Amtrak Northeast Corridor (NEC) Climate Change Vulnerability Assessment

Phase I: Final Report

September 30, 2014

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1.0 INTRODUCTION

1.1 BACKGROUND

The increasing frequency of extreme weather events brought upon by changing climate conditions has caused major disruptions to transportation systems over the past few years, including mass transit operators and regional operators like Amtrak. As a result, there is a growing recognition within the rail industry of the importance of understanding and evaluating the risks associated with extreme weather events and changing climate conditions. With a large portfolio of assets and infrastructure, much of which is vulnerable to the risks of extreme weather events, Amtrak has initiated a first phase in its assessment of the potential impacts of climate change on its operations. This initial phase seeks to examine Amtrak owned assets and operations along the Northeast Corridor (NEC) and its connecting corridor spines including Springfield, Albany, and Harrisburg (Keystone Corridor) Lines. Although Amtrak's NEC confirmed a reasonable level of resilience during such storms as Superstorm Sandy, the event demonstrated the strength of future storms and their potential impacts on rail operations.

1.2 PURPOSE OF THE STUDY

The purpose of this Phase I study was to research, analyze and report results on a pre-selected list of data items in support of a full-scale vulnerability assessment to take place during a Phase II. Overall, this preliminary study was used to identify:

1. Availability of Amtrak NEC rail asset data;
2. Gaps in Amtrak NEC rail asset data;
3. Typical climate change impacts to rail assets and the general availability of climate change data for the northeast region of the United States;
4. Availability of applicable climate change vulnerability assessment methodologies, focusing primarily on methodologies that assess infrastructure and fixed assets using a risk-hazard (RH) approach[1] and methodologies designed for use by transportation organizations; and
5. A recommended climate change vulnerability assessment approach for Amtrak to use as a lens through which to view its construction and capital planning projects and activities.

This report provides a summary of the findings of this research and analysis, and provides recommendations for scoping the activities of a Phase II full-scale vulnerability assessment going forward. This Phase I Report document is also designed to be used as a discussion and decision-support tool for Amtrak's Northeast Corridor Infrastructure and Investment Development (NECIID) Department. NECIID may choose to distribute this document to other divisions and departments within Amtrak, or to relevant external stakeholders, for educational and/or planning purposes.

2.0 APPROACH

2.1 TASK I: IDENTIFYING VULNERABILITY ASSESSMENT METHODOLOGIES

In conducting the methodologies research, various types of documents were reviewed to develop a working 'methodologies matrix' (See Appendix B). In order to conduct this research, and develop the methodology matrix, a set of documents was reviewed that consisted primarily of two types: 1) guidance manuals with

[1] A risk-hazard (RH) approach describes the impact consequences that results when a physical asset is exposed to, or interacts with, a hazard (e.g. extreme temperatures). Inherent sensitivities of physical assets also contribute to the over risk for impact. Source: Turner, et.al. (2003).

specific steps and approaches to conducting vulnerability assessments; and 2) case study reports that provide examples of how methodologies (or elements of methodologies) have been utilized, including lessons learned (See Appendix A for these methodology resources). Methodologies were also collected through discussions with subject matter experts (SMEs) at the University of Birmingham. These methodologies were compared to one another using a predetermined set of criteria, and were also evaluated against the findings of the rail asset data research, and the climate change data research. This comparison to the research results helped determine which methodologies could potentially be utilized for a full scale vulnerability assessment, given the availability of existing rail asset and climate change data. These methodologies and their different merits and demerits were reviewed in preliminary discussion with Amtrak. The recommended approach for Phase II was developed based on this research, review, and preliminary discussion.

2.2 TASK 2: RAIL ASSETS

Rail assets are defined as a single, unique piece of rolling stock (e.g., locomotives, rail cars, maintenance vehicles) or infrastructure such as bridges, tunnels, stations, facilities, and components of systems including but not limited to track infrastructure and the traction power supply system. Assets work together as part of a system to support and sustain railroad operations. Assets also include people and information, but for the purpose of this study, only the "physical" assets are considered. Further, out of the physical assets, only those that are "fixed" are included in the study. Therefore, such rolling stock assets as locomotives and railcars are not included. Although rail assets vary in value and significance to the overall system, the significance of each asset type or class was also not considered in this study.

In order to have a detailed understanding of the risks and impacts to Amtrak's NEC and connecting corridor rail assets as a result of the predicted climatic changes, it is first necessary to understand the nature of the assets; specifically identifying them by type (or class), location, and other pertinent characteristics or attributes. For this phase of the project, an initial list of the rail infrastructure assets located along the Northeast Corridor (NEC) and its connecting corridor spines was developed. Assets identified included key components of the track infrastructure (e.g., turnouts, crossings, interlockings, junctions [main-branch, high volume]); electrical power /traction power supply system (e.g. electric power supply, electric substations, overhead catenary systems [OCS] structures and catenary, substations, frequency converters, commercial power interface); and signal system, as well as bridges/culverts; tunnels (e.g., subterranean, subaqueous); stations; and maintenance/ operations facilities (e.g., servicing facilities for locomotives and cars, repair facilities, storage yards, Maintenance of Way [MoW]). Further, when the information was available, asset characteristics were recorded to include general information (e.g., asset name, asset type), location information (e.g., city, state, line, section), ownership information (e.g., rail line owner, asset owner and operator), vulnerability information (e.g., exposed shoreline/riverbank, within storm surge zone), and structural information (e.g., type, subtype, length).

Assets were recorded only if they are located immediately along the right-of-way of the NEC and the connecting corridor spines. Using the traction power supply system as an example, the frequency converter stations and electric substations which are found along the right-of-way were added to the list; however, the commercial power plants and other offsite electricity infrastructure were not included, regardless of their significance to railroad operations. For ease of use, assets were compiled into a Microsoft Excel based file. Using Excel will allow Amtrak and other stakeholders to search and sort the list based on any of the individual asset characteristics.

Rail assets were added to the Excel-based list regardless of their ownership. As an example, Amtrak owns and operates the entire Harrisburg and Springfield Lines; however, it does not own and operate the entire NEC and Albany Line. In various instances, especially in the states of New York, Connecticut, Rhode Island, and Massachusetts, rail assets are owned by freight railroad companies or the individual states and typically operated by their respective state departments of transportation or transit agencies. In gathering information on the bridges, particular emphasis was made to identify those which cross bodies of water versus those that cross under or over roadways; the undergrade and overhead/overpass bridges. This was due to the observation that in general, these bridges are more vulnerable to extreme weather events such as flooding than the bridges which cross roadways. For a more detailed analysis of the asset vulnerabilities, please see Section 3.3.2. Priority of research time was also given to identifying assets along the NEC as opposed to assets along the connecting corridor spines.

2.2.1 Identifying Rail Assets

To identify NEC and connecting corridor rail assets, research was performed on sources provided by Amtrak as well as those which were publically available. Similarly, discussions with Amtrak subject matter experts (SME) and the materials they provided enabled further identification of assets. The source materials used in this task are identified in Table 1. Many of the source materials, especially those provided by Amtrak, provided information on locations of the majority of the major assets including the stations, bridges, or other assets which were under construction or where future construction projects are scheduled. To identify the smaller and more numerous assets such as the smaller bridges, culverts, and tunnels; Google Earth, Google Maps, and other publically available sources were used.

The accuracy and level of detail of Google Earth is such that satellite photos of the entire NEC and connecting corridor spines were analyzed to identify storage yards, stations, bridges/culverts, tunnels, and junctions. This approach proved effective as the majority of assets in the list were identified in this manner. Using Google Earth; bridges, culverts, and other assets with a length of less than twenty feet could be routinely, consistently, and accurately identified. Once identified, characteristics such as length and geographic features crossed could be gathered using tools in the Google Earth suite (i.e. ruler) as well as geographic databases contained in Google Maps. In many cases the type of structure could be identified using the Street View tool in Google Maps. This occurred when a road ran adjacent to the railroad right-of-way and a 360° view from the road enabled rail infrastructure to be clearly seen. Many bridge characteristics such as bridge type (e.g., through truss, deck plate girder, plate girder, concrete/ stone arch) could be identified this way. With the high density of roadways in the Mid-Atlantic and Northeast region, identifying asset characteristics using the Street View of Google Maps proved to be effective. Once identified, the rail assets were cross-referenced with other sources to determine the accuracy of the findings or if further information on a particular asset could be obtained.

Another source which also proved to be effective was the NEC North and South End Storm Surge Vulnerability Database from the Surging Seas interactive SLR mapping tool. This source provided by Amtrak identifies the segments of the NEC which are within a ten foot storm surge (above existing sea levels). The rail segments are further classified as those which may have storm surge vulnerability based on their exposure to coastal open water (e.g., ocean, bay, estuary) and those that while are more inland and/or protected, still have a ten foot storm surge exposure. Not only were the segments added to the list, but assets which fall within these ten foot storm surge segments were also noted.

Once added to the list, assets were assigned a unique numeric identifier numbered sequentially based on geography. For instance, assets were numbered either from north to south as in the NEC, Albany, and Springfield Lines; or west to east as in the Harrisburg Line. Sorting the list based on geography will enable Amtrak or other stakeholders to identify the location of the assets and their proximity to other assets, and will also allow for a more efficient cross-check once additional asset lists and information are identified. In the next phase of this project, the gathering of geographic coordinates for all assets will enable Amtrak to transfer the list to a Geographic Information System (GIS) spatial database. For the numerous assets without an official Amtrak name or identifier, the assets were given names based on the body of water for which they crossed or in some examples, the closest geographical feature or point of interest (e.g., mountain peak, state park) to them.

Table 1. Sources of Amtrak Asset Data

Sources
Amtrak Provided Sources • Amtrak Security Asset List • Amtrak Heavy Rail Conditions Location List • Amtrak NEC Assets List • Amtrak NEC Stations List • 2011 Engineering State of Good Repair Report • NEC North End 10-foot Storm Surge Vulnerability Database • NEC South End 10-foot Storm Surge Vulnerability Database
Discussions with Amtrak Employees • Glenn Sullivan - Sandy Impact • Dan Tasker - Electric Traction
Publically Available Sources • The Amtrak Vision for the Northeast Corridor – 2012 Update Report • Critical Infrastructure Needs on the Northeast Corridor – January 2013 • Freight and Passenger Rail in America's Transportation System – Joseph H. Boardman Testimony before the Railroads, Pipelines, and Hazardous Materials Subcommittee of the House Transportation and Infrastructure Committee – March 5, 2013 • The Future of Passenger Rail: What's Next for the Northeast Corridor, Testimony of Joseph H. Boardman, Testimony of Joseph H. Boardman before the Senate committee on Commerce, Science, and Transportation • The Northeast corridor Infrastructure Master Plan • Google Maps • Google Earth • Amtrak and Commuter Railroad Timetables

3.0 SUMMARY OF FINDINGS

3.1 RAIL ASSETS DATA FINDINGS

Rail assets identified include key components of the track infrastructure; electrical power /traction power supply system; and signal system, as well as bridges/culverts; tunnels; stations; and maintenance/ operations facilities. In total, over 800 assets along the NEC and the connecting corridor spines were identified (See Appendix C, Asset Database, for a complete list of assets identified under Phase I). Specifically, 330 bridges/culverts, 177 stations, 110 interlockings/junctions, 39 tunnels, 29 MoW facilities, 25 traction power assets (e.g., substations, converter stations), and zero communication/signal system assets were identified. As for a summary of assets identified by line, 592 are located on the NEC, 121 on the Albany Line, 80 on the Harrisburg Line, and 39 on the Springfield Line. In addition to the assets identified, the asset list contains 113 storm surge vulnerable segments on the NEC. These segments are not considered assets, but were included in the asset list and used to identify the assets located within a storm surge zone, or segment, of the corridor. The information was gathered using the following Amtrak provided databases: NEC North End 10-foot Storm Surge Vulnerability Database and NEC South End 10-foot Storm Surge Vulnerability Database.

