Assessing the Vulnerability of Tennessee Transportation Assets to Extreme Weather

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13. ABSTRACT (Maximum 200 words)

Tennessee Department of Transportation (TDOT) was awarded a grant from the Federal Highway Administration (FHWA) to perform an extreme weather vulnerability assessment of transportation infrastructure in the state. The geographical scope of this vulnerability assessment includes all major transportation infrastructure located within Tennessee. The temporal scope extends through calendar year 2040, a time frame that aligns with capital and rehabilitation cycles, and the horizon year of current Long Range Transportation Plans.

During the course of this project, the study team endeavored to incorporate the information and opinions provided by stakeholders, including those representing government functions, economic sectors, transportation modes, geographic regions and political jurisdictions. The mechanism for enabling stakeholder involvement was a working group, the Tennessee Extreme Weather and Transportation Adaptation Partnership (TEWTAP), whose role was to guide and advise the project and review project results. In addition, other stakeholders were invited to offer input and provide data through focus group meetings that were held in each of TDOT's four regions. Collectively, participants represented multiple transportation and non-transportation related entities, including federal, state and local government officials; freight shippers and carriers; transit operators; metropolitan planning organizations (MPOs); regional planning organizations (RPOs); and DOT representatives from states that border Tennessee.

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Table of Contents

List of Figures

List of Tables

Executive Summary

Introduction

Within the State of Tennessee is a vast transportation system that includes highways, railroads, waterways, airports, pipelines, transit services and intermodal connections, in addition to the facilities utilized to manage and maintain transportation operations. Extreme weather can damage transportation infrastructure and disrupt travel mobility, resulting in public health, economic, social and ecological impacts whose consequences can seriously threaten the viability of individual communities and entire regions. Over the past three decades, the state has experienced more than fifteen weather disasters that each resulted in over $1 billion in impacts. Moreover, in just the past few years, the Nashville region alone has experienced its worst flooding in recorded history, a major hailstorm that caused widespread damage, several tornadoes, a lengthy heat wave, and an extended period of severe cold that resulted in freezing and bursting of water lines that had been in use for over 100 years.

Enhancing the resiliency of Tennessee's transportation system is not only vital to the well-being of the state, but to other parts of the nation as well. The interconnectivity of the U.S. transportation system is heavily dependent on Tennessee's transportation infrastructure as major east-west and north-south corridors. Beyond corridor-scale implications, disruptions caused by extreme weather can significantly affect specific locations such as Memphis, which serves as a key multimodal hub in the regional and national transportation network.

For these reasons, the Tennessee Department of Transportation (TDOT) sought and was awarded a grant from the Federal Highway Administration (FHWA) to perform an extreme weather vulnerability assessment of transportation infrastructure in the state. The geographical scope of this vulnerability assessment includes all major transportation infrastructure located within Tennessee. The temporal scope extends through calendar year 2040, a time frame that aligns with capital and rehabilitation cycles, and the horizon year of current Long Range Transportation Plans.

During the course of this project, the study team endeavored to incorporate the information and opinions provided by stakeholders, including those representing government functions, economic sectors, transportation modes, geographic regions and political jurisdictions. The mechanism for enabling stakeholder involvement was a working group, the Tennessee Extreme Weather and Transportation Adaptation Partnership (TEWTAP), whose role was to guide and advise the project and review project results. In addition, other stakeholders were invited to offer input and provide data through focus group meetings that were held in each of TDOT's four regions. Collectively, participants represented multiple transportation and non-transportation related entities, including federal, state and local government officials; freight shippers and carriers; transit operators; metropolitan planning organizations (MPOs); regional planning organizations (RPOs); and DOT representatives from states that border Tennessee.

Study Approach and Results

The study involved performance of five basic tasks:

1) Developing an inventory of transportation assets.
2) Identifying those assets considered critical to transportation system operation.
3) Determining extreme weather scenarios to which critical transportation assets may be exposed.
4) Assessing the impacts to these assets should an extreme weather scenario occur.
5) Combining this information into an overall measure of vulnerability.

The transportation asset inventory of interest consisted of 12 different infrastructure categories. *Road*, *rail*, *navigable waterway*, *air*, *pipeline* and *transit* systems represent the lifelines of passenger and freight mobility within the state. *Rail yards*, *ports*, *locks* and *bridges* are specific facilities in the transportation system that can be essential for continuity of operations. Finally, the importance of support systems, particularly *maintenance facilities* and *traffic operations centers*, is often overlooked in creating a transportation asset inventory.

The definition of a "critical" transportation asset emphasized system connectivity, while also supporting community travel needs. A critical transportation asset was defined as any portion of the transportation system without which there would be an immediate, direct and substantial disruption to the transportation system at the local, regional or national level. Performance criteria associated with this definition were applied to the transportation asset inventory, leading to the generation of a statewide map of critical transportation assets.

The National Weather Service (NWS) has long been interested in tracking extreme weather events, starting in the 1950s with the establishment of an information system to characterize those events in the U.S. There have been over 27,000 such events in the state since NWS established this information system. The different types of extreme weather events experienced in Tennessee were grouped into nine aggregate weather event categories. The average annual occurrence of each of these types of weather events was compiled for each county in Tennessee. The most frequently occurring extreme weather events in Tennessee have been classified as hydrologic (e.g., flooding), strong winds, and winter events, with certain counties frequently exposed to these hazards.

An assessment of extreme weather in the past provided a baseline for understanding what might occur over the planning period horizon. Future projections of extreme weather were generated using FHWA tools and other climate models along with trend analyses of historic weather events. The results indicated that portions of Tennessee are likely to experience dramatic warming coupled with an increase in precipitation; an increase in strong straight-line winds and tornadic activity are also anticipated.

The project utilized a comprehensive on-line survey, administered to a broad range of transportation stakeholders, to assess the potential impacts (asset damage and system disruption) to each asset type when exposed to specific extreme weather scenarios.

Respondents were asked to evaluate the impacts according to a four-point qualitative scale (nominal, moderate, significant, and catastrophic). The survey was sent to slightly over 400 stakeholders considered knowledgeable about various transportation assets and the project received 220 responses. This is a very high response rate for a survey of this kind, perhaps indicative of the level of concern about extreme weather within the transportation community.

A vulnerability score (annual frequency of a given weather event multiplied by the impact score for an exposed asset type) was derived for each unique weather/asset combination and mapped for every county in Tennessee. The inventory of critical assets was superimposed on the vulnerability maps in order to determine the locations where certain asset types appear to have the greatest potential vulnerability.

The study produced several important findings:

1) As expected, various regions of the state are more prone to certain types of extreme weather events.
2) High winds and heavy precipitation (flooding) are the events of greatest concern across the state and to multiple transportation asset classes.
3) Winter weather is primarily an issue for certain counties in East Tennessee; however, future climate projections suggest that this may become a declining concern.
4) Shelby County (Memphis) and Davidson County (Nashville) are the locations in the state with the most vulnerability to extreme weather.
5) The greatest single concern is the potential for flooding in the Memphis area. The area has “dodged a bullet” in the past because local streams have not been at capacity when the Mississippi River has flooded. Coupled with higher precipitation levels projected for this area, a future flooding event could have serious implications for passenger and freight transport, both locally and more widespread given the importance of Memphis to the regional and national transportation system.
6) There is a propensity for rockslides in the state, particularly in Middle and East Tennessee, where steep slopes and limestone formations are prevalent. Areas with relatively high hydrologic vulnerability scores in locations with significant rockslide potential warrant special consideration.

Opportunities to Enhance TDOT Policies and Procedures

An important component of this study was to examine how the vulnerability assessment results can be utilized to enhance existing TDOT policies and procedures. Opportunities may exist to integrate the results from this project into a variety of agency activities, in particular:

- **Risk-based Transportation Asset Management Plan (TAMP)**. Congress, in Moving Ahead for Progress in the 21st Century Act (MAP-21), mandated that each state department of transportation develop a risk-based TAMP for its highways and bridges, although states are encouraged to include other infrastructure assets as well. TDOT is presently engaged in a separate activity to develop its plan. This extreme weather vulnerability project can provide valuable input to TDOT’s risk-based TAMP in several ways. First, the transportation asset inventory and identification of critical transportation assets performed in this study can be utilized directly by the risk-based TAMP. This would be helpful not only in compiling a list of critical road and bridge assets, but also in expanding the plan to other transportation infrastructure assets. Second, the risk assessment methodology used to determine extreme weather vulnerability could be applied to other risks under consideration in the risk-based TAMP. This could provide a consistent, systematic approach to evaluating all potential risks that may be incurred by the state's transportation system, not just extreme weather risks. Finally, the results of this study can serve as the extreme weather portion of the overall risk assessment for state transportation infrastructure.

- **FHWA Order 5520**. The other recent development is the December 2014 issuance of a new directive by FHWA, Order 5520 (Transportation System Preparedness and Resilience to Climate Change and Extreme Weather Events). It is now official FHWA policy to integrate consideration of climate and extreme weather risks into its planning, operations, policies and programs. This new order formalizes FHWA's commitment to this issue, guides the agency's implementation of relevant MAP-21 provisions and recent Executive Orders, and identifies how FHWA intends to lead the transportation industry in making the nation's highways more resilient. Since TDOT policy is in alignment with FHWA policy, TDOT's response to this study's findings and recommendations presents an opportunity to pursue a course of action consistent with FHWA's commitment and expectations.

Next Steps

This project represents TDOT's first attempt to understand the impacts of extreme weather on transportation assets across the state. The study represents a starting point for integrating extreme weather risk into the agency's management, planning and operations. It also serves as a foundation that TDOT can build upon by performing follow-on activities based on the results of the extreme weather vulnerability assessment. The following initiatives are recommended for implementation.

Adaptation Project Planning

This extreme weather vulnerability assessment was an ambitious undertaking due to the number and types of transportation assets and the size of the study region. Thousands of network segments and facilities were included in the effort. The study methodology had to place each specific asset into a generic asset category. This limited the ability to examine in detail the unique characteristics associated with the asset that might impact its damage potential and resilience in the face of particular extreme weather events.

The study does serve as a valuable screening process to identify a manageable number of critical assets that warrant more detailed study of their vulnerability and the merits of potential adaptation strategies. It is strongly recommended that TDOT select 15-20 specific critical assets identified as highly vulnerable for a follow-on study. The results of this effort will advance TDOT's understanding of its extreme weather vulnerability in key locations. This more detailed analysis is an opportunity for the agency to engage in more formal adaptation planning. The proposed project would also involve many divisions within TDOT, thereby providing opportunities for agency personnel to become more familiar with this developing concern and garner experience that can be used to incorporate extreme weather considerations into TDOT policies and procedures.

Coordination With Risk-Based Transportation Asset Management Plan

Because of the obvious connections between the extreme weather project and TDOT's risk-based transportation asset management plan, a series of meetings and perhaps a formal structure could be organized to facilitate the transfer of relevant information from this assessment to the TAMP process. This could help to ensure that there is no replication of effort or inconsistency in the way in which extreme weather risks were evaluated in this study and how they are being addressed in the TAMP.

Communicating Site-Specific Results to Local Stakeholders

This study has provided a holistic view of how extreme weather may impact transportation asset vulnerability across the state. Given that each region in the state will experience different forms of extreme weather and contain different critical asset portfolios, it would be beneficial to develop a series of "briefing books" that communicate the results of this study tailored to each region based on their unique situation. These briefing books could serve as an important resource for communities to reference in order to integrate findings into their respective transportation planning and operations.

Extreme Weather Vulnerability Assessment Tool Development

As part of its pilot program, FHWA has shown a strong interest in transferring decision-support tools developed in one location to other states and regions. Two methodologies were developed in this project that offer the potential to supplement the tools FHWA has already produced:

1) The process used to extract and assemble National Weather Service data to produce historic frequencies of various extreme weather events.
2) Techniques used in designing, administering and evaluating the responses of an online survey to generate estimates of the impact of various extreme weather events on various types of transportation infrastructure.

