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Asset Management, Extreme Weather, and Proxy Indicators

Final Report

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16. Abstract

This report presents the results of a Climate Resiliency Pilot Project conducted by the Kentucky Transportation Cabinet (KYTC) in collaboration with the University of Kentucky Transportation Center and sponsored in part by the Federal Highway Administration (FHWA). The primary objectives of the Pilot Study are to enhance KYTC's asset management program by developing processes that account for the impacts of extreme weather on the transportation system. Two major asset classes were considered in this project – bridges and pavement – as well as two major climate-related stressors – extreme heat and extreme precipitation. Within this context, the report presents two technical analyses. The first describes the development and implementation of a screening tool that employs existing data already gathered by KYTC bridge inspectors to assess bridge sensitivity to flooding. The second describes a methodology for utilizing downscaled climate projection data to model pavement performance within the context of a projected warmer and wetter environment. In addition to these two technical analyses, the report presents KYTC process improvement strategies that were identified for the potential to enhance KYTC's assent management program. These include improved FHWA Emergency Relief (ER) project monitoring, the creation of a resilience-themed GIS database, and the formation of a KYTC Resilience Working Group.

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EXECUTIVE SUMMARY

Accounting for the effects of extreme weather and climate change on transportation assets poses a real challenge to agencies managing these assets. Climate models predict conditions that will gradually differ over the next century compared to those encountered historically. For Kentucky, these models generally predict a warmer and wetter environment. These conditions are already being experienced in Kentucky, as 2012 was the hottest year on record and 2018 was the wettest. As these climate trends continue to progress, they will likely lead to an increased frequency of extreme weather events, particularly those associated with extreme heat and precipitation. Because it is unclear the extent to which Kentucky's transportation system will be affected by these changes, research is needed to identify potential impacts and develop mitigation strategies.

This pilot project serves as a building block for the Kentucky Transportation Cabinet (KYTC) in its efforts to develop a more robust risk-based asset management program. This pilot considers the two major climate threats in Kentucky – extreme heat and extreme precipitation – and develops methodologies for analyzing their potential impacts to two major asset classes – pavements and bridges. A better understanding of how these changing climate conditions may affect KYTC's transportation infrastructure will lead to better planning, budgeting, and system resilience.

This project was comprised of three separate but related efforts designed to enhance KYTC's ability to effectively perform asset management planning within the context of extreme weather. The first is a technical analysis that develops a screening tool for identifying bridge sensitivity to flooding. The second is a technical analysis that develops a methodology for incorporating climate projection data into pavement design and performance monitoring. The third is an assessment of processes within KYTC that could be improved to promote better asset management practices.

Developing Bridge Sensitivity Indicators to Flooding

The objective of the first technical analysis was to provide KYTC with a high-level, asset screening tool that uses National Bridge Inventory (NBI) data to develop flood and scour risk indicators. The tool was designed to let engineers, maintenance workers, and other stakeholders quickly discern risk to structures. Because the tool is predominantly based on NBI elements, it may be easily replicable by other transportation agencies. The tool is comprised of three categories of indicators:

- The Structural Condition score offers insights into bridges and culverts that are susceptible to high-magnitude flooding and geomorphic instabilities. It can be used to quickly discern the overall structural integrity of a bridge based on NBI data.
- The Geomorphic Sensitivity score indicates the sensitivity of a bridge based on its environment, such as bank composition, vegetation cover, erosion control features, and channel sinuosity. As a score, Geomorphic Sensitivity is dependent primarily on channel condition, scour potential, and observed scour. This index uses a combination of data from the NBI and KYTC.
- The Criticality score measures how integral an asset is to the transportation network. The criticality score incorporates NBI elements pertaining to detour length, structure replacement value, structure length, traffic volume, and truck volume.

For each of these parameters, the NBI elements are reclassified, weighted, and combined according to criteria established by KYTC bridge engineers. The reclassified values range from 1 to 3, where 3 indicates higher sensitivity. Combining each scoring area – Structural Condition, Geomorphic Sensitivity, and Criticality - results in a composite Bridge and Culvert Sensitivity Index (BCSI) rating. This was calculated for all bridges (over water) and culverts included in Kentucky's NBI, which totaled 12,459. Figure 1 presents a subset summary of the results for the 7,322 KYTC owned bridges in the NBI.

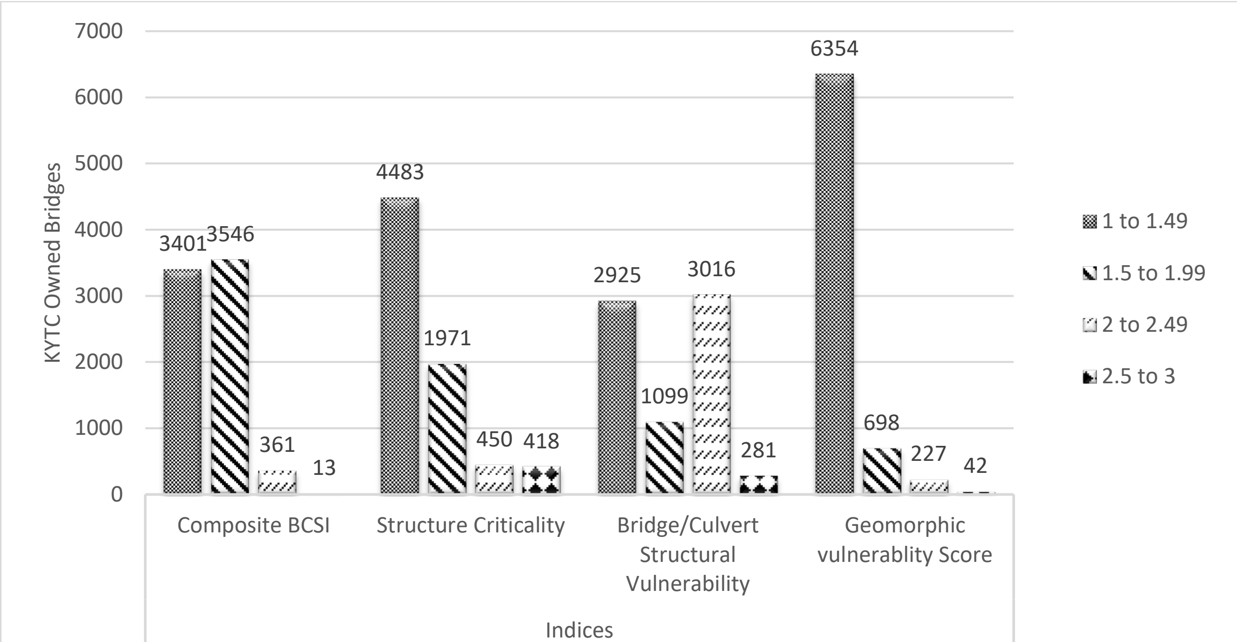

Figure 1 Composite BCSI and Component Index Rating for all KYTC Bridges (over water) and Culverts Included in the NBI.

Computing scores for the four indices described here, then evaluating the results using statistical and geospatial analyses, will help agencies quickly identify areas within their jurisdiction in which there are structures that call out for greater scrutiny. This mode of analysis can delineate spatial variabilities in structural performance to understand what issues contribute to higher index scores and in turn guide the selection of appropriate countermeasures.

Modeling pavement performance to extreme heat in future climate scenarios

The second technical analysis included in this report investigates the viability of using climate projection data to model pavement performance. This study utilizes Pavement ME, the Mechanistic Empirical Pavement Design software developed from the National Cooperative Highway Research Program (NCHRP) 1-37A project. KYTC uses Pavement ME in its pavement design and performance monitoring program. Pavement ME calculates the elastic modulus for each layer of pavement for each hour based on the temperature provided. The elastic modulus change is used to calculate the damage to the pavement.

For this analysis, climate projection data were obtained from the World Climate Research Programme's (WCRP's) Coupled Model Intercomparison Project Phase 5 (CMIP5) multi-model dataset. Because this effort was designed to be a proof of concept to analyze the impacts of extreme weather, the Representative Concentration Pathway (RCP) scenario corresponding with the highest greenhouse gas levels (RCP8.5) was selected. Data processing resulted in two datasets of projected climate data, each representing future 20-year time periods (2020-2039, and 2040-2059). Using the historical Pavement ME data as a reference, the projected climate data were interpolated to the hourly level, and systematically combined with existing weather observations pertaining to wind speed, percent sunshine, and relative humidity, as required by Pavement ME. The projected climate file showed an increased average annual temperature for the study area of just over 3 degrees Fahrenheit (°F).

Pavement performance was predicted for both a 20-year and 40-year anticipated pavement life. In each of the pavement design projections, Pavement ME results demonstrated increased pavement distress levels associated with asphalt surface rutting and wheel path fatigue cracking. The predicted distresses, however, were within the normal variation of the existing climate locations across the state. As a result the increases are not high enough to warrant altering the pavement design to withstand such hotter conditions. With the method now developed, it can be shared with other transportation agencies, who may face more challenging projections. Additionally, KYTC can revisit the simulation in 5-10 years to see how climate prediction updates may revise the outcome.

KYTC process improvements

In addition to the two technical analyses, this pilot identified opportunities whereby KYTC processes could be improved to better account for extreme weather and promote system resilience. Two of these process improvements involved updating how KYTC tracks and monitors its involvement in the Federal Highway Administration (FHWA) Emergency Relief Program (ER). Through this project, a centralized Geographic Information System (GIS) database was developed to track the locations and details for ER projects going back to 2009. This database will assist KYTC in fulfilling its 23 CFR Part 667 requirements. In addition, internal processes that KYTC uses to assign activities to ER projects were updated to better account for activities outside the immediate scope of ER activities, such as National Environmental Policy Act (NEPA) analyses triggered by an ER event.

Other process improvements were identified and are included in this report as next steps for KYTC to pursue following this project. These include:

1. Continued integration of KYTC systems that track and monitor all costs associated with ER events. KYTC would ultimately like to be able to track costs associated with smaller events as well, but ER events would serve as a first step in that direction.
2. Development of KYTC maintenance activities that can proactively prepare for extreme precipitation in advance of the event.
3. Establishment of a Resiliency Working Group.
4. Continued incorporation of extreme weather risk into asset management and KYTC's Transportation Asset Management Plan (TAMP).

Introduction to the Project

Project Purpose

The Federal Highway Administration (FHWA's) call to incorporate risk management into asset management plans has prompted changes in how transportation agencies identify risks, collect information on asset vulnerability, and develop more robust management practices. The Moving Ahead for Progress in the 21st Century Act (MAP-21) adopted requirements for States to "develop and implement risk-based asset management plans for the National Highway System (NHS) to improve or preserve the condition of the assets and the performance of the system." These requirements were carried through in the Fixing America's Surface Transportation (FAST) Act, which added provisions on critical infrastructure in asset management planning. To meet these requirements, the Kentucky Transportation Cabinet (KYTC) developed a risk-based asset management plan for its NHS assets. Through the results of this pilot project, KYTC anticipates developing and refining a more robust asset management program and being able to share its experiences with other transportation agencies. This opportunity allows for improved asset management practices through enhanced risk management strategies.

Extreme weather events that negatively affect KYTC's transportation assets have become more frequent over the past several decades. These events damage assets, increase mitigation and maintenance costs, and further strain already-stretched transportation budgets. This pilot project improves KYTC's management of its pavement and bridges against threats from extreme weather. This enhances current efforts to keep highways safe using fiscally responsible methods. Safer, well-maintained roads will improve the quality of life for Kentuckians.

Goals

This project builds on KYTC's recent and ongoing work that investigates transportation asset vulnerability to natural hazards. The goal is to establish a framework for identifying asset risks associated with extreme weather, and incorporate that information into the management of the transportation system across all levels. It is broadly understood that extreme weather events can have immense consequences for transportation systems in the form of increased costs, budgetary impacts, and reduced life cycles. However, accounting for the likelihood of extreme weather events affecting different asset classes is less clear, and methods need to be developed for anticipating impacts and identifying appropriate mitigation and monitoring strategies that minimize potential risks.

Scope

The project presents methodologies for identifying the sensitivity of two asset classes - pavement and bridges - to two types of extreme weather - extreme heat and extreme precipitation (and resulting flood). The project results help KYTC improve its transportation program so that funds budgeted for maintenance, replacement, mitigation, and inspections can better account for the effects of extreme weather on assets.

Specifically, this pilot project centers on three major initiatives undertaken to improve KYTC's ability to account for the impacts of extreme weather in its asset management program:

1. *Develop and refine flood sensitivity indicators for bridges*: Through this project, a methodology was developed that utilizes existing data collected by KYTC through its bridge inspection program to identify bridges potentially sensitive to flooding. The data is comprised of both NBI data and additional scour-risk data collected by KYTC bridge inspectors. Weighted formulas

were developed to calculate indicators for Structural Condition, Geomorphic Sensitivity, and Criticality. Combining these three scores together resulted in a Bridge and Culvert Sensitivity Index (BCSI) rating. KYTC anticipates using the BCSI to better inform project prioritization and asset management practices.

2. *Develop a methodology for incorporating the effects of projected warmer temperatures on pavement design and performance monitoring*: Through this project, a proof of concept methodology was developed that incorporates downscaled climate projection data as an input for Pavement ME, a pavement design and performance monitoring software program used by KYTC. This proof of concept successfully demonstrated the viability of using climate projection data to model the impacts of extreme weather on pavement performance. Further research will be needed to further develop the relationship between extreme temperatures and modeled pavement performance.
3. *Identify opportunities for KYTC process improvements that promote transportation system resiliency to extreme weather*. Several KYTC processes were identified:
    - Documentation for Emergency Relief (ER) projects were brought into a central database and the records were codified in a geographic information system (GIS).
    - The process whereby KYTC divisions report and bill to ER projects was updated, so that all ER activities, including those involving the National Environmental Policy Act (NEPA), would be appropriately billed and funded.
    - KYTC's project prioritization scoring process, entitled the Strategic Highway Investment Formula for Tomorrow (SHIFT), was identified as a potential area to implement the BCSI developed through this project
    - Continued development of the risk register to further incorporate extreme weather threats was identified for future versions of the Transportation Asset Management Plan (TAMP).
    - Opportunities to bring together multiple data sources already collected by KYTC to better account for and communicate risks associated with extreme weather.

Background

Kentucky is located within the Southeast region of the United States. The climate of the Southeast is seasonal and influenced by a number of factors including latitude, topography, and proximity to large bodies of water (Kunkel et al., 2013). Because Kentucky lies on the northwest corner of the region, it also shares characteristics with the Midwestern region directly to its north. Kentucky has a moderate humid climate with abundant rainfall. The climate across the state is affected by geographical attributes such as hills, mountains, rivers, lakes, and plains (Arnold 2018). Two high-pressure systems affect the region, causing the area to experience extreme heat and moisture during the summer months. According to existing research, climate extremes will continue to affect the state (Kunkel et al., 2013).

The effects of climate changes on transportation assets poses great uncertainty and challenges to transportation agencies. In order to prepare for these challenges and to mitigate the potential effects, risk-based asset management plans should be employed. TAMPs serve as a focal point for information about assets, management strategies, long-term expenditure forecasts, and business processes (FHWA 2017). TAMPs typically rely upon gradual, predictable deterioration curves. However, as climate-related information are incorporated into these plans, the approach will need to be adjusted due to weather events being neither gradual nor predictable (USDOT 2013).

Risk management and asset management are complimentary disciplines. By modifying plans to include risk management, TAMPs can be used in relation to environmental threats. Instead of focusing on their prevention, plans must focus on minimizing their effects. A risk-based asset management program can do just that. By providing accurate inventories of assets and their condition, practicing regular maintenance, prioritizing critical assets in a hierarchical form, and mapping assets using GIS capabilities, agencies can be better prepared for specific scenarios (USDOT 2013). Officials need to determine what climate stresses the transportation system might face in the future, how vulnerable the system will likely be to these stresses, and what strategies can be considered to avoid, minimize, or mitigate potential consequences (Meyer et al., 2015). The intent is to ingrain preparation for climate-based extreme weather events as a basic goal or objective of asset management programs (USDOT 2013).

A vital part of studying climate is analyzing the history of climate effects. In past research, data parameters from 1901 through 2011 have served as historical reference points. (Peterson et al., 2008; Kunkel et al., 2013) These indicators included maximum temperature, minimum temperature, and precipitation throughout the contiguous United States (Peterson et al., 2008). The historical climate conditions are meant to provide a perspective on what has been happening in each region and what types of extreme events have been noteworthy (Kunkel et al., 2013).

