



Improving Transportation Resiliency

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Kentucky Transportation Center
College of Engineering, University of Kentucky, Lexington, Kentucky

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Kentucky Transportation Cabinet
Commonwealth of Kentucky

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Research Report
KTC-26-20

Improving Transportation Resiliency

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16. Abstract Transportation agencies are increasingly more challenged by the effects of extreme weather and national hazards on transportation assets. Severe weather events in Kentucky have become more frequent and more costly. These extreme events damage transportation assets, increase maintenance costs and strain transportation budgets. Climate models predict changing conditions to occur over the next century that differ from historical data. In Kentucky, models predict a warmer and wetter environment. The goal of this research is to help KYTC plan for extreme weather and natural hazards events, as well as absorb, recover from, and adapt to the resulting damage. Researchers determined where Kentucky transportation assets experienced damage from climate events and explored the consequences of not taking action to improve the resilience of Kentucky's infrastructure. They utilized KYTC operations management system data to create GIS maps of roadway damages incurred from weather events. Climate data from Oak Ridge National Laboratory was sourced and combined with the records of damages. Then, researchers modeled the relationship between weather events and impacts to the transportation system. The result of the study is a four-step framework for a cost-benefit analysis the practitioners can use to determine the amount of damage that a weather event could cause. The framework can be used to calculate direct costs of project design, materials, and labor, as well as indirect costs and benefits to the community. Practitioners can target improvements to create a more resilient transportation system. Harlan County was used as a case study and showed that narrow roads, mountainous terrain, and lack of route redundancy created transportation system vulnerability.			
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Table of Contents

Executive Summary	1
Chapter 1 Study Approach	3
1.1 Literature Review	4
Chapter 2 Roadway Damages Database	6
2.1 Source Data	6
2.2 Analysis	7
2.3 Discussion	11
Chapter 3 Climate Modeling	13
3.1 Data	13
3.2 Precipitation	13
3.3 Maximum Daily Temperature	15
3.4 Minimum Daily Temperature	16
3.5 Implications	18
Chapter 4 Impacts Assessment	19
4.1 Climate Records	20
4.2 Linking Climate Records to Damages Database	20
4.3 Probability and Magnitude of Impacts	20
4.4 Comparing Historical to Future	23
4.5 Discussion	24
Chapter 5 Other Impacts	25
5.1 Transportation Asset Inventory	25
5.2 Earthquake	26
5.3 Wind	27
5.4 Extreme Heat	27
5.5 Wildfire	28
5.6 Sinkholes	29
Chapter 6 Cost of Inaction	31
6.1 Kentucky’s Vulnerabilities	31
6.1 Conceptualizing a Cost-Benefit Analysis of Resilience	31
6.1.1 A System of Systems	31
6.1.2 Data-Driven Cost-Benefit Analysis	32
6.2 Case Study: US 421 in Harlan County	32
6.2.1 Historical Vulnerability	32
6.2.2 General Steps of a Resilience-Focused Cost-Benefit Analysis	33
6.3 Conclusions	36
References	45
Appendix A Expanded Literature Review	47
Appendix B Storm Events in Roadway Damages Database (2015 – 2022)	55