Both of these methods could be transformed into software tools that could be made widely available to other organizations involved in performing extreme weather vulnerability assessments. In addition to enhancing the FHWA resilience toolbox, TDOT would be nationally recognized as an innovator in helping to establish best practices for addressing a critical and emerging transportation challenge.

1. Introduction

The State of Tennessee is comprised of several distinct geographical regions. The lowlands of West Tennessee are bordered by the Mississippi River on the west and a portion of the Tennessee River on the east. Middle Tennessee is characterized by rolling hills and river valleys, extending eastward to the Cumberland Plateau. East Tennessee is dominated by the Appalachian and Smoky Mountains.

This varied topography leads to diverse climate conditions that produce various forms of extreme weather. Frequent storms bring excessive rainfall that often lead to local and widespread flooding, as well as rock slides and sink holes. Storm events can be accompanied by damaging winds and hail, and may occur as tornadoes. Yet, extended dry periods characterized by excessive heat are also prevalent, increasing the threat of drought. Winter storms and severe cold temperatures with the potential to paralyze an area for an extended period of time are also common.

Tennessee has experienced a growing number of extreme weather events over the past three decades, including more than fifteen weather disasters that each resulted in over $1 billion in impacts. In just the past few years, the Nashville region alone has experienced its worst flooding in recorded history, a major hailstorm that caused widespread damage, several tornadoes, a lengthy heat wave, and an extended period of severe cold that resulted in freezing and bursting of water lines that had been in use for over 100 years. The impact to the state's transportation system from extreme weather during a single month, August 2013, is another indication of what is at stake (see Figure 1.1). Moreover, many of these forms of extreme weather are projected to occur more frequently and/or intensify in the coming years.

Tennessee contains a vast transportation system that includes highways, railroads, waterways, airports, pipelines, transit services and intermodal connections, in addition to the facilities utilized to manage and maintain transportation operations. Extreme weather can damage transportation infrastructure and disrupt travel mobility, resulting in public health, economic, social and ecological impacts whose consequences can seriously threaten the viability of individual communities and entire regions.

Enhancing the resiliency of Tennessee's transportation system is not only vital to the well-being of the state, but to other parts of the nation as well. The interconnectivity of the U.S. transportation system is heavily dependent on Tennessee's transportation infrastructure as major east-west and north-south corridors. Beyond corridor-scale implications, disruptions caused by extreme weather can significantly affect specific locations such as Memphis, which serves as a key multimodal hub in the regional and national transportation network.

Figure 1.1 - Sample of Extreme Weather Transportation Impacts in Tennessee: August 2013

Given what is at stake, the Tennessee Department of Transportation (TDOT) sought and was awarded a grant from the Federal Highway Administration (FHWA) to perform an extreme weather vulnerability assessment of transportation infrastructure in the state. The geographical scope of this vulnerability assessment includes all major transportation infrastructure located within Tennessee. The temporal scope extends through calendar year 2040, a time frame that aligns with capital and rehabilitation cycles, and the horizon year of current Long Range Transportation Plans.

This report describes the activities performed in carrying out the extreme weather vulnerability assessment project, including presentation of study results and implications. It was conducted with the following objectives in mind:

- Understand the vulnerability of Tennessee's overall transportation system to current and anticipated extreme weather events.
- Identify segments and facilities that are deemed critical to transportation mobility and highly vulnerable to extreme weather.
- Inform the development of adaptation strategies that involve short-term and long-term implementation.
- Leverage available information and develop analysis techniques to improve the decision-making process.
- Promote greater stakeholder collaboration and coordination in dealing with the transportation impacts associated with anticipated extreme weather events.
- Raise public awareness about extreme weather vulnerability and the ability to manage these concerns through infrastructure adaptation.

These objectives also support TDOT's long-term goal of growing economic opportunity through strategic investment in critical regional infrastructure.

During the course of this project, the study team endeavored to incorporate the information and opinions provided by stakeholders, including those representing government functions, economic sectors, transportation modes, geographic regions and political jurisdictions. The mechanism for enabling stakeholder involvement involved the establishment of a working group, the Tennessee Extreme Weather and Transportation Adaptation Partnership (TEWTAP), whose role was to guide and advise the project and review project results. The membership organizations participating in the TEWTAP were:

- Chattanooga-Hamilton County/North Georgia Transportation Planning Organization
- Clarksville Urbanized Area Metropolitan Planning Organization
- Knoxville Regional Transportation Planning Organization
- Memphis Urban Area Metropolitan Planning Organization
- Nashville Area Metropolitan Planning Organization
- National Weather Service, Nashville Weather Forecast Office
- Tennessee Department of Economic and Community Development
- Tennessee Department of Environment and Conservation
- Tennessee Department of Safety
- Tennessee Emergency Management Agency
- U.S. Army Corps of Engineers

In addition, other stakeholders were invited to offer input and provide data through focus group meetings that were held in each of TDOT's four regions. Collectively, participants represented multiple transportation and non-transportation related entities, including federal, state and local government officials; freight shippers and carriers; transit operators; metropolitan planning organizations (MPOs), regional planning organizations (RPOs); and DOT representatives from states that border Tennessee.

2. Study Approach

FHWA has developed a conceptual framework for measuring climate-related vulnerability in the transportation context that involves identifying which critical assets are exposed to extreme weather events and how sensitive the assets are to those events. As shown in Figure 2.1, the TDOT study worked within this framework to identify five basic tasks to determine vulnerability:
1) Developing an inventory of transportation assets.
2) Identifying those assets considered critical to transportation system operation.
3) Determining extreme weather scenarios to which critical transportation assets may be exposed.
4) Assessing the impacts to these assets should an extreme weather scenario occur.
5) Combining this information into an overall measure of vulnerability.

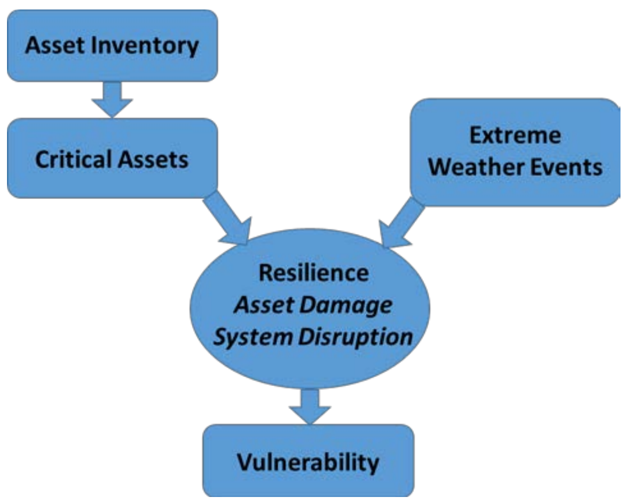

Figure 2.1 - Extreme Weather Vulnerability Assessment Methodology

The initial step in the process involves compiling an inventory of all transportation assets being considered in the study. This can include both the transportation infrastructure utilized directly in moving passengers and freight, as well as the facilities that interface with this infrastructure to manage transport operations. The size and complexity of this inventory depends on the number of modes under consideration and the geographical extent of the study area.

Once the transportation asset inventory is complete, it is necessary to delineate those assets that are deemed critical to maintaining a high degree of system operability. This step is important in identifying the assets most vital to maintaining system performance. For example, a segment of the Interstate highway system likely carries more signficiant volumes of passenger and freight vehicles than a local roadway. Defining critical transportation assets from the full inventory has the added benefit of reducing the vulnerability assessment to a more manageable number of locations.

Concurrent with identifying critical transportation assets is an effort to describe the types of extreme weather events to which these assets might be exposed. The frequency and type of extreme weather events will depend on the geographic location of the study area, its topography and climate. Developing this portfolio of extreme weather events relies on both historic weather observations and future climate scenarios.

The critical transportation assets are then exposed to the extreme weather scenarios, for the purpose of evaluating how well a particular critical transportation asset can endure and recover from each type of event that it might experience. It is important for this evaluation to consider the impacts of physical damage as well as disruption during the time when the asset is unable to sustain normal operations.

The culmination of this methodology is combining the frequency with which critical transportation assets may be exposed to various extreme weather events and the consequences of the event, should it occur. The resulting “score” (a composite measure of the projected likelihood and consequence of the event) represents the vulnerability of an asset to extreme weather. It stands to reason that the higher the vulnerability score, the more attention the asset warrants in terms of improving its resilience.

3. Transportation Asset Inventory

As mentioned previously, the challenge that building an asset inventory presents is to capture the breadth and depth of the transportation system within the study area to ensure that any potentially key asset is not excluded. For this study, doing so represented an ambitious task given the size of the state and the extent of its transportation system. The transportation asset inventory for the state was defined to consist of the following[1]:

- Roads (Interstate, state, and U.S. highways)
- Railroads
- Rail yards
- Navigable waterways
- Ports
- Locks
- Bridges
- Airport runways
- Maintenance and salt facilities
- Transportation support systems (TDOT buildings)
- Transit (transfer hubs, terminals, fleet storage)
- Pipelines (oil and natural gas)

These assets were included because they represent the lifelines of passenger and freight mobility within the state, are transactional points in the transportation system that can be essential for continuity of operations, or are fundamental to controlling and maintaining system performance to desired levels.

A comprehensive data collection effort was then undertaken to identify the geographic location of individual assets within each asset type, as well as corresponding characteristics. This involved the utilization of multiple sources of information, including the U.S. Bureau of Transportation Statistics, U.S. Department of Homeland Security, TDOT headquarters and regional offices, Tennessee Emergency Management Agency, third party data providers through a licensing arrangement with commercial software providers, and regional transit operators. To the maximum extent possible, data was sought that was already available in a geographic information systems (GIS) database or could be easily converted to a GIS format.

The resulting information was assembled into a GIS database that included all of Tennessee as well as a 10-mile buffer zone into bordering states. The buffer zone was included to capture transportation assets contiguous to the state, recognizing that the transportation infrastructure in one area is often part of a broader, interdependent regional system.

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[1] Any tunnel located on a critical segment of the transportation system was considered part of that segment, although the maps show the location of these tunnels as a separate icon.

4. Critical Transportation Assets

In offering guidance for defining what constitutes a critical asset, FHWA has acknowledged that there can be wide variation in this definition depending on the goals of the particular study such that there is no “one size fits all approach.” For this project, the definition of a “critical” transportation asset emphasized the importance of system connectivity, while also supporting local travel needs. A critical transportation asset was therefore defined as any portion of the transportation system without which there would be an immediate, direct and substantial disruption to the transportation system at the local, regional or national level.

Each transportation asset in the compiled inventory was subjected to a review of how well its characteristics satisfied the criticality standard. However, there is no common attribute applicable to all transportation asset types that can be uniformly applied to establish what makes an asset “critical.” This can be attributed in part to differences in the role that each type of asset plays as part of an integrated transportation system, differences in the attributes that describe operational features, and the availability of data to characterize those attributes. For example, the amount of cargo carried on a rail segment is known and can be used to describe the significance of that segment, whereas the volume of natural gas shipped by pipeline is not known. However, the pipeline diameter is provided as an attribute, and that information can be used as a proxy measure to indicate whether the pipeline segment is part of a transmission line as opposed to being used for local distribution.

A review of the available data for each asset and identifying thresholds recognized as valuable in distinguishing the importance of transportation assets resulted in the selection of criteria to be used in determining criticality for each asset type, respectively. For example, the Federal Railroad Administration has classified certain rail segments as part of the “strategic national railroad network,” and these segments were all deemed critical. Similarly, runways of 6,000 feet in length or more are generally capable of landing large, commercial jets, and were therefore also deemed critical in the study. The specific critera for determining criticality and supporting information are listed in Appendix A.