Context of Pilot

KYTC has made significant strides in recent years with incorporating asset management philosophy into its core processes. KYTC participated in an asset management gap analysis with assistance from FHWA in 2015. The gap analysis revealed areas where KYTC needed to focus to implement a TAMP. Areas to focus on included the expanded use of technology and easy-to-access current data, historic trends, and forecasts pertaining to asset condition, and budget allocations to improve and sustain the condition of assets in a state of good repair. While the gap analysis focused on the primary risks of budget and personnel, this easily could translate into the efforts to include extreme weather risks as well. Making these data accessible will be critical for their incorporation into the TAMP and the management of KYTC's assets.

Kentucky's first TAMP was initiated in 2016, and the initial draft was submitted to FHWA in 2018. During the development of the TAMP the life cycle planning used national deterioration models for pavements and bridges. KYTC is developing state-specific models for deterioration for both asset classes. National and state level deterioration models do not address the impact of natural disasters on assets. Knowing the potential impacts and costs at an asset class level allows for better plan development with costs that more accurately reflect addressing these impacts as projects are developed.

KYTC currently develops fundamental life cycle cost information for pavement to compare materials used in pavement construction. The fundamental life cycle cost information has also been used to determine needed funding to meet performance objectives for pavement rehabilitation projects, the asphalt resurfacing program, and pavement preservation efforts. KYTC is building a database of initial construction costs for several preventive maintenance treatments. The database contains information on the remaining service intervals a preventative treatment adds to a specific segment of pavement. As the pavement preventive maintenance database develops, it will enhance KYTC's life cycle cost information. This process will be further improved once extreme weather factors are added to the existing process.

In 2018, a statewide vulnerability assessment of natural hazards most likely to impact the Commonwealth's transportation network was completed. KYTC worked with the University of Kentucky Transportation Center (KTC) to develop and perform the assessment, which centered on the state's NHS. The vulnerability assessment documented the natural hazards most common in Kentucky and mapped where they have occurred most frequently (Blandford et al., 2018).

Data for the assessment were gathered and produced through multiple channels. Existing meteorological and geological data were obtained from:

- Midwest Regional Climate Center [MRCC])
- Historical data related to severe storm events (National Weather Service [NWS])
- Climate projections (Oak Ridge National Laboratory [ORNL] Climate Change Science Institute)
- Geological data related to sinkholes, landslides, and earthquakes from the Kentucky Geological Survey (KGS) and U.S. Geological Survey (USGS)

Additionally, KYTC personnel and KTC researchers developed a workshop-based methodology to collect local expert knowledge from transportation personnel. The methodology included facilitated mapping and keypad rating exercises on highway system vulnerabilities. Workshops were held at all 12 KYTC districts in 2016-17.

Data from the mapping exercises and keypad ranking exercises were gathered and analyzed in GIS. Data were broken down to identify and examine the vulnerabilities of each highway segment using FHWA's

Vulnerability Assessment Scoring Tool (VAST). The result of that analysis was a district-level prioritized ranking of NHS segments based on their vulnerability to extreme weather and natural hazard events. A district vulnerability assessment report was developed to highlight the five most vulnerable assets in each district and discuss their vulnerabilities in detail. Using this methodology, district-level workshops were held by the project team at all twelve of the KYTC districts in the state. Results from the vulnerability assessment were included as part of KYTC's TAMP.

Knowing which areas are most prone to each type of disaster will focus the use of inspections and monitoring equipment. Additionally, assets can be constructed or retrofitted to abate the impacts of disasters. However, those modifications add significant cost to the project. Knowing where applying those methods will have the highest likelihood of mitigating a failure caused by a disaster will assist the KYTC in spending limited project funds most effectively.

Developing a Bridge Sensitivity Index for Flooding

Although bridge failures happen infrequently, their occurrence greatly affects the integrity and function of transportation networks. Bridge failures and closures disrupt traffic flow, hinder economic activity, and result in unanticipated and burdensome expenses for transportation agencies that manage bridge and culvert structures. Several research studies dating to the early 1990s have sought to catalogue where and why bridge failures have occurred in the United States. Harik et al.'s (1990) research investigated documented bridge failures from 1951 to 1988, focusing on Kentucky. The research identified 114 bridge failures throughout the United States during this period — 35 in Kentucky and 79 elsewhere. While the numbers for Kentucky are high compared to the rest of the country, the study's methodology clarifies why the state was overrepresented. The record of bridge failures was compiled through a search of three periodicals — the Engineering News Record, New York Times, and Louisville Courier-Journal. Only the most newsworthy events likely warranted coverage in national publications (just one of the Kentucky bridge failures featured in them). In Kentucky, short-span bridges 100 feet or less in length were the most frequently afflicted structures. Most of these were the product of vehicles exceeding posted weight limits. Of the bridge failures documented outside of Kentucky, 42 resulted from collisions by ships, trucks, trains, and other vehicles; 29 failures were attributed to natural phenomenon (e.g., flooding, scour, and wind events).

Recent work has yielded more exhaustive records of bridge failures. Many of these studies have found that bridge failures are often the product of hydraulic forcings (Wardhana and Hadipriono, 2003; Deng and Cai, 2010; Wright et al. 2012; Lin et al., 2014; Andersen et al., 2017; Flint et al., 2017; Montalvo and Cook, 2017). In this report, hydraulic forcings is a catch-all term which encompasses flooding, scour, and other perturbations attributable to flowing water. Through a study of over 500 bridge failures during the 1989-2000 period, Wardhana and Hadipriono (2003) concluded that flooding and scour factored into 53% of them. Surveying 36 historical bridge failures in the United States, Lin et al. (2014) determined 64% of the failures resulted from local scour while channel migration was the primary cause for 14%. Failures initiated by contraction scour and bed degradation were less common. Seventy-five percent of scour-induced bridge failures were the byproduct of high-magnitude flooding, with debris loading implicated in half. Most recently, Montalvo and Cook (2017) reviewed 428 vehicular bridge collapses that occurred between 1992 and 2008, analyzing pre-collapse assessment data to understand which factors contributed to failure. Of the collapsed bridges, 46% were rated structurally deficient in their most recent inspection. Roughly 55% of the bridges collapsed due to hydraulic forcings. However, most of the collapses stemming from hydraulic forcings had NBI Scour Critical Ratings between 4 and 8, indicating they had been rated as scour stable. By itself, this measure does not necessarily capture the sensitivity of bridges and culverts to hydraulic forcings and geomorphic instabilities.

Recognizing the threat powerful hydraulic forcings pose to bridges and culverts, this report presents a methodology for hierarchically analyzing bridges and culverts to determine their sensitivity to flooding, scour, and other geomorphic instabilities. Although originally developed specifically for KYTC, the framework can be implemented by other transportation agencies wanting to quickly appraise bridge and culvert inventories. Because the methodology supports a hierarchical form of analysis, agencies can use it to detect patterns of sensitivity at the regional or district scales, as well as to identify individual structures that warrant additional field inspections. Although the methodology mainly leverages NBI data, it also takes advantage of unique data collection procedures used by KYTC to perform geomorphic assessments. The methodology does not only account for geomorphic and environmental characteristics, however, it also considers a structure's condition and criticality. Condition in particular strongly influences a structure's response to hydraulic forcings. For example, Anderson et al. (2017) uncovered strong correlations between bridge damage inflicted by Tropical Storm Irene and bridge rating assessment characteristics (e.g., NBI ratings for substructure and channel and structural adequacy). They argued that integrating stream geomorphic data into bridge rating systems produce richer, more insightful evaluations of bridge sensitivity.

The methodology described here is used to generate scores for four indices, each of which tackles structural sensitivity from different angles — 1) Structural Condition, 2) Geomorphic Sensitivity, 3) Criticality, and 4) Bridge and Culvert Sensitivity Index (BCSI). The BCSI, by integrating the first three indices, offers a comprehensive representation of a structure's sensitivity to hydraulic forcings. The methodology and the resultant indices are grounded in the risk assessment literature and previous work on bridge ratings. Specifically, their foundation lies in recent efforts to characterize the geomorphic stability of stream channels in the vicinity of bridges and culverts (e.g., Johnson et al., 1999; Johnson, 2005, 2006; Johnson and Whittington, 2011) as well as techniques for performing stream reconnaissance (e.g., Thorne et al., 1996; Thorne, 1998; Klein et al., 2009). The methodology borrows from Johnson and Whittington (2011) in its approach to developing semi-quantitative ratings for structures. Unlike previous rating systems, it does not require the collection of additional field data. Although some rapid geomorphic assessments can be completed in under two hours, given the limited number of bridge inspectors in Kentucky and the abundance of structures owned by KYTC (over 7,300, including bridges [passing over water] and culverts), it is not practical to expect that inspectors can undertake additional duties in the field. Taking advantage of existing information is a cost-effective option and lets KYTC — or any agency — determine where it needs to conduct more thorough evaluations of district-level construction and maintenance practices or individual structures.

The Structural Condition and Criticality Indices rely entirely on NBI data. The Geomorphic Sensitivity index, however, also incorporates data from two proprietary metrics calculated by KYTC and which are not submitted as part of federal reporting requirements. For each index, each piece of raw datum is rescaled on a scale from 1 to 3 using rules that were derived through literature reviews and in consultation with KYTC Bridge Maintenance personnel. Next, each component is multiplied by a weight and then summed to arrive at a score for the index (cf. Johnson and Whittington 2011). The range of possible scores for each index is also from 1 to 3, paralleling the FHWA's bridge rating system which assigns structures to one of three categories: good, fair, poor. Here, a score of 1 equates to low sensitivity/criticality, 2 to medium sensitivity/criticality, and 3 to high sensitivity/criticality. It is possible to devise other approaches to scoring, but maintaining the 1-3 rating system is straightforward and therefore facilitates interpretation, particularly among non-engineers (e.g., policymakers, planners, the general public). The low–medium–high terminology was chosen deliberately to avoid confusion that could arise had the FHWA's rating system been applied in its original form. The following sections further clarify the nature of each index and provide worked examples for computing each one. They also summarize key findings from the analysis of KYTC's bridge and culvert inventory.

Sensitivity Indices

Structural Condition Index for Bridges and Culverts

For bridges, the Structural Condition Index is calculated using NBI Items 58-60, while NBI Item 62 alone is used to score culverts. This section first describes how to calculate the index for bridges first and then discusses culverts.

NBI Items 58-60 rate the condition of a structure's deck, superstructure, and substructure, respectively. Using the original NBI rating for each element as a starting point, scores are rescaled based on the rules in

Table 1. For example, if a bridge receives a score of 6 for the deck, the rescaled score is 2, indicating medium sensitivity. After the original scores for each item are rescaled, they are multiplied by the weights. The deck and superstructure both receive a weight of 0.25; the weight for the substructure is 0.50. The justification for assigning a higher weight to the substructure is that it consists of bridge features most directly exposed to and therefore likely to be impacted by hydraulic forcings. A substructure in poor condition before a flood occurs may be more sensitive to the effects flooding, scour, and debris flow. After item scores are multiplied by their assigned weights, they are summed to arrive at Structural Condition score (S_i):

$$\text{(Eq. 1) Structural Condition } (S_i) = \sum_{i=1}^{n} f_i w_i$$

where f_i is the ith factor (i.e., deck, superstructure, substructure) and w_i is the ith weight from Table 1 assigned to the respective factor.

Table 1 Rescaling Rules for Structural Condition Index.

NBI Scoring Range	Rescaled Score
7-9	1 (Low)
5-6	2 (Medium)
0-4	3 (High)

Table 2 provides a worked example of calculating the Structural Condition index for a hypothetical bridge. The first two columns list the NBI items and original scores for each component. The third column presents rescaled scores, while the final column provides the weighted scores. The Structural Condition score is highlighted at the bottom of the table. A score of 1.75 indicates low-medium sensitivity, which suggests the structure probably does not require greater attention from inspectors in the short term to determine whether repairs or the installation of targeted countermeasures are needed. Given the substructure's score, the bridge could be sensitive to severe hydraulic forcings. With continued deterioration, it will likely warrant greater scrutiny. While the Structural Condition Index captures a structure's sensitivity to hydraulic forcings and geomorphic instabilities, it also serves as a useful proxy for overall structural integrity.

Table 2 Example Calculation for Structural Condition Index

NBI Item	Original Score	Rescaled Score	Weighted Score
Deck (Item 58)	7	1	0.25
Superstructure (Item 59)	6	2	0.50
Substructure (Item 60)	5	2	1.00
Total Weighted Score			1.75

Culvert Structural Sensitivity

Only the score for NBI Item 62 (Culverts) is used to calculate the Structural Condition index for culverts. Because culverts are rated using a single score, applying weights is unnecessary. Table 3 summarizes the rescaling rules for culverts.

Table 3 Rescaling Rules for Culverts

NBI Scoring Range	Rescaled Score
7-9	1 (Low)
5-6	2 (Medium)
0-4	3 (High)

Geomorphic Sensitivity Index

The Geomorphic Sensitivity Index evaluates a structure's sensitivity to geomorphic instabilities such as scour, bank erosion, and channel migration. It leverages data on channel condition, scour potential, and observed scour. The index is calculated using three items from the NBI and two KYTC-specific factors — 1) NBI Item 61: Channel and Channel Protection; 2) NBI Item 71: Waterway Adequacy, 3) NBI Item 113: Scour Critical Bridges, 4) KYTC Factor 1: Scour Observed, and 5) KYTC Factor 2: Scour Risk Calculation. Neither of KYTC's factors are reported to the FHWA as part of its mandatory reporting obligations. Although NBI Item 71 (Waterway Adequacy) is not concerned exclusively with the impacts of flooding or bridge-environment interactions, it is included because it addresses the likelihood of a structure being overtopped during significant flooding events and the attendant traffic consequences (e.g., delays). The methodology for calculating the Geomorphic Sensitivity Index is the same as the methodology used for the Structural Condition Index. Raw data are collected, analyzed, and then rescaled according to the rules summarized in Tables 4 and 5 and weighted according to Table 6.

Table 4 Rescaling Rules for NBI Items Included in Geomorphic Sensitivity Index

	NBI Scoring Range	Rescaled Score
Channel and Channel Protection Scores (NBI Item 61)	7-9	1 (Low)
	5-6	2 (Medium)
	0-4	3 (High)
Waterway Adequacy Scores (NBI Item 71)	7-9	1 (Low)
	5-6	2 (Medium)
	0-4	3 (High)
Scour Critical Bridges Scores (NBI Item 113)	8 or 5	1 (Low)
	7	2 (Medium)
	0-4	3 (High)

Table 5 Rescaling Rules for KYTC Scour Metrics Included in Geomorphic Sensitivity Index

	Original Score	Rescaled Score
Scour Observed Score (KYTC Metric)	2 (No Scour)	1 (Low)
	3 (Minor Scour)	2 (Medium)
	4 (Moderate Scour)	2 (Medium)
	5 (Major Scour)	3 (High)
Scour Risk Calculation (KYTC Metric)	< 300	1 (Low)
	> = 300	3 (High)

Table 6 Weights for Geomorphic Sensitivity Score

NBI/KYTC Factor	Weight
Channel and Channel Protection	0.20
Waterway Adequacy	0.20
Scour Critical Bridges and Observed Scour (KYTC)	0.30
Scour Risk Calculation (KYTC)	0.30

Scour Critical Bridges (NBI Item 113) and Scour Observed (KYTC Factor 1) can be combined into a single variable. A look-up table (Table 7) is used to assign the correct score for this metric. First, along the y-axis, is the rescaled Scour Observed score. Then, along the x-axis, is the correct Scour Critical Bridges score. The cell which represents the intersection point of those items contains the rescaled score used to compute the Geomorphic Sensitivity Index. For example, if the Scour Observed Score is 2

(Moderate) and the Scour Critical Bridges Score is 8, the rescaled score for the combined Scour Observed-Scour Critical Bridges metric is 2 (Medium).