This asset data gathering phase was an initial effort to identify and list the assets which are present on the NEC and connecting corridor spines. It is recommended that in the next phase of work, a more detailed and targeted review of assets be completed. The next section discusses the initial data gaps in this phase of work, as well as a recommended approach for identifying the remaining assets and other missing information.

3.2 INITIAL ASSET DATA GAPS

As a general observation, a great deal of information was gathered for asset classes including the bridges/culverts, tunnels, and stations, while substantially less information was gathered for key components of the communication, signal, and the electrical power/traction supply system (i.e., secondary substations). In this initial phase, the readily-available asset reports tended to focus on bridges, tunnels, and stations. Other data gathering approaches also focused on these assets. As an example, using satellite photographs, it was much easier to identify bridges than key components of the communication, signal, and the electrical power/traction supply system.

Regardless of asset class, for majority of assets identified, a sufficient amount of attribute-level information was gathered including asset location information (e.g., city, state, geographic location in reference to other nearby assets) and asset owner/operator information. The technology available including Google Earth and Google Maps not only allowed assets to be identified (in most instances), but it allowed their respective locations to be identified as well. Although asset attribute-level information was available in many instances, other some asset attributes were more difficult to obtain. As a result, further research needs to be conducted to verify and obtain such information to include asset name, structure length (if applicable), Amtrak assigned asset number (e.g., identification [ID] number), milepost, and construction year. As for the asset name, in many cases the names of assets were not known; so therefore, names were added using bodies of water crossed or nearby geographic features (e.g., mountains, state parks) traversed. The information below provides further information on the initial asset data gaps for the various asset classes.

- **Bridges/culverts** – The vast majority of bridges along the NEC and connecting corridor spines which cross bodies of water were added to the asset data list. In most cases information on asset information was also identified, but more research needs to be conducted to obtain such attribute-level information including milepost, Amtrak assigned ID numbers, year built, and length. Out of the 330 bridges in the asset list, approximately 189 (or roughly 57%) of the assets already have bridge lengths. Still more research needs to occur to identify the lengths of the remaining bridges. Because this effort focused on the bridges which cross bodies of water, additional research needs to occur to identify the undergrade bridges, those railroad bridges which cross over or under roadways.

- **Stations** – The vast majority of the stations along the NEC and connecting corridor spines were added to the asset data list. Information was verified from a number of sources including Amtrak and commuter railroad operator timetables. A great deal of information was also gathered on notable station attributes including the station owner and operator.

- **Interlocking/Junctions** – Although the interlockings and junctions were the third highest asset class in terms of total assets identified, more research needs to be performed to verify the accuracy of the data already contained within the asset list and to locate and identify additional interlockings and junctions throughout the NEC and connecting corridor spines.

- **Tunnels** – The vast majority of tunnels along the NEC and connecting corridor spines were added to the asset data list. In most cases information on the tunnel attributes were identified, but similar to the bridges and culverts, more research needs to be conducted to obtain such information as milepost, Amtrak assigned identification numbers, year built, and length. Out of the 39 tunnels identified, approximately 31 (or roughly 79%) of the assets already have tunnel lengths. Still more research needs to occur to identify the lengths of the remaining tunnels.

- **Maintenance of Way (MoW) and Operations Facilities** – The vast majority of the MoW and Operations Facilities along the NEC and connecting corridor spines were identified. Future research must be focused on verifying the accuracy of the data and obtaining asset attributes for those facilities including the year the facility was constructed.

- **Traction Power Supply System** (e.g., Substations, Secondary Substations, Converter Stations) – Compared to other asset classes, less information on traction power supply system assets were identified. It is highly recommended that a high priority be placed on identifying the key components of the traction power system in a future data gathering phase.

- **Communication/Signal System** – No assets were identified for the communications and signal system. It is highly recommended that a high priority be placed on identifying the key components of the communications and signal system in a future data gathering phase.

It is recommended that the following actions be followed during any subsequent research gathering efforts. Doing so will assist Amtrak in developing a more comprehensive asset list, and better align this effort to other ongoing Amtrak initiatives. The recommendations include:

- Align Amtrak Asset Numbers (ID Numbers) with those Amtrak uses in other systems such as Maximo.
- Include in the list those key components of the traction power supply system which supply and transfer power to the corridor (e.g., power plants, substations), but are not necessarily found along the right-of-way. These components are just as critical as other components of the system, but are located off-corridor.
- Add geographic coordinates for all assets, using the unique identifier found in the asset list as reference.

- Coordinate and leverage other Amtrak initiatives including the Condition Assessment which also has a data gathering component.
- Leverage the Federal Railroad Administration (FRA) geographic databases including the FTA Network which is available via the United States Department of Transportation (DOT) National Transportation Atlas Database (NTAD).

3.3 CLIMATE CHANGE DATA

3.3.1 Summary of Existing Climate Change Data

"Climate data" in this section refers to the projections of the likely outcomes of climate change as predicted by climate models. It does not refer to the raw data used as inputs to the models. The Intergovernmental Panel on Climate Change (IPCC) is the primary scientific organization on climate change, established in 1988 within the United Nations. Its mandate is to provide the information needed to support the United Nations Framework Convention on Climate Change (UNFCCC), which is the main international treaty on climate change. The goal of the UNFCCC is to "stabilize greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic (i.e., human-induced) interference with the climate system".

The IPCC is not a research organization in that it does not carry out its own original research, nor does it directly monitor climate, weather, sea level rise, or related phenomena. It does not "own" the climate models or computing power or other assets necessary for making predictions. Instead, the IPCC is an aggregator: its assessments and other reports are syntheses of scientific results published in the literature, including peer-reviewed and non-peer-reviewed sources.

The IPCC releases regular assessments reports containing scientific, technical and socio-economic information relevant to understanding the causes of climate change, its potential impacts, its risks, and options for adaptation and mitigation. The contributors to the literature from which IPCC draws its information, and who also review and comment on IPCC drafts reports, include thousands climate, weather, social, environmental, and other scientists and experts from all over the world, and as such IPCC reports constitute a consensus of scientific opinion at the time of publication.

The United States Global Change Research Program (USGCRP) in its National Assessments (2009, 2014)[2] provides regional projections based on the output from Air-Ocean General Circulation Models (AOGCMs) down-scaled to regions by such organizations as the National Oceanic and Atmospheric Administration (NOAA), the National Aeronautic and Space Administration (NASA), and the National Center for Atmospheric Research (NCAR). Most regional climate projections can be traced back to these organizations. Projections are typically categorized by temporal intervals, often short-term projections being defined general in the range of 2015-2030, mid-term as 2030-2080, and long-term as 2080-2100.

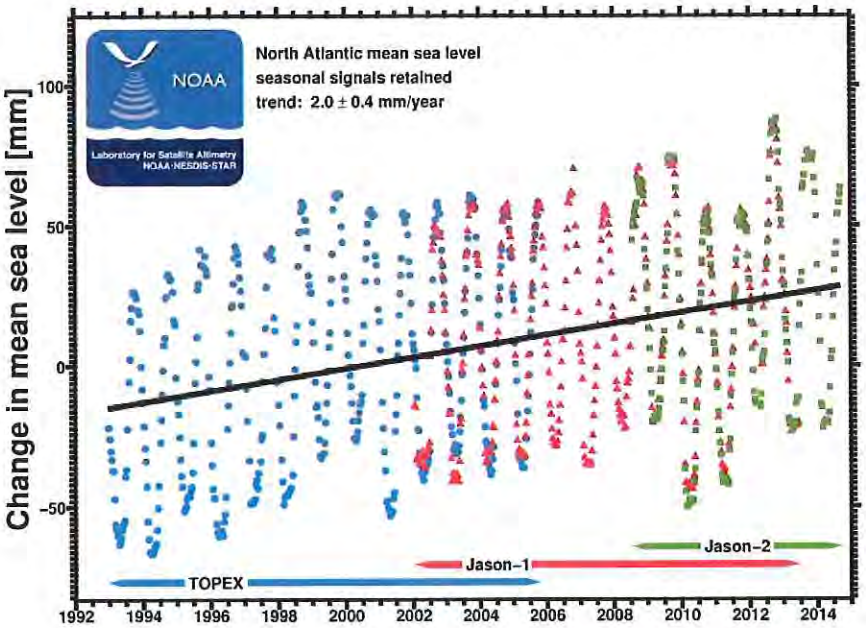
3.3.2 Recent Climate Change Trends and Projected Changes

Over the past two to three decades, significant changes in climate have already been observed, and their impacts felt. This has been the case for a variety of climate change hazards, including extreme temperatures of heat and cold, precipitation patterns and intensity, storminess, and sea level rise. For example, Figure 1 represents the output of satellite measurements taken of sea level along the North

[2] http://nca2009.globalchange.gov/ and http://nca2014.globalchange.gov/

Atlantic coast since 1992, showing a steady increase in sea level that is observable even over a short time-frame of twenty years. Scientists at the United States Geological Survey (USGS) report that this rate has started to increase due to the reduced strength in the Gulf Stream causing warmer, more thermally expansive water to accumulate along the East Coast.

Figure 1. Trends in sea level rise, northeast US[3]



Data source: NOAA http://ibis.grdl.noaa.gov/SAT/SeaLevelRise/slr/slr_sla_na_keep_txj1j2.png

Local assessments of sea level rise have been made or are underway for many locations up and down the NEC, these are usually a product of regional, state, or local initiatives as part of broad effort in the Northeast to gauge the impacts of climate change for planning purposes (See Appendix D for examples of these state-based studies). These assessments typically take the form of detailed GIS maps, often developed by climate change scientists at research universities for reports or climate change planning events. They typically integrate elevation data with sea level rise projections, with the more sophisticated including storm surge modeling results and/or historical data from real events such as Superstorm Sandy.

Climate projections for the Northeast include an average temperature increase in the range of 4.5 °F to 10 °F by the 2080s, with relative sea-level rise within a range of 1 to 4 feet by 2100.[4] The uncertainty in sea level rise is due to its dependence on the rate of greenhouse gas (GHG) emissions, ice sheet melting, rates of local land subsidence, changes in Gulf Stream dynamics, and other factors that are not static. The output of regional models is a first step towards downscaling climate information to a level at which it is useful for decision makers. For more granular assessments of sea level rise, a more geographically focused approach is needed. However, Table 2 outlines at a high level climate change hazard projections by state along the NEC.