The criticality criteria were subsequently applied to the transportation assets located in Tennessee as well as the 10-mile buffer into bordering states. While reliance on databases furnished by a variety of sources provided a wealth of information to support this endeavor, there is always a concern about the accuracy and completeness of such large-scale databases. For this reason, interactions with stakeholders at regional focus group meetings were utilized as an important element in “ground truthing” the asset inventory, its characteristics and degree of criticality. These engagements served as a valuable opportunity to learn of county and city transportation assets (e.g., operations centers, maintenance facilities and arterials) that are considered to be critical transportation assets from a local perspective.

These regional stakeholder focus group meetings were well attended and held in each of the four TDOT regions. Attendees ranged from TDOT maintenance personnel, county planning organizations, county engineers, members of MPOs, local airport authorities, and transit representatives, to private consultants and city sustainability offices. The attendance sheets for these meetings are attached at Appendix H.

During these meetings, large critical assets maps were displayed and participants were asked to verify the initial selection of “critical” assets, including the removal or addition of assets deemed non-critical or critical, respectively, from these local perspectives. The participants also had unique, “on-the-ground” knowledge regarding what extreme weather events were of most concern in their respective regions and which assets were most vulnerable to particular extreme weather events.

These meetings proved valuable to our understanding of critical assets and how particular assets respond to various extreme weather events. They also revealed that many assets may not rise to the level of “critical”, but should still be noted. Accordingly, a separate asset category, “important”, was also developed. For example, salt and maintenance facilities nearby these “important” assets were classified as critical, with the understanding that TDOT and local personnel would be knowledgeable about the location of important facilities and would attempt to maintain access to these centers in the event of extreme weather.

Appendix B displays maps of the state’s critical transportation assets, shown separately for each of TDOT’s four regions. For each region, these assets are divided among two maps to improve legibility. A third map is also included to display the critical transportation assets as they appear in the major urban area of each region, respectively, presented at a finer scale. Figure 4.1 displays the critical transportation assets for the Nashville area.

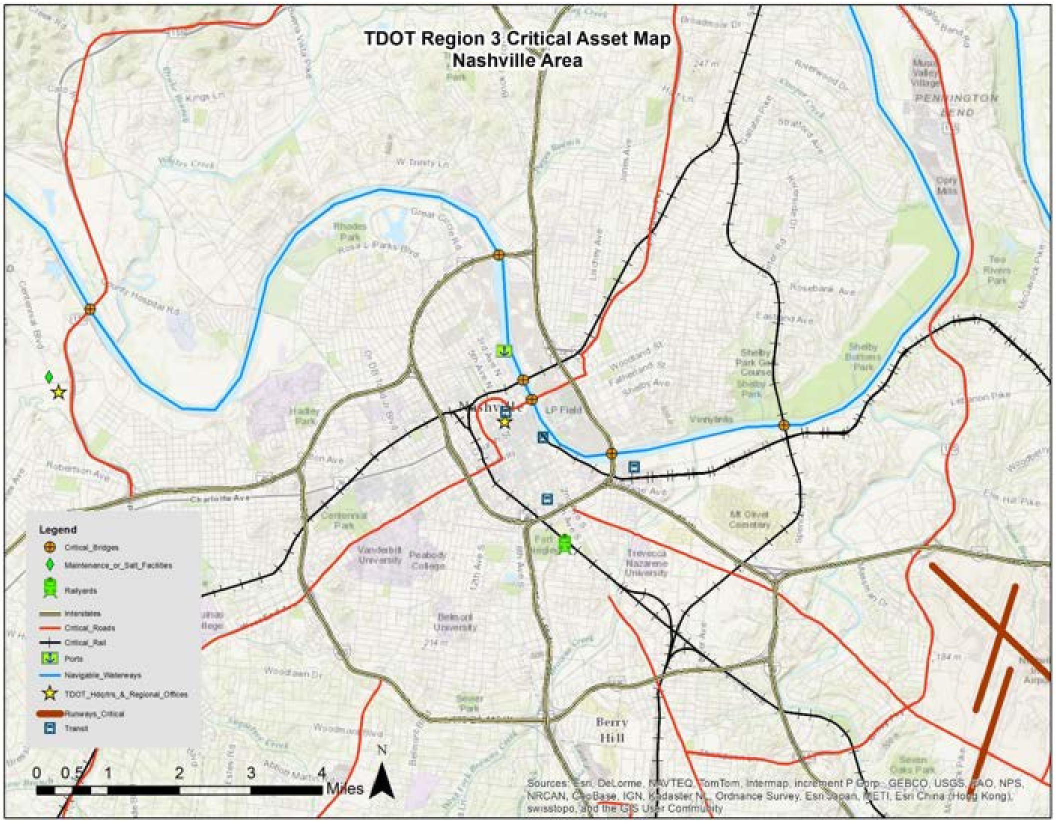

Figure 4.1- Critical Transportation Assets in Nashville Area

More detailed information (e.g., road segment lengths, freight volumes, pipeline termini location, etc.) regarding the selected critical assets exists in the attribute tables of the GIS shapefiles that comprise the critical asset database. Some of these shapefiles are publicly avaialable, but many were obtained from the Department of Homeland Security and are not publicly available. Readers of this report that have an interest in obtaining any of the information contained in the attribute tables should contact TDOT.

5. Extreme Weather Scenarios

The National Weather Service (NWS) has long been interested in tracking extreme weather events, starting in the 1950s with the establishment of an information system to characterize such occurrences in the U.S. Referred to as the storm events database, it contains the records of storms and other weather phenomena having sufficient intensity to cause loss of life, injuries, significant property damage, and/or disruption to commerce. The database also includes entries for other important meteorological events, such as record maximum or minimum temperatures, or precipitation that occurs in connection with another event.

The database contains records beginning in January 1950, catalogued according to the county where the extreme weather event was observed. Changes have occurred in the data collection process as new event types have been added over time. Beginning in 1950 through 1954, only tornado events were recorded. From 1955 through 1995, in addition to tornadoes, thunderstorm wind and hail events were also included. Since 1996, 45 additional extreme weather event types have been added, bringing the total number of event types to 48.

Within Tennessee, since the inception of this NWS database, 23 of the 48 different extreme weather event types have been observed with some degree of regularity[2]. The definitions for each of these event types are provided in Appendix C.

As new extreme weather event types have been included, values for locations, impacts, narratives and any other event specific information have remained consistent. For analysis purposes, this provides an opportunity to perform direct comparisons across event types over time, subject to taking into account that the frequency of occurrence needs to be normalized by the number of years for which certain event types have been recorded.

One caveat worth noting is the intensity threshold that the NWS uses for an event to be considered for database inclusion (i.e., loss of life, injuries, significant property damage, and/or disruption to commerce). This suggests that extreme weather events with similar characteristics are more likely to meet the intensity threshold in more heavily populated areas where more people and infrastructure are potentially exposed. This may result in a larger number of observations in the database from urbanized areas. However, this also aligns with locations that contain a preponderance of critical transportation assets given the larger number of people and businesses dependent on continuity of transportation operations in those areas.

5.1 Historical Analysis of Extreme Weather in Tennessee

The NWS storm event types that have occurred in Tennessee are listed in Table 5.1. Collectively, there have been over 27,000 such events in the state since the NWS established this information system.

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[2] Tropical depressions, tropical storms and wildfires have also been observed in Tennessee, but so rarely recorded in the NWS database that these event types were subsequently removed from consideration.

Cold/wind chill	Frost freeze	Lightning
Drought	Funnel cloud	Sleet
Dust devil	Hail	Strong wind
Excessive heat	Heat	Thunderstorm wind
Extreme cold/wind chill	Heavy rain	Tornado
Flash flood	Heavy snow	Winter storm
Flood	High wind	Winter weather
Freezing fog	Ice storm	

Table 5.1 - Tennessee Extreme Weather Events

In the context of this project, it is important to note that many of these event types do not represent unique weather, but rather gradations of the severity of certain weather forms. For example, "excessive cold/wind chill" represents conditions that are more severe than "cold/wind chill". Another example is the relationship between "funnel cloud", "dust devil", and "tornado", all of which represent circular wind rotation. Because of these relationships, the twenty-three event types were aggregated into nine extreme weather event categories as shown in Table 5.2.

For each of the nine aggregate weather event categories, the annual average number of recorded events was compiled for each of the ninety-five counties that comprise the state (see Figure 5.1). The results appear in Appendix D.

Aggregate Weather Event Type	**National Weather Service Event Type**
Cold	Cold/wind chill Extreme cold/wind chill
Hot	Heat Excessive heat
Wind	Strong wind High wind Thunderstorm wind
Twister	Funnel cloud Dust devil Tornado
Hydrologic	Heavy rain Flash flood Flood
Lightning	Lightning
Hail	Hail
Drought	Drought
Winter	Winter weather Sleet

	Freezing fog Frost freeze Heavy snow Winter storm Ice storm

Table 5.2 - Aggregate Extreme Weather Event Grouping

Figure 5.1 - Tennessee County Map

The color-coding on each map shows the frequency quartiles based on the number of events for that aggregate extreme event category; therefore, a "red" county on one map will correspond to a different frequency of observation compared to a "red" county on another map. For these reasons, these exhibits should be used judiciously when comparing activity across extreme weather categories.

Some interesting observations can be made in reviewing these results[3]. *Cold* weather has been a very rare event, never observed in most counties. By contrast, with the exception of East Tennessee, the remaining counties in the state have witnessed *drought* conditions on many occasions, with the most prevalent areas located in the western part of the state and across a north-south swath in Middle Tennessee; in many of those areas, it is on average an annual occurrence. Historically, damaging *hail* and *lightning*, although frequently observed, follow a somewhat random geographical pattern in terms of the frequency of such events. *Hot* temperature events reflect a pattern that would be considered rather intuitive for Tennessee given its varied topography. *Twister* events have been reported in every county in the state since historical records have been kept, with more of these events having been observed in Middle and Western Tennessee, where temperatures are generally warmer and the topography more conducive to tornado destruction. *Winter* extreme weather events have been most prevalent in the Smoky Mountain regions of East Tennessee and along portions of the Cumberland Plateau in the eastern part of Middle Tennessee.

The most frequently occurring extreme weather in Tennessee have been those associated with *hydrologic* (Figure 5.2), *wind* (Figure 5.3) and *winter* (Figure 5.4) events. Heavy precipitation and various forms of flooding have been experienced more than a dozen times in nearly every Tennessee county. Notable areas where such events have been most commonly observed

[3] The extent to which the geographical area may vary from county-to-county was not considered in this analysis.

(multiple times annually) is a region comprised of counties located in Middle Tennessee and select other counties within the state, particularly Shelby County. Various forms of damaging straight-line winds have posed a significant hazard to all counties within the state. The East and Middle Tennessee regions, along with Shelby County, are most heavily represented in this regard. Although all counties in the state experience a winter event on average at least once a year, the dominant area of occurrence, as expected, is in East Tennessee.