Table 7 Look-Up Table to Assign Scores for the Scour Observed-Scour Critical Bridges Metric

		Scour Critical							
		1	2	3	4	5	7	8	9
Scour Observed	None (1)	H (3)	H (3)	H (3)	H (3)	L (1)	M (2)	L (1)	L (1)
	Minor (2)	H (3)	H (3)	H (3)	H (3)	L (1)	M (2)	L (1)	L (1)
	Moderate (2)	H (3)	H (3)	H (3)	H (3)	M (2)	H (3)	M (2)	L (1)
	Major (3)	H (3)	H (3)	H (3)	H (3)	H (3)	H (3)	H (3)	H (3)

Additional explanation of KYTC's Scour Risk Calculation is also warranted. It provides a semi-quantitative evaluation of a structure's sensitivity to scour. Computing it requires bridge inspectors to perform a combination of direct measurements and visual assessments. Factors which are visually appraised are scored using categorical, qualitative criteria. Eight scour risk factors are needed to prepare a Scour Risk Calculation — 1) element skew to flow, 2) local scour, 3) debris, 4) channel erosion/protection, 5) channel migration, 6) contraction scour, 7) floodplain condition and dynamics, and 8) bed material. The following bullet points elaborate on these variables:

- Element skew to flow measures the angle between a straight line drawn from the centerline of a substructure unit to the direction of incoming flow. Higher skew angles are generally associated with more intense scour.
- Local scour refers to the maximum local scour depth around any substructure unit.
- The debris factor captures the amount of debris blocking the hydraulic opening of a structure. When a hydraulic opening is reduced in size it creates a jet effect which increases flow velocity and therefore the likelihood of scour.
- The channel erosion/protection variable is based on several measurements including bank erosion, vegetation cover, the condition of erosion control features (e.g., rip rap, gabions, check dams, guide banks), and channel sinuosity.
- Contraction scour occurs where water passes through a narrowed opening— KYTC's Bridge Inspection Procedures Manual has guidance on visual cues that signal the presence of contraction scour.
- To understand channel migration, inspectors use historical cross-sectional data, bank shape, and the identification of soil stains on substructure units to determine whether a channel has migrated since bridge construction.
- Like the channel erosion/protection variable, floodplain conditions and dynamics account for several variables, including evidence of flow (e.g., whether biophysical indicators suggest the occurrence of overbank flow), lateral/tributary inflows, vegetation cover, obstructions (e.g., fill, buildings, trash, debris, retaining walls), and floodplain width.
- The bed material factor is the simple documentation of the type of sediment of which the streambed is composed (e.g., gravel, sand, silt).

Once all necessary data have been collected, scores are assigned to each of the eight factors based on rules elaborated in KYTC's Bridge Inspection Procedures Manual. Under KYTC's existing procedure, structures that receive a score greater than or equal to 300 are flagged as high risk and warrant further investigation. If a structure scores less than 300 it is deemed a low risk, indicating lower risk to scour. Accordingly, this existing logic has been applied to the rescaling rules outlined in Table 5.

After scores have been rescaled, they are multiplied by the weighting factors listed in Table 6 to compute the Geomorphic Sensitivity Index (G_i). Weights were developed in consultation with personnel in KYTC's Bridge Maintenance Division. They reflect the relative importance of each item in determining a bridge's geomorphic sensitivity to flooding. Although this method employs two metrics (Scour Observed and Scour Risk Calculation) that not all transportation agencies may collect data on, agencies could modify the approach described here by using only the NBI elements and assigning an equal weight to each (0.33) or by substituting in proprietary metrics on which they collect data and assigning commensurate weights to them.

$$\text{(Eq. 2)} \quad \text{Geomorphic Sensitivity Index } (G_i) = \sum_{i=1}^{n} f_i \, w_i$$

where f_i is the ith factor (i.e., channel and channel protection, waterway adequacy, scour critical bridges, observed scour) and w_i is the ith weight assigned to individual factors.

Table 8 provides a worked example for calculating the Geomorphic Sensitivity Metric. The first two columns list the NBI/KYTC item and their original scores, the third column the rescaled scores, the final column the weighted score. The Geomorphic Sensitivity Index score is highlighted at the bottom of the table.

Table 8 Example Calculation for Geomorphic Sensitivity Index

NBI/KYTC Item	Original Score	Rescaled Score	Weighted Score
Channel and Channel Protection	6	2	0.4
Waterway Adequacy	8	1	0.2
Scour Critical Bridges and Observed Scour	7 (SC); 2 (OS)	2	0.6
Scour Risk Calculation	250	1	0.3
Total Weighted Score			1.5

The hypothetical structure in this example has a Geomorphic Sensitivity Index score of 1.50, which is in the low–medium range and intimates that the structure's geomorphic sensitivity to prevailing boundary conditions likely do not call for immediate corrective action by maintenance personnel. It is probable the structure would not fail as the result of geomorphic instabilities and could withstand the design flood (and in all likelihood discharges of a higher magnitude) without being significantly compromised by scour, bank erosion, or channel migration. Nonetheless, the presence of minor scour and bank slumping and lateral channel migration (as per the score for Channel and Channel Protection [NBI Item 61]) perhaps warrants further monitoring to observe whether progressive changes in channel geometry occur or the magnitude and rate of bank erosion increases. While the approach to monitoring would vary among agencies, one strategy to maintain surveillance on structures with high Geomorphic Sensitivity Index scores — or any index — is to establish thresholds for index scores as well as individual metrics which go into the calculation of the index. When a threshold is crossed, it is automatically flagged in a bridge management system.

Criticality Index

The Criticality Index measures how integral an asset is to a transportation network. The shuttering of critical assets is consequential for traffic flows and degrades the overall performance of a network, which in turn negatively affects the movement of people and economic activity (Johnson and Whittington, 2011; Balijepalli and Oppong, 2014). To identify appropriate measures for the Criticality Index, guidance from academic publications and transportation agencies (e.g., FHWA, 2011; Utah DOT, 2014; Omenzetter et al., 2015; Moruza et al., 2016; New Hampshire DOT, 2018) was reviewed. Additionally, input was solicited and received from subject-matter experts in KYTC's Bridge Maintenance and Planning Divisions to determine what factors are most useful for quantifying asset criticality in Kentucky. Greater weight was accorded to discussions with KYTC personnel because they are most familiar with bridge and culvert performance in the state and possess insights into what indicators are useful for evaluating structures and the role each plays in the overall operation and functionality of the state's transportation networks.

The Criticality Index is calculated using five NBI elements — 1) NBI Item 19: Bypass Detour Length, 2) NBI Item 29: Average Daily Traffic (ADT), 3) NBI Item 49: Structure Length, 4) NBI Item 104: Highway System of the Inventory Route, and 5) NBI Item 109: Average Daily Truck Traffic. As with the components of the Structural Condition and Geomorphic Sensitivity Indices, scoring ranges are used to assign a rescaled score to each item. KYTC Bridge Maintenance personnel helped identify threshold values for each category and define categorical ranges. The selection of a couple of these items requires a bit of explanation. To calculate Average Daily Truck Traffic, NBI Item 109 — which indicates the percentage of daily traffic comprised of trucks — is multiplied by the ADT (NBI Item 29). This value is subtracted from ADT to ensure passenger vehicle traffic and truck traffic remain strictly partitioned. Structure Length functions as a proxy for both the time needed to restore a closed structure (cf. Utah DOT, 2014) and the expense of repairs or replacement. A general rule of thumb is that repairing or replacing lengthier structures requires more planning, costs more, and takes longer than do shorter facilities. Additionally, Structure Length serves as a proxy for structure complexity. After each factor is rescaled according to Table 9, they are weighted according to the rules laid out in Table 10. The bypass/detour length is assigned the highest weight, followed by ADT. KYTC staff emphasized the overarching importance of bypass/detour length in determining a structure's criticality.

Table 9 Rescaling Rules for Criticality Index

	NBI Scoring Range	**Rescaled Score**
Bypass, Detour Length Scores (NBI Item 19)	< 5 miles	1 (Low)
	5 – 20 miles	2 (Medium)
	> 20 miles	3 (High)
ADT Scores (NBI Item 29)	< 2,500	1 (Low)
	2,500 – 5,000	2 (Medium)
	> 5,000	3 (High)
Structure Length Scores (NBI Item 49)	< 500 feet	1 (Low)
	≥ 500 feet	3 (High)
Highway System of Inventory Route (NBI Item 104)	0 (Inventory Route is Not on the NHS)	1 (Low)
	1 (Inventory Route is on the NHS)	3 (High)
Average Daily Truck Traffic (NBI Item 109)	< 500	1 (Low)
	500 – 4,000	2 (Medium)
	> 4,000	3 (High)

Table 10 Weights for Criticality Score

NBI Factor	Weight
Bypass, Detour Length	0.45
Average Daily Traffic	0.20
Structure Length	0.10
Highway System of the Inventory Route	0.05
Average Daily Truck Traffic	0.20

Once each factor is weighted, they are summed (Eq. 3) to arrive at the Criticality score (C_i):

$$\text{(Eq. 3)} \qquad \text{Criticality Index } (C_i) = \sum_{i=1}^{n} f_i \, w_i$$

where f_i is the ith factor (bypass, detour length; ADT; structure length average daily truck traffic) and w_i is the ith weight assigned to each factor.

Table 11 provides a worked example for calculating the Criticality Index. The first two columns list the NBI item and original scores/values, the third column rescaled scores, and the last column the weighted scores. The Criticality Index score for the hypothetical structure is 1.85, placing it just shy of the medium rating for criticality (the threshold for this category is 2). The long bypass/detour indicates that drivers would have significantly longer commutes were the structure to be closed for any period of time. The scores for ADT and average daily truck traffic indicate a large number of drivers will incur impacts from a potential closure. The score of 1.85 also reflects the outsized impacts of bypass/detour length and daily traffic (both passenger vehicle and truck) on Criticality, which account for 75% of the final score's weight. As such, while the Criticality Index captures the financial consequences of closure for a transportation agency, this plays a minor role. Most of these impacts are inferred through the inclusion of structure length. While this is an imperfect proxy to gauge potential repair costs, because there is often a correlation between structure length, structure complexity, and potential repair and replacement costs, it gives agencies a rough idea of the expense involved in fixing a structure damaged sufficiently to require closure. Greater importance is thus accorded to the impacts suffered by drivers, but while bypass/detour length and traffic are focused on the immediate consequences of closure for network users, rerouting traffic exposes other assets to more vehicles and therefore increases wearing. This may translate, eventually, into additional maintenance or replacement costs for agencies when they have to fix assets that receive greater exposure to traffic due to the original closure — sooner than would have been the case had normal operating conditions prevailed.

Table 11 Example Calculation for Criticality Index

NBI Item	Original Score	Rescaled Score	Weighted Score
Bypass, Detour Length	12 miles	2	0.90
ADT	3,800	2	0.40
Structure Length	345 feet	1	0.10
Highway System of the Inventory Route	0	1	0.05
Average Daily Truck Traffic	580	2	0.40
Total Weighted Score			1.85

Bridge and Culvert Sensitivity Index (BCSI)

The BCSI brings together information from the three indices described previously to produce a holistic representation of how sensitive a structure is to hydraulic forcings. It combines the Structural Condition

Index, Geomorphic Sensitivity Index, and Criticality Index into a single measure. Computing BCSI scores follows the same methodology used for the other indices. After calculating scores for the other indices, those values are weighted (Table 12) and summed.

Table 12 Weights for Composite BCSI

Index	Weight
Structural Condition	0.50
Geomorphic Sensitivity	0.25
Criticality	0.25

The Structural Condition Index receives the greatest weight (0.50) because previous research has found that structures in a poorer condition have a higher likelihood of being damaged by flood events. Structures in poor condition may also suffer damage at lower Geomorphic Sensitivity Index thresholds than structures rated as being in good condition. The other indices are equally weighted (0.25). Weighted scores are summed (Eq. 4) to arrive at the BCSI score:

$$\text{(Eq. 4)} \qquad \text{BCSI } (BCSI_i) = \sum_{i=1}^{n} f_i \, w_i$$

where f_i is the ith score (Bridge/Structural Condition, Geomorphic Sensitivity, Criticality) and w_i is the ith weight assigned to each index score.

Table 13 Example Calculation for Composite BCSI

Index	Original Score	Weighted Score
Structural Condition	1.75	0.875
Geomorphic Sensitivity	1.50	0.375
Criticality	1.85	0.463
Total Weighted Score		1.713

Table 13 contains a worked example for calculating the BCSI. The first two columns list the indices and original scores, respectively, while the third column lists weighted scores; the BCSI score is highlighted at the bottom of the table. This example draws from the examples described in previous sections. It demonstrates the interactive effects when all three indices are combined into a single index. The structure earns a BCSI score of 1.713, indicating low-medium sensitivity. In all likelihood, a structure receiving a score in this range is at low risk of being damaged by hydraulic forcings. Structures which score at or above 2 on any of the four indices likely merit close inspection and monitoring and could be flagged as being at-risk in an agency's bridge management system. Ultimately, agencies would need to determine threshold scores that are appropriate given its context. In some cases, threshold scores may vary by region based on the predominant geological and geomorphological characteristics and criticality.

Analysis and Findings

This section presents our analysis of Kentucky's bridges and culverts and highlights some key findings. The dataset used contains 7,322 structures from the NBI that are owned and maintained by KYTC. Most of the records were complete, although a few modifications were required to deal with issues resulting from missing or incomplete data. Table 14 describes how each challenge was addressed. This section demonstrates — through a combination of statistical and geospatial analysis — the methodologies outlined in the previous sections and provides a high-level snapshot of the sensitivity of KYTC-owned structures to hydraulic forcings.

Table 14 Techniques Used to Correct Data Omissions and Incompleteness

Problem	Resolution
Missing values needed to calculate criticality for interstate bridges	Bridges automatically assigned a score of 3 for Criticality
ADT value missing or -1	Bridges automatically assigned a score of 1 for ADT
Average Daily Truck Traffic value missing or -1	Average Daily Truck Traffic omitted from Criticality score
Scour Critical Bridges value is missing	Scour Critical Bridges assigned a score of 3
Scour Observed is not available or unobservable	Scour Observed omitted from Geomorphic Sensitivity equation
Scour Risk Calculation missing	Scour Risk Calculation omitted from Geomorphic Sensitivity equation

Figure 2 illustrates the analytical framework used during the assessments (and which corresponds to the presentation in this section) and reflects the kind of approach other agencies could use to identify areas in which bridge and culvert sensitivity is a widespread problem as well as the conditions of individual structures. The hierarchical approach to analysis followed here begins with a synoptic evaluation focused on the condition and performance of structures at the statewide level, the goal of which is to determine where variability exists between regions or districts (which refers to the organizational or administrative units an agency has established to facilitate operations) and identify potential explanations for differences. At this level, basic summary statistics and statistical tests (e.g., Analysis of Variance [ANOVA]) are prioritized to generate a comprehensive picture of an agency's inventory of structures. Next, hot spot analysis lets practitioners execute a more focused analysis and zoom in on particular areas in which there are clusters of sensitive bridges and culverts. Hot spot analysis is a useful tool for refining the synoptic analysis as it can identify places within regions and districts that pose maintenance challenges. High-level statistics provide coarse resolution — and while they can help agency staff identify regions or districts that have larger populations of sensitive structures, they cannot entirely account for why inter-region or -district variability exists. For example, it may be only a small portion of a region or district that has numerous sensitive structures that are a dominant control on top-level performance. Hot spot analysis can open up new lines of inquiry and conversation, focusing agency staff on what is going wrong (or right) in areas with clusters of similarly performing structures. It may facilitate the identification of factors related to environmental boundary conditions or agency policies and practices that affect patterns of structure sensitivity. An examination of individual structures follows hot spot analysis. Here, agency staff can pinpoint structures that merit additional field investigations and determine what countermeasures or remedial actions are necessary to protect structures against hydraulic forcings. It is possible the analysis of individual structures — if common drivers of sensitivity are identified — can feed back into high-level activities such as policy development and maintenance practices. The analytical framework proposed here is meant to be recursive, so that agency staff, irrespective of what level of analysis they are working on, continually question what factors influence performance and brainstorm strategies to improve performance.