[3] TOPEX, Jason-1 and Jason-2 are a series of NASA satellite oceanography missions to monitor global ocean circulation and analyze the connections between the ocean and the atmosphere to improve global climate forecasts and predictions.
[4] http://nca2014.globalchange.gov/report/regions/northeast

Table 2. Climate change projections by state along the NEC

State	Sea Level Rise	Storm Surge	Extreme Heat Events	Extreme Precipitation Events
Massachusetts	• 3.8 feet by 2100[5] • 3-6 feet by 2100[6]	• Boston 100% chance of 5-10+ foot storm surge event by 2100[7] • Boston storm surge +7.5 feet by 2050[8]	• Boston +30-60 days/year over 100°F by 2100 • Boston +51-71 EHE[9] days by 2099[10] • Boston +60 EHE days by 2100[11]	Increase in precipitation per event.[12]
Rhode Island	• 2-6 feet by 2010 • 3.7 feet by 2100[13]	• Providence 100% chance of 7-10 foot storm surge event by 2100[14]	• +41-63 EHE days/year by 2099[15] • +30-50 days/year over 90 °F by 2100	Increase in precipitation per event.
Connecticut	• 1-5 feet by 2050 • New Haven 3.8 feet by 2100[16]	• New Haven 100% chance of 6-9+ feet by 2100[17]	• +30-50 days/year over 90 °F by 2100[18] • Hartford +52 EHE Days by 2100[19]	Increase in precipitation per event.
New York	• 31 inches by 2050[20] • 2 feet by 2080[21] • NYC 3.9 feet by 2100[22]	• NYC 100% chance of a 6-9+foot storm surge event by 2100[23]	• NYC +53-75 EHE days/year by 2099[24] • NYC +20 days/year over 90 °F by 2026[25]	Increase in precipitation per event.
New Jersey	• Newark 3.9 feet by 2100[26]	• Newark 100% chance of 6-9+ foot storm surge event by 2100[27]	• Newark +53-68 EHE days/year by 2099[28] • Newark +60 EHE Days by 2100[29]	Increase in precipitation per event.

[5] Climate Central, 2012, http://sealevel.climatecentral.org/ssrf/massachusetts
[6] Boston Harbor Association, 2013, "Preparing for the Rising Tide"
[7] Climate Central, 2012, http://sealevel.climatecentral.org/ssrf/massachusetts
[8] Boston Harbor Association, 2013, "Preparing for the Rising Tide"
[9] EHE (excessive heat event) days are defined as days with conditions that are historically associated with significant heat-related morbidity and mortality, and are tied to the ambient climate of the region/city in question.
[10] Greene et al. 2011
[11] NRDC, 2012
[12] Between 1958 and 2010, the Northeast saw a 70% increase in the amount of rain falling in extreme precipitation events. This trend is expected to continue, but it is difficult to forecast precisely.
[13] Climate Central, 2012, http://sealevel.climatecentral.org/ssrf/rhode-island
[14] Climate Central, 2012, http://sealevel.climatecentral.org/ssrf/rhode-island
[15] Greene et al, 2011
[16] Climate Central, 2012, http://sealevel.climatecentral.org/ssrf/connecticut
[17] Climate Central, 2012, http://sealevel.climatecentral.org/ssrf/connecticut
[18] National Climate Assessment 2009
[19] NRDC, 2012
[20] PlanNYC website
[21] New York Office of Emergency Management, 2012
[22] Climate Central, 2100, http://sealevel.climatecentral.org/ssrf/new-york
[23] Climate Central, 2100, http://sealevel.climatecentral.org/ssrf/new-york
[24] Greene et al, 2011
[25] Patz, J.A., et al. 2014
[26] Climate Central, New Jersey, 2012, http://sealevel.climatecentral.org/ssrf/new-jersey
[27] Climate Central, New Jersey, 2012, http://sealevel.climatecentral.org/ssrf/new-jersey
[28] Greene et al, 2011
[29] NRDC, 2012, http://www.nrdc.org/globalwarming/killer-heat/

State	Sea Level Rise	Storm Surge	Extreme Heat Events	Extreme Precipitation Events
Pennsylvania	• Philadelphia: limited available predictions, but $10km^2$ are less than 3 feet above current high water mark.[30]	• Philadelphia: limited available predictions, but $10km^2$ are less than 3 feet above current high water mark.	• Philadelphia +51-73 EHE days/year by 2099[31] • Philadelphia +67 EHE days by 2100[32]	Increase in precipitation per event.
Delaware	• 1.6-5 feet by 2100[33] • Wilmington 4.2 feet by 2100[34]	• 100% change of 4-7+ foot storm surge event by 2100[35]	• Similar to Baltimore, smaller heat island effect[36]	Increase in precipitation per event.
Maryland	• 3.7 feet by 2100, 5.7 for structures built to last beyond 2100[37] • Baltimore 4 feet by 2100[38]	• 100% chance of 6-9+ foot storm surge event by 2100[39]	• +60 days over 90 by 2050[40] • Baltimore +38-69 EHE days by 2099[41] • Baltimore +61 EHE Days by 2100[42]	Increase in precipitation per event.
Washington, DC	• 4 feet by 2100[43]	• 98% chance of 8-10 foot storm surge event by 2100[44]	• +60 days over 90 by 2050[45] • 46-69 by 2099[46] • +52 EHE Days by 2100[47]	Increase in precipitation per event.

Local assessments of climate change hazards have been made or are underway for many locations up and down the NEC. These are usually a product of regional, state, or local initiatives as part of broad effort in the Northeast to gauge the impacts of climate change for planning purposes (See Appendix D for examples of these state-based studies). These assessments typically take the form of detailed GIS maps, often developed by climate change scientists at research universities for reports or climate change planning events. They typically integrate elevation data with sea level rise projections, with the more sophisticated including storm surge modeling results and/or historical data from real events such as Superstorm Sandy.

The most obvious and damaging heat-related impact of climate change is summer heat waves. The length and intensity of summer heat waves in the Northeast are expected to increase substantially by the end of this century. Cities across the Northeast are projected to average 20 days per summer over 100°F by 2100 compared to an average of 1 between 1961 and 1990, and some inland cities such as Philadelphia, PA and Hartford, CT could average as much as 30 days.[48]

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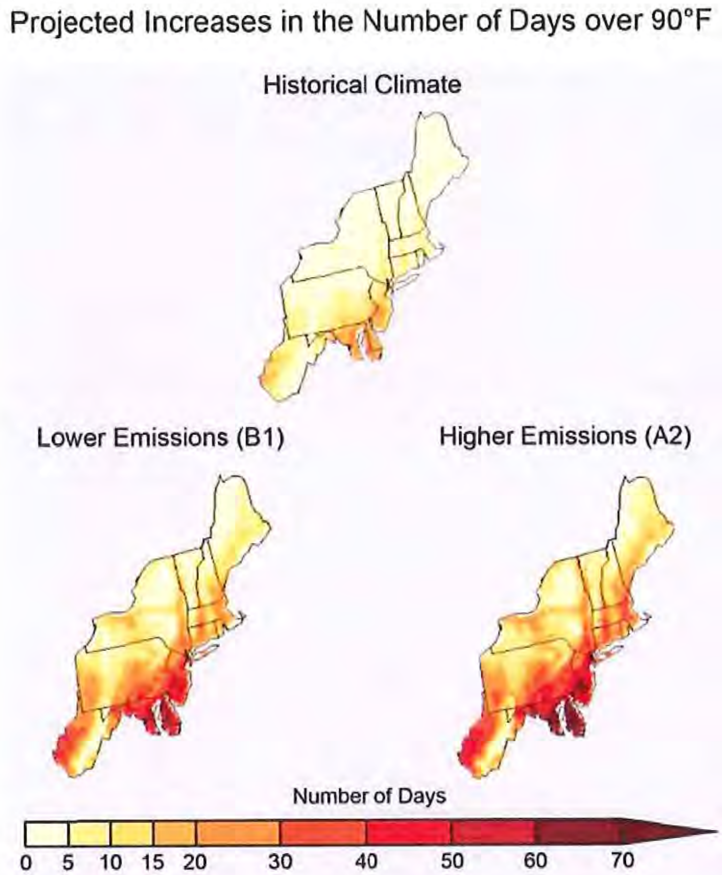
30 EPA, 2014
31 Greene et al, 2011
32 NRDC, 2012, http://www.nrdc.org/globalwarming/killer-heat/
33 Wilmington Area Planning Council, January 2011
34 Climate Central, 2012 http://sealevel.climatecentral.org/ssrf/delaware
35 Climate Central, 2012 http://sealevel.climatecentral.org/ssrf/delaware
36 Wilmington, DE is not a large population center, and projections on EHE and morbidity tend to focus on large cities, therefore EHE days are not reported in the literature
37 State of Maryland, 2014
38 Climate Central, 2012 http://sealevel.climatecentral.org/ssrf/maryland
39 Climate Central, 2012, http://sealevel.climatecentral.org/ssrf/maryland
40 National Climate Assessment, 2014
41 Greene et al, 2011
42 NRDC, 2012
43 Climate Central, 2012 http://sealevel.climatecentral.org/ssrf/dc
44 Climate Central, 2012, http://sealevel.climatecentral.org/ssrf/dc
45 National Climate Assessment, 2014
46 Greene et al, 2011
47 NRDC, 2012
48 Union of Concerned Scientists, Confronting Climate Change in the U.S. Northeast, 2007

Climate projections by the National Climatic Data Center show the following pattern (Figure 2) for summer heat waves across the Northeast U.S.

Figure 2. Projected temperature increases, northeast US



Data source: 2009 National Climate Assessment, US Global Change Research Program

3.3.3 Climate Change Impacts to Rail

Climate change will directly and indirectly affect rail service in several different ways. Table 3 outlines typical impacts of climate change on rail:

Table 3. Climate Change Hazards and their Impacts on Rail Assets

Hazard	Asset or Risk
Extreme Heat	Track expansion and buckling, catenary expansions/ sagging, switch failures, overheating of equipment, other failures of the infrastructure, and track work bans during hot weather (due to heat stress for workers).
Extreme Cold	Brittle or fractured tracks, other failures of the infrastructure, and track work bans during cold weather (due to cold stress for workers).

Hazard	Asset or Risk
Precipitation	Flooding of tracks, stations, tunnels, storage yards, and equipment; short-circuiting of electrical substations, signal infrastructure, utility lines, and equipment; bridge scouring; degradation of rail ties (water collection in concrete ties, insect damage in wood ties); increased salt corrosion of catenary and bridges (especially steel bridges, stringer bridges, rebar in reinforced concrete piers and abutments); extended wet-levels of bridges and tunnels; clogging of bridge deck and tunnel drainage systems; debris in right-of-way; landslides; erosion/fouling of embankments, track ballast, and sub-ballast; sediment accumulation in culverts/drainage systems; etc.
Winter Precipitation	Broken rails, icing and contraction of the catenary, ice and snow in the traction motors of locomotives, heavy ice / snow accumulation on tracks, switch failures, freezing of water in concrete ties, etc.
Wind	Speed restrictions, falling trees on railway, etc.
Sea level rise	Long-term/permanent track flooding

Tables 4 and 5 identify vulnerability factors and elements for consideration. The factors are grouped into those that are common across asset classes and those that are unique to a given asset class. For each vulnerability factor identified, vulnerability elements have also been added as a means to compare the varying levels of vulnerability for each factor. Vulnerability elements such as these will enable risk managers to weigh the severity of the vulnerability, and ultimately their impact based on climate change and extreme weather events. For each proposed vulnerability factor, there are three vulnerability elements listed left to right from lower to higher vulnerability.