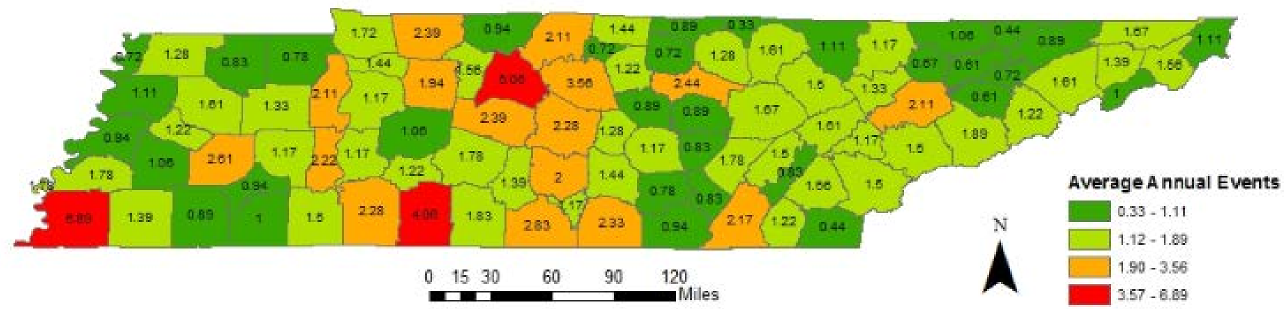

Figure 5.1 - Average Annual Hydrologic Events by County

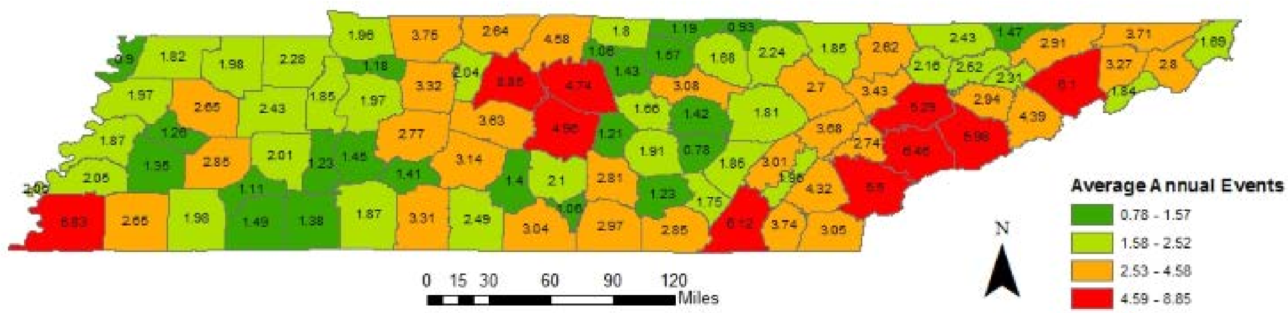

Figure 5.2 - Average Annual Wind Events by County

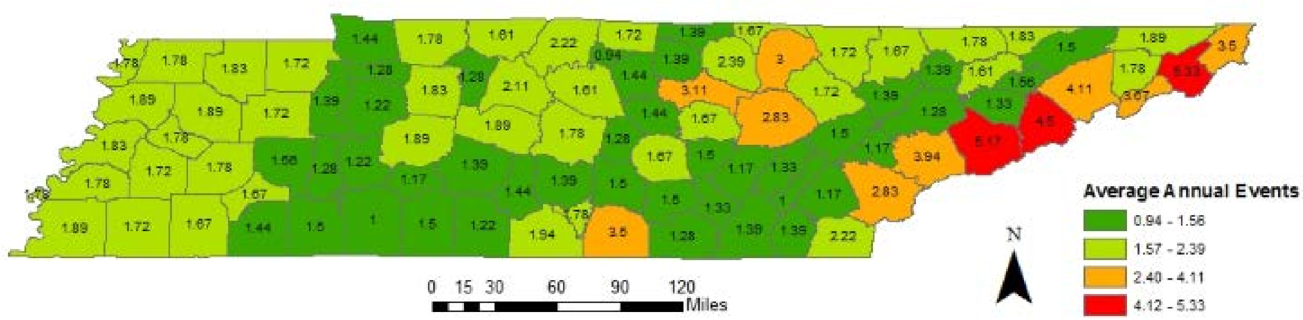

Figure 5.3 - Average Annual Winter Events by County

When considering all of the NWS extreme weather events that have occurred in Tennessee since database inception, one can generate the average number of annual extreme weather events experienced by each county within the state. This information is presented in Figure 5.5. The obvious conclusion is that every county in Tennessee experiences several extreme weather events in a typical year, suggesting that no location in the state is immune from the hazards associated with extreme weather. However, two counties, Davidson (Nashville) and Shelby (Memphis), stand out in terms of the expected number of such events on an annual basis.

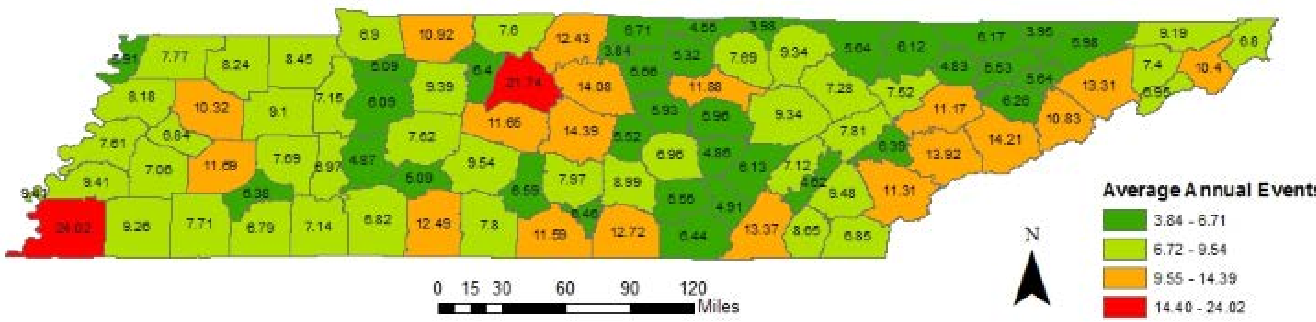

Figure 5.4 - Average Annual Extreme Weather Events by County

5.2 Future Extreme Weather Scenarios

An assessment of extreme weather that the state has experienced in the past provides a baseline for recognizing the extent to which Tennessee is exposed to these events, including where and what types of events have been occurring. As the ultimate goal is to understand what might occur over the planning period horizon, this information needs to be considered in concert with what might be anticipated in the future. In developing these projections, climate models and trend analyses were utilized, as discussed below.

A statewide vulnerability assessment presents unique challenges in projecting future weather conditions involving temperature and precipitation. Although considerable activity has been focused on developing climate models to aid this process, making such projections involves an understanding of many complex weather-related variables and interactions. As a result, the confidence one can have in the predictive results diminishes as one downscales from a regional to a more local level.

Several climate models were reviewed, with an eye towards their applicability to the project scope. Of particular interest was the work of the World Climate Research Programme, which established the Coupled Model Intercomparison Project (CMIP) to develop climate models and improve the accuracy of their projections. CMIP has proceeded in four sequential phases thus far, CMIP1 thru CMIP5 (there is no CMIP4), involving various methods of data collection, analysis, simulations, control runs, and input variability. CMIP data comes from virtually every global climate modeling group in the world and are used to inform the formal reports of the Intergovernmental Panel on Climate Change (IPCC), the leading international organization on climate change.

For this reason, the FHWA Climate Data Processing Tool received serious consideration. This tool allows users to apply downscaled CMIP3 or CMIP5 data to analyze a small geographical area for future precipitation and temperature values. CMIP divides a geographical region into 12 km x 12 km grids, and the FHWA tool allows for a maximum of four cells to be processed together at one time to obtain data for that area. It was quickly discovered, however, that using these small grids to cover an area the size of Tennessee would be extremely cumbersome. Consequently, the project took a hybrid approach that initially utilized data provided by other sources before making use of the FHWA tool.

The first step involved reviewing climate data on a broader, county-wide scope. Researchers at the University of Georgia used CMIP3 data to generate downscaled monthly averages of both precipitation and temperature for every county located in Tennessee. The data contains projections of these monthly averages for each year through the end of the 21st century.

The project used the CMIP3 data for the period of 2035-2045 (i.e., the end of the project study period) as the basis for projecting future precipitation and temperature conditions. For comparison with the recent past, historical (observed) data were utilized to obtain monthly precipitation and temperature data for each county in Tennessee for the period of 2000-2010 (most recent complete decade). In both cases, this provided 120 observations (10 years times 12 months per year) of total monthly precipitation and average monthly temperature for each county for each analysis period.

From these data points, the top 90th percentile and the bottom 10th percentile values were selected from each county in order to obtain the extreme highs and lows (for both total monthly precipitation and average monthly temperature) that have been observed (during 2000-2010) and that can be expected in the future (2035-2045). This approach provided insight into the net change in temperature and precipitation lows and highs that each county could be expected to experience in the future as compared to what is being observed now. The results are shown in Figures 5.6 - 5.9.

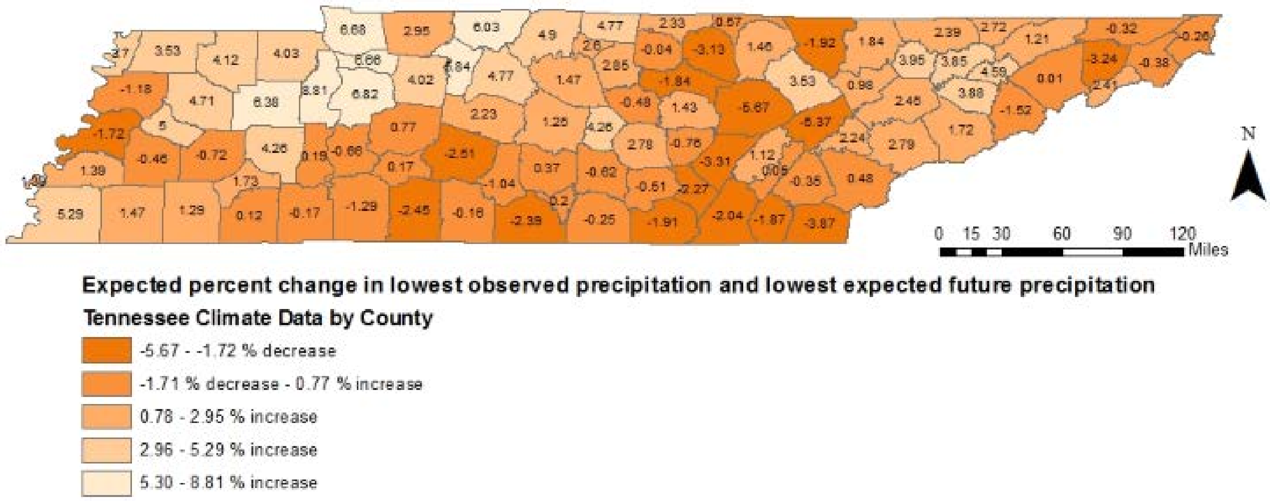

Figure 5.5 - Percent Change in Low Precipitation Values

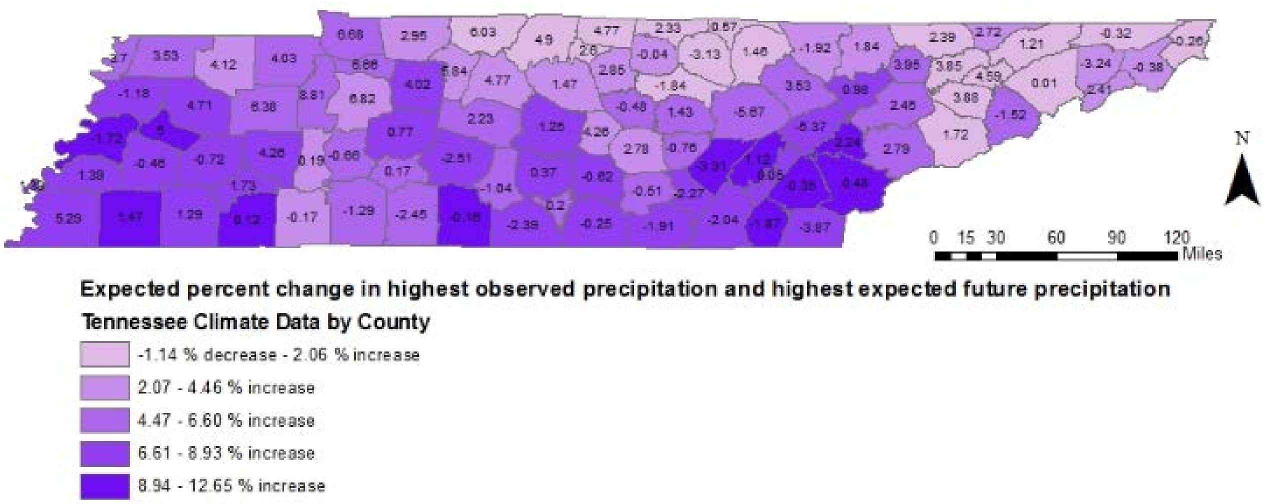

Figure 5.6 - Percent Change in High Precipitation Values

As shown in Figure 5.6, the southern portions of Tennessee and much of the Cumberland Plateau are expected to see low precipitation periods that are even drier than today, suggesting a growing concern of future drought in these areas. Interestingly, many of these same locations are also expected to experience high precipitation periods that are wetter than today (see Figure 5.7). This suggests that these areas may see more short duration, intense heavy precipitation events with long periods of dryness in between, which is consistent with the observed trends across the U.S.[4] This combination can be particularly troublesome in terms of the ability of the ground to absorb water, especially when the soil is compacted as is common practice to prepare the soil foundations around constructed transportation infrastructure. Flooding and flash flooding can more readily ensue, and such weather can also exacerbate conditions that encourage rockslides.