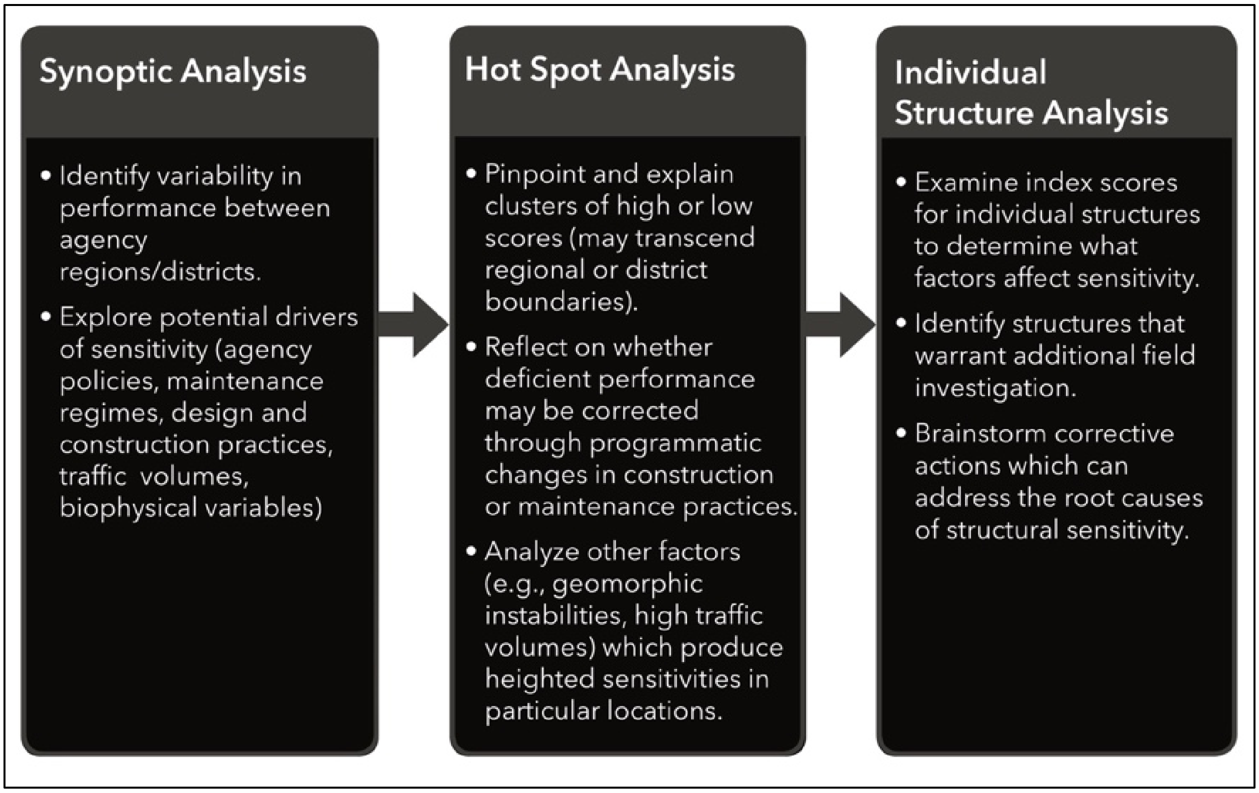

Figure 2 Hierarchical Framework for Analyzing Bridge and Culvert Inventories

Synoptic Analysis

JMP Pro 14 was used for all high-level statistical analysis. Table 15 summarizes the mean and median scores for all indices for each KYTC district. For the BCSI, mean scores range from 1.36 to 1.64. Districts 5 and 11 stand out, with both having mean and median scores above 1.60. For the Structural Condition Index, mean scores range between 1.37 and 1.81. Both Districts 5 and 11 are noteworthy, with mean values of 1.81 and 1.76, respectively. Geomorphic Sensitivity Index scores are generally low, ranging from 1.08 to 1.33, which indicates geomorphic instabilities do not cause widespread problems across entire districts. Criticality Index scores range between 1.38 and 1.71. District 5 scores at 1.71, which is likely the product of a significant portion of the district encompassing the Louisville Metro area, where traffic volumes tend to be high. Districts in the eastern portion of the state also have elevated Criticality Index scores, likely because many detour routes are longer than those in more urban locations. In general, the mean Structural Condition Index scores are greater than the BCSI. Accordingly, scores for the Geomorphic Sensitivity and Criticality Indices dampen the effects of Structural Condition in the BCSI scores.

Table 15 Summary Statistics for Kentucky's Structure Inventory. N = 7,322 (Median scores indicated in parentheses).

District	Number of Structures	BCSI	Structural Condition	Geomorphic Sensitivity	Criticality
1	979	1.50 (1.55)	1.61 (1.75)	1.28 (1.20)	1.52 (1.45)
2	1,041	1.41 (1.40)	1.51 (1.50)	1.18 (1.20)	1.45 (1.45)
3	488	1.47 (1.54)	1.60 (1.75)	1.21 (1.20)	1.45 (1.45)
4	567	1.35 (1.28)	1.38 (1.00)	1.26 (1.20)	1.38 (1.45)

District	Number of Structures	BCSI	Structural Condition	Geomorphic Sensitivity	Criticality
5	475	1.64 (1.66)	1.81 (2.00)	1.24 (1.20)	1.71 (1.45)
6	384	1.50 (1.55)	1.64 (2.00)	1.25 (1.30)	1.49 (1.45)
7	568	1.51 (1.55)	1.66 (2.00)	1.23 (1.20)	1.49 (1.45)
8	466	1.52 (1.55)	1.69 (2.00)	1.18 (1.20)	1.50 (1.45)
9	622	1.55 (1.60)	1.67 (2.00)	1.25 (1.20)	1.60 (1.45)
10	507	1.33 (1.28)	1.37 (1.00)	1.08 (1.00)	1.48 (1.45)
11	620	1.61 (1.66)	1.76 (2.00)	1.33 (1.20)	1.60 (1.45)
12	604	1.47 (1.43)	1.52 (1.50)	1.16 (1.00)	1.69 (1.70)

To determine whether statistically significant differences in mean scores exist between KYTC districts, ANOVA was used. The null hypothesis of ANOVA is that all treatment groups share a common mean. In this case, a treatment group is a KYTC district. For all four indices — BCSI, Structural Condition, Geomorphic Sensitivity, and Criticality — mean scores across all districts are not equal ($p < 0.0001$). While ANOVA is useful for determining if there are differences in means, it does not indicate where the most pronounced differences between districts exist. To compare the means of individual districts and identify statistically significant differences, Tukey's Honestly Significant Difference (HSD) was used. Tukey's HSD works by developing pairwise comparisons for all treatment groups (i.e., districts). Here, only the Tukey HSD results for the BCSI scores are presented. JMP Pro generates a report to highlight where statistically significant differences between districts or groups of districts are present. Interpretation is relatively straightforward. In Table 16, statistically similar groups are indicated by the shaded letters. Thus, Districts 5 and 11 (red shading) form a single group that significantly differs from all others. In some cases, a single district can occupy two or more groups. For example, Districts 8, 7, 1, and 6 can belong to either the group shaded in yellow or green. This indicates that the mean values for those districts are such that they could belong — statistically — to either group.

Table 16 Tukey HSD Results for BCSI Scores

District	Group Membership					Mean
5	**A**					1.64
11	**A**					1.61
9		**B**				1.55
8		**B**	**C**			1.52
7		**B**	**C**			1.51
1		**B**	**C**			1.50
6		**B**	**C**			1.50
12			**C**			1.47
3			**C**			1.47
2				**D**		1.41
4					**E**	1.35
10					**E**	1.33

Hot Spot Analysis

ArcGIS Pro's Hot Spot Analysis was used to identify clusters of low and high scores for each index. This tool calculates the Getis-Ord Gi* statistic for each point in a dataset (see Getis and Ord, 1992, 1995 for an explanation of the statistic's derivation). In the most basic terms, hot spots are areas where a structure with a high sensitivity or criticality score is proximate to other structures with high scores. High z-scores and small p-values are associated with the clustering of high values. Conversely, cold spots occur where a structure with a low sensitivity or criticality score is surrounded by other structures with low scores. Low negative z-scores and small p-values occur where low values are clustered. The Hot Spot Analysis tool identifies structures that participate in clusters at the 99th, 95th, and 90th percentile confidence intervals. In the maps that follow, different confidence intervals are denoted by the varying color saturation of dots (i.e., structures). Figures 3 through 6 reproduce the results of the hot spot analyses. Figure 3 delineates cold and hot spots for BCSI; Figure 4 through 6 depict cold and hot spots for Structural Condition, Geomorphic Sensitivity, and Criticality, respectively.

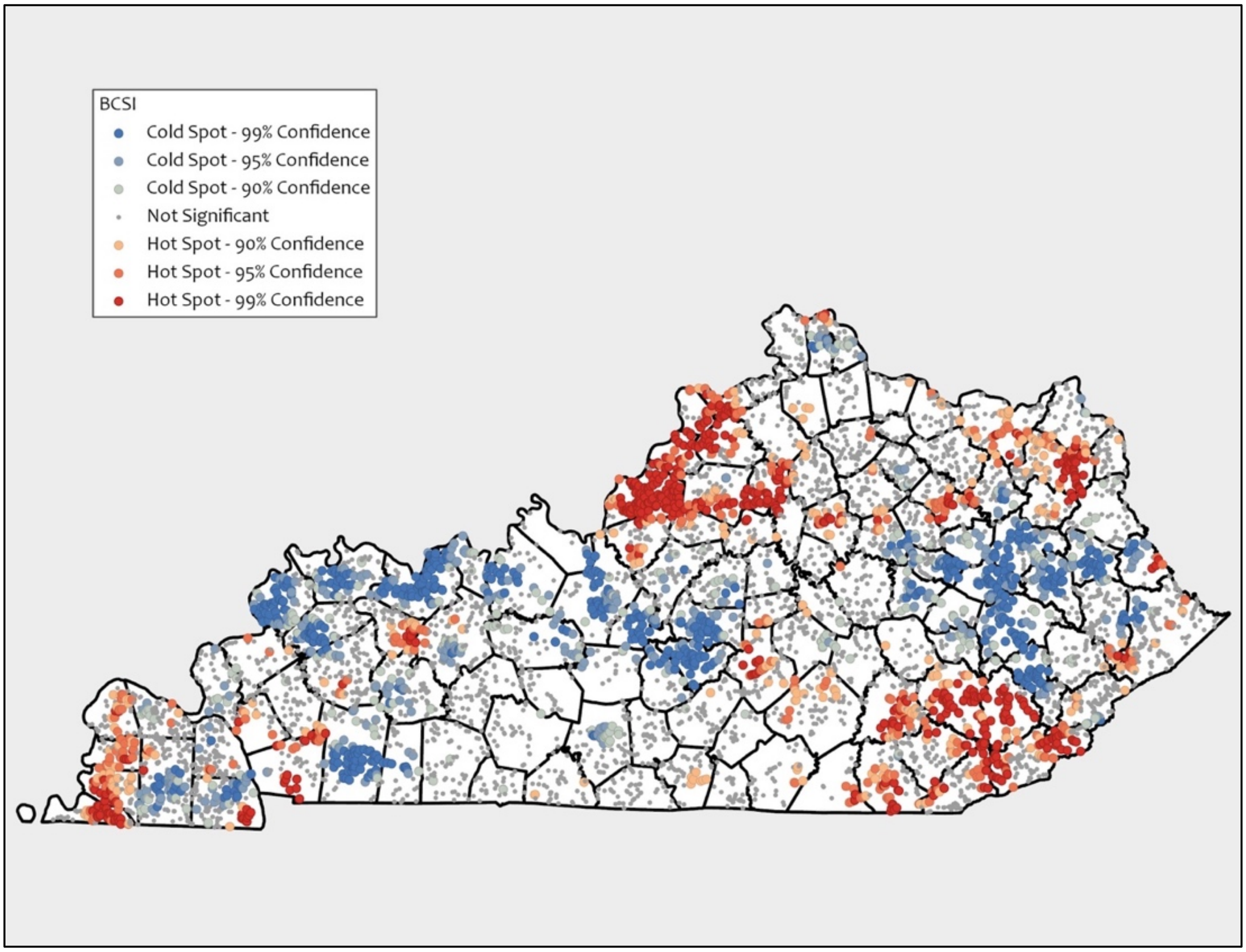

Figure 3 BCSI Hot Spot Analysis

BCSI hot spots are most pronounced in the north-central portion of Kentucky (District 5), primarily around the city of Louisville and extending northeastward, and in the southeastern part of the state (District 11). Smaller pockets of high BCSI scores are concentrated in the far-western and northeastern portions of Kentucky (Districts 1 and 9, respectively). Extending across the central third of the state is a conspicuous and — mostly — unbroken band of lower BCSI scores which spans multiple districts. Results of the hot spot analysis are consistent with the ANOVA findings, with Districts 5 and 11 singled out as having BCSI scores significantly higher than other KYTC districts. According to the Tukey HSD analysis, Districts 1 and 9 are statistically similar and could occupy the same group, which this assessment appears to substantiate. But hot spot analysis is more adept at detecting clusters in districts which contribute to overall scoring trends.

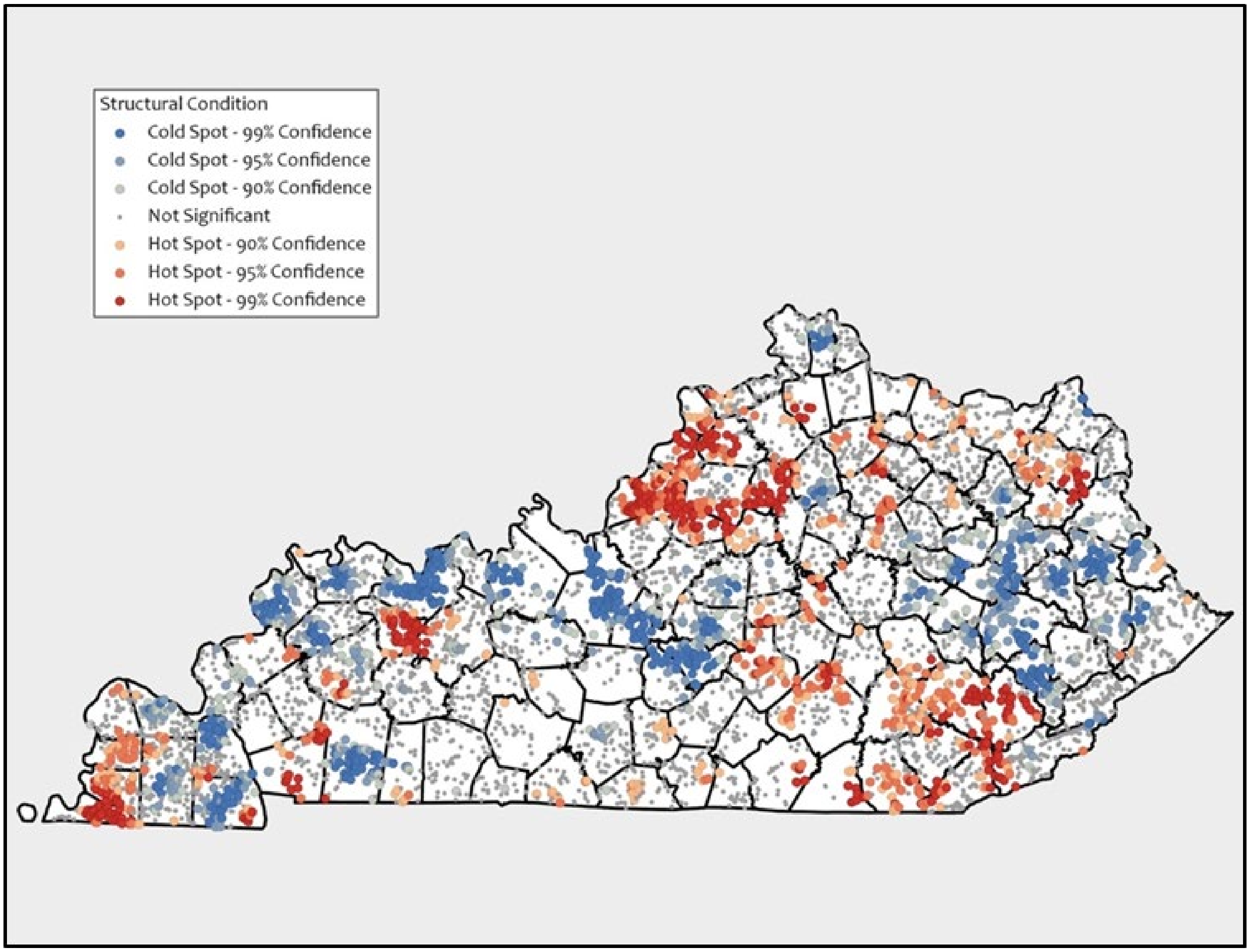

Figure 4 Structural Condition Hotspot Analysis

Further investigation into hot spot analyses for the Structural Condition, Geomorphic Sensitivity, and Criticality Indices underscores some of the factors that drive overarching trends in the BCSI. Recall Structural Condition accounts for 50 percent of the BCSI. The similarities between the BCSI and Structural Condition hot spot analyses are noticeable. Districts 1, 5, and 11 have clear hot spots, while there are smaller pockets of District 9 with elevated scores. Geomorphic Sensitivity appears to amplify the BCSI scores in these four districts as well. Although full watershed or geomorphic analyses do not fall within the ambit of this project, several tentative explanations may be ventured for why these regions of Kentucky are more geomorphically problematic than others. In District 1, the most distinctive cluster of high Geomorphic Sensitivity Index scores lies to the west of the Land Between the Lakes National Recreation Area. Much of this area is situated within or near the New Madrid Seismic Zone, which suggests tectonic activity may contribute to geomorphic instabilities throughout the region (cf. Boyd and Schumm, 1995).