List of Figures

Figure 2.1 Federally Declared Natural Disasters By Year in Kentucky	6
Figure 2.2 Estimated Disaster Repair and Recovery Costs to Kentucky's Transportation System By Year (2023 Dollars Adjusted for Inflation)	7
Figure 2.3 Estimated Repair and Recovery Costs By KYTC District, 2009 – 2022 (Millions of 2023 Dollars Adjusted for Inflation)	8
Figure 2.4 Map of Estimated Repair and Recovery Costs By KYTC District, 2009 – 2022 (Millions of 2023 Dollars Adjusted for Inflation)	8
Figure 2.5 District 10 Map of the Ten Most Impacted Roads From 2009 to 2022	9
Figure 2.6 District 11 Map of the Ten Most Impacted Roads From 2009 to 2022	10
Figure 2.7 District 12 Map of the Ten Most Impacted Roads From 2009 to 2022	11
Figure 3.1 Percent Change in Average Annual Precipitation From the Historical (1980 – 2004) to Future Projected (2026 – 2050) Periods By County	14
Figure 3.2 Future Projected (2026 – 2050) Total Yearly Precipitation By County	15
Figure 3.3 Rise in Average Daily Maximum Temperature By County From the Historical Period (1980 – 2004) to the Future Period (2026 – 2050)	16
Figure 3.4 Change in the Average Number of Days Per Year With Highs Greater Than 100°F By County From the Historical Period (1980 – 2004) to the Future Period (2026 – 2050)	16
Figure 3.5 Change in Average Daily Minimum Temperature By County Between the Historical Period (1980 – 2004) and Future Period (2026 – 2050)	17
Figure 3.6 Change in Average Number of Days Per Year With Minimum Temperature Below 32°F By County Between the Historical Period (1980 – 2004) and Future Period (2026 – 2050)	18
Figure 4.1 Flowchart Summarizing Methods Used to Calculate Future Climate Impacts to the Transportation System	19
Figure 5.1 Maximum Peak Ground Acceleration With 2% Probability of Exceedance in 50 Years Per County	27
Figure 5.2 Average Annual Number of Days By County With Maximum Temperature at or Above 100°F	28
Figure 5.3 Total Acres Burned Due to Wildfire.	29
Figure 5.4 Total Acres Per County of Sinkhole Formations	30
Figure 6.1 Map of US 421 in Harlan County	33
Figure 6.2 US 421 Steep Slopes	37
Figure 6.3 US 421 Steep Cliff, Curve	37
Figure 6.4 US 421 Limited Space and Right of Way	38
Figure 6.5 US 421 Steep Grade, Unsigned, Poor Visibility	38
Figure 6.6 US 421 Narrow Lanes, No Shoulder	39
Figure 6.7 US 421 Mountains, No Shoulder	39
Figure 6.8 US 421 Curve, No Shoulder, Limited Visibility, Trees Fall Across Roadway	40
Figure 6.9 US 421 Wider Right of Way, Four-Lane Sections With Median in Less Rural Areas	40
Figure 6.10 US 421 Wider Right of Way and Shoulders, Cut Through Mountain	41
Figure 6.11 US 421 Landslide/Washout	41
Figure 6.12 US 421 Bridge Crossing Water	42
Figure 6.13 US 421 Bridge Crossing Railroad	42

Figure 6.14 US 421 Flood Wall in Harlan.....	43
Figure 6.15 US 421 Quarry	43
Figure 6.16 US 421 Flatter Terrain Toward Virginia, Possible Evacuation Route	44
Figure 6.17 US 421 Emergency Services	44

List of Tables

Table 2.1 District 10 Most Impacted Routes	9
Table 2.2 District 11 Most Impacted Routes.....	10
Table 2.3 District 12 Most Impacted Routes.....	11
Table 3.1 Projected Change in Precipitation From the Historical Period (1980 – 2004) to the Future Period (2026 – 2050)	14
Table 3.2 Change in Daily Maximum Temperatures (in Degrees Fahrenheit) Between the Historical Period (1980 – 2004) and Future Period (2026 – 2050)	15
Table 3.3 Change in Minimum Temperatures (in Degrees Fahrenheit) Between the Historical Period (1980 – 2004) and Future Period (2026 – 2050)	17
Table 4.1 Roadway Damage Probabilities By District for Each Daily Precipitation Threshold	21
Table 4.2 Estimated Impacts Associated With Each Precipitation Event That Resulted in Damages (in Thousands of Dollars)	22
Table 4.3 Magnitudes Per Grouped Districts and Precipitation Thresholds (In Thousands Of Dollars).....	22
Table 4.4 Projected Increase in Precipitation-Induced Annual Impacts to the Transportation System (in Thousands of 2023 Dollars)	23
Table 5.1 Summary of Transportation Asset Classes	25

Executive Summary

Accounting for effects of extreme weather and natural hazards on transportation assets is a significant challenge to the agencies managing them. Climate models predict conditions that will gradually differ over the next century compared to historical conditions. For Kentucky, these models generally predict a warmer and wetter environment. Extreme weather events that cause damage to Kentucky communities have become more frequent and costly in recent years, and this trend is likely to continue. These events damage KYTC transportation assets, increase mitigation and maintenance costs, and further strain already-stretched transportation budgets.

The goal with this research is to enhance the capabilities of KYTC to plan for, absorb, recover from, and adapt to damage resulting from extreme weather and associated natural hazards, thereby increasing the strength and resilience of transportation infrastructure. The research also explores the long-term consequences of not taking action to improve resilience by examining a local case study.