Table 4. Common Vulnerability Factors

Vulnerability Factors	Vulnerability Elements		
	⟵ *Lower Vulnerability*		*Higher Vulnerability* ⟶
Location of Asset	Surface (at grade)	Subterranean	Subaqueous
Flood Zone	Located in no flood zone	Located in a 10 year flood zone	Located in a 50+ year flood zone
Flooding – Single Storm Event	Heavy rain	Heavy snow melt	Hurricanes, Nor'easters
Proximity to Exposed Water	No Water	River	Bay/Ocean
Freeze/ Thaw Cycle	<30 days of above and below 32F	30-89 days of above and below 32F	>90 days of above and below 32F
Accessibility	Easily accessible	Moderately accessible	Inaccessible (no close set-on locations)
Heat	Expected to receive <5 days of 100+°F temps.	Expected to receive 5-14 days of 100+°F temps.	Expected to receive >15 days of 100+°F temps.
Cold	Expected to receive <5 days of <32+°F temps.	Expected to receive 5-14 days of <32+°F temps.	Expected to receive >15 days of <32+°F temps.
Wind	Average wind speed <5 mph	Average wind speed 6-9 mph	Average wind speed >10 mph
Rock Slides	No potential for rock slides	Moderate potential for rock slides	Great potential for rock slides
Infrastructure Age	Less than 20 years old	20-99 years old	Greater than 100 years old

Although there are some vulnerability factors that can be applied across all asset classes as shown in the table above, many factors are unique to that specific asset class. Below are a sampling of vulnerability factors which are unique to a given asset type, or class. The bullets in the table are the proposed vulnerability factors listed in descending vulnerability order from top to bottom. The bridges and tunnels are used as an example.

Table 5. Unique Vulnerability Factors (Bridge and tunnel sample)

Bridges	Tunnels
Length of Longest Span or Channel Span (Recoverability) • Greater than 200 feet • 100-199 feet • Less than 100 feet	Length of Tunnel • Greater than 5000 feet • 1000-4999 feet • Less than 1000 feet
Structure/Superstructure Type • Moveable - through truss (no backup power) • Moveable - through truss (backup power) • Moveable - deck plate girder, plate girder (no backup power) • Moveable - deck plate girder, plate girder (backup power) • Fixed - through truss • Fixed - deck plate girder, plate girder, • Fixed - concrete, stone arch	Structure Type • Subaqueous - brick lined, unreinforced concrete lined • Subaqueous - reinforced concrete lined • Subaqueous - natural rock, no lining • Subterranean - Cut-and-Cover - brick lined, unreinforced concrete lined • Subterranean - Cut-and-Cover - reinforced concrete lined • Subterranean - Cut-and-Cover - natural rock, no lining • Subterranean - Bored - brick lined, unreinforced concrete lined • Subterranean - Bored - reinforced concrete lined • Subterranean - Bored - natural rock, no lining
Substructure Type • Stone/Masonry/Steel Columns • Unreinforced Concrete • Reinforced Concrete	

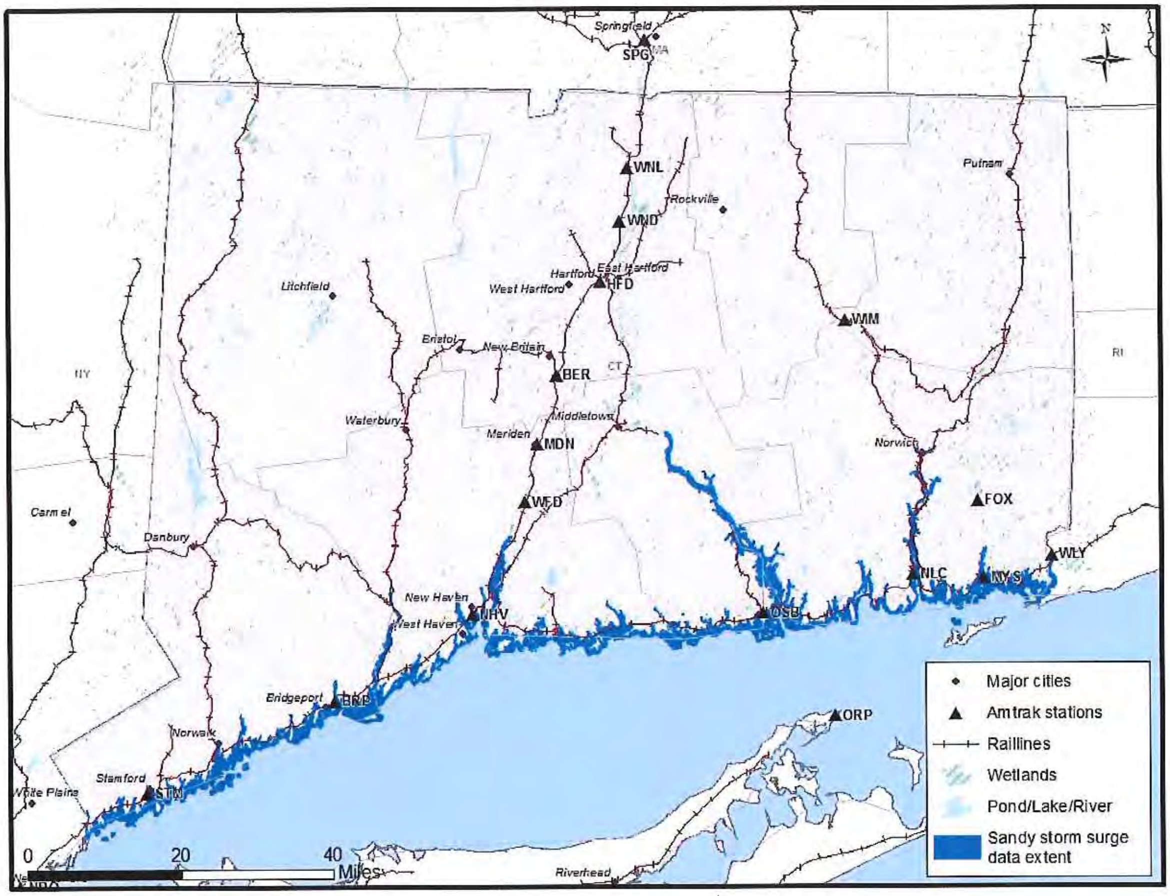
3.3.4 Using Existing Climate Change Data to Analyze NEC Vulnerability

There is a wealth of climate change data and forecast products available. Many of them are scientifically credible efforts to make realistic projections of where societal vulnerabilities lie and generate results useful in decision-making. While most models were not created for the purpose of guiding specific planning or preparation efforts, they do provide a general picture of where climate change hazards will occur, and can help focus risk assessments to areas where critical vulnerabilities might lie. More intense modeling and mapping would be needed to confirm these vulnerabilities and suggest adaptation strategies.

Figure 3 is provided as a sample to illustrate how a mapping tool like GIS, using inputs of climate change and NEC asset data, can generate visual representations of rail asset risk to climate change, in this case as a result of Superstorm Sandy. Typically, all that is needed to generate this type of map is data on the location of an asset of interest, and the outputs of climate change models for a particular hazard of interest and a particular year of interest.

From Amtrak's perspective, many areas through which the Northeast Corridor travels have already received preliminary assessments of how sea level rise will alter the coastline; where temperatures are predicted to spike to unprecedented highs and lows; and how precipitation patterns are expected to alter over the coming 10-80 years. It is unlikely that existing data will provide enough information upon which to base engineering or procurement decisions in its current form. However, it is certainly possible for Amtrak to begin assessing vulnerability of its critical assets in order to incorporate the impacts of climate change into general planning discussions.

Figure 3. Storm surge extent from Superstorm Sandy (10/29/2012) and Amtrak station locations and rail lines in Connecticut.



Data sources: FEMA, NWI, ESRI, FRA, HSIP 2013

3.4 VULNERABILITY ASSESSMENT METHODOLOGIES

3.4.1 Types of Vulnerability Assessment Methodologies

The document review of methodologies, in conjunction with the SME input process, revealed three types of asset vulnerability methodologies:

- Qualitative
- Semi-quantitative
- Quantitative

Table 6 illustrates each of these methodologies with a brief description, representative list of justifications for using the methodology type, and a sample result of the methodology type:

Table 6. Methodology Types

Methodology Type	Description	Justifications for Use	Sample Result
Qualitative	Qualitative vulnerability assessments typically require a modest level of data input, and result in a set of preliminary conclusions about an asset's or a system's vulnerabilities to climate change. Qualitative outcomes are often used to focus future, quantitative-based approaches in pursuit of empirical results.	1. Lack of sufficient asset / operational data or climate change data required to conduct a more quantitative-based analysis 2. When the purpose of the study is to generate a high-level overview of asset vulnerability, or system-wide vulnerabilities 3. Qualitative results can narrow the focus of future quantitative assessments 4. Qualitative results in the form of a narrative report can be effective in introducing the general concepts of climate change impacts to different levels or departments of an organization	Narrative-based vulnerability assessment report with recommendations on conducting future, targeted analysis using more quantitative-based methodologies
Semi-quantitative	Semi-quantitative vulnerability analyses requiring enough data to determine, on a scaled system, the relative significance of climate change impacts on an asset class or system.	1. Lack of sufficient asset / operational data or climate change data required to conduct a more quantitative-based analysis 2. When the purpose of the study is to generate a high-level understanding of how assets differ in their relative vulnerability to climate change impacts 3. Semi-quantitative results can indicate high priority assets or systems based on their relative vulnerability, which can aid in narrowing the focus of future quantitative analyses.	Primarily narrative report describing the results of a simplified, numerical or graphical ranking system used to generate an asset list that indicates relative vulnerability to climate change impacts, such as a "stop light" approach using red, yellow, green for relative rankings
Quantitative	Quantitative vulnerability analyses insert robust data inputs within mathematical models to generate numerical results, often in the form of statistical probabilities associated with the climate change impacts on an asset or operation.	1. Sufficient amount of asset / operational data and climate change data to conduct a quantitative analysis 2. When the purpose of the study is to generate more definitive results to be used in organizational decision-making, investment planning, maintenance scheduling, resilience and adaptation planning, etc.	Numerical-based report including results of modeling and analysis, along with a narrative describing the implications of those results

3.4.2 Prioritization within the Vulnerability Assessment Process

While the original intent of the methodology research under Phase I was to focus on risk-hazard approaches to assess asset impacts, the research also revealed additional "impact areas" that could be analyzed under a climate change vulnerability assessment. These impact areas generally cut across different vulnerability perspectives (e.g. operator, passenger, local rail and freight rail partners), and can, if evaluated, generate a more holistic understanding of operational, system, program, and planning level impacts. Impact areas may also be deemed the "priority areas" of a study. While they are subject to revision, priority areas are often identified upfront to:

- Ensure that the outcome of the vulnerability assessment process is relevant to the organization's purpose for conducting the study, and that the results provide information needed to drive decision-making; and

- Determine the analytical approach to be taken under the vulnerability study.

Table 7 below outlines representative vulnerability perspectives and impact areas (including assets) that could be incorporated into future, NEC climate change vulnerability assessments.