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[4] See "Extreme Weather" a report by the National Climate Assessment.

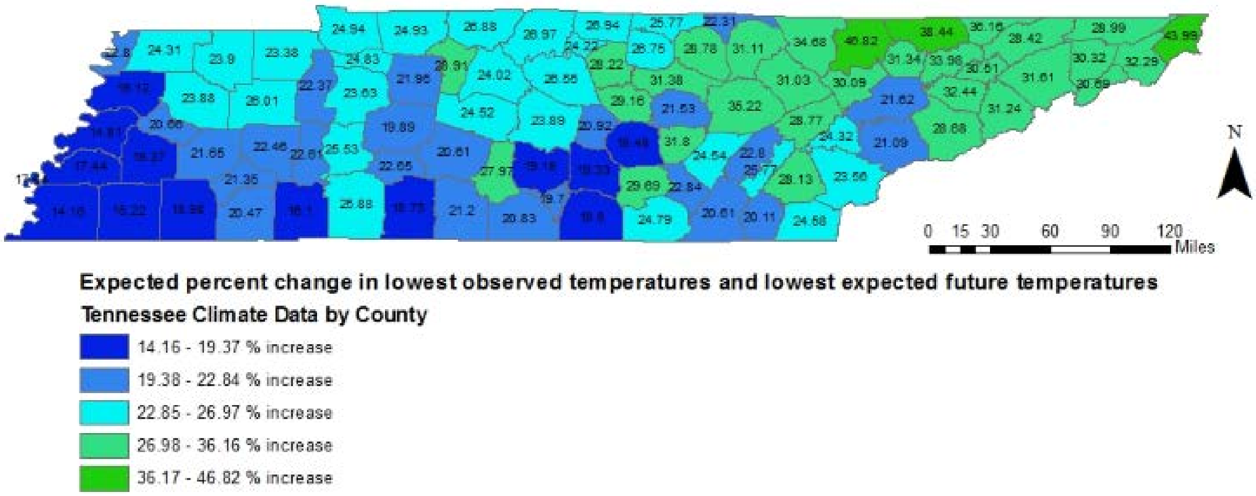

Figure 5.7 - Percent Change in Low Temperature Values

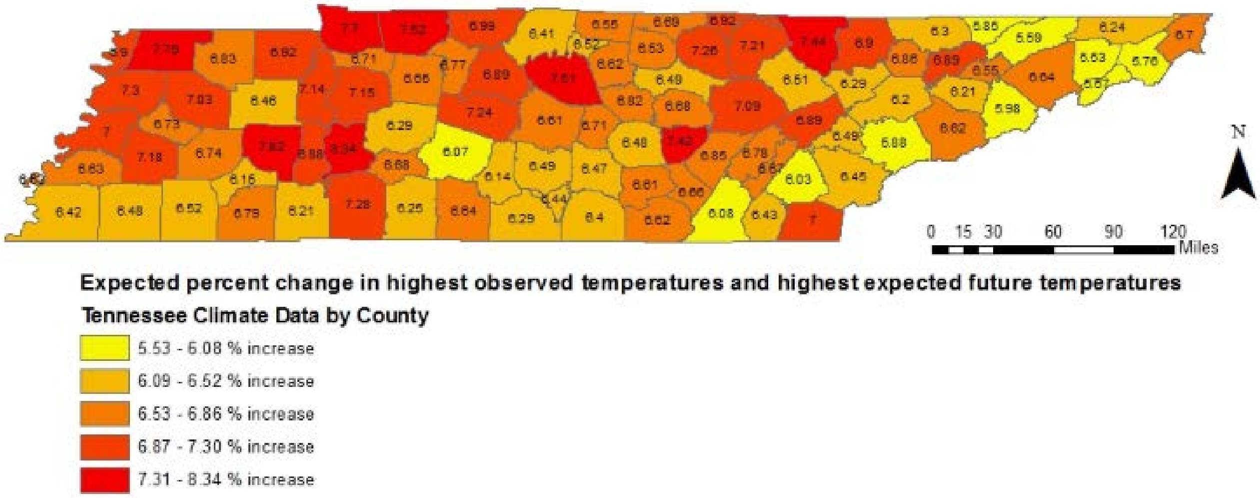

Figure 5.8 - Percent Change in High Temperature Values

Similar projections for future temperature are presented for low and high temperature conditions, respectively. Figure 5.8 depicts a projection of dramatic warming across the entire state, such that the coldest periods may be much warmer than they are now. The most significant warming is expected to occur in East Tennessee, which is also where historically there have been the most frequent winter weather events; thus, resulting in possibly less concern for winter weather vulnerability in that region. As shown in Figure 5.9, some warming will also occur throughout the state for the hottest periods of the year.

Recognizing that most of the critical transportation assets are located in or near highly-urbanized areas in Tennessee, the FHWA tool was then utilized to provide a more detailed analysis of future precipitation and temperature extremes in the state's four major cities (Chattanooga, Knoxville, Memphis, and Nashville).

Although the FHWA tool allows users to select from CMIP3 or CMIP5 data, the CMIP5 data represents the most recent advancements in climate modeling. Accordingly, the project selected CMIP5 data from the FHWA tool to run projections for these cities. The project utilized all 21 available climate models in the FHWA tool to obtain the most robust current data available, and to reduce biases that may be present in any one model. The results for both future precipitation and temperature are shown in Appendix E. Consistent with the more general county-level data, downscaled projections show significant increases in temperature and precipitation.

Whereas climate forecast models have been developed for projecting future temperature and precipitation conditions, performing a similar exercise involving other forms of extreme weather remains more of a challenge. Based on what the state has experienced in the past, strong straight-line winds and wind funnels represent two other types of extreme weather events that are known to be particularly destructive for which some indication of future trends would be helpful.

To address this consideration, the NWS storm database was utilized in performing a time series analysis, focused on thunderstorm winds and tornadoes, respectively. These two event types were selected as representative of straight-line winds and wind funnels, respectively, being the most severe events in their respective aggregate weather categories and with over fifty years of NWS observations. Sufficient data existed to perform a time series analysis for these specific forms of extreme weather at the state level, but not at the county level as in the case of temperature and precipitation[5].

Figure 5.10 displays a graph showing the annual number of reported thunderstorm winds in Tennessee from 1955 through 2013, along with a line showing the best-fit linear regression results. The regression result has a positive slope, indicating an increasing number of thunderstorm wind events occurring over the past couple of decades, and this observed trend may continue. A similar analysis was performed for tornado events, as shown in Figure 5.11. Here, although the pattern of observed tornado events is more volatile from year-to-year, these events have also been generally increasing over time, as indicated by the regression results[6].

[5] The sample sizes in some counties were considered too small to support a county-level analysis; hence the information was aggregated to the state level.
[6] It is unknown as to how much of the increases in reported thunderstorm wind and tornado events are due to more rigorous monitoring/recording practices or expansion of populous areas such that the event might trigger the NWS damage reporting threshold.