The research examines where Kentucky transportation assets have experienced damage from climate and natural hazards. Working with the Kentucky Transportation Cabinet (KYTC), KTC researchers collected records and developed a GIS database of roadway damages incurred from emergency events, including both federally declared emergencies and other non-declared emergencies coded within KYTC's Operations Management System (OMS). Within this roadway damages database, 99.5% of the damages (by cost) resulted from severe storm weather events that triggered such hazards as flooding, erosion, subsidence, and landslides. While experienced across the Commonwealth, these impacts were most severe along roads in mountainous areas of eastern Kentucky. KYTC Districts 10, 11, and 12 experienced 90.5% of the estimated \$546 million in response and recovery costs between 2009 and 2022.

To better understand such extreme weather events and to forecast their future frequency, we obtained historically observed climate data and future projected climate data downscaled to Kentucky from the Oak Ridge National Laboratory (ORNL) Climate Change Science Institute. The data was produced on a 4-kilometer grid, which provided daily precipitation totals and daily maximum and minimum temperatures. We aggregated this data to the Kentucky county level and calculated annual averages and totals for two timeframes: the historical period (1980 to 2004) and the future period (2026 to 2050). The results demonstrate that Kentucky is projected to have a warmer and wetter climate in the coming years. Precipitation is projected to increase by 2.7%. The number of days with rainfall greater than one inch are projected to increase by 7% in the future period compared to the historical period. The average daily high temperature is projected to rise by 2 degrees Fahrenheit, while the average daily low temperature is projected to rise by 3 degrees Fahrenheit.

With the climate data and the detailed records of damages, we sought to model the relationship between weather events and impacts to the transportation system. First, we calculated the likelihood of precipitation that resulted in damages to the transportation system for the years 2015 to 2022. We classified precipitation in terms of severity, with severity being defined as the maximum daily precipitation. Precipitation totals were grouped into thresholds of less than one inch, one to two inches, two to three inches, three to four inches, four to five inches, and greater than five inches. For each KYTC district, we calculated the number of days of precipitation over the time period for each of these thresholds.

Next, for each site where damage occurred, we identified the maximum daily precipitation associated with the weather event leading to the damages. We then summed the number of damage events per district as associated with each of the precipitation thresholds. Comparing the number of instances of damage with the overall number

of times precipitation exceeded each of the thresholds yielded a probability of damage for each district and for each of the precipitation thresholds. For example, in District 12, rainfalls over 2 inches have a 60% likelihood of causing damage. These probabilities were then applied to the larger sets of climate data: the historical period (1980 to 2004) for which we have daily precipitation observations, and the future period (2026 to 2050) for which we have daily precipitation model projections. This yields an annual average number of damage events for each district and for each precipitation threshold for both time periods. Comparing the historical climate data with the future projected climate data shows that the future will be characterized by more days of rainfall above the precipitation thresholds, which is projected to lead to more instances of roadway damages.

Lastly, we calculated the magnitude of this increase. We first determined the total impacts from these precipitation events for the years in which we have data, 2015 to 2022. Impacts are calculated in terms of dollars incurred for response and recovery for each of the events on record. These dollar totals were calculated by district and for each precipitation threshold associated with the event, so that an overall average cost per event could be calculated. These average costs were then applied to the historical period and the future period according to the modeled frequency of events and adjusted for inflation. This yields a modeled historical magnitude, as well as a projected future magnitude. Comparing the two demonstrates a 31% increase in annual impacts from the modeled historical period (\$54 million statewide) and the projected future period (\$71 million statewide). If climate projections hold true and no remedial action is taken, these impacts will further strain already stretched maintenance budgets.

To put these findings in context, we performed a cost-benefit analysis for a case study in Harlan County. This county, located on the southeast edge of Kentucky, has been subjected to many of the recent severe weather events and has sustained over 9 million dollars in damages. As more storms inevitably affect them, it will be worth considering the cost of repeatedly repairing the assets versus building new systems that can better withstand the upcoming weather events.

We developed a four-step framework for a cost-benefit analysis in this type of situation. Practitioners should consider the current environment and the causes of vulnerability, identify alternatives that can build resilience into the system, and then evaluate direct costs and indirect costs. This kind of analysis should aim to quantify as many metrics as possible, while not losing sight of the overall goals of the resiliency improvement program. In the case of the Harlan County case study, we identified that the narrow roads, mountainous terrain, and lack of route redundancy created system vulnerabilities. Potential alternatives included creating route redundancy, rerouting through less vulnerable terrain, widening roads, and stabilizing bridges. The direct costs of these solutions comprise tangible aspects like project design, materials, and labor. The indirect costs and benefits include ancillary effects such as travel metrics, road safety, the ability to support the economy, and the health of citizens.