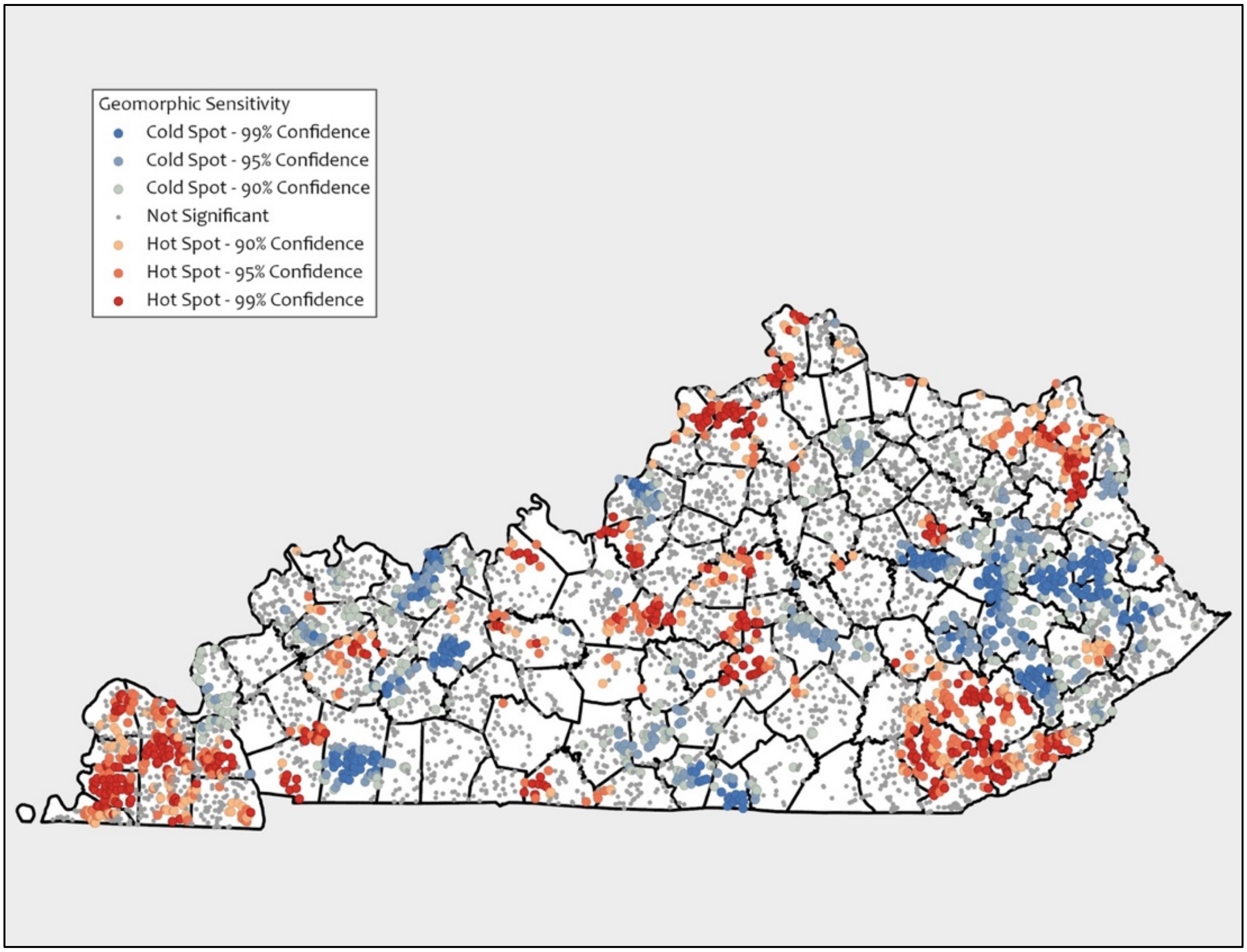

Figure 5 Geomorphic Sensitivity Hot Spot Analysis

The most intense clustering in District 5 is found located along a band that parallels the Kentucky River from the northern portion of Franklin County downstream toward its junction with the Ohio River. Some of this clustering may be attributable the highly erodible shale in the region. High Geomorphic Sensitivity Index scores in Districts 9 and 11 are likely attributable to the considerable topographic relief present in these areas. The terrain is more mountainous, with the headwaters of the Middle Fork Kentucky River and South Fork Kentucky River both located in the area. Streams located in the upper and upper-middle portions of watersheds generally have higher potential stream power because of steeper gradients, which increases their capacity to move sediment (e.g., instigate bridge scour).

With respect to the Criticality Index, a noticeable hot spot blankets the extreme eastern portion of the state. Clusters of high scores are visible in the Louisville Metro area as well the Interstate 64 corridor, which connects Louisville and Lexington. The length of detour routes accounts for roughly half of the criticality score. In eastern Kentucky, high Criticality Index scores arise primarily from long detour routes — it is predominantly rural, and vehicles have few alternative route options if a structure closes. Conversely, the hot spots around Louisville and on routes leading to and from the city along major interstate corridors are more the product of higher ADT counts.

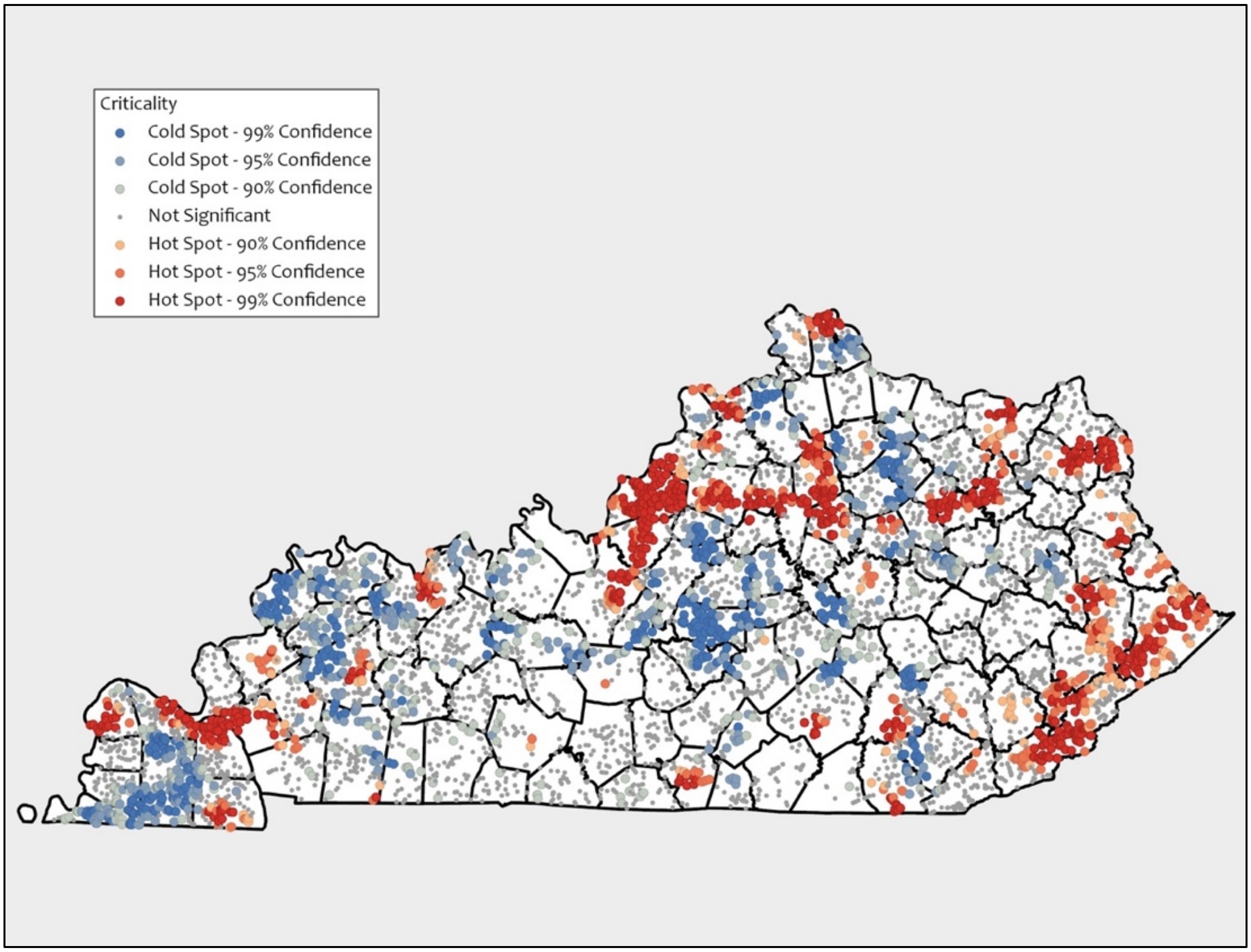

Figure 6 Criticality Hot Spot Analysis

One caveat associated with hot sport analysis is worth noting. Bridges included within a hot spot do not necessarily have very high scores. As the summary statistics in Table 17 indicated, the mean scores for all indices in all districts ranged from 1.11 to 1.81, firmly in the low-medium realm of sensitivity. Whatever information is gleaned from hot spot analysis requires proper contextualization. For example, the data in Table 17 summarize the number of structures in each district with scores greater than or equal to 2.0 for each metric. Information generated from hot spot analysis must be supplemented by additional investigations. That being said, it is critical to note that the results broadly conformed to the expectations of KYTC personnel with respect to higher-scoring districts and hot spots.

Table 17 Structures with Ratings of Medium (2.0) or Higher for Each Category

District	BCSI	Structural Condition	Geomorphic Sensitivity	Criticality
1	55	481	69	103
2	26	366	22	92
3	11	214	12	12
4	12	157	35	42
5	81	303	19	110
6	23	197	17	54
7	26	207	15	70
8	11	276	15	58
9	42	322	23	70
10	3	120	1	27
11	47	368	15	76
12	32	225	26	77
Totals	369 (5.0%)	3,297 (45.0%)	269 (3.7%)	791 (10.8%)

While the BCSI offers a balanced picture of structural condition and sensitivity, it remains critical to determine where there are high scores in other categories to evaluate whether preventative maintenance action is necessary. For example, if a bridge is in good structural condition but has a high Geomorphic Sensitivity Index score, it may nonetheless be at risk when exposed to severe hydraulic forcings (e.g., rapid channel migration threatens abutments). Looking at Table 17, it is apparent the most significant issues exist with Structural Condition, with approximately 45% of the inventory scoring at or above 2.0. While it is true many of these structures demand close attention during future inspections, structures with medium sensitivity/criticality around 2.0 remain within the range of acceptability, although they could be more sensitive to flooding and scour. A score of 2.0 or higher in any category does not necessarily mean immediate corrective actions are needed. Comparatively, a much smaller percentage of the inventory exhibits high scores for Geomorphic Sensitivity and Criticality — 3.7% and 10.8%, respectively.

Individual Structure Analysis

It is beyond the scope of this project to analyze individual structures. Furthermore, transportation agencies have sophisticated bridge management systems or databases in which procedures can be used to extract information on structures exceeding a particular threshold score for any of the indices. However, it is worth briefly exploring how information on bridges and culverts may be rapidly viewed in an online mapping environment. For this project, a simple map was created in ArcGIS Online —there are a number of other platforms, sources, and libraries available to build interactive and equally usable online maps (e.g., Carto, Mapbox, Leaflet). Figure 7 offers an illustration of the ArcGIS Online environment. On the left-hand side the contents of the map are visible and layers may be switched on and off by the user. To investigate an individual structure, users merely have to click on a blue dot to elicit a pop-up window that contains the structure identification number, KYTC district in which it is located, the year built, and scores for each of the four indices. Users could also filter the structures by district, score ranges, or other criteria to view what interests them most. This intuitive layout can let anyone, from KYTC staff to policymakers and legislators to members of the public, acquire information on a specific structure. But it is critical to note that viewing structure performance in this environment should be regarded not as the end of investigation, but a starting point to decide where on-the-ground inspections are needed.

Given agencies now have greater reporting requirements under MAP-21, it is probable more organizations will explore integrating online mapping as a part of their performance dashboards. For example, the Iowa Department of Transportation has developed a similar approach to reporting the condition of bridges using ESRI Story Maps.

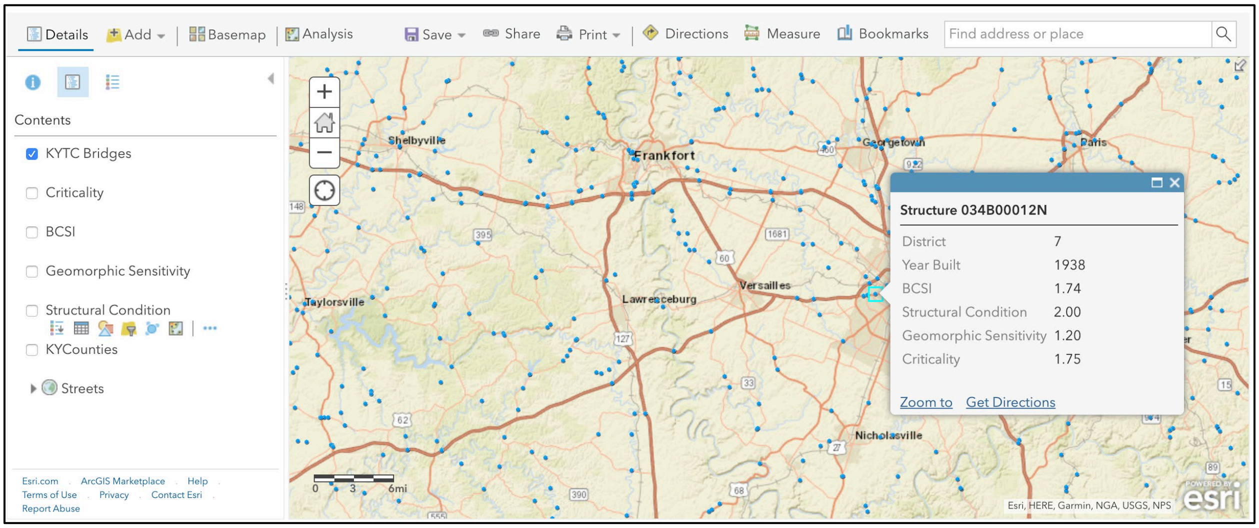

Figure 7 Online Retrieval of Individual Structure Analysis

Conclusions

The methodology described in this chapter for analyzing bridge and culvert sensitivity to hydraulic forcings is straightforward and can be implemented without performing additional fieldwork on top of regular inspections. This is critical. Frequently, the first impulse when trying to address a problem is to immediately conduct original fieldwork — when synthesizing available information can produce equally sharp insights. When resources are limited, agencies benefit from asking whether it is possible to use existing data to uncover stories that have either been overlooked or underreported. Although the methodology emphasizes hydraulic forcings due the attention it pays to geomorphic dynamics, it can also generate a comprehensive snapshot of the condition of a transportation agency's bridge and culvert inventory.

Computing scores for the four indices described here, then evaluating the results using statistical and geospatial analyses, will help agencies quickly identify areas within their jurisdiction in which there are structures that call out for greater scrutiny. This mode of analysis can delineate spatial variabilities in structural performance to understand what issues contribute to higher index scores and in turn guide the selection of appropriate countermeasures. Users who decide to experiment with the methodology presented here should bear in mind that all of the results it produces are high level. While they accurately represent the performance and sensitivity of an entire inventory, decisions about where to direct future investments should not be made based on these results alone. Ideally, agencies, after locating clusters of structures or the regions in which structural sensitivity is high, will look more closely at individual structures to better understand why they are sensitive and how that sensitivity can be mitigated. Only with this knowledge can agencies make informed decisions about not just countermeasures but also project prioritization. There is no substitute for context-specific knowledge produced through careful fieldwork.

There are many analytical possibilities for evaluating the condition of bridges and culverts beyond what this chapter has explored. The methodology presented here is best viewed as a springboard to inform a structure management program — it cannot provide the final word on management decisions. Future avenues of inquiry include determining whether there are correlations between the indices and bridge age or construction materials. Additionally, it could be useful to develop a set of heuristics for bridge maintenance staff to use to select bridges for closer inspection. For example, are there specific threshold values, or combinations of threshold values, for each metric that, once crossed, should trigger a detailed review of a bridge's historical trend lines with respect to performance and condition (or a more exhaustive field inspection)? It is also possible the formulas included in this paper will merit revision based on further investigations or the identification of statistical relationships between index values and failure rates or the frequency of maintenance work. Nonetheless, the methodology is a cost-effective and simple way of characterizing structural sensitivities at the inventory level. It can be implemented quickly, even by transportation professionals who do not routinely perform significant quantitative analysis, through the use of relatively simple spreadsheets and automated spatial analysis.

MODELING THE EFFECTS OF A WARMER CLIMATE ON PAVEMENT PERFORMANCE

Background

Average annual temperatures are on the rise and projections forecast the trend will continue (Kunkel et al., 2013). Temperatures in the lower 48 states are projected to increase about 4.1°F by 2050 relative to 2010. Areas farther inland will warm more than coastal areas, and projections show a larger increase in summer temperature than winter temperature (Meyer et al., 2015). Additionally, the occurrences of extreme temperatures follow a trend similar to the mean temperatures. An upward trend over the last three decades shows more occurrences of extreme maximum temperatures (Kunkel et al., 2013). When analyzing climate data, it is useful to measure historical data and generate future projections concurrently (Peterson et al., 2008).