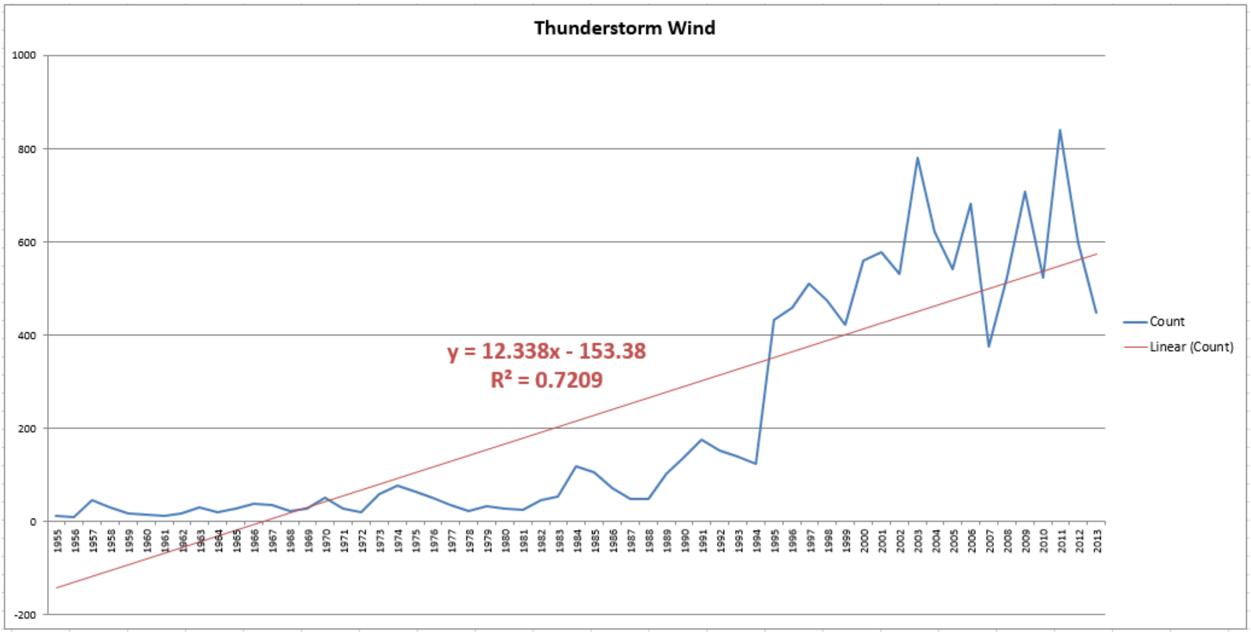

Figure 5.9 - Thunderstorm Wind Trend Analysis

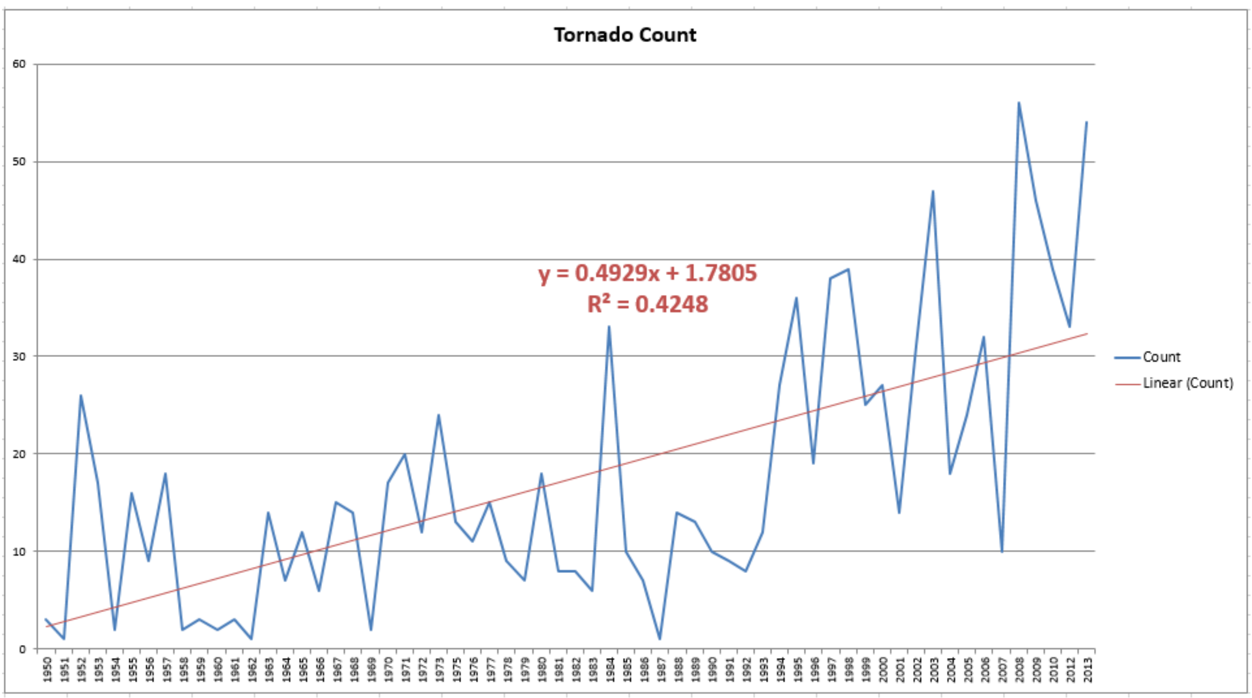

Figure 5.10 - Tornado Trend Analysis

The extent to which future extreme weather events will pose a threat to transportation infrastructure should consider the relative frequency of events. As shown in Table 5.3, these vary considerably by extreme weather category. While there is a tendency to want to focus on more frequently observed events, that conclusion cannot be reached until an analysis of impacts (direct and indirect) has been performed.

Aggregate Weather Event Category	Average Annual Occurrence Per County
Cold	0.10
Lightning	0.20
Hot	0.22
Twister	0.27
Drought	0.55
Hail	0.95
Hydrologic	1.50
Winter	1.85
Wind	2.65

Table 5.3 - Average Annual Extreme Weather per County by Event Category

6. Impacts of Extreme Weather on Critical Assets

One of the most difficult aspects of performing any vulnerability assessment is the ability to accurately estimate the asset damage and loss associated with an undesirable event should it occur. In very few cases is there sufficient empirical data to produce, with confidence, monetary estimates of asset damage and loss. For this reason, transportation extreme weather vulnerability assessments have predominantly relied on a qualitative approach to measuring these impacts. Oftentimes, these qualitative estimates are made by convening a small panel of experts to establish those values.

This project also pursued a qualitative approach for impact assessment, but utilized a more comprehensive methodology. Impact assessment in this case involved 12 asset categories and 9 aggregate weather event types, meaning that there are potentially 108 unique combinations of assets being exposed to weather events. In order to pare this number to a more manageable level, a multimodal group of transportation experts was asked to identify those combinations for which the impacts would be so small that the asset would not experience any vulnerability by being exposed to the weather event (e.g., locks can be expected to function properly when exposed to excessively hot temperatures). These experts were able to eliminate 22 asset-weather combinations from the original set.

The project then proceeded with the design and administration of a comprehensive survey in which a broad range of transportation stakeholders, geographically spread across the state, were contacted to complete. The survey was structured as an on-line instrument, with embedded logic that directed each stakeholder to answer questions only pertaining to aspects of transportation to which they considered themselves competent to respond. The survey consisted of a series of weather scenarios for each asset type, with the scenarios corresponding to events with the potential to impact the asset sufficiently to cause damage and/or disruption. Respondents were asked to evaluate the impacts according to a four-point qualitative scale (nominal, moderate, significant, catastrophic); the respondent also had the option to answer that the scenario was not applicable or that they were unsure of how to respond. The entire survey form appears in Appendix F.

The survey was sent to slightly over 400 stakeholders considered knowledgeable about various transportation assets and the project received 220 responses. This is considered a very high response rate for a survey of this kind, perhaps indicative of the level of concern about extreme weather within the transportation community. Table 6.1 presents the number of respondents according to their role as a transportation professional. Table 6.2 presents the number of responses received for each asset type. Note that the total exceeds the number of survey respondents as many respondents felt comfortable answering questions pertaining to more than one asset type.

The qualitative rankings were converted into a numerical score by assigning values as follows: nominal=1, moderate=2, significant=3 and catastrophic=4. An average qualitative score was then generated for each weather event and asset type combination based on the number of responses that were completed. The resulting impact assessment scores are displayed in Table 6.3.

Role	Count
Freight Carrier	19
State Government	73
Federal Government	10
Regional Planning Organization	3
Local Government/MPO	72
Shipper	3
Academic	6
Transit Provider	8
Airport Authority	2
Other	6
Did Not Specify	18
Total	**220**

Table 6.1 - Survey Respondents by Transportation Role

Asset Type	Count
Navigable Waterways	22
Ports	17
Roads	160
Railroads	38
Rail Yards	27
Airport Runways	14
Locks	14
Maintenance and Salt Facilities	44
Bridges Over Navigable Waterways	66
TDOT Buildings	24
Transit	36
Pipelines	6

Table 6.2 - Survey Respondents by Asset Type

In reviewing the results, it appears that respondents considered that virtually all of these extreme weather events would have at least a moderate (direct and/or indirect) impact on the transportation asset type in question. However, there were some combinations that led to different conclusions. Twisters (tornadoes) were considered a destructive force sufficient to cause significant damage to any transportation asset exposed to such an event. By contrast, strong winds are not expected to have much impact on the operability of bridges over navigable waterways, nor would excessively hot temperatures affect transit operations.

	Hot	Wind	Twister	Hail	Lightning	Winter	Cold	Hydrologic	Drought
Navigable Waterways		2.396		2.750	2.571	2.455	2.378	2.250	2.723
Ports		2.458	3.321	2.583		2.667	2.335	2.125	2.403
Roads		2.417		2.667	2.429	2.286	2.400	2.375	2.389
Railroads	2.078	2.366	3.099	2.505		2.918	2.351	2.381	
Rail Yards	2.208	2.175	3.092	2.304		2.472	2.253	2.227	
Airport Runways	2.091	2.107	3.119	2.462	2.333	2.665	2.433	2.192	
Locks	2.125	2.417	3.136	2.700	2.700	2.836	2.661	2.211	
Maintenance and Salt Facilities		2.261	3.225	2.333		2.625	2.350	2.208	
Bridges Over Navigable Waterways	2.094	1.068	2.821	2.152		2.688	2.406	2.330	2.300
TDOT Buildings		2.042	3.036	2.200		2.551	2.238	2.056	
Transit	1.154	2.419	3.315	2.500	2.375	2.772	2.451	2.411	
Pipelines	2.000			2.000	2.000	2.500	2.500	2.500	2.000

Table 6.3 - Impact Scores by Asset Type and Aggregate Weather Category

7. Vulnerability Assessment Results

The vulnerability assessment process concluded by multiplying the annual expected frequency of each type of extreme weather event and the impact score for the asset type when exposed to the particular extreme weather event. This vulnerability score was derived separately for each county in Tennessee, since each county has unique weather event frequencies associated with its location.

Appendix G presents maps of vulnerability scores for every county in Tennessee for each asset-weather combination for which impact assessments were performed. Table 7.1 displays a map showing the vulnerability scores for roads exposed to an extreme hydrologic event.

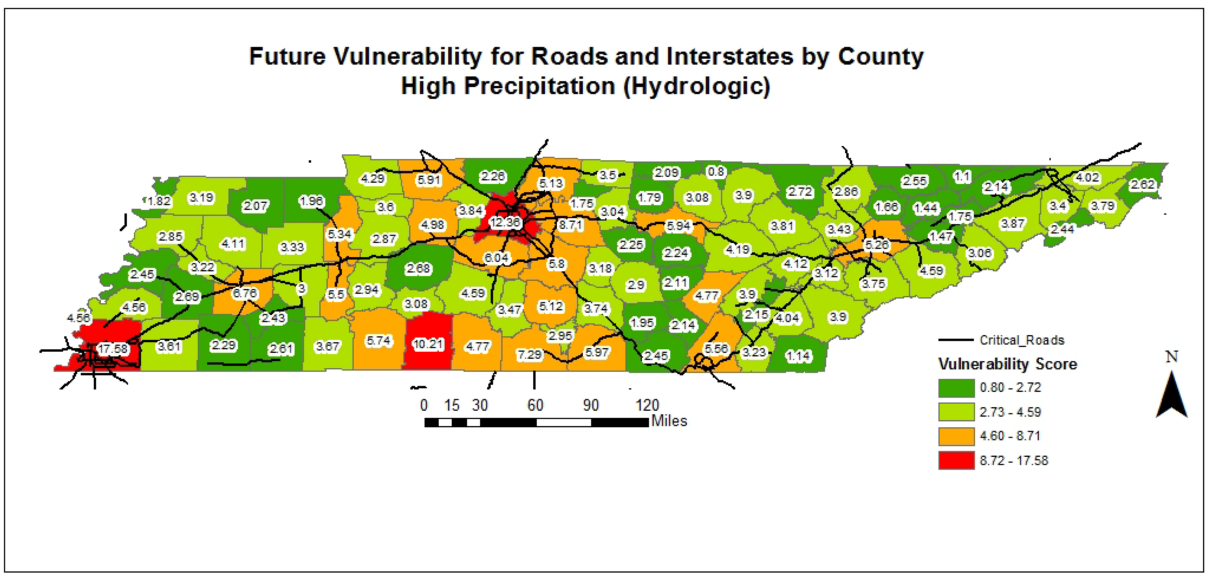

Figure 7.1 - Vulnerability Scores for Critical Roads Exposed to an Extreme Hydrologic Event

The map clearly shows that the location with the greatest vulnerability to critical roads from a hydrologic event is Shelby County (Memphis). This is not surprising as Memphis is located on the lower Mississippi River in a relatively flat section where “pooling” of water from upstream flow naturally occurs. Should a heavy precipitation event occur in Shelby County, there is significant potential for severe flooding with corresponding damage to roads and/or severe disruption to freight and passenger transport. This problem is exacerbated by an increase in precipitation that is expected in the future.

Since vulnerability scores vary by county within and between maps, it became important to establish a threshold score value to distinguish locations that warrant more serious consideration as having critical assets with high potential vulnerability. The project set a vulnerability score threshold of 15.0 to make this distinction[7].
Utilizing this threshold, the critical assets appearing in Table 7.1 were identified as being particularly vulnerable, listed according to their county location and the extreme weather event of concern. What is particularly interesting in reviewing these results is that most of the extreme weather categories are not represented on this list, either because of a relatively low expected frequency of occurrence or because the transportation assets were considered capable of withstanding the effect of these events without considerable damage or disruption.

Referring to the list, outside of roads in Sevier County, winter weather did not appear to be that serious of a concern. With regard to heavy precipitation, Davidson County and Shelby County emerged as problematic for all transportation assets located in their jurisdictions[8]. By contrast, many different asset types in several locations have the potential to be impacted by strong winds. Notable in this regard are vulnerabilities associated with roads, with many counties having vulnerability scores for wind that exceed the threshold. This result makes intuitive sense as strong winds have been known to be problematic in terms of downed trees and power lines that often make roads impassable.

One additional factor worth noting is the propensity for rockslides in the state, particularly in Middle and East Tennessee, where steep slopes and limestone formations are prevalent. Figure 7.2 shows the locations of high risk rockslide areas, superimposed on the critical roads in Davidson County, a county that has a high hydrologic vulnerability score. Clearly, this combination of high hydrologic vulnerability scores in locations with significant rockslide potential warrants special consideration[9].