Altogether, this type of cost-benefit analysis puts each alternative within the frame of its adaptability to threats. Our approach also re-emphasized the idea of a “system of systems”; that is, we must consider how vulnerable assets connect with other infrastructure and how complimentary investments can support each other. Transportation systems affect surrounding regions, the local and state economy, and the lives of residents. Investing in their resilience will benefit all.

Chapter 1 Study Approach

In December 2021, western Kentucky was struck by a devastating tornado outbreak that killed seventy people and resulted in damages estimated to cost over four billion dollars. In July 2022, eastern Kentucky was struck by catastrophic flash flooding that killed forty people, washed away homes, and critically damaged infrastructure such as roads, bridges, and power lines. Unfortunately, these events are part of a larger trend. Kentucky is increasingly experiencing the impacts of extreme weather and associated natural hazards. These events damage assets, increase mitigation and maintenance costs, and further strain already-stretched transportation budgets. Responding to and repairing damage from such events consumes a growing share of KYTC funds.

Our transportation infrastructure was designed to handle a broad range of climate impacts based on historic observations and trends, but climate conditions are becoming more extreme and there is uncertainty about how the system will sustain the fluctuations. Climate models worldwide predict conditions that will gradually differ over the next century compared to those encountered historically. For Kentucky, the climate will shift toward more heat and increased precipitation. These conditions, in turn, may lead to related disasters such as flooding, landslides, and sinkholes. The weather events and associated repair costs pose a significant threat to the safety, reliability, effectiveness, and sustainability of transportation infrastructure and operations.

However, it is possible to mitigate the severity of extreme weather consequences by increasing system resilience. A more resilient infrastructure system will be able to adapt to the changing climate conditions and withstand extreme weather events and other emergency situations. It will be able to maintain critical functions during a disruption and require less time and fewer resources to recover functions that have failed. To that end, this project aims to comprehensively identify transportation vulnerabilities to extreme weather and inform future investments in improving system resilience.

In this report, we detail the steps taken to meet the project goals. We begin by analyzing transportation asset classes and determining the historical extent to which these classes have been impacted by extreme weather and natural hazards. The state is divided into regions and existing climate models are used to determine projected precipitation and temperature changes over the lifecycle of the asset classes in those regions. Then, we use the historical record and the projected precipitation and temperature changes to project the future impacts of extreme weather to transportation assets across the Kentucky regions. This analysis identifies extreme precipitation as the primary driver of road and bridge damage in Kentucky. Extreme precipitation triggers numerous types of hazards, including flash flooding, scour, erosion, subsidence, washouts, landslides, mudslides, and rockfalls. The results are used to calculate the costs of action versus inaction and determine where and how resiliency improvements would be most beneficial. This research will help direct KYTC project investments and improve KYTC's ability to leverage federal funding for resiliency improvements.

As part of this project, the team helped draft KYTC's first Transportation Resiliency Improvement Plan (TRIP), which was approved by the Federal Highway Administration in Summer 2023. The TRIP assists KYTC in its efforts to prepare for, respond to, and withstand future extreme weather and natural hazard events affecting the transportation system. The KYTC TRIP draws heavily on a risk-based vulnerability assessment of Kentucky's National Highway

System completed by KTC in 2018.¹ The assessment identifies flooding, landslides, earthquakes, and sinkholes as the most significant threats to the NHS. Further research completed by KTC in 2019 worked with KYTC to further explore flood vulnerability and develop a methodology for modeling extreme heat impacts to pavements.²

1.1 Literature Review

A literature review was conducted to help inform the direction of this project. The review helped to define relevant terms and metrics in the topic of resilience, synthesize federal guidance for resiliency improvement plans, recognize Kentucky's specific needs, and learn from other agencies. While the full review is included as Appendix A, the following section summarizes the high points of this review.

Resilience is defined as the ability to reduce the magnitude or duration of disruptive events. Resilience can be accomplished by anticipating, absorbing, adapting to, or rapidly recovering from disruption. In simplest terms, resilient systems can maintain critical functions during a disruption and require less time and fewer resources to recover functions that have failed. Planners can increase resilience by reducing the sensitivity of the assets to extreme events and/or by enhancing the adaptive capacity of the assets.

