportation system by acting as a forum for resilience discussions and for identifying actions and strategies that can be taken by transportation agencies to make the system more resilient.

Summary of Recommendations

The recommendations made in this study are presented below as a summary of the key points in this report.

ARC Recommendation 1: Resilience as a system characteristic and as a planning factor needs to be reinforced in planning guidance and adopted policies and goals. For example, the current transportation plan talks about resilience as a federally required planning factor, but it does not include examples of how disruptions to the transportation system can impact mobility or accessibility. The illustration on page 11 of the transportation plan, which shows "how a robust and diverse transportation system helps seven hypothetical residents of the Atlanta region win their own individual futures," should include in a plan update an illustration of how a resilient system fosters efficient mobility. The goal "Improve Reliability" should be redefined as "Improve Reliability and Resilience."

ARC Recommendation 2: Key community facilities that would likely become even more important in an emergency should be analyzed from the perspective of road access, and the impacts of that access being disrupted. Regional facilities and assets should be identified based on the following criteria: usage (e.g., AADT, truck trips or ridership), economic importance (access to key industrial, business or educational areas (e.g., Fulton Industrial Park or Buckhead), lifeline importance (e.g., access to medical centers), and availability of detour routes. A map of critical facilities and assets would then be developed that could form the basis of a vulnerability assessment.

ARC Recommendation 3: Presentation of climate change projected data can have an important effect on people's understanding of the challenges facing a particular region. The ways are often used to present such data, either in tables or maps. ARC should, when possible, used maps to show likely changes in temperature and precipitation as such a depiction are much easier to comprehend.

ARC Recommendation 4: Higher temperatures, and prolonged consecutive days of high temperatures, are likely to be one of the most important future climate stressors facing the Atlanta region. Not only might this have an impact on transportation system performance (e.g., lower train speeds), but such temperature conditions could have a significant consequence to users of the system and those working outside (such as highway construction workers). Similar to the approach in Austin (and elsewhere), an ARC resilience study should identify the threshold temperature ranges that will likely affect transportation system condition and performance, compare them to what is likely going to occur, and identify strategies to mitigate these impacts. Particular attention should be given to the impact of higher temperatures on transit riders, pedestrians and bicyclists. Public health input should be sought in determining what temperature levels constitute unhealthy conditions whereby physical activity outdoors should be discouraged.

ARC Recommendation 5: ARC should obtain a license for ArcHydro and link its input to computer models that project future precipitation levels. The two need to go together. ArcHydro simply estimates the spatial extent of flooding given the amount and intensity of rainfall. Thus, the need for projections of future precipitation levels. More is said about this in a companion report on methods and tools.

ARC Recommendation 6: ARC should consider a pilot study in the counties with the most up-to-date FEMA maps given that these maps provide a valuable tool for identifying potential flood zones near transportation facilities. The intent of the pilot study would be to illustrate how FEMA maps could be used in such an assessment and provide guidance to individual counties on how they can conduct their own resilience study.

ARC Recommendation 7: A resilience study for the Atlanta region transportation system should begin with an examination of GDOT maintenance records to determine which locations on the road network currently flood most often. Interview with maintenance personnel should also accompany this examination.

ARC Recommendation 8: In the absence of accurate and precise elevation data, a resilience study will have to rely on interpolated estimates generated from the DEM for the region. This is not very accurate but should provide at least a +/- estimate of within one foot of true elevation, which could be accurate enough to determine whether flood levels would overtop the asset. A more accurate approach would be to engage the Georgia Tech research team on its approach to estimating road elevations.

ARC Recommendation 9: In the longer term, ARC should consider buying LiDAR coverage for its region. Not only does such data provide important elevation and locational information for transportation assets, it can also be used for a wide range of planning purposes.

ARC Recommendation 10: The GDOT asset management system provides useful data on bridge condition and other performance characteristics. This data base should be heavily used for the bridge component of the resilience study.

ARC Recommendation 11: A risk-based project prioritization methodology should be used by ARC to prioritize the project locations where investment can occur to enhance transportation system resilience. One such method has been suggested in this section. ARC might want to modify or define a different set of criteria for prioritization, but the lack of data on the database location and condition of many of the key assets (e.g., culverts) severely limits a modeling or more quantitative approach.

ARC Recommendation 12: ARC should adopt a series of questions for incorporating resilience into the evaluation process. These questions could be developed into a resilience index reflecting how the questions are answered. Once a more comprehensive resilience study is completed, these questions could be replaced with more quantitative information on the likely resilience benefits of individual projects.

ARC Recommendation 13: After a resilience study has been completed and a list of high risk locations/facilities/assets has been identified, ARC should monitor over time how the risk at these locations is being addressed through investments. This could simply be a metric that identifies the number of high risk locations on a biennial basis.

ARC Recommendation 14: In the short term, ARC should adopt a performance measure that monitors incident response times for major crashes on the highway network. This data could originate from the HERO system or possibly from police records for roads not covered by the HERO service.

ARC Recommendation 15: Given the focus of the Atlanta Region's Plan, the ARC should describe and portray system resilience as a critical characteristic of the system that enables and supports the achievement of other policy goals.