Table 7. Impact Areas across Vulnerability Perspectives

	Impact Areas						
Vulnerability Perspective	Existing Assets	Future Assets	Safety	System Schedule	Maintenance Schedule	Lifecycle Costs	Geographic Segment of NEC
Operator	✓	✓	✓	✓	✓	✓	✓
Passenger	✓		✓	✓			
Partners	✓	✓		✓			✓

In many instances, beginning with an asset-level vulnerability study can provide the necessary information to facilitate a vulnerability study of an organization's systems, operations, programs and/or planning processes. For example, an analysis of Amtrak asset vulnerability between Philadelphia, PA and Newark, NJ can provide the data necessary to understand how scheduling between that city pair could be disrupted by climate change impacts, the safety concerns associated with those impacts, as well as passenger satisfaction implications given the expectation of delays. Under this scenario, the perspective of the operator and the passenger could be considered to determine a relative level of vulnerability from each perspective.

It is important to note that any of the three types of methodologies (as outlined in Section 3.4.1) can be used to conduct vulnerability assessments of various impact areas from different perspectives, provided the requisite level of data is available. In some instances, multiple impact areas can be prioritized and selected for analysis under the same vulnerability analysis. Similarly, multiple methodology types can be used to evaluate one impact area.

3.4.3 Summary of Methodologies Researched

Methodologies of the qualitative, semi-quantitative and quantitative types were identified and reviewed during the research process. These methodologies are outlined in the methodologies matrix in Appendix B. Throughout the review process, information on key methodology characteristics was gathered and organized by categories into the methodologies matrix. Categories of key characteristic data were as follows:

- Summary of the methodology;
- Type of methodology;
- Asset data/ information requirements;
- Climate change data requirements;
- Vulnerability perspective(s) of the methodology;
- Incorporate of financial impacts;
- Perceived or documented shortfalls of the methodology

The approaches in the methodologies matrix are meant to be illustrative examples of the types of qualitative, semi-quantitative and quantitative methodologies that currently exist. The information gathered on each methodology was used to facilitate an understanding of each methodology type's process, requirements, and results, facilitating a comparison of the methodology types and a determination of its suitability for application under Phase II.

3.4.4 Criteria for Reviewing and Comparing Methodologies

The methodologies identified and reviewed were compared based on a pre-selected list of criteria. Appendix E contains a complete narrative description of each criterion listed here:

- Criterion 1. Availability of Asset Data
- Criterion 2. Availability of Climate Change Data in the Northeast United States
- Criterion 3. Temporal Scale of the Assessment
- Criterion 4. Vulnerability Perspective
- Criterion 5. Financial Vulnerability

Of these criteria, the most significant criterion in comparing and selecting a methodology going forward was criterion 1, availability of asset data. For this, the asset list was compared to the data requirements of the sample methodologies under each methodology type. This criterion extended not only to the availability of information on the existence/location of assets, but also on certain characteristic data of those assets. Characterization data included:

- Asset location (e.g. coordinates of an asset's location)
- Physical characteristics (e.g. engineering specifications)
- Historical performance during extreme weather (e.g. damage or resilience)
- Lifecycle phase (e.g. age of the asset, repair history, schedule for repair or replacement)
- System criticality (e.g. criticality of the asset in maintaining a functioning network)
- Current and future demand (e.g. current and predicted future passenger load)

The results of the climate change data research were also compared to the methodologies to verify the capacity to perform more quantitative, climate data driven analyses based on the availability of climate change data in the northeast US. Methodologies that were capable of incorporating some form of financial analysis were also identified and included in the methodologies matrix based on an Amtrak's interest in considering this form of analysis.

4.0 RECOMMENDED APPROACH TO VULNERABILITY ASSESSMENT

4.1 PHASED APPROACH FRAMEWORK

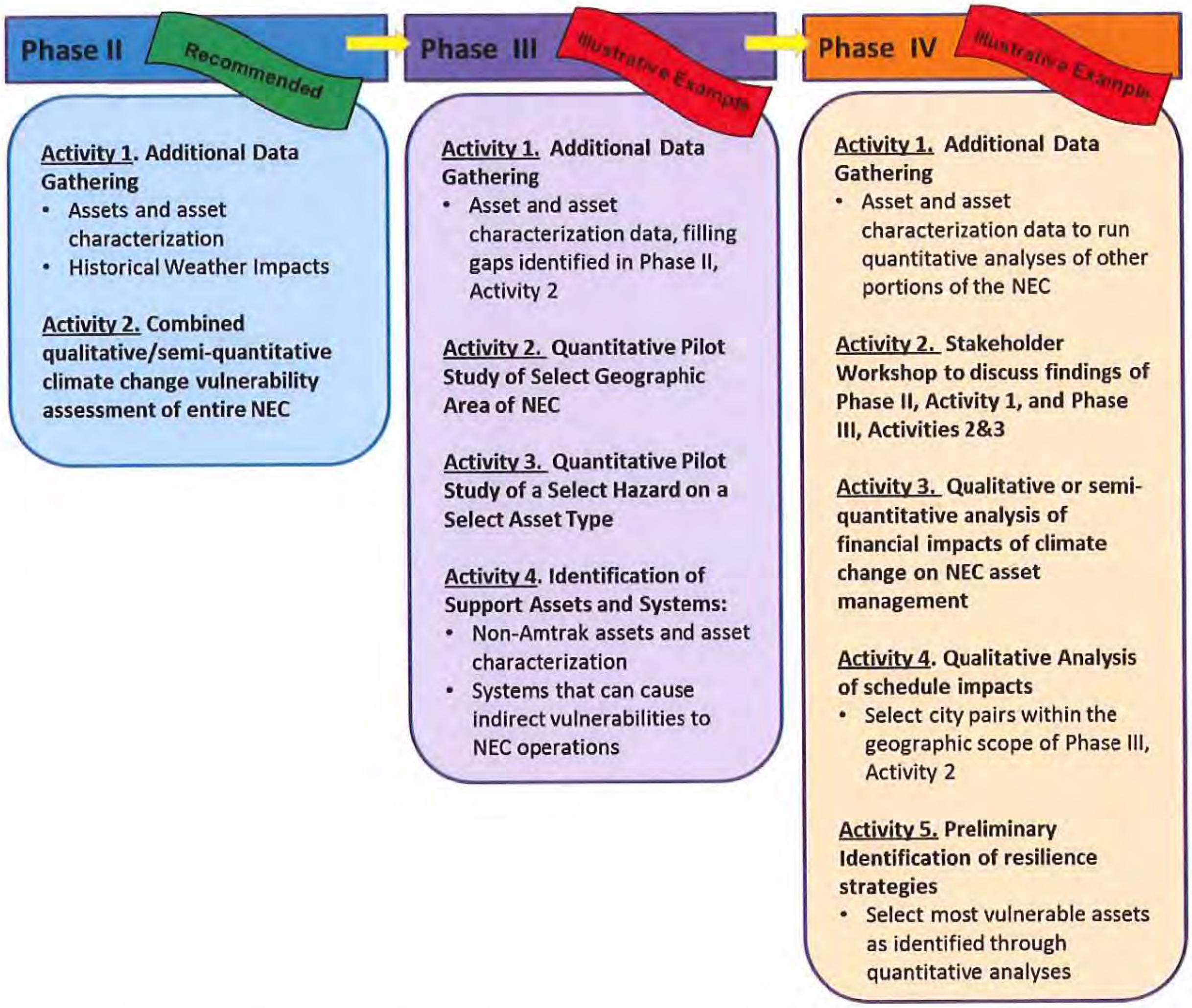
It is the recommendation of this report that any future, full-scale NEC vulnerability study be conducted using a phased approach framework. A phased approach would include a series of activities that would enable Amtrak to begin the vulnerability assessment process using a qualitative or semi-quantitative methodology, with an assumption that, over time, additional information and data could be identified and made available to conduct quantitative-based assessments. This methodology would be similar to the one used by Rail Safety and Standards Board (UK) (RSSB) to conduct a preliminary, high-level assessment of vulnerabilities across Britain's Network Rail system as a way to identify areas of highest vulnerability, and to identify areas of data deficiency.

This phased approach was identified through SME interviews, and was selected as the best available option based on the current availability of NEC asset data. In addition, preliminary discussions with Amtrak confirmed that a phased approach could facilitate internal organizational discussion regarding priority-setting for more comprehensive, quantitative vulnerability assessments, in addition to serving as an introductory document for Amtrak personnel (e.g. asset managers, schedulers, engineering, maintenance of way, etc.) to learn about vulnerability assessment options. The phased approach will allow Amtrak to visualize how additional impact areas or priorities could be incorporated into the assessment process over time, and how a gradual increase in data availability can lead to more quantitative and definitive vulnerability analyses for more informed discussions both within Amtrak and with external stakeholders on the topic of climate change vulnerability and resilience planning in response to confirmed risk. Additional justifications for using a phased approach are as follows:

- Creates opportunities for data gaps to be identified and filled, enabling a gradual progression towards more quantitative and definitive risk analysis in future phases;
- Provides the opportunity to take results and lessons learned from previous steps (e.g. pilot studies) and incorporate those into subsequent phases of the assessment process;
- Provides flexibility, enabling phases to be modified during time of shifting priorities within the organization;
- Provides time for climate change data to mature with the expectation that the latest climate change data will generate a more robust understanding of vulnerabilities;
- Enables the gradual integration of climate change issues into Amtrak's decision-making processes, operations, planning, and management;
- Enables a phased approach to funding the vulnerability study, while providing real results to demonstrate progress to management along the way;
- Provides time to identify key stakeholders in the vulnerability assessment process, and to engage in stakeholder outreach.

The recommended phased approach is represented in Figure 4.

Figure 4. Phased approach framework with proposed activities



Based on the findings of this Phase I report, it is recommended that Phase II consist of two activities: 1) additional data collection on Amtrak owned NEC assets and their characteristics, and 2) the completion of a high-level vulnerability analysis of the entire NEC using both qualitative and semi-quantitative methodologies.

Activity 1, additional data collection, would primarily serve to fill the remaining data needs of the research methodology chosen in Activity 2. For this, it is recommended that data on historical performance of assets during extreme weather events be collected to the extent that this data is available. This data might include information on when an asset failed to function, and under what weather conditions this failure occurred; the geographic location of the failure; the length of time the asset lost functionality; the results of the lost function on neighboring/interconnected assets (if applicable); and any characterization of system or scheduling disruptions caused by an asset failure. Activity 1 would secondarily serve to fill other data gaps as identified in this report, emphasizing asset characterization data and asset location data as available.

Activity 2 would utilize the information in the asset database (from this Phase I Report), and the information gathered from Activity 1 under Phase II on historical performance of assets, to run a qualitative and semi-quantitative analysis of the vulnerability of the entire NEC to the impacts of climate change.

As a first step in the analysis, a sensitivity factor would be assigned to different assets or different asset classes, depending upon the assets location, and the climate hazard considered most likely to impose risk on the asset (e.g. "X" miles of track [asset] exposed to extreme heat [climate hazard]). This sensitivity factor can be generated using the historical performance data of the asset[49] (e.g. how many times a year did these "X" miles of track fail during days when temperatures were 95 degrees or above).