[7] Some exceptions were made when the vulnerability score was slightly under this number.
[8] No locks are located on the lower Mississippi River; hence it is not an asset of concern in Shelby County.
[9] It is well known that water, more than any other factor, is most likely to cause previously stable slopes to fail and slide (see Geology, by Chernicoff & Whitney, 4th Ed., Prentice Hall 2007).

	Wind	Hydrologic	Winter
Navigable Waterways	Davidson Shelby	Davidson Shelby	
Ports	Davidson Hamilton Shelby	Davidson Shelby	
Roads	Blount Davidson Greene Hamilton Knox Munroe Rutherford Sevier Shelby Wilson	Davidson Shelby	Sevier
Railroads	Davidson Shelby	Davidson Shelby	
Rail Yards	Davidson Shelby	Davidson Shelby	
Airport Runways	Blount Davidson Hamilton Shelby	Davidson Shelby	
Locks	Davidson Hamilton	Davidson	
Maintenance and Salt Facilities	Blount Davidson Greene Hamilton Sevier Shelby	Davidson Shelby	
Bridges Over Navigable Waterways		Davidson Shelby	
TDOT Buildings	Davidson Shelby	Davidson Shelby	
Transit	Davidson Hamilton Shelby	Davidson Shelby	
Pipelines		Davidson Shelby	

Table 7.1 – Locations of Most Vulnerable Critical Assets by Weather Category

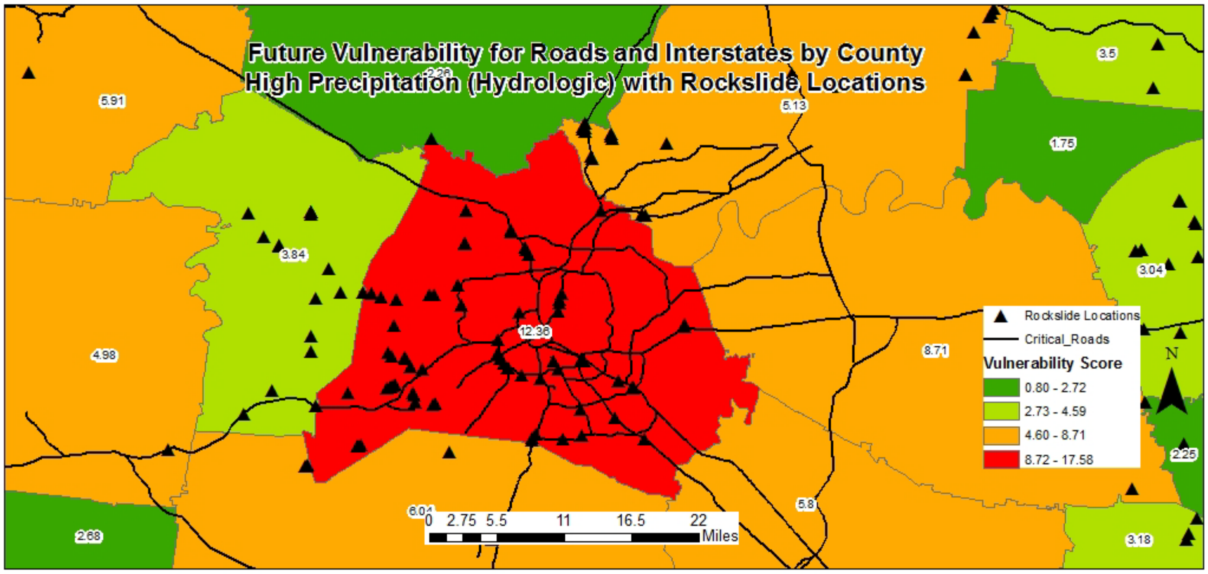

Figure 7.2 - Rockslide Locations in Davidson County Relative to Critical Roads

8. Opportunities to Enhance TDOT Policies and Procedures

An important component of this study is an examination of how the vulnerability assessment results can be utilized to enhance existing TDOT policies and procedures. Opportunities may exist to integrate the results from this project into a variety of agency activities. The following are examples where this might be possible:

- Enhance the priority of transportation investments that reduce vulnerability or provide alternative capacity for at-risk transportation assets.
- Factor information on vulnerable assets into TDOT's process for developing the State Transportation Improvement Program (STIP).
- Make adjustments to maintenance plans and procedures.
- Modify road design policies and parameters.
- Consider changes in the way TDOT designs, constructs and repairs bridges.
- Assess implications for the materials that TDOT selects for use in building roads and bridges.
- Integrate vulnerability assessment results into hazard mitigation planning and emergency management.
- Consider the impacts of extreme weather as part of the environmental review process.
- Identify new data collection activities to better characterize and monitor the condition of vulnerable assets.
- Encourage MPOs to include extreme weather vulnerability issues in updates of their Long Range Transportation Plans[10].

The extent to which these opportunities may be realized depends on the manner in which they are introduced into the policy discussion. It is therefore helpful to review how other agencies are addressing this consideration after having conducted a transportation vulnerability assessment. The following is a summary of a national scan that was performed with this objective in mind.

Several states are in the process of exploring these considerations. Virginia Department of Transportation has developed a decision-support tool that utilizes assessment results in establishing priorities among projects identified in its transportation plan. In a similar vein, Alaska is developing a list of questions that take extreme weather into account when planning a project. Washington has used its assessment results in environmental impact statements and environmental assessments to address the relationship of the transportation project to a changing climate. Hawaii has gone one step further, having successfully passed legislation that modifies its transportation policies to reflect vulnerability assessment findings[11].

Similar initiatives are underway at a more local level. The Boston MPO has developed an interactive, web-based tool that maps the transportation network, natural flood zones, bridge

[10] The Chattanooga-Hamilton County Regional Planning Agency is actively engaged in this consideration.
[11] See Hawaii Climate Adaptation Initiative Act, H.B. 1714, 2014.

condition, emergency routes, and emergency support facilities. During project evaluations, the MPO asks, "Will the project enable the facility to function in extreme weather conditions?" and "Does it improve a facility that provides redundancy in a vulnerable area?" The Los Angeles County Metropolitan Transportation Authority has added climate adaptation considerations into its construction contracts; the contractor must consider future climate impacts in the design and construction of the project. In Vermont, the Chittenden County MPO is working to integrate climate change adaptation, hazard mitigation, and transportation into a single planning document.

It is clear from this review that the issue of incorporating extreme weather vulnerability assessment findings into transportation agency policies and procedures is in its infancy, and no clear path for doing so has emerged. However, there are two recent national developments that TDOT should leverage to advance its ability to accomplish this objective:

- **Risk-based Transportation Asset Management Plan (TAMP)**. Congress, in Moving Ahead for Progress in the 21st Century Act (MAP-21), mandated that each state department of transportation develop a risk-based TAMP for its highways and bridges, although states are encouraged to include other infrastructure assets as well. TDOT is presently engaged in a separate activity to develop its plan. This extreme weather vulnerability project can provide valuable input to TDOT's risk-based TAMP in several ways. First, the transportation asset inventory and identification of critical transportation assets performed in this study can be utilized directly by the risk-based TAMP. This would be helpful not only in compiling a list of critical road and bridge assets, but also in expanding the plan to other transportation infrastructure assets. Second, the risk assessment methodology used to determine extreme weather vulnerability could be applied to other risks under consideration in the risk-based TAMP. This could provide a consistent, systematic approach to evaluating all potential risks that may be incurred by the state's transportation system, not just extreme weather risks. Finally, the results of this study can serve as the extreme weather portion of the overall risk assessment for state transportation infrastructure.

- **FHWA Order 5520**. The other recent development is the December 2014 issuance of a new directive by FHWA, Order 5520 (Transportation System Preparedness and Resilience to Climate Change and Extreme Weather Events). It is now official FHWA policy to integrate consideration of climate and extreme weather risks into its planning, operations, policies and programs. This new order formalizes FHWA's commitment to this issue, guides the agency's implementation of relevant MAP-21 provisions and recent Executive Orders, and identifies how FHWA intends to lead the transportation industry in making the nation's highways more resilient. Since TDOT policy is in alignment with FHWA policy, TDOT's response to this study's findings and recommendations presents an opportunity to pursue a course of action consistent with the direction of FHWA's commitment and expectations.

9. Next Steps

This project represents TDOT's first attempt to understand the impacts of extreme weather on transportation assets across the state. The study represents a starting point for integrating extreme weather risk into the agency's management, planning and operational practices. It also serves as a foundation that TDOT can build upon by performing follow-on activities based on the results of the extreme weather vulnerability assessment. The following initiatives are recommended for implementation.

9.1 Adaptation Project Planning

This extreme weather vulnerability assessment was an ambitious undertaking due to the number and types of transportation assets and the size of the study region. Thousands of network segments and facilities were included in the effort. The study methodology had to place each specific asset into a generic asset category. This limited the ability to examine in detail the unique characteristics associated with the asset that might impact its damage potential and resilience in the face of particular extreme weather events.

The study does serve as a valuable screening process to identify a manageable number of critical assets that warrant more detailed study of their vulnerability and the merits of potential adaptation strategies. It is strongly suggested that TDOT select 15-20 specific critical assets identified as highly vulnerable for a follow-on study. The results of this effort will advance TDOT's understanding of its extreme weather vulnerability in key locations. This more detailed analysis is an opportunity for the agency to engage in more formal adaptation planning. The proposed project would also involve many divisions within TDOT, thereby providing opportunities for agency personnel to become more familiar with this developing concern and garner experience that can be used to incorporate these considerations into TDOT policies and procedures.

9.2 Coordination With Risk-Based Asset Management Plan

Because of the obvious connections between the extreme weather project and TDOT's risk-based transportation asset management plan, a series of meetings and perhaps a formal structure could be organized to facilitate the transfer of relevant information from this assessment to the TAMP process. This could help to ensure that there is no replication of effort or inconsistency in the way in which extreme weather risks were evaluated in this study and how they are being addressed in the asset management plan.

9.3 Communicating Site-Specific Results to Local Stakeholders

This study has provided a holistic view of how extreme weather may impact transportation asset vulnerability across the state. Given that each region in the state will experience different forms of extreme weather and contain different critical asset portfolios, it would be beneficial to develop a series of “briefing books” that communicate the results of this study tailored to each region based on their unique situation. These briefing books could serve as an important resource for communities to reference in order to integrate findings into their respective transportation planning and operations.

The briefing books could identify the “top” critical assets in each of the four regions and address in more detail the specific vulnerabilities associated with those assets. The briefing books would not have to follow a set format and could be tailored to address the needs of each TDOT Region. We anticipate that these briefing books would be concise documents intended to be easily referenced and useful to local planners.

9.4 Extreme Weather Vulnerability Assessment Tool Development

As part of its pilot program, FHWA has shown a strong interest in transferring decision-support tools developed in one location that have the potential to be a valuable resource to other states and regions. This was the motivation behind FHWA’s supporting development of the Gulf Coast tools, which has led to the dissemination of the CMIP and VAST applications. In the TDOT extreme weather project, two methodologies were developed that offer the potential to supplement the tools that FHWA has already produced:

1) The process used to extract and assemble National Weather Service data to produce historic frequencies of various extreme weather events.
2) Techniques used in designing, administering and evaluating the responses of an online survey to generate estimates of the impact of various extreme weather events on various types of transportation infrastructure.

Both of these developments could be transformed into software tools that could be made available to other organizations involved in performing extreme weather vulnerability assessments. In addition to enhancing the FHWA resilience toolbox, TDOT would be nationally recognized as an innovator in helping to establish best practices for addressing a critical and emerging transportation challenge.