In the transportation context, extreme weather vulnerability is a function of an asset's exposure to climate effects, sensitivity to climate effects, and adaptive capacity. Increasing resilience, therefore, can mean protecting infrastructure from extreme weather, providing flexible alternatives, or building an efficient repair plan.

Many literature sources stressed the importance of flexibility over robustness. Robustness refers to strengthening or hardening the infrastructure, while flexibility refers to increasing adaptive capacity in terms of recovering from a disaster. Other types of resilience include rebound – the ability to restore conditions and systems that have been damaged by extreme events, graceful extensibility – the ability to extend performance and mitigate the consequences of surprising events to avoid sudden and catastrophic failure, and sustained adaptability – the ability to transform, balance, and trade off multiple system dimensions in response to evolving system and environmental conditions over the long term. The flexibility within the definition of resilience highlights the need for flexible thinking when developing a resiliency improvement plan.

Equally important is the notion of transportation infrastructure as a “system of systems.” When extreme weather events occur, there are direct and indirect pathways of disruption. Direct pathways of disruption consist of abrupt impacts to physical infrastructure and non-physical factors such as human health, behavior, and decision-making. Indirect pathways of disruption result from interconnections with other critical infrastructure and social systems. In the past, these indirect disruptions have been secondary to the direct disruptions. Specific vulnerable assets were fixed under a “break-and-repair” mentality, with little regard to the impacts to assets nearby or to the overall system. However, as we build resilience into our transportation system, it is important to broaden the outlook and focus on network-wide management of vulnerability.

¹ Blandford, Schurman, and Wallace, “Assessing Transportation Assets for Vulnerability to Extreme Weather and Other Natural Hazards.”

² Blandford et al., “Kentucky Pilot Project on Asset Management, Extreme Weather, and Proxy Indicators: Final Report.”

Some federal guidance exists for integrating resiliency into a system. During our literature review, we examined three documents that helped guide our approach. First, the National Infrastructure Advisory Council's (NIAC) report on Transportation Sector Resilience examined the common challenges of building resiliency into a transportation system and provided general recommended strategies. Their approach began by baselining current risks in a quantitative manner, then developed the analytical tools and models that can identify emerging risks and interdependencies, and finally, used those results to operationalize resiliency into funding, guidance, and practices.

Next, FHWA's Vulnerability Assessment and Adaptation Framework laid out a structured process for building climate adaptations into transportation infrastructure. The document detailed how to assess the vulnerability of a transportation asset or system. The recommended approaches relied on empirical qualitative data such as stakeholder input, analytical quantitative data such as hardness measurements, or some combination of both. We combined the qualitative and quantitative methods in our assessment. In this approach, there are many ways to appraise risk: we considered the level of use of an asset, the degree of redundancy in the system, and the value of an asset in terms of cost of replacement, economic loss, environmental impacts, cultural values, or loss of life. The Framework offered guidance for identifying, analyzing, and prioritizing adaptation options. Any number of adaptation solutions can be considered; they can be natural, structural, or policy based. They caution against choosing a strategy that is too generic, instead encouraging the creation of specific and detailed solutions. The guide also recommended performing an economic analysis to evaluate potential improvements, which can include both quantitative and qualitative data. We relied on this source to guide our economic analysis approach.

Lastly, FHWA's "Synthesis of Approaches for Addressing Resilience in Project Development" provided more specific guidance in terms of data, adaptation strategies, and economic analyses. It recommended using downscaled CMIP3 and CMIP5 climate data and hydrology predictions. The five main adaptation strategies were advanced preparation, increased redundancy, physical barrier protections, modified infrastructure designs, and relocation of assets. Any of these five strategies could be considered for various asset classes in Kentucky. To evaluate adaptation options, the authors endorsed benefit-cost analysis, net present value, lifecycle cost analysis, and/or economic impact analysis. These enhanced analyses consider repair costs as well as socioeconomic; they also account for uncertainties or risks inherent in the assumptions of future climate scenarios.

Using Kentucky's previous resilience efforts and FHWA guidance to inform our process, we developed a framework to assess vulnerability, compared historic climate data to projected climate data, and predicted the statewide impacts if action is not taken. The findings underscore the need to start building resilience in our transportation system. A more resilient infrastructure system will be able to adapt to the changing climate conditions and withstand extreme weather events. This can help support KYTC's mission of providing a safe, efficient, environmentally sound, and fiscally responsible transportation system that delivers economic opportunity and enhances the quality of life in Kentucky.