There are several ways to measure the trends in extreme heat. One simple method sums the number of hot summer days that have historically occurred and compares it to the number projected. This method has already shown an increase: the number of days with temperatures above 90°F has been increasing since 1970 (Peterson et al., 2008). It can be noted that, although 90°F is a common threshold, other sources have measured based on 95°F or even 100°F (Kunkel et al., 2013). Another way to analyze extreme heat trends is to measure the number of hot days in a row. Oftentimes, this is measured by assessing the change in the number of days with temperatures above the 90^{th} percentile. This analyzes both minimum temperatures and maximum temperatures. It may also measure days with a maximum temperature above a certain threshold (i.e. 95°F). When using this method to analyze data since 1960, minimum temperatures show a greater increase than maximum temperatures. This means nights will not get as cool and pavement temperatures may retain heat more readily (Peterson et al., 2008).

Climate projections show that the upward trend in temperatures will continue. Most climate projections are derived from global climate models, which provide projections for changes in mean temperature, among other variables, and utilize a range of realistic scenarios of future greenhouse gas emissions (Peterson et al., 2008).

Infrastructure is designed to withstand certain types and frequency of extreme weather, including extreme heat. However, as heat gets more intense, it will place additional stress on infrastructure (Meyer et al., 2015). Sustained high temperatures can cause asphalt pavement to soften, resulting in rutting and shoving. High heat may be accompanied by drought conditions, causing asphalt pavement to crack and make it more sensitive to water when it does rain (FHWA 2018). This likely will require evaluation of chip sealing and crack sealing products (USDOT 2013). It can also stress the steel in bridges through thermal expansion (Meyer et al., 2015). More frequent and extensive thermal expansion places an even greater importance on properly cleaned and functioning bridge expansion joints (USDOT 2013). Tangentially, the increase in extreme heat could also lead to load restrictions on roads because pavement damage and buckling will disrupt vehicle movements. Premature deterioration of infrastructure costs agencies in maintenance, operations, and rebuilding costs (Meyer et al., 2015).

Extreme weather also causes other environmental events that have an effect on infrastructure. For example, long-lasting high temperatures can lead to droughts that bring increased numbers of wildfires that damage structures. Additionally, higher temperatures can contribute to more severe hurricanes. While this does not directly affect Kentucky, extreme weather events and natural disasters may have far-reaching effects for the entire country (USDOT 2013).

Maintenance needs and activities are also impacted by extreme heat. While temperature extremes will increase the need for maintenance work, they will simultaneously reduce the ability to perform maintenance tasks. High temperatures limit the number of hours that road crew maintenance personnel can work. Restrictions typically begin at 85°F. Depending on the humidity and heat stress index, heat exhaustion can occur at 105°F (Peterson et al., 2008).

When transportation agencies are considering how extreme weather will affect asset management, it is imperative that data are utilized. It is equally important to know how to understand and apply the data effectively. This data-driven approach relies on a few things: determining thresholds, determining mitigation measures, and creating a comprehensive how-to-guide that can be used for multiple purposes.

High temperatures impact infrastructure, materials, and maintenance personnel. Thresholds are required in order to determine when high temperatures pose a risk (Peterson et al., 2008). Extreme weather occasions can be indexed by duration, temperature, or effect on safety. It is important to point out that the selection of threshold temperatures to calculate extreme metrics is somewhat arbitrary because impacts-relevant thresholds are highly variable due to the diverse climate of the U.S. (Kunkel et al., 2013). However, establishing thresholds and determining some method of indexing data is an important first step in risk-based asset management.

Consecutive warm days is one metric for evaluating heat waves. In general, implications to transportation commence when the heat index is at least 105°F for 3 hours or more and the overnight minimum is around 80°F or higher. These thresholds may be refined depending on the entity it is affecting (Peterson et al., 2008). A common technique is summing the number of 4-day duration episodes with extreme hot and cold temperatures, which exceeds a threshold for a 1 in 5-year recurrence interval. When planning for transportation and/or asset management, impact assessments should consider not only the mean change, but also the range of these changes. For example, the predicted increase in global mean temperature will be more profound in the summer months (Kunkel et al., 2013).

To improve planning efforts for risk-based programs, a two-step process can be used. First, designers need to increase structure resiliency. This includes creating highways, bridges, and ferries to last decades and be more adaptable to weather extremes. Second, asset inventories should be expanded to be more complete, more easily located, and inclusive of geospatial data that can be contained in GIS formats. Asset analysis may be quantitative or qualitative. Currently, many asset databases are not readily available, which makes it hard to utilize them in an extreme weather situation (USDOT 2013).

Pavement Design and Performance Monitoring

The current state of practice for pavement design developed by the American Association of State Highway and Transportation Officials (AASHTO), utilizes the Pavement ME design process. This design process is essentially a performance prediction tool that is used to predict the performance of a pavement structure over time, given specific design characteristics, traffic loadings and climate conditions.

The Pavement ME process utilizes an incremental damage approach to predict the pavement performance. Current truck traffic loads with an applied annual growth rate were applied to the pavement structure which had been modified based on the climate data; these traffic loads yielded specific stresses and strains within the structure which were then associated with an incremental damage to the pavement structure. Transfer functions developed by calibration with actual in-service pavements were used to relate the incremental damage to pavement distresses.

The Enhanced Integrated Climatic Model (EICM) is a one-dimensional coupled heat and moisture flow model initially developed for the FHWA and adapted for use with Pavement ME. It has been refined and was utilized by the AASHTO version of Pavement ME at the time this analysis was performed. A more recent Pavement ME software version released in 2018 utilizes Modern-Era Retrospective analysis for Research and Applications, Version 2 (MERRA-2) climate data produced by the National Aeronautics and Space Administration (NASA).

The EICM is utilized to vary the material properties throughout a pavement structure based on environmental conditions, including both moisture and temperature impacts on material strengths. As an example, subgrade materials (soils and granular bases) increase in moisture content from rainfall. This increase in moisture generally causes their in-situ strength to decrease. In addition, Hot Mix Asphalt (HMA) material strength is influenced by temperature, as temperature increases, they become weaker. Each of these situations undergo a seasonal variation, which impacts the pavement performance.

KYTC typically designs non-interstate pavements for 20 years and interstates for 40 years. Those values are typical compared to the current practice. Other values for humidity and cloud cover are not modified to isolate the effects of temperature and precipitation on the pavement design life. The Pavement ME calculates the elastic modulus for each layer of pavement for each hour based on the temperature provided. The elastic modulus change is used to calculate the damage to the pavement.

This analysis is designed as a proof of concept that identifies impacts on pavement performance resulting from temperature increases associated with future climate scenarios. This analysis investigates the viability of using climate projection data to model pavement performance using Pavement ME. The analysis is composed of four steps:

1. Accessing climate projection data downscaled for Kentucky and historical climate data from Pavement ME.
2. Processing the data to produce average daily temperature and precipitation readings, adjusted for projected extreme weather occurrences.
3. Interpolating the climate projection data to the hourly level and matching it with historical data from the Pavement ME software climate file.
4. Analyzing pavement performance using Pavement ME against the future climate scenarios.

The area of the state most likely to first experience extreme heat that impacts pavement performance will be western Kentucky, based on information obtained from the statewide vulnerability assessment. The routes most critical to remain in good repair for economic development and quality of life are the interstates. Therefore, this proof of concept focuses on parameters used in that part of the state.

The historical climate file from Pavement ME includes hourly weather observations collected from weather stations throughout the state for temperature, precipitation, percent sunshine, wind speed, and relative humidity. Of these five weather observation types, only two (temperature and precipitation) are generally included in downscaled climate projection data, and these are at the daily level. The following analysis provides a method for processing this data in such a way as to be included as an input for Pavement ME.

Climate Data

Historical Climate Data

The historical climate data file in Pavement ME pertaining to the years 1980 to 1999 was used as a point of reference for interpolating the climate projection data. The 1980 to 1999 time frame was selected so that leap years evenly matched those in the two projected 20-year time periods (2020 to 2039 and 2040 to 2059) used in this analysis. In order to successfully match and interpolate the data at hourly intervals, daily precipitation totals, maximum daily temperatures, and minimum daily temperatures were needed to be calculated and ranked by month and year. The following describes how this was achieved.

Precipitation data from the Pavement ME historical record were totaled for each day in a spreadsheet. The daily precipitation totals were then ranked for each month/year. For example, the day in January of 1980 with the highest precipitation total received a ranking of 1, while the day in January of 1980 with the second highest total received a ranking of 2, and so on. Typically for each month in the historic record, somewhere around half of the days included some amount of precipitation. To continue the ranking on days without precipitation, average daily percent sunshine was used. The ranking resumed on the day with the lowest percent of average sunshine and continued until all days were ranked for each month.

Similarly, daily maximum and minimum temperatures were determined. The difference between the maximum and minimum daily temperature became the daily temperature spread. Similar to the precipitation data, each day in each month was ranked according to maximum temperature as well as minimum temperature, resulting in both a maximum ranking and minimum ranking.

In addition to the daily weather tabulations, further analysis needed to be conducted on the hourly temperature and precipitation data. For the hourly precipitation data, a calculation was made to reflect the percent of each individual day's precipitation that fell at each hour in that day. For example, if the wettest day in January of 1980 involved 1 inch of precipitation that fell evenly between the hours of 2 and 4 pm, then those two hours would each have a daily precipitation percentage of 50 percent, while every other hour in that day would have a daily precipitation percentage of 0 percent. A similar calculation was made for hourly temperature readings. Instead of percent of total daily precipitation being calculated here, the calculation was based on the hourly temperature's relative location within the overall daily maximum and minimum temperature spread (calculated as percent of daily temperature spread above the daily minimum temperature). These hourly calculations were used as the basis for later interpolating the climate projection data from the daily to the hourly level.

Climate Projection Data

Guidance from FHWA's *Vulnerability Assessment and Adaptation Framework* (https://www.fhwa.dot.gov/environment/sustainability/resilience/adaptation_framework/) and the USDOT's *Coupled Model Intercomparison Project (CMIP) Climate Data Processing Tool* (https://toolkit.climate.gov/tool/cmip-climate-data-processing-tool) were used to identify and obtain statistically downscaled climate projection data for Kentucky. These resources were created for transportation agencies seeking to incorporate climate projection data into transportation planning, maintenance, and adaptation activities. Following their guidance, downscaled climate projection data were obtained from the CMIP5 multi-model dataset. Because this effort was designed to be a proof of concept to analyze the impacts of extreme weather, the highest emissions scenario (RCP8.5) was selected. Appendix 1 contains a more detailed description of the future projected climate data.

Climate data were obtained for four grid cells along the Interstate 65 corridor in Warren County and Simpson County (southwestern Kentucky) near the city of Bowling Green. The spatial extent of each grid cell is 1/8 degree (approximately 12 kilometers across). With 21 models included in the projections, and 4 grid cells included for each model, this resulted in over 1.2 million data points pertaining to daily precipitation, maximum temperature, and minimum temperature.

A summary overview of the downloaded climate projection data was produced using FHWA's CMIP Climate Data Processing Tool. The projected climate data were summarized for the two future time periods of 2020-2039, and 2040-2059, as well as a baseline time period of 1965-1999 (the baseline range of years is different here than the baseline range of years from the historical data obtained from the Pavement ME software). The projected climate data demonstrate a steady rise in temperatures and a slight increase in precipitation in the future scenarios. These data are summarized in Appendix 2.

The raw data from the climate projections were in the form of millimeters for precipitation and degrees Celsius for temperature. These were converted to inches and degrees Fahrenheit, respectively, at the outset to match the Pavement ME historical climate data. Within each of the 21 climate projection datasets, daily precipitation, maximum temperature and minimum temperature were averaged across each of the 4 grid cells.

The same method used to rank the historical climate data from Pavement ME was then used to analyze and rank the data in each of the 21 climate models pertaining to the daily precipitation totals, maximum temperature, and minimum temperature per month per year. Data across all of the models were averaged according to these rankings. For example, each of the 21 models would have daily precipitation totals from January 2020 ranked from 1 (day with the most precipitation) to 31 (day with the least precipitation). Across the 21 models, the daily precipitation totals were averaged for each of those rankings from 1 to 31 (corresponding to the 31 days in January). The output was the average highest precipitation day in January 2020, the average second highest precipitation day in 2020, and so forth. A similar method was used to produce the daily average per month per year rankings for maximum temperature and minimum temperature across the 21 models.

This method was used to reduce the amount of data flattening that occurs when averaging across multiple models. The method yielded the average wettest day, average warmest day, average coldest day, and every day in between for each month in each year. Even with this method though, some flattening inevitably occurred. For example, Models 1-10 may have a particularly wet January 2020 and dry January 2021, while Models 11-21 may have a particularly dry January 2020 and wet January 2021. In this scenario, each of the models predicts a wet and dry January in consecutive years. However a simple average across all models yields average precipitation in January of both years, and flattens out the extremes that each of the models are actually predicting.

To address this issue, instances of heavy precipitation, intense heat, and intense cold were identified in each of the model projections. This was accomplished by establishing thresholds in the data. For example, a count was made per model of daily precipitation events greater than 1 inch, 2 inches, 3 inches, 4 inches and 5 inches. These counts were then averaged across the 21 models to identify an average number of high precipitation events for each of the time periods. Similar calculations were made for the historical data from Pavement ME.

Table 18 shows the number of days per 20-year time period of heavy precipitation. The first column contains data from the historical time period of 1980 to 1999 as obtained directly from the Pavement ME software. The next two columns are number of days with heavy precipitation for the time periods of 2020 to 2039 and 2040 to 2059. These data represent the average number of days with heavy precipitation across the 21 climate projection models.

Table 18 Number of days where precipitation exceeded thresholds.

Daily Precipitation Total	Historical: 1980 to 1999	Projected average: 2020 to 2039	Projected average: 2040 to 2059
1” to 2”	162	166	166
2” to 3”	20	18	20
3” to 4”	2	3	3

Daily Precipitation Total	Historical: 1980 to 1999	Projected average: 2020 to 2039	Projected average: 2040 to 2059
4” to 5”	0	0	0
5” or more	0	0	0

Similarly, maximum daily temperature readings above 95, 96, 97, 98, 99, 100, 101, 102, 103, 104, 105, 106 and 107°F were counted for each of the 21 models and then averaged. The same count was made for the average number of daily minimum temperatures below 10 through -10 degrees for each time period.

These precipitation and temperature thresholds were used as a basis to amend the climate projection data in such a way as to better account for extreme instances of precipitation, heat, and cold. For example, the average number of days across the 21 climate projection models where the maximum temperature was above 103°F was 11 days for the first time period (2020 to 2039) and 43 days for the second time period (2040 to 2059). When finalizing the climate profile data then, the data were amended so that the hottest (by rank) 11 days from the first time period were adjusted (if needed) to be above the 103°F threshold, and the 43 hottest days from the second time period were similarly adjusted, if needed. This method was performed for each of the thresholds established for maximum daily temperature, minimum daily temperature, and total daily precipitation.

The climate projection data for each time period were then matched to the historical climate data from Pavement ME. The daily rankings of temperature and precipitation per month per year were used to match the datasets together. For example, the coldest ranked January day in the first year of the climate projection data (2020) was matched to the coldest ranked January day in the first year of the historical climate data (1980), and the daily maximum and minimum temperatures for that day were appended accordingly. A similar method was used to append the future precipitation data to the historical data.

Once the daily maximum temperature, minimum temperature, and total precipitation were established for each day in the two projected future time periods and matched to the historical data, these daily weather data needed to be interpolated further in order to reflect hourly approximations. To do so, the hourly calculations made on the historical Pavement ME climate data were used as the basis for interpolating the future projected climate data. In the example provided previously, the wettest day in January 1980 involved 1 inch of precipitation that fell evenly (0.5 inches per hour) between the hours of 2 and 4 pm. If, for example, the wettest projected day in January of 2020 involved 1.4 inches of precipitation, than when interpolating this data to the hourly level, the hours of 2 pm to 4 pm would now be 0.7 inches per hour.

The result of all the data processing was two datasets of climate projection data, each representing 20 years that was matched to the historical Pavement ME climate data and interpolated to the hourly level. In doing so, the historical Pavement ME data pertaining to wind speed, relative humidity, and percent sunshine remained constant and was able to be systematically matched to the future projected data. The resulting datasets were then in the proper format to be used as climate input files for the Pavement ME software.

Pavement Performance Analysis

For this analysis, Pavement ME Version 2.31 software was utilized. This software contains climate data covering 1995 through 2015. Weather data used included hourly readings for temperature, precipitation, sunshine, humidity and wind speed. This historical data were utilized to adjust the pavement parameters previously mentioned. For pavement designs beyond 20 years, the data were replicated for future years. Data were available for seven climate stations across Kentucky. In addition to these standard climate stations used for routine analysis, an expanded climate file was developed from the climate projections over the next 40 years for the Bowling Green area of Kentucky. The distribution of mean annual temperature over the life of the climate data is provided in Figure 1. It may be seen from this figure that the proposed climate file increases the overall temperate for the Bowling Green area by a little over 3°F.