These sensitivity factors are then applied to the assets under projected climate conditions to see how those assets might perform/fail in the future. For example, if the number of days above 95 degrees is set to increase from 20 to 40 days within the next 50 years, what is the relative probability that "X" miles of track will fail on an annual basis? Using these resulting probabilities, a semi-quantitative analysis can be generated, such as a table listing assets most probable, somewhat probable, and unlikely to have an increase in failure rate due to a certain weather conditions in the future.

The purpose of this analysis would be to generate a preliminary understanding of which geographic areas of the NEC are most vulnerable, which Amtrak assets or asset classes along the NEC are most vulnerable, and if there is a particular climate hazard of greatest threat to the corridor. This information will be used to help set the priorities of the activities in future phases.

Under Phases III and IV in Figure 3, a selection of example activities is presented. These activities would build on the accomplishments and results of the prior phases, and illustrate the steady increase in data availability to execute more quantitative vulnerability assessments. In conjunction, activities that extend beyond an analysis of Amtrak owned assets can be incorporated into the overall vulnerability assessment framework. The examples provided of Phase III and IV are included in this report to provide a conceptual understanding of these other activities available to Amtrak in conducting a comprehensive vulnerability assessment to include, for example, the vulnerabilities inherent in the assets and systems upon which Amtrak operations depend (e.g. electric grid, local and freight rail infrastructure); stakeholder concerns and processes for collaboration; issues of safety; and capacity planning for the future of the NEC.

It is also recommended that activity results be shared with the NEC Futures program, as deemed appropriate by Amtrak. While activities of future phases may be selected to align with the priorities and planning processes of the NEC Futures program, Amtrak's own NEC vulnerability study may enable the organization to take a leading role in shaping the objectives and scope of the NEC Futures climate change analyses, including the incorporation of Amtrak's vulnerability assessment results into the Tier I and Tier II assessments.

Activities that include the execution of vulnerability assessment would draw from the existing approaches researched and identified in the methodologies matrix, utilizing either a complete methodology or elements of a methodology. This multi-approach design is meant to provide flexibility, and to enable a gradual progression of the assessment process through a set of sequential phases that build on one another.

[49] If historical performance data is not available, generic sensitivity factors for rail assets can be applied, although the results are less specific to Amtrak assets and their geographic location.

4.2 VULNERABILITY ASSESSMENT ACTIVITIES UNDER PHASES II AND III

Table 8 on pages 25 and 26 provides an overview of the assessment-based activities under Phases II and III. This description includes task data requirements; a case study example (where applicable); and the expected outcomes or results of the activity. This table can be used to facilitate an internal discussion of vulnerability assessment options, and to determine a best-fit strategy given Amtrak's priorities going forward. The phased approach should be designed in a manner that reflects Amtrak's priorities, while also allowing the flexibility for those priorities to change over time.

Following this Phase I report, Phase II would launch the early stages of a full-scale vulnerability assessment (based on agreed upon priorities), with an initial recommendation of conducting a high-level vulnerability assessment of the entire NEC corridor. Asset data identified in this Phase I report, in addition to information on historical weather events, would be used to conduct this high-level study using qualitative and quantitative methodologies. Additional opportunities for targeted, quantitative analyses are also recommended as supplementary assessment studies under Phase III. These additional activities would be dependent upon the extent of climate knowledge, and the availability of asset information.

5.0 SUMMARY OF NEXT STEPS

Based on the information revealed during the execution of Phase I, and based on the assessment of that information as outlined in this report, a summary of the 'next steps' are recommended here:

- Amtrak's NECIID team reviews the findings of this report, with particular emphasis on the identified gaps in asset data. These data gaps will need to be filled prior to the execution of any quantitative approach to assessing climate change vulnerabilities of the NEC under the proposed phased approach framework. Methods for prioritizing and filling data gaps should be identified - an activity strongly encouraged during Phase II.
- Amtrak's NECIID team reviews the recommended phased approach framework for assessing climate change vulnerability with an emphasis on:
    - Resource requirements and management buy-in needed in order to launch Phase 2; and
    - Setting internal, organizational priorities for conducting a climate change vulnerability assessment to determine (preliminarily) the activities to fall under the phases of the vulnerability assessment.

  For setting internal priorities, it may be beneficial to distribute this document with relevant divisions and key personnel across Amtrak. Following this document-share, a series of internal meetings could be held to facilitate organizational-wide discussion of Amtrak's priorities and the activities to implement going forward.

Table 8. Vulnerability Assessment Activities under Phases II and III

Phase	Activity	Description	Geographic Scope	Expected Method Type	Data Requirements	Case Study Example	Expected Outcomes and their Potential Uses
II	**High-level Vulnerability Assessment NEC system**	This analysis would provide a high-level portrait of NEC vulnerability using a qualitative methodology.	Entire area of NEC	Qualitative	1. Historical data on weather impacts to rail assets 2. Northeast climate change scenario predictions of different future intervals (e.g. 20, 50, 80 years out) 3. Asset data set identified through Phase I Report	Tomorrow's Railway and Climate Change Adaptation: Phase 1 Report	1. Provide a narrative report of NEC assets most likely to be impacted by climate change, enabling future semi-quantitative and quantitative analyses to focus on these assets specifically. 2. Provide an introductory analysis of NEC climate vulnerability that could be distributed across Amtrak lines of business, and used as a framework for internal discussion and decision-making regarding the prioritization of vulnerability study next steps.
III	**Conduct Pilot Study of Select Geographic Area of NEC**	This analysis could be used to generate a detailed vulnerability assessment of a pre-selected segment of the NEC. Priority in selecting the segment of study would be given first to portions of the NEC for which there is currently a sufficient amount of data to conduct the analysis and second to segments that are of high risk to climate change impacts based on historical information.	Selected segment(s) of NEC	Semi-quantitative or quantitative	1. Complete asset characterization data of all assets within the selected segment including studies on asset behavior (reaction to weather) 2. Historical data on weather impacts to assets 3. Climate change data specific to the selected segment of NEC, including data on all hazards of interest	Operations and Management, Adapting to Extreme Climate Change: Phase 3 Report	1. Provide an example of the results generated by a semi-quantitative / quantitative analysis. 2. Confirm the data types needed to conduct a quantitative based analysis in other segments of the NEC. 3. Provide preliminary, quantitative results to be shared internally with Amtrak, and externally with stakeholders.

Phase	Activity	Description	Geographic Scope	Expected Method Type	Data Requirements	Case Study Example	Expected Outcomes and their Potential Uses
III	**Conduct Pilot Study of a Select Hazard on a Select Asset Type**	This analysis would highlight vulnerabilities between an asset-hazard pair (e.g. track-heat interactions). Priority would be given first to asset-hazard pairs for which there are sufficient data to conduct a quantitative analysis, and second to asset-hazard pairs that are of interest or concern to Amtrak based on historical information or future planning.	Entire area or segment(s) of NEC	Semi-quantitative or quantitative	1. Complete asset characterization data on the pre-selected asset under study including studies on asset behavior (reaction to weather) 2. Historical data on weather impacts to assets 3. Climate change data specific to the hazard under study	Operations and Management, Adapting to Extreme Climate Change: Phase 3 Report	1. Provide an example of results generated by an asset-hazard analysis. 2. Confirm data types needed to conduct this type of analysis to identify future data needs 3. Provide preliminary, quantitative results to be shared internally with Amtrak, and externally with stakeholders.

APPENDIX A: METHODOLOGY RESOURCES

Resource List of Methodologies *(included within Appendix B, Methodologies Matrix)*

Synthesis and Assessment Product 4.7: Impacts of Climate Change and Variability on Transportation Systems and Infrastructure: Gulf Coast Study, Phase I, U.S. Climate Change Science Program (USGCRP) http://www.georgetownclimate.org/resources/synthesis-and-assessment-product-sap-47-impacts-of-climate-variability-and-change-on-trans, 2008

Impact of Climate Change on Road Infrastructure, Austroads Inc., https://www.onlinepublications.austroads.com.au/items/AP-R234-04, 2004

Adapting to Climate Change: Canada's First National Engineering Vulnerability Assessment of Public Infrastructure, Canadian Council of Professional Engineers www.pievc.ca/e/adapting_to_climate_change_report_final.pdf 2008

Living with a Rising Bay: Vulnerability and Adaptation in San Francisco Bay and on its Shoreline, San Francisco Bay Conservation and Development Commission, www.bcdc.ca.gov/BPA/LivingWithRisingBay.pdf 2011

Costing Asset Protection: An All Hazards Guide for Transportation Agencies, Transportation Research Board of the National Academies, http://www.trb.org/Main/Blurbs/160337.aspx 2009

Climate Change Adaptation Strategy and Framework Revision B, The U.K. Highways Agency within the Department for Transport, http://assets.highways.gov.uk/about-us/climate-change/CCAF_Strategy_and_Vol_1_Rev_B_Nov.pdf 2009

Assessing Vulnerability and Risk of Climate Change Effects on Transportation Infrastructure: Pilot of the Conceptual, US DOT, Federal Highway Administration, Office of Planning, Environment, and Realty http://www.fhwa.dot.gov/environment/climate_change/adaptation/ongoing_and_current_research/vulnerability_assessment_pilots/conceptual_model62410.cfm 2014

Climate Change Vulnerability and Risk Assessment of New Jersey's Transportation Infrastructure, Cambridge Systematics, on behalf of NJTPA, http://www.camsys.com/pubs/CCVR_REPORT_FINAL.pdf 2011

Adaptation Assessment Guidebook, New York City Panel on Climate Change (NCPP), http://onlinelibrary.wiley.com/doi/10.1111/j.1749-6632.2010.05324.x/abstract, 2010

Adapting to Rising Tides – Transportation Vulnerability and Risk Assessment Pilot Project, San Francisco Bay Conservation and Development Commission (BCDC) http://www.mtc.ca.gov/planning/climate/Rising_Tides_Briefing_Book.pdf 2011

Tomorrow's Railway and Climate Change Adaptation: Phase 1 Report, Research Programme, Rail Safety and Standards Board (RSSB), http://www.rssb.co.uk/Pages/research-catalogue/T925.aspx 2010

Operations and Management, Adapting to Extreme Climate Change: Phase 3 Report, Research Programme, Rail Safety and Standards Board (RSSB), http://www.rssb.co.uk/Pages/research-catalogue/T925.aspx 2011

Additional Climate Change Vulnerability Assessment Resources *(Not included in Appendix A, Methodologies Matrix)*

Climate Change Vulnerability Assessment, Risk Assessment, and Adaptation Approaches, Federal Highway Administration (FHWA), http://www.fhwa.dot.gov/environment/climate_change/adaptation/publications_and_tools/vulnerability_assessment/ 2009

Assessing Vulnerability and Risk of Climate Change Effects on Transportation Infrastructure: Hampton Roads Virginia Pilot, FHWA, http://www.virginia.edu/crmes/fhwa_climate/files/finalReport.pdf 2011

Projecting Climate Change Impacts on the Transportation System: A GIS-Based Approach for Network-Level Culvert Infrastructure Management, Transportation Research Board (TRB) http://docs.trb.org/prp/14-2813.pdf 2014

Optimal Recovery Sequencing for Critical Infrastructure Resilience Assessment, Sandia National Laboratories http://prod.sandia.gov/techlib/access-control.cgi/2010/106237.pdf 2010