Chapter 2 Roadway Damages Database

The annual number of federally declared natural disasters has risen over the last three-plus decades in Kentucky (Figure 2.1). From 1980 to 1999, the Commonwealth averaged 0.75 declared disasters per year, whereas from 2000 to 2022 that number more than doubled to 1.83. Part of this increase can be attributed to changing standards in terms of what qualifies as a federal disaster. However, most of this increase can be attributed to a rise in the frequency of extreme weather events.

The 59 declared emergencies over this period can be broken down into five types of disasters, and any given event may include more than one disaster type. These include:

- Flooding. Factored in 44 (75%) of the declared disasters.
- Wind. Factored in 36 (61%) of the declared disasters.
- Landslides. Factored in 25 (42%) of the declared disasters.
- Winter weather (snow and ice). Factored in 10 (17%) of the declared disasters.
- Wildfire. Factored in 4 (7%) of the declared disasters.

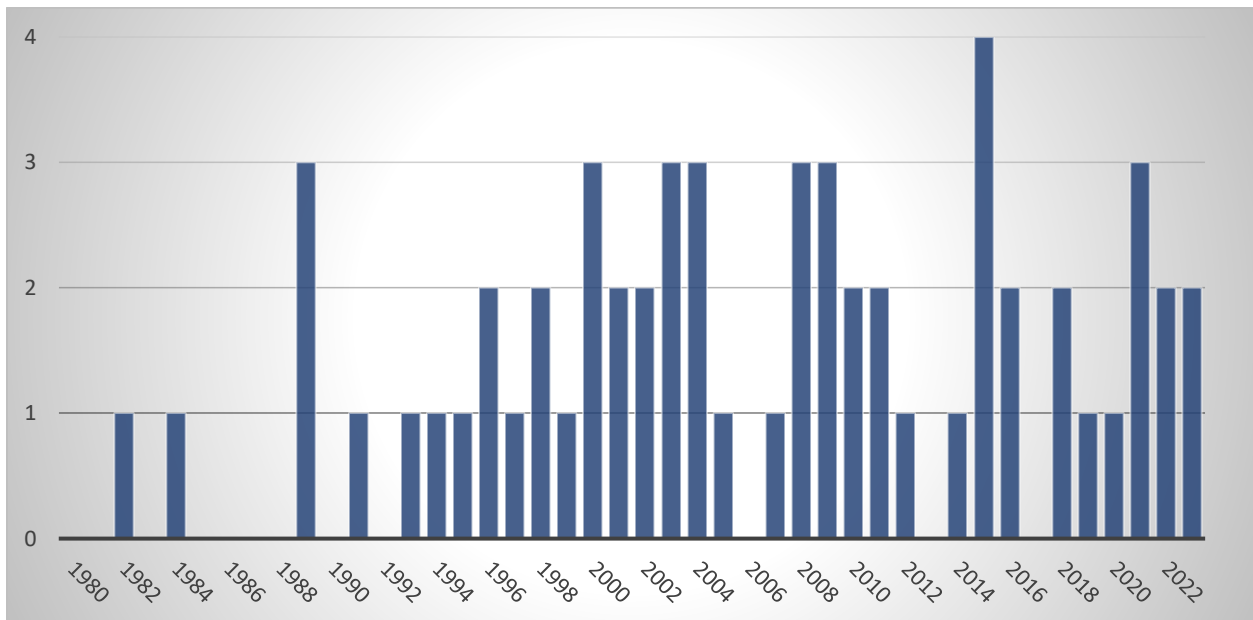


Figure 2.1 Federally Declared Natural Disasters By Year in Kentucky

Each of these events were declared an emergency due to their negative impacts on Kentucky communities. However, the impacts vary in their extent and intensity across different types of community assets. To better understand how these events impact the transportation system, we worked with KYTC to collect data pertaining to roadway damage associated with severe weather and other natural hazards.

2.1 Source Data

Our project team has worked with KYTC since 2018 to maintain a centralized database of road and bridge impacts/damages that have resulted from weather and other natural causes. The database comprises over 10,000 records covering the years 2009 to 2022. The data includes information on the causal event, when and where damage occurred (county, route, milepoint), the nature of the damage, the action taken to repair/respond, and the

costs associated with these actions. All data has been georeferenced in a GIS database based on the route and milepoint for the incident (relative to appropriate KYTC linear referenced system for the year in which the event occurred).