The Pavement ME process utilizes an incremental damage approach to predict the pavement performance. Truck traffic loads are applied to the pavement structure which has been modified based on the climate data, these traffic loads yield specific stresses and strains within the structure which are then associated with an incremental damage to the pavement structure. Transfer functions developed by calibration with actual in-service pavements are used to relate the incremental damage to pavement distresses.

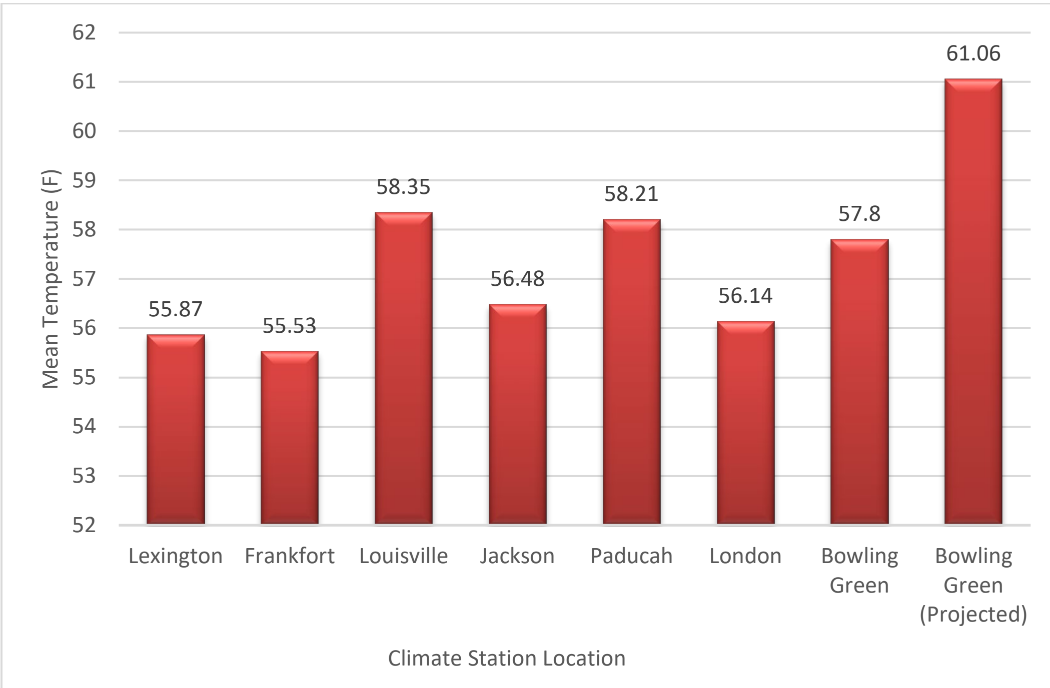

Figure 8 Mean annual air temperature. The projected climate scenarios are represented by Bowling Green (proposed).

Results

The Pavement ME software was run for a standard current pavement design in the Bowling Green area, one of the warmer regions of the state. The other data inputs such as traffic and pavement design were held to current data so that the only variation in running the pavement model was climate. The climate data was used in its current form and then was replaced with revised climate data that was the result of the projection modeling. In each of the pavement design projections using the climate data previously discussed, the software predicted pavement distresses of asphalt surface rutting and wheel path fatigue cracking. These distresses are currently utilized to evaluate potential pavement designs within Kentucky. Pavement performance was predicted for both a 20-year and 40-year anticipated pavement life. The results of these model runs are given in Figures 9 and 10.

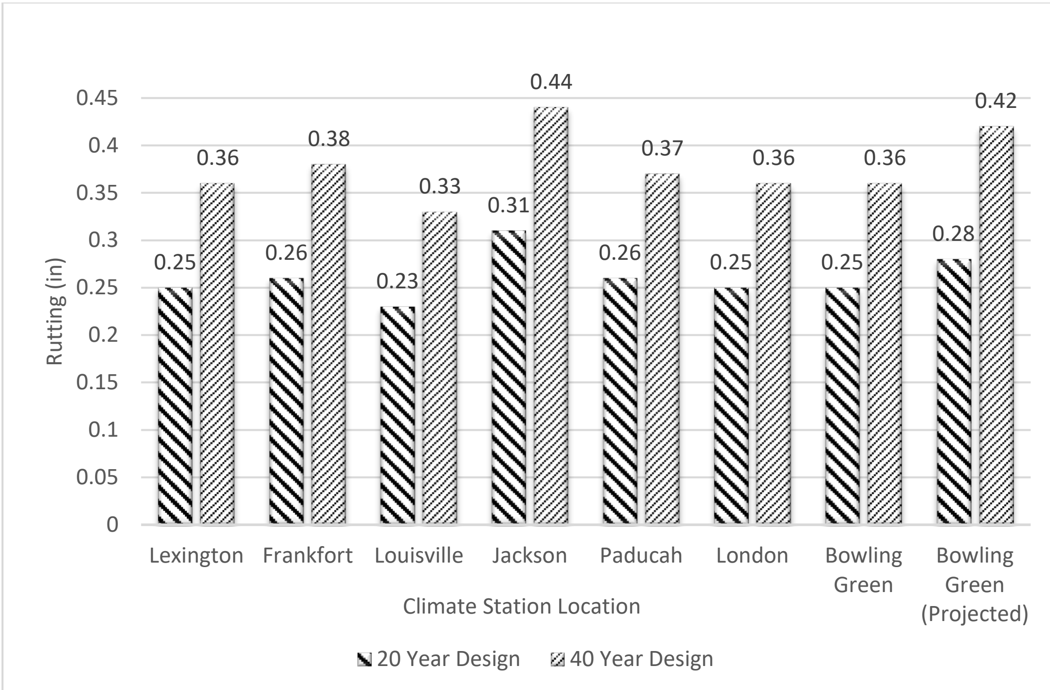

Figure 9 Predicted asphalt rutting.

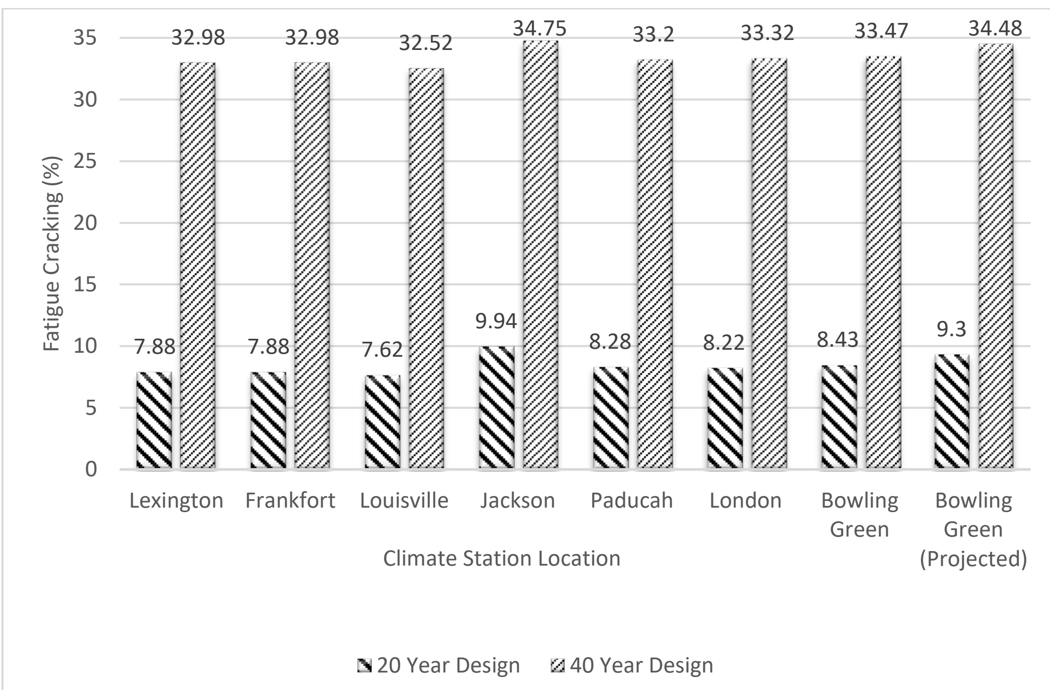

Figure 10 Predicted fatigue cracking.

Pavement distresses displayed in Figures 9 and 10 are within the normal variation of the existing climate locations across the state. At the present time, the design process used in Kentucky based on the Pavement ME software does not differentiate between different climate stations. It may also be seen from these results that the differences between the actual and proposed climate data for Bowling Green did not significantly change the predicted distresses at the 20-year and 40-year design levels. The magnitude of these differences would normally not lead to any change in design strategy based on how designs are currently conducted in Kentucky.

Kentucky normally generates a 20-year structural design of pavements while planning a 40-year life cycle meaning that there is a planned rehabilitation project included in the life cycle analysis. Typical distress values would be less than 10 percent fatigue cracking and 0.25 inches of rutting. These are typical design threshold values that are used statewide. As can be seen from the data, even one of the current climate areas (Jackson) could exceed this limit. However at the present time, this would not be considered a significant enough difference to warrant a change in design. These designs were completed with a reliability of 95 percent, so there is only a 5 percent chance that there would ever be a distress greater than those indicated.

Discussion

This proof of concept demonstrates the viability of using climate projection data as an input for pavement design and performance monitoring software. For Kentucky, the Pavement ME model predicts an increase in pavement rutting and fatigue cracking as a result of the warmer climate scenario. However, these increases are within an acceptable range in terms of pavement performance and are not high enough to warrant altering the pavement design to withstand such hotter conditions. In one sense, this is good news for Kentucky in that the models indicate the current pavement design will remain adequate going forward. In other areas of the U.S., where climate models predict a greater increase in temperature and/or the pavement design differs, these predicted impacts may be more pronounced.

This analysis was only a proof of concept exercise, and further research is needed to better understand the viability of using data from climate models as an input to pavement design software. A thorough sensitivity analysis could investigate at what levels temperature increases begin to result in more pavement damage. Similarly, changes in pavement design could be tested against climate projection models that vary according to different future emissions levels.

As climate models improve and pavement design models are updated, this analysis could be repeated to determine if the impacts are more or less significant. Phase 6 of the Coupled Model Intercomparison Project (CMIP6) is currently underway, and data should be available from this global project in the coming years. As transportation agencies continue to better improve their asset management and life cycle planning strategies, understanding and incorporating this climate projection data into such strategies will improve system performance and resilience.

RESULTS AND INTEGRATION ACTIONS

Process Improvements

ER Procedures

FHWA ER requirements from MAP-21 section 1315(b) were codified into 23 CFR Part 667. As a part of these requirements, state DOTs have been mandated to perform evaluations to determine if there have been any Federal-aid bridges, roads or highways that have had ER repairs performed on two or more occasions. For assets that have been damaged and repaired two or more times, KYTC is required to evaluate reasonable build alternatives during the design of the repair that would integrate resilient design techniques to help minimize the effect of future natural hazard events. During this project, it was recognized that KYTC lacked a system that could track and locate ER events. It was recognized that a master database of all ER events along with a GIS based tracking system was needed to monitor such events. As a part of this project, a GIS based tracking system has been developed that will allow personnel to access data and locate past ER events. Data for the system on ER events that have involved FHWA reimbursement have been obtained for events back to 2009. Records prior to 2009 have not been obtained but efforts are still on-going to locate these records. Figure 11 is a map of the 563 ER locations that have been identified to date.

District	Total Costs
1	$2,555,000
2	$2,052,600
3	$420,387
4	$2,062,307
5	$458,500
6	$3,191,500
7	$500,637
8	$698,284
9	$3,055,197
10	$2,009,500
11	$25,038,000
12	$9,599,493

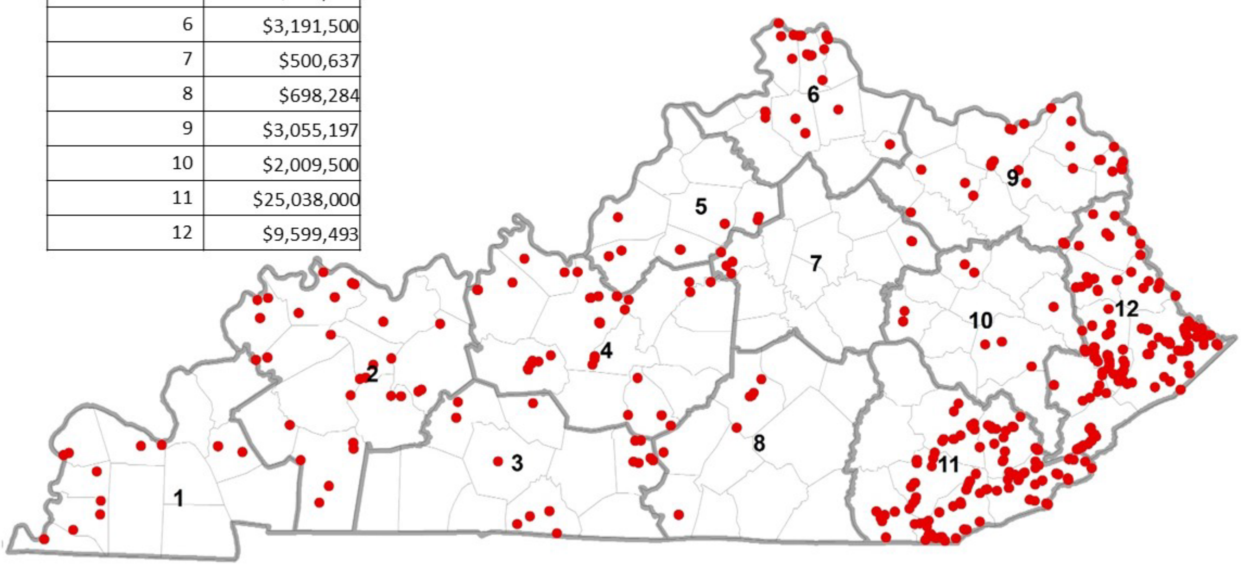

Figure 11 Locations and total costs by KYTC district of ER events from 2009 to 2018 documented as part of this pilot project. Red dots indicate center point locations of assets damaged in the events

The tracking system will enable KYTC personnel to identify damaged assets and coordinate the development of repair alternates with FHWA and Design personnel to help fulfill 23 CFR Part 667 requirements. From the locations documented so far, 19 sites have been identified as having been damaged and included repeatedly as ER sites (Figure 12).

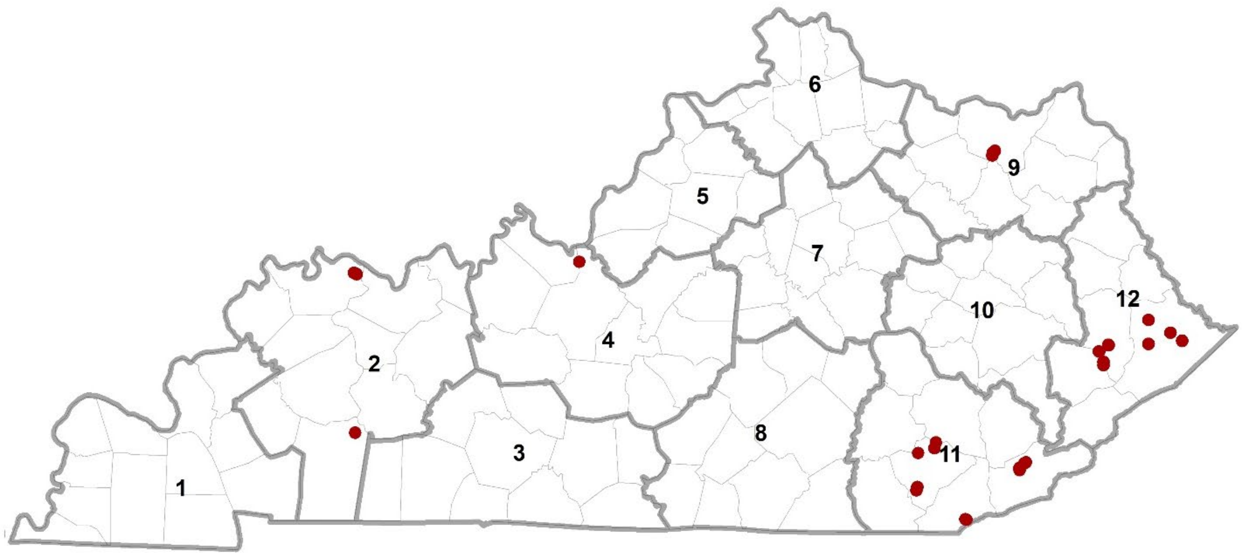

Figure 12 Locations (red dots) of assets repeatedly damaged since 2009

NEPA Coordination and Documentation

This pilot project included an assessment of the process and procedures regarding KYTC projects that are reimbursed through FHWA's ER Program. A review was conducted of historical ER events and an assessment was performed of how these events were processed by KYTC. The assessment found that notifications and processing of required paperwork for reimbursement were not happening in a timely manner. Notification to KYTC's Division of Environmental Analysis (KYTC-DEA) that an ER event had occurred was frequently delayed, resulting in final approval of a NEPA document as much as a year in some case from the date of the original event. These circumstances were causing delays in funding reimbursement to KYTC from FHWA, as well as causing FHWA to be delayed in completing the necessary paperwork to close out ER events. These delays were identified as a critical item that needed to be addressed for two reasons. First, the long period of time it was taking to complete the environmental document was preventing the ER incident from being processed through FHWA, thus delaying reimbursement back to KYTC for repairs. Secondly, in cases where notifications to various resources agencies (e.g. U.S. Corps of Engineers; State Historical Preservation Officer) were required, untimely delays were preventing the notifications from being provided in time frames that had been established through programmatic agreements.