Flood Risk Assessment: A Methodological Framework
http://www.ntua.gr/hazard/publications/EWRA_2007.Pistrika.pdf 2010

Assessing the Sensitivity of Transportation Assets to Extreme Weather Events and Climate Change, TRB, http://docs.trb.org/prp/13-3165.pdf 2010

Weather and climate change implications for surface transportation in the USA, World Meteorological Organization (WMO), http://www.wmo.int/pages/publications/bulletin_en/archive/58_2_en/documents/58_2_mcguirk_en.pdf 2009

Climate resilient infrastructure: Preparing for a changing climate, Secretary of State for Environment, Food and Rural Affairs, United Kingdom, https://www.gov.uk/government/publications/climate-resilient-infrastructure-preparing-for-a-changing-climate 2011

Appendix B. Methodologies Matrix

Methodology name	Source of methodology	Brief summary of methodology	Type of methodology (qualitative, semi-quantitative, quantitative)	Level of asset data required to complete methodology	What type of climate data does it require? (GIS modeling, general projections, etc.)	What is the vulnerability perspective? (Operator: direct asset impacts, system impacts, OR Passenger: trips impacted,	Does the methodology incorporate costs of impacts (to assets, system, repair, delays and cancellations)	Additional notes about the methodologies, including potential shortfalls
Synthesis and Assessment Product 4.7: Impacts of Climate Change and Variability on Transportation Systems and Infrastructure: Gulf Coast Study, Phase I, 2008	U.S. Climate Change Science Program	This methodology focuses on the Gulf Coast and examines the potential impacts of climate change on vulnerable transportation systems and infrastructure. This study finds highways, ports, and rail infrastructure are particularly vulnerable to projected sea level rise (SLR) and future storm surges. In addition, the maintenance of infrastructure (such as rail and highways) is projected to be vulnerable to increasing temperatures while bridges are projected to be especially vulnerable to changes in precipitation and flooding.	Quantitative	1 (physical characteristics)	• GIS data for lat/log of assets • Global climate models (GCM) monthly values for temperature, precipitation, and potential evapotranspiration (temperature, percipitation, SLR, storminess) • Regional Tide Records • Regional Sea Level Trends • Regional Subsidence	**Operator:** Direct asset impacts on port, rail, and airport facility inundation, highway and railway miles damaged/inundated, miles of pipeline damaged	This report does not attempt to estimate the total costs of protecting, maintaining, and replacing Gulf Coast transportation infrastructure due to damage caused by climate change. It does include a case study on Hurricane Katrina in section 4.3.1 that provides examples of the efforts associated with addressing the impacts of the hurricane.	This assessment does not take into account the possible dampening of surge effects due to distance inland from coastal areas and the buffering qualities of both ecological systems (barrier islands, wetlands, marshes) and the built environment.
Impact of Climate Change on Road Infrastructure, 2004	Austroads Inc.	This report uses a vulnerability assessment to investigate how projected climate effects will affect road infrastructure. The climate effects were projected based on the IPCC SRES A2 scenario providing temperature, precipitation and moisture for 2100. This paper focuses on select road system components including: pavement performance, road use demand, and road design and maintenance; additional modeling tools were utilized to make the connection between climate projections and road system component (e.g., Pavement Life Cycle Costing (PLCC) model, and the Highway Development and Management Version 4 (HDM-4) model).	Quantitative	3 (physical characteristics, lifecycle phase, current and future demand)	• Local and global SLR projections • Local and global precipitation, temperature, and potential evapotranspiration data	**Operator:** Direct asset impacts on road deterioration, pavement performance, population displacement	Yes, for pavement deterioration (maintenance and rehabilitation)	N/A
Adapting to Climate Change: Canada's First National Engineering Vulnerability Assessment of Public Infrastructure, 2008	Canadian Council of Professional Engineers	In 2008, Engineers Canada conducted this engineering vulnerability assessment on four categories of Canadian public infrastructure: stormwater and wastewater, water resources, roads and associated structures, and buildings. The report provides an assessment of vulnerability based on case studies. Key findings of transportation infrastructure vulnerabilities to climate change include: (1) infrastructure systems studied were generally resilient to discrete, one-time, climate events; and (2) infrastructure systems were particularly vulnerable to long-term cumulative impacts.	Qualitative	2 (physical characteristics, lifecycle phase)	General projections on: • Temperature • Precipitation • SLR	**Operator:** direct asset impacts and system impacts	No	Does not actually provide a specific methodology, but discusses the process of developing one and the aspects an entity may want to include in a vulnerability assessment.

Living with a Rising Bay: Vulnerability and Adaptation in San Francisco Bay and on its Shoreline, 2011	San Francisco Bay Conservation and Development Commission	This report assesses the vulnerability of San Francisco Bay and its shoreline to the impacts of climate change, identifies information needs for future vulnerability assessments, and suggests near-term and long-term strategies to address climate change impacts.	Quantitative	1 (physical characteristics)	General climate projections for SLR only	**Operator and Community:** direct asset impacts to shoreline, development, and infrastructure	No, but discusses other reports that have made local cost predictions for levees and building stock costs from climate related impacts.	none
Costing Asset Protection: An All Hazards Guide for Transportation Agencies, 2009	Transportation Research Board of the National Academies	The National Cooperative Highway Research Program (NCHRP) produced the Costing Asset Protection: An All Hazards Guide for Transportation Agencies (CAPTA) report in order to provide transportation owners and operators with resource allocation guidelines for safety and security investments. The CAPTA methodology is available to the public as a computer-based spreadsheet model providing a means to analyze assets, relevant threats and hazards, and consequence levels of interest in a common framework.	Quantitative	2 (asset location, system criticality)	• Outcome-based data (not traditional cliamte data): • Data on outcomes or impacts of climate hazards on assets, such as impacts typical from extreme flooding, temperature, etc.	**Operator:** Direct impact to road bridges, road tunnels, transit/rail bridges, transit/rail tunnels, transit/rail stations, administrative and support facilities, ferries, and fleets.	Yes, this method includes a tool that requires inputs on assets of interest, asset attributes or characterisctics, and the climate hazard of concern. The output is a generic list of possible countermeasures for reducing risk, including a rough order of magnitude of the costs associated with implementing thouse countermeasures.	This CAPTA methodology employs a consequence-driven approach.
Climate Change Adaptation Strategy and Framework Revision B, 2009	The U.K. Highways Agency within the Department for Transport	The United Kingdom has developed a seven-phase process for assisting transportation decision-makers in addressing climate change impacts on highways. This approach provides methodologies for vulnerability assessment, risk assessment, and adaptation.	Qualitative	3 (asset location, physical characteristics, system criticality)	General global predictions: • Temperature • Seasonal rainfall • Wind speed • SLR	**Operator and Passenger:** System impacts and direct asset impacts (flooding impact traffic patterns, and weather accelerating wear and tear of on roads)	Does include highways Agency resource costs; professional costs; works costs; and, other indirect costs.	Is very high level and imprecise. Focus is more on prioritization and less on vuln. assessment.
Assessing Vulnerability and Risk of Climate Change Effects on Transportation Infrastructure: Pilot of the Conceptual, 2014	US DOT, Federal Highway Administration, Office of Planning, Environment, and Realty	DOT's FHWA developed a conceptual Vulnerability and Risk Assessment model that consists of three primary components: 1) develop inventory of assets, 2) gather climate information, and 3) assess the risk to assets and the transpiration system as a whole from projected climate change.	Qualitative	5 (physical characteristics, historical performance, lifecycle phase, system criticality, current and future demand)	Historical and projected climate data, nonspecific.	**Operator:** Direct asset impacts	Not in a quantitative manner, only states one should think about costs.	Very broad, functions as a general method for going about vulnerability assessments.
Climate Change Vulnerability and Risk Assessment of New Jersey's Transportation Infrastructure, 2011	Cambridge Systematics, on behalf of NJTPA	The Conceptual Risk Assessment Model was developed to assist transportation agencies in identifying infrastructure at risk for exposure to climate change stressors and determining which threats carry the most significant consequences. It incorporates the following summary steps: 1. Build an inventory of relevant assets and determine which are critical; 2. Gather information on potential future climate scenarios; 3. Assess the potential vulnerability and resilience of critical assets.	Quantitative	2 (physical characteristics, system criticality)	• GCM projection data (SLR, temperature, precipitation) • GIS modeling for SLR, storm surge, drought, inland flooding.	**Operator:** Direct asset impacts, specifically digital elevation model (DEM) analysis for inundation of assets	No, but suggests as a next step.	Many rail lines are situated on low-lying lands proximate to the Delaware River. Several small segments of the River Line would be potentially vulnerable in 2100, along with significant portions of freight track. With the exception of Amtrak (for which no impact is shown), there is a significant increase in vulnerable track miles for all rail types between 2050 and 2100.
Adaptation Assessment Guidebook, 2010	New York City Panel on Climate Change (NCPP)	This Appendix to the overall report lays out a multi-step process to help stakeholders create an inventory of their at-risk infrastructure and develop adaptation strategies to address those identified risks.	Semi-quantitative	2 (physical characteristics, historical performance)	Uniform climate projections developed by the NPCC	**Operator:** Direct asset impacts	Does not say how to, but states that when you characterize risk of climate change on infrastructure you should develop a "magnitude of consequence" variable that should include the change in capital and operating costs and the impact to the local economy.	N/A

Adapting to Rising Tides - transportation vulnerability and risk assessment pilot project (Briefing Book), 2011	San Francisco Bay Conservation and Development Commission (BCDC)	This report seeks to increase the preparedness and resilience of Bay Area communities to climate change related impacts. It involves evaluating potential shoreline impacts, vulnerabilities, and risks; identifying effective adaptation strategies; and developing and refining adaptation planning tools and resources that will be useful to communities throughout the Bay Area.	Quantitative and Qualitative	**4** (physical characteristics, lifecycle phase, system criticality, current and future demand)	• General climate projections for SLR only • GIS based scenarios for inundation mapping	**Opereator:** Direct asset impact (quantitative), **Operator and Passenger:** System impacts (qualitative)	To some extent, they incorporate O&M costs into their calculation of the sensitivity of an asset to inundation by SLR. They also incorporate capital improvement cost into their risk analysis consequence criteria as a way to quantify risk for impact scenarios.	This is a good report, not too rail centric but it is a thorough methodology. An interesting comment: Determining the criticality of one asset over another was not politically acceptable, given that the assessment would have been largely based on professional judgment and limited data.
Tomorrow's Railway and Climate Change Adaptation: Phase 1 Report, 2010	Research Programme, Rail Safety and Standards Board (RSSB)	This report covers the outputs from Phase 1 of the research project T925 "Tomorrow's Railway and Climate Change Adaptation (TRaCCA)"	Qualitative	**5** (physical characteristics, historical performance, lifecycle phase, system criticality, current and	Historical and projected climate data, nonspecific.	**Operator:** Direct asset impacts	No	N/A
Operations and Management, Adapting to Extreme Climate Change: Phase 3 Report, 2011	Research Programme, Rail Safety and Standards Board (RSSB)	This report presents the findings from the RSSB and Network Rail sponsored T925 "Tomorrow's Railway and Climate Change Adaptation (TRaCCA)". This report includes findings from Phase 2 of TRaCCA, which included a quantitative analysis of a portion of Network Rails owned assets along the West Coast Main Line (WCML). This report also includes findings from Phase 3, an expanded, semi-quantitative analysis of selected priority topics covering the whole of Brittain's railway network.	Semi-quantitative Quantitative	**5** (physical characteristics, historical performance, lifecycle phase, system criticality, current and future demand)	Historical and projected climate data, nonspecific.	**Operator:** Direct asset impacts	No	N/A