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Appendix A
Criteria For Determining Critical Transportation Assets

Type of Infrastructure	*Criterion*	*Measure of Criticality*	*Comments*
Roads	Heavy traffic usage and locally-defined critical arterials	Roads having one or more of the following characteristics: 1) classified as part of the Interstate highway system, 2) having current average annual daily traffic (AADT) of 25,000 vehicles or more, or future projected AADT (in 2040) of 50,000 vehicles or more, or 3) roads designated as critical from a local stakeholder perspective	FHWA recommends that high-volume routes be defined at 50,000 AADT, while acknowledging that states will vary in their approach to defining high-volume routes. Tennessee is a more rural state, and based on the AADT of its interstates and other highly traveled roads, a value of 50% of the FHWA's recommendation was deemed appropriate when examining current traffic volume data. For future traffic, a threshold of 50,000 AADT was adopted, corresponding to FHWA's previously recommended value and indicative of where growth in traffic demand is projected to occur. In addition, arterials identified as critical through stakeholder meetings were included.
Bridges	Bridges where critical transportation segments from multiple modes intersect	Road or rail bridge on a critical transport segment that passes over a navigable waterway	Should that bridge fail, it causes the potential disruption to two major transportation corridors.
Rail	National importance	Identified by the Federal Railroad Administration as being part of the strategic national rail network (STRACNET)	Represent national defense considerations or heavily utilized rail freight activity.
	Heavy traffic usage	Annual cargo of 40 million gross tons or more moved across a rail segment	
	Major rail yard	Yard processing capacity of 1,000 rail cars or more or identified through stakeholder involvement	Threshold for a rail yard in which significant activity would be expected.
Waterway	Major port	Berth length of 1,000 feet or more	A measure of how many "parking spots" may exist at a port and therefore an indication of cargo volume/use.

Type of Infrastructure	*Criterion*	*Measure of Criticality*	*Comments*
	Navigable waterway	All navigable waterways considered critical to marine freight transport	The Wolf River was excluded from this consideration based on local stakeholder input that no significant freight activity occurs on this portion of the waterway network.
	Lock	All locks deemed critical	Without the operability of a lock, no marine freight can move downriver or upriver from that point.
Airport	Major airport	Runway length of 6,000 feet or more	Runway length is a determinant for being able to serve commercial aircraft of a reasonable size. Commercial airports with runway lengths of 6,000 feet or more were deemed critical; other airports with comparable runway lengths were deemed important.
Pipeline	Major natural gas or oil pipeline	Pipeline diameter of 10" or more (both natural gas and oil)	Pipe diameter is a proxy measure for volume of flow through pipeline segment. Diameters of 10" or more are more likely to be transmission lines.
Transit	Fleet storage or maintenance facility; main transfer hubs	As defined by Standard Industrial Classification (SIC) code, supplemented by information provided by local transit operators	This included major transit hubs within the four largest cities, such as large bus transfer stations or fleet storage locations. The Memphis Amtrak station was also included due to its connection to the national passenger rail system.
Maintenance/salt facility; TDOT offices	Essential to maintaining transportation system operability	Locations where maintenance facilities, salt repositories, or traffic control systems are situated	Maintenance/salt facilities were classified as critical if they: 1) were located in the four largest cities in the study area (Chattanooga, Knoxville, Memphis, Nashville), or 2) were located near an Interstate highway.

Appendix C
National Weather Service Extreme Weather Event Types Recorded In Tennessee

Cold/Wind Chill – Period of low temperatures or wind chill temperatures reaching or exceeding locally/regionally defined advisory (typical value is -18^{o} F or colder) conditions, on a widespread or localized basis. There can be situations where advisory criteria are not met, but the combination of seasonably cold temperatures and low wind chill values (roughly 15^{o} F below normal) must result in a fatality. In these situations, a cold/wind chill event may be documented if the weather conditions were the primary cause of death as determined by a medical examiner or coroner. Normally, cold/wind chill conditions should cause human and/or economic impact. This event is only used if a fatality/injury does not occur during a Winter Precipitation event.

Drought - A deficiency of moisture that results in adverse impacts on people, animals, or vegetation over a sizeable area. Conceptually, drought is a protracted period of deficient precipitation resulting in extensive damage to crops, resulting in loss of yield. There are different kinds of drought: meteorological, agricultural, hydrological, and social-economic. Droughts are rated as D0, D1, D2, D3, or D4 based on the intensity of the moisture deficiency and other factors. A drought event is included in the database when the drought is rated as a D2 classification, or higher.

Dust Devil - A ground-based, rotating column of air, not in contact with a cloud base, usually of short duration, rendered visible by dust, sand, or other debris picked up from the ground, resulting in a fatality, injury, or damage. Dust devils usually result from intense, localized heating interacting with the micro-scale wind field. Dust devils that do not produce a fatality, injury, or significant damage are also entered as an event if they are unusually large, noteworthy, or create strong public interest.

Excessive Heat - This results from a combination of high temperatures (well above normal) and high humidity. An Excessive Heat event is reported in the database whenever heat index values meet or exceed locally/regionally established excessive heat warning thresholds, on a widespread or localized basis. Fatalities (directly-related) or major impacts to human health occurring during excessive heat warning conditions are reported using this event category. Fatalities or impacts to human health occurring when conditions meet locally/regionally defined heat advisory criteria are reported within the Heat event category instead.

Extreme Cold/Wind Chill - A period of extremely low temperatures or wind chill temperatures reaching or exceeding locally/regionally defined warning criteria (typical value around -35^{o} F or colder), on a widespread or localized basis. Normally these conditions should cause significant human and/or economic impact. However, if fatalities occur with cold temperatures/wind chills but extreme cold/wind chill criteria are not met, the event is recorded in the database as a Cold/Wind Chill event. This event is only used if a fatality/injury does not occur during a Winter Precipitation event.

Flash Flood - A rapid and extreme flow of high water into a normally dry area, or a rapid water level rise in a stream or creek above a predetermined flood level, beginning within six hours of the causative event (e.g., intense rainfall, dam failure, ice jam-related), on a widespread or localized basis. Ongoing flooding can intensify to flash flooding in cases where intense rainfall results in a rapid surge of rising flood waters.

Flood - Any high flow, overflow, or inundation by water which causes or threatens damage. In general, this would mean the inundation of a normally dry area caused by an increased water level in an established watercourse, or ponding of water, generally occurring more than six hours after the causative event, and posing a threat to life or property. This can be on a widespread or localized basis. River flooding may be included in the Flood category. However, such entries should be confined only to the effects of the river flooding, such as roads and bridges washed out, homes and businesses damaged, and the dollar estimates of such damage.

Freezing Fog - Fog which freezes on contact with exposed objects and forms a coating of rime and/or glaze, on a widespread or localized basis, resulting in an impact on transportation, commerce, or individuals. Freezing fog can occur with any visibility of six miles or less. Even small accumulations of ice can have an impact.

Frost/Freeze - A surface air temperature of 32^{o} F or lower, or the formation of ice crystals on the ground or other surfaces, over a widespread or localized area for a period of time long enough to cause human or economic impact.

Funnel Cloud - A rotating, visible extension of a cloud pendant from a convective cloud with circulation not reaching the ground. This would include cold-air funnels which typically form in a shallow, cool air mass behind a cold front. The funnel cloud should be large, noteworthy, or create strong public interest to be included in the database.

Hail - Frozen precipitation in the form of balls or irregular lumps of ice. Hail 3/4 of an inch or larger in diameter will be entered. Hail accumulations of smaller size which cause property and/or crop damage, or casualties, are also recorded.

Heat - A period of heat resulting from the combination of high temperatures (above normal) and relative humidity. A Heat event occurs and is recorded whenever heat index values meet or exceed locally/regionally established advisory thresholds. Fatalities or major impacts on human health occurring when ambient weather conditions meet heat advisory criteria are reported using the Heat category. If the ambient weather conditions are below heat advisory criteria, a Heat event entry is permissible only if a directly-related fatality occurred due to unseasonably warm weather, and not man-made environments.

Heavy Rain – An unusually large amount of rain which does not cause a Flash Flood or Flood, but causes damage or other human/economic impact. Heavy rain situations, resulting in urban and/or small stream flooding, are classified as a Heavy Rain event or another suitable event that occurred at the same time.

Heavy Snow - Snow accumulation meeting or exceeding locally/regionally defined 12 and/or 24 hour warning criteria, on a widespread or localized basis. This could mean such values as 4, 6, or 8 inches or more in 12 hours or less; or 6, 8, or 10 inches in 24 hours or less. In some heavy snow events, structural damage, due to the excessive weight of snow accumulations, may occur in the few days following the meteorological end of the event.

High Wind - Sustained non-convective winds of 35 knots (40 mph) or greater lasting for one hour or longer or winds (sustained or gusts) of 50 knots (58 mph) for any duration (or otherwise locally/regionally defined), on a widespread or localized basis. In some mountainous areas, the above numerical values are 43 knots (50 mph) and 65 knots (75 mph), respectively. The High Wind event name is not used for severe local storms, tropical cyclones, or winter storm events. Events with winds less than the High Wind event threshold numbers, resulting in fatalities, injuries, or significant property damage, are encoded as a Strong Wind event.

Ice Storm - Ice accretion meeting or exceeding locally/regionally defined warning criteria (typical value is 1/4 or 1/2 inch or more), on a widespread or localized basis. This event is also recorded for a fatality/injury that results from hypothermia in a power loss situation due to an ice storm.

Lightning - A sudden electrical discharge from a thunderstorm, resulting in a fatality, injury, and/or damage directly related to the lightning strike. Anyone seeking or receiving medical attention following a lightning incident is counted as a lightning injury. Anyone reporting numbness, a tingling sensation, a headache, or other pain following a lightning incident, whether or not they receive treatment, is also counted as an injury.

Sleet - Sleet accumulations meeting or exceeding locally/regionally defined warning criteria (typical value is ½ inch or more).

Strong Wind - Non-convective winds gusting less than 50 knots (58 mph), or sustained winds less than 35 knots (40 mph), resulting in a fatality, injury, or damage. Inland counties which experience strong winds/damage associated with tropical cyclones are recorded under the Tropical Depression or Tropical Storm category, as appropriate, rather than as a Strong Wind event.

Thunderstorm Wind - Winds arising from convection (occurring within 30 minutes of lightning being observed or detected), with speeds of at least 50 knots (58 mph), or winds of any speed (non-severe thunderstorm winds below 50 knots) producing a fatality, injury, or damage. Maximum sustained winds or wind gusts (measured or estimated) equal to or greater than 50 knots (58 mph) are always entered. Events with maximum sustained winds or wind gusts less than 50 knots (58 mph) are entered only if they result in fatalities, injuries, or serious property damage.

Tornado - A violently rotating column of air, extending to or from a cumuliform cloud or underneath a cumuliform cloud, to the ground, and often (but not always) visible as a condensation funnel. In order for a vortex to be classified as a tornado, it must be in contact with the ground and extend to/from the cloud base, and there should be some semblance of ground-based visual effects such as dust/dirt rotational markings/swirls, or structural or vegetative damage or disturbance. An Enhanced Fujita (EF) or Fujita (F) Damage Scale value is entered, depending on the year of occurrence.

Winter Storm - A winter weather event which has more than one significant hazard (i.e., heavy snow and blowing snow; snow and ice; snow and sleet; sleet and ice; or snow, sleet and ice) and meets or exceeds locally/regionally defined 12 and/or 24 hour warning criteria for at least one of the precipitation elements, on a widespread or localized basis. Normally, a Winter Storm would pose a threat to life or property.

Winter Weather - A winter precipitation event that causes a death, injury, or a significant impact to commerce or transportation but does not meet locally/regionally defined warning criteria. A Winter Weather event could result from one or more winter precipitation types (snow, or blowing/drifting snow, or freezing rain/drizzle), on a widespread or localized basis.