In order to reduce these unnecessary delays it was recognized by KYTC Management that specific delegated points of contact needed to be established between District Maintenance personnel, District Environmental Coordinators, KYTC-DEA, and the State Highway Engineers Office. By establishing these points of contact, initial notification between the Districts and KYTC-DEA regarding emergency repairs is now happening in a matter of days instead of weeks or months. Also, the coordination between the State Highway Engineer's Office and KYTC-DEA has resulted in environmental documents being completed and processed in a more expedited manner. An example of this process improvement is how ER Projects have been handled recently. In 2018 alone, KYTC had 252 ER sites throughout the state resulting from various natural hazard events. Of these 252 sites, to date KYTC has completed the necessary NEPA assessment and environmental document for 247 of these ER sites within a 5 month time period. This improvement has expedited the process by which KYTC is reimbursed. While this process has improved, it is recognized that a formal written KYTC procedure needs to be developed and formally implemented regarding how ER projects should be addressed and processed by KYTC. KYTC is actively developing this procedure that will further document process and responsibilities within KYTC to help ensure further improvement in this program.

Events Occurrence/Post-Event Documentation

During the process of this pilot project an assessment was performed of what information is being collected after a natural hazard event has occurred and repairs are made to transportation assets. Currently KYTC completes a Detailed Damage Inspection Report after an event when seeking reimbursement for asset repairs through the ER Program. While these reports capture very basic information regarding event occurrences, the majority of information collected in these reports pertains to details regarding the repairs made to the asset. Critical information regarding the storm event or natural hazard occurrence is not being collected. It is recognized that in order to begin to fully understand the effects of natural hazards on transportation assets more detailed information for all major natural hazard events that cause damage to KYTC assets is necessary. Once event information is collected, future analysis can be performed to attempt to correlate the effects from event occurrences on asset degradation and effects to an asset life cycle. In order to capture event information moving forward, the pilot project has identified a need to develop a standardized post event report that documents vital information regarding the natural hazard event that has occurred. This report should be developed to capture all major natural hazard events that have either caused damage to a KYTC asset or from a closure of an asset from a natural hazard event. This documentation should include all events, even those that are not candidates to be reimbursed through FHWA and FEMA.

As a result of this deficiency, KYTC will need to initiate a process to collect basic information after a natural hazard event has occurred that has caused asset closure or after an emergency repair resulting from the occurrence. Post event documentation should include the following basic information:

- KYTC District where event occurred
- Date(s) of event
- Type of event
- Description of event
- Asset involved (roadway, bridge, other)
- Asset identification (RT_UNIQUE or Bridge ID)
- Mile points
- GPS coordinates
- If closure occurred, duration of closure, length of closure; length of detour.
- Details of repairs made to asset
- Post event inspection result documentation
- Did repairs require mitigation activities outside of KYTC right-of-way

The goal here is not to develop and implement another tool that will be cumbersome for KYTC personnel to document ER events. Several things are required for this to be successfully developed and implemented. First, there will need to be buy-in from administration and staff. The ability to implement the program with a phone-based or device application (app), such as ESRI Collector, in order for district maintenance personnel to be able to easily collect that information, document, and submit it to a central

KYTC database. It will also require integration between the multiple data sources that could be provided into the app. Some work has been done in this regard to compile the multiple big data sources into one platform, but more work is needed to integrate this into a reporting mechanism.

Developing and implementing this system would require funding and dedicated personnel. District level personnel involved with event response and repairs would need to be trained to use the system. Personnel would be needed to implement the system and begin collecting data. Funding would need to be set aside to develop the system, and funding would need to be available for personnel to bill hours to in order to successfully implement the system. Dedicated personnel would also be needed to coordinate the activities, manage the system, and monitor implementation. Data collection and integration will need to be conducted between district maintenance personnel and a representative in KYTC central office that will maintain a master database of post-event documentation.

At this time, integrating the effects of extreme weather into asset management and life cycle planning is difficult to pursue lacking the data. Data collected in the future would constitute the foundation for beginning this process. Such data could be analyzed to identify correlations between extreme weather events and asset degradation. Where correlations are found, they could begin to be factored into deterioration curves and life cycle planning.

Resiliency Working Group

The concept of resiliency to natural hazard events and the integration of its effects into asset management requires the coordination of multiple divisions within KYTC. This pilot has identified the need for the formation of a resiliency working group to be developed within KYTC. The working group would meet at a minimum biannually to foster communication, collaboration, and promote best practices to improve resiliency. The working group should include team members from each of the divisions of Planning, Highway Design, Environmental Analysis, Maintenance, Traffic Operations, and Program Management. In addition, district staff representing each branch within the district organizational structure needs to be included. The success of the Resiliency Working Group will rely on buy in, support, and participation among senior management, all divisions, and district staffs.

Example of initiatives this working group could pursue include:

- Presentation of KYTC activities around the state that promote resiliency. KYTC has twelve districts, and this group could serve as a venue through which communication and collaboration is promoted.
- Coordination with metropolitan planning organizations (MPOs) to identify opportunities for cooperation and integration of transportation resiliency activities.
- Support for and participation in storm water management and flood mitigation activities that are going on involving other state agencies. Continued coordination with the U.S. Army Corps of Engineers Silver Jackets program that identifies issues regarding natural hazard risk, mitigation, and resilience.
- Identification of strategies that improve transportation system resiliency, particularly for high risk assets. This could include activities such as culvert and drain clean outs and waterway channel maintenance. Activities could either be regularly scheduled or in anticipation of heavy rainfall events.

Lessons Learned

Challenges:

How and Why this Project Deviated from the Proposed Research Plan

At the outset of the project, the research team identified two asset classes for consideration in this work: bridges and pavement. With these asset classes in mind, the team began to consider historical and potential future impacts associated with extreme weather. Because Kentucky is an inland state, it does not face some of the challenges that coastal states do, such as sea level rise, storm surge, and inundation. The project team settled on two potential extreme weather threats to analyze in regards to bridges and pavement: extreme precipitation and extreme heat.

Initial consideration was given to develop a methodology for analyzing pavement performance in response to flooding. The team discovered quickly that developing such a methodology based on historical events was not feasible, due to the nature of available data. Pavement conditions have been historically evaluated statewide using a variety of methods. Beginning in 2009 the KYTC began collecting more detailed International Roughness Index (IRI) data, but distress data was based on visual inspection and aggregated at several hundred feet. Beginning in 2013 the KYTC started collecting distress data with a laser crack measuring system (LCMS). The LCMS data is being integrated into a new pavement management system but is not available at this time. Pavement management data is not detailed enough to determine damage from extreme weather. As stated previously, those pavement sections are measured in hundreds of feet and damage most often occurs in smaller sections.

Initial plans for analyzing the impacts of extreme precipitation and flooding on bridges was to track historic damage from flooding through a review of special bridge inspections conducted after flood events paired with climate data. However, bridge inspection reports after flooding events have not been uniformly collected, coded, or reported. No system is in place to collect and track data associated with damage to assets from natural hazard events. The need was identified and recognized through the course of this pilot project, and addressing this need is included as a potential next step to follow up this project.

The initial plan for this project included using historical cost data from previous extreme weather events to analyze the impact of extreme weather on life cycle planning. KYTC uses two different cost tracking systems. The Operations Management System (OMS) stores daily data on employee labor costs, equipment usage and material usage. That information is tied to both the type of work completed and the county, route and section of road where the activity was performed. The inclusion of contract information is optional and the system is not widely used for this purpose. For emergency response activities, specific OMS codes are produced to track costs and activities associated with the response. However, usage of these codes in not universal, and data input into OMS is incomplete. eMARS is a system used by KYTC to track contractor payments, including those associated with natural hazard response. eMARS includes delivery order information and may contain accurate county-level location data but does not necessarily contain route, route segment within a county, or daily breakdown of bulk delivery orders.

To get a complete picture of the cost impacts of extreme weather, both data sources would need to be combined while ensuring that data overlaps are addressed. This would require a detail review by dates, counties and work types that would be very time consuming. There was not time in the current project scope to fully analyze and integrate both sets of cost data.

Integrating Extreme Weather into Asset Management Planning

KYTC completed and submitted its initial TAMP to FHWA in summer of 2018. Included in the TAMP were results from KYTC's statewide vulnerability assessment of the NHS to natural hazards, including extreme weather. Additionally, the TAMP included several statements on the Risk Register pertaining to extreme precipitation and flooding.

Much of the work that went into developing the TAMP took place before this pilot project was fully up and running. As such, it has been a challenge to fully incorporate the results of this research into the plan. Nonetheless, KYTC has identified opportunities to update the TAMP before its final submittal in 2019. The results from this project's analysis of ER event locations will be included in the TAMP. The 19 road segment locations identified as having been repeatedly damaged and therefore subject to Section 667 requirements will also be included. Additional consideration will be made to update the Risk Register to more fully account for threats associated with extreme weather.

Assessing Asset Risk

The top priority for KYTC for improved pavement durability, and therefore life cycle, is improved construction of the pavement, particularly at the joints and appropriate uniform compaction. Improving the pavement construction overshadows other potential impacts, including the impacts of extreme weather. In meetings with pavement management personnel, the primary source of pavement deterioration was identified to be poor construction. Effects of extreme weather on pavement is lower on the list of pavement impacts. Given this, trying to isolate the impacts of extreme weather on pavement performance is difficult.

At this time there is not a mechanism to evaluate the impacts of extreme heat on pavements. Initial findings indicate that there is minimal risk to pavements using Pavement ME methods as potential temperature increases are already appropriately considered. Many rural pavement structures in Kentucky were designed prior to Pavement ME or were never actually designed and just evolved from unpaved surfaces. How extreme heat may affect pavements will take additional data collection and research.

To prioritize bridges potentially susceptible to flooding the researchers developed an index that will use primarily NBI data. Where there is not NBI, data already collected by bridge inspectors in Kentucky was used. No additional data collection was a goal if possible.

Overcoming Challenges

During the course of this project, it was quickly realized there would not be sufficient data available to analyze the historical relationship between extreme weather, such as extreme heat and extreme precipitation, and asset degradation. As a result, this project changed directions to consider analysis from a design perspective. Research focused on how climate data is used in pavement design and could be potentially used in a predictive method to anticipate reduced life cycle due to temperature increase. If a reduction in the design life resulted from the increase in temperature, then this could be applied at an asset class level for life cycle planning. The researchers explored if increasing both average temperatures and extreme temperatures affected the anticipated design life of existing pavement designs. If the reduction in design life could be determined, then that could be incorporated into life cycle planning for pavements. Climate projection information could be used to determine how far into the future this anticipated reduction in life cycle might be expected to start needing to be addressed for planning purposes. Researchers looked at several climate projections to determine a reasonable first attempt to project temperature data over 20 year periods. This data was then used in Pavement ME, replacing the currently used method of project historical climate data. That was the only factor changed in the Pavement ME tables and a mix design recently used in western Kentucky, the typically warmest area of Kentucky, was analyzed. The results were an insignificant decrease in pavement design life. Our interpretation is that pavement designers already account for an appropriate amount of fluctuation in temperature as part of the Pavement ME process and no changes based on possible temperature increases are warranted at this time. That is good news for pavement designers and taxpayers.

Recommendations

The BCSI assessment can be used by states with existing data. Scour observed and the scour risk calculation are data that KYTC collects that are not required by FHWA for the NBI submittal. If a state highway agency wishes to apply the BCSI assessment tool to its inventory, that data would need to either be replaced with similar data collected by the state highway agency or removed from the calculation. These two pieces enhance the assessment tool but the remaining data provided through NBI would provide valuable information even without it.

NEXT STEPS

- Establish the Resiliency Working Group with participating divisions and the group's responsibilities by policy. Once the group members are appointed, senior leadership will provide their charge and resources to accomplish the charge.
- Develop a resiliency-themed KYTC data archive, including web-based mapping and databases. This would include all data and mapping related to the statewide vulnerability of the NHS, the BCSI, and other related risk and resiliency themed data and information.
- Incorporate the results of the BCSI created through this project into the next SHIFT cycle of project prioritization and selection. KYTC decided that data used in the evaluation process must be available for all assets within an asset class, or at least a sub class. So if the BCSI will be used, it needs to be able to review all state-managed structures reported in the NBI. As the index was developed using almost entirely NBI reported data and using data that is currently collected by bridge inspectors, this challenge can be met. KYTC will need to decide how to incorporate the BCSI score into the data process for project selection.
- Universal acceptance and input of data into OMS using codes associated with ER activities needs to occur to better capture cost data for natural hazard events. Further research is needed to combine OMS cost data with eMARS data to fully understand all costs associated with ER events. Once this is accomplished, this data can be used to establish trends in maintenance and operations costs to KYTC. This would provide a fuller understanding of emergency costs and lead to more informed planning and budgeting.
- Proactively set up processes whereby work can be undertaken in advance of anticipated severe weather events. For example, when weather forecasts indicate a significant rainfall event in coming days, have a contract in place for contractors to clear out storm drains and culverts prior to the event. Ensuring that all drainage structures are cleaned on a routine basis and drainage structures prone to flooding concerns are addressed more frequently goes a long way to mitigating flooding impacts. How that work is distributed between state and contract forces is part of the decision along with the financial commitment.
- Develop a more comprehensive transportation asset inventory. KYTC does not currently maintain a comprehensive database of the locations or characteristics of culverts and pipes that are shorter than 20 feet in length. Developing and maintaining such a database would promote KYTC's asset management efforts and improve its ability to mitigate the impacts of extreme precipitation.
- Sensitivity analysis of extreme heat and pavement performance. Identify thresholds in extreme heat whereby pavement degradation is pronounced. Identify how extreme heat events impact different pavement conditions found in different areas of the state.

APPENDICES

Appendix 1: References

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Appendix 2: Summary Comparison of Historical and Projected Climate Data

Downloaded data pertains to four grid cells in southwestern Kentucky, centered along I-65 in Warren and Simpson counties.

Temperature and Precipitation Parameters	**Baseline Observed (1965-1999)**	**Projected Time Period 1 (2020-2039)**	**Projected Time Period 2 (2040-2059)**
Average Annual Mean Temperature (° F)	57.3	60.6	62.8
Average Annual Maximum Temperature (° F)	68.1	71.5	73.7
Average Annual Minimum Temperature (° F)	46.4	49.7	51.8
Hottest Temperature of the Year (° F)	97.2	101.7	104.0
Average Number of Days per Year above 95°F	6.1	27.7	48.0
Average Number of Days per Year above 100°F	0.6	3.5	9.7
Average Number of Days per Year above 105°F	0.0	0.1	0.7
Average Number of Days per Year above 110°F	0.0	0.0	0.0
Maximum Number of Consecutive Days per Year above 95°F	2.7	9.3	16.3
Maximum Number of Consecutive Days per Year above 100°F	0.3	1.8	4.1
Maximum Number of Consecutive Days per Year above 105°F	0.0	0.1	0.5
Maximum Number of Consecutive Days per Year above 110°F	0.0	0.0	0.0
Average Total Annual Precipitation	51.1	53.6	54.1
"Very Heavy" 24-hr Precipitation Amount (defined as 95th percentile precipitation)	0.9	0.9	0.9
"Extremely Heavy" 24-hr Precipitation Amount (defined as 99th percentile precipitation)	1.6	1.8	1.7
Average Number of Baseline "Very Heavy" Precipitation Events per Year (0.9 inches in 24 hours)	11.8	13.7	13.8
Average Number of Baseline "Extremely Heavy" Precipitation Events per Year (1.6 inches in 24 hours)	2.4	3.5	3.6