Appendix B. Methodology Matrx - Explanation Tab

The methodologies listed in this matrix are the product of research under Phase I of Amtrak's Northeast Corridor (NEC) Climate Change Vulnerability Assessment, and are listed in no particular order. They are provided as additional reference to Section 3.4.3 of the Phase I Report, ond are included to offer summary information of the methodologies researched. For a more complete understanding of each methodology, it is recommended that the original document be reviewed. These documents and their internet source are listed in

Column	Explanation
Methodology name	Includes name of the methodology as identified through the title of the methodology document or case study document.
Source of methodology	Includes name of the organization that developed the methodology, or executed the case study.
Brief summary of methodology	Provides a high-level summary of the approach of the methodology or case study, in some instances highlighting the purpose of developing or using the methodology; the key findings typical of the methodology; and the priorities addressed under the methodology.
Type of methodology	Each methodology identified in the matrix can be categorized by a methodology 'type'. This column identifies the named methodology as one of three possible vulnerability assessment types: qualitative, semi-quantitative, or quantitative.
Level of asset data required to complete methodology	Each named methodology requires different types of rail asset information in order to conduct the assessment. These different data types can be grouped into the following categories: • Asset Location (coordinates of asset location) • Physical characteristics (e.g. engineering specifications, physical condition) • Historical performance during extreme weather (e.g. documented damage or resilience) • Lifecycle phase (e.g. age of the asset, repair history, schedule for repair or replacement) • System criticality (e.g. criticality of the asset in maintaining a functioning network) • Current and future demand (e.g. current and predicted future passenger load) This column includes a value that reflects the total number of data categories needed to conduct the named methodology (with a range of 1 - 6). For example, if a methodology requires both location data and system criticality data, the numerical value in this column would be 2, reflecting the requirement for these two different types of asset data. Based on these numerical values, a general understanding of level of effort (LOE) to conduct these methodologies from a data-gathering perspective can be determined. In general, those methodologies that have a lower numerical value require less data, while those with a higher numerical value require more data.
What type of climate data is required?	Includes information on the types of climate change data or tools required to run the methodology, including global or local projections of increases/decreases in climate hazards (e.g. temperature, sea-level rise (SLR), precipitation); percentage probability of those climate hazards increasing in intensity or frequency in the future; historical climate or weather data; and the need to use geographic information system (GIS) or other mapping tools.
What is the vulnerability perspective?	Indicates the different ways in which an asset or system can be considered vulnerable depending on the viewpoint of different entities involved in the system under study (e.g. transit *operator*; *passenger* of the transit system; *partner* of the operator or co-user of the system).
Does the methodology incorporate costs of impacts?	Indicates whether or not the methodolgy includes tools or calculations for evaluating the costs associated with climate change impacts to assets or the system as a whole.
Additional notes about the methodologies, including potential shortfalls	Includes any additional, high-level information about the methodology captured duing Booz Allen's review of the document, and considered relevant for inclusion in the summary matrix. Potential shortfalls of the methodologies are also are outlined where relevant. In some intances, shortfalls were identified within the document text, or from Booz Allen's general analysis of the methodology.

Definitions (terms used within methdology matrix)

Evapotranspiration: the water lost to the atmosphere from the ground surface, the groundwater table, and the transpiration of plants. *Source:* http://water.usgs.gov/edu/watercycleevapotranspiration.html

Subsidence: the phenomenon of rocks and sediment falling in on itself due to the withrawal of large amounts of water otherwise responsible for holding the rock together. *Source:* http://water.usgs.gov/edu/earthgwlandsubside.html

APPENDIX C

Withheld in full

(b) 5

APPENDIX D: STATE AND REGIONAL CLIMATE CHANGE STUDIES

The following brief summaries are illustrative examples of assessments that have been conducted, or are underway for, key locations along the Northeast Corridor. This list is not intended to be comprehensive, but to provide a sense of the data and analysis that have already been collected and developed, and the entities that have been involved:

Climate Central Surging Seas[1]: Surging Seas is a web-based tool developed as part of a project reported in a 2012 paper in Environmental Research Letters (peer-reviewed) which combines high-resolution GIS elevation data and a new tidal model to produce sea level rise projections for most U.S. coast, including each of the Northeast coastal states.

Risingsea.net[2]: Risingsea.net is a site that has aggregated a large set of sea level rise maps, mostly for the East Coast. The data and information come from credible sources such as the U.S. Environmental Protection Agency, although it should be noted that not all the maps are the most current versions and these should be evaluated on a case-by-case basis for accuracy.

Boston, MA: The City of Boston produces a Climate Action Plan every three years, with the most recent being launched in October 2013.[3] Both the City of Boston and the Boston Harbor Association are conducting ongoing sea level rise vulnerability assessments within a scenario of a two-foot sea level rise by 2050, and up to six feet by 2100, also are considering the effects of enhanced storm surge from both nor'easters and hurricanes, and the changes in the 100-year floodplain that would arise from the transformation of Boston's coastline. The data sources used for these reports include city maps developed locally that show inundation from sea level rise under various scenarios developed by NOAA, NCAR, and other scientific bodies, although the authors hasten to point out that these maps are for research and discussion purposes only, not for detailed analyses.

Providence, RI: The City of Providence hosts information on the impacts of sea level rise on its community data web site.[4] The scenario used by the maps posted on the City's planning website is a 20-foot rise in sea level. This exceeds most projections out to 2100 by a substantial margin, but could include the effects of storm-surge as well as 100-year floor scenarios (documentation missing).

Connecticut and New York/Long Island Sound: The Greater Bridgeport Regional Council and other quasi-governmental entities around Long Island sounds have partnered with the Nature Conservancy to develop an interactive tool to help cities and towns visualize and plan for sea level rise.[5] The result is a visualization tool that shows coastal inundation under sea level rise and storm conditions, including confidence levels in the certainty of the maps.[6]

Port Authority of New York/New Jersey: As part of the broader PlaNYC Climate Change Adaptation Task Force (in which Amtrak participated), the Port Authority evaluated the vulnerability of its infrastructure

[1] http://sealevel.climatecentral.org
[2] http://maps.risingsea.net/index.html
[3] www.cityofboston.gov/climate
[4] http://provplan.org/data-and-information/map-entry/sea-level-rise
[5] http://coastalresilience.org/geographies/new-york-and-connecticut
[6] http://maps.coastalresilience.org/nyct/#

to a range of climate change effects. The goal was to determine which elements of its infrastructure might be affected by the climate change projections for three decades: the 2020s, the 2050s, and the 2080s. Because this was explicitly aimed at studying infrastructure, the availability of elevation data at specific sites was a significant part of the effort. Climate data and information on the expected climate conditions in each time frame were provided by a panel of scientists convened for the purpose by Mayor Michael Bloomberg, who developed custom climate data and projections for New York City.7

[7] New York City Panel on Climate Change (June, 2013) Climate Risk Information 2013: Observations, Climate Change Projections, and Maps, June 2013

APPENDIX E: METHODOLOGY COMPARISON CRITERIA

Criterion 1. Availability of Asset Data

The extent of information available on Amtrak assets along the NEC, Harrisburg Line, Springfield Line and the Albany Line was the primary determinant for assembling the recommended approach in Section 4.0. Asset information types collected included, but were not limited to:

- Asset location (e.g. coordinates of an asset's location)
- Physical characteristics (e.g. engineering specifications)
- Historical performance during extreme weather (e.g. damage or resilience)
- Lifecycle phase (e.g. age of the asset, repair history, schedule for repair or replacement)
- System criticality (e.g. criticality of the asset in maintaining a functioning network)
- Current and future demand (e.g. current and predicted future passenger load)

Different methodology types require different levels of detail in the data items listed above. For example, where data is more readily available for an asset type, there is greater opportunity to utilize a quantitative methodology. Where data is less available for an asset class, a qualitative methodology may be recommended. Qualitative methodologies may also be used to analyze potential vulnerabilities of future assets during Phase II.

Criterion 2. Availability of Climate Change Data in the Northeast United States

The availability and granularity of climate data for the northeast US will be another factor in selecting a methodology (or methodologies) for recommendation to Amtrak. The best available science from NOAA and other academic sources will be compared to the climate data needs of various methodologies under consideration for recommendation. In some instances, climate change data will be available with enough granularity to conduct a more robust analyses using quantitative methods (e.g. predictive models for flooding and coastal inundation). For some climate hazards, such as strong winds, data may be less readily available, and an analysis would be at either a semi-quantitate or even qualitative level.

Criterion 3. Temporal Scale of the Assessment

The temporal scale, or length of time the vulnerability analysis is expected to cover, will be an additional determinant of which methodology (or methodologies) is recommended. In general, the predictive capabilities of climate models that span to 20 years are greater, and generally more accurate, than those spanning 50 to 100 years. It may be the case that for a long-lived asset (such as a tunnel that may have a 100+ year lifecycle) different methodologies could be utilized to develop a series of vulnerability snapshots throughout the lifecycle of the asset. For example, a tunnel might undergo three separate assessments: a quantitative vulnerability analysis in its first 20 years; a semi-quantitative analysis for the next 30 years; and a qualitative analysis for the last 50, each coinciding with the level of detail in the climate change projections over these three timeframes. Again, these analyses are contingent upon the availability of asset data cited in criteria 1 and 2.

Criterion 4. Vulnerability Perspective

Again, a variety of methodologies exist for conducting vulnerability assessments of transportation systems. While many of these methodologies reflect some version of the risk-hazard approach (i.e. a climate hazard is applied to the asset to determine its sensitivity to the hazard and overall vulnerability of the asset over time), these methodologies can also be used to generate portraits of vulnerability from perspectives beyond direct asset impacts. For example these methodologies (or their results) can demonstrate how asset disruptions manifest into service disruptions - such as delays, malfunctions while en-route, and cancellations - and are focused on the resilience of the journey from the passenger and operator perspective. Some methodologies can be used to analyze the resilience of a single city pair trip, while others can evaluate a more complex, multi-city journey. These analyses are useful in understanding the operational, safety, and potentially financial implications of climate change to the system as a whole.

Criterion 5. Financial Vulnerability

Some risk-hazard approach methodologies enable an understanding of the financial impacts associated with an asset's vulnerability and resilience. Amtrak has expressed interest in incorporating this form of analysis into a potential Phase II vulnerability assessment. Given this interest, the inclusion of cost analysis factors may be considered a significant criterion in selecting the vulnerability assessment methodologies for Phase II. Financial vulnerability approaches will require data on an asset's present and future value to the extent this is available and/or able to be estimated. Financial vulnerability studies can feed into future cost/benefit studies that evaluate opportunities to build resilience into asset procurement, repair schedules, system-wide planning, etc.

APPENDIX F: ADDITIONAL REFERENCES

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