The database has been compiled from three separate but related KYTC sources:

- **Federal Highway Administration Emergency Relief Program (FHWA ER)** assists transportation agencies in responding to natural disasters that have been declared a federal emergency. The FHWA ER program reimburses agencies for repair and recovery costs to highways that are part of the federal aid route system. The database includes FHWA ER records back to 2009, though records prior to 2015 are likely incomplete.
- **Federal Emergency Management Agency (FEMA) Public Assistance** assists transportation agencies with repair and recovery costs associated with federally declared emergencies that were not reimbursed through FHWA-ER or occurred on routes that are not part of the federal aid system. The database includes FEMA reimbursement records from 2018 to the present.
- **Operations Management System (OMS)** is an internal system KYTC uses to track the costs of labor, equipment, and materials for maintenance projects. In the event of a natural disaster, a disaster code is issued, and all repair and recovery costs can be linked to this code. For this project, OMS records associated with disaster codes from 2015 to 2022 are included. The OMS system includes overlapping records with the FHWA ER and FEMA data, which required the identification and removal of duplicate records.

2.2 Analysis

Figure 2.2 shows the estimated dollars per year in repair and recovery costs. The years 2018 through 2022 mark a significant increase in costs, with each year topping \$70 million, and the costliest year being 2022 at \$131 million.

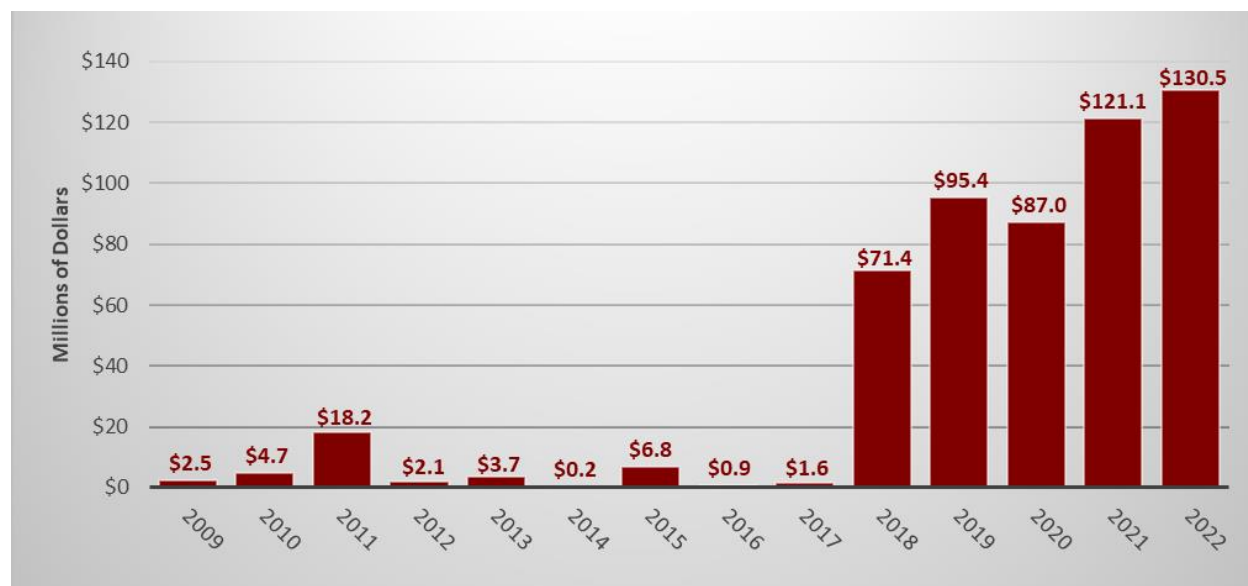


Figure 2.2 Estimated Disaster Repair and Recovery Costs to Kentucky's Transportation System By Year (2023 Dollars Adjusted for Inflation)

Figures 2.3 and 2.4 show the estimated dollars spent across all years by KYTC district. The mountainous Districts of 10, 11, and 12 experienced the worst impacts from climate and natural hazards, accounting for 90% of the total \$545 million damages by cost. District 11 leads the way at \$248 million over the fourteen-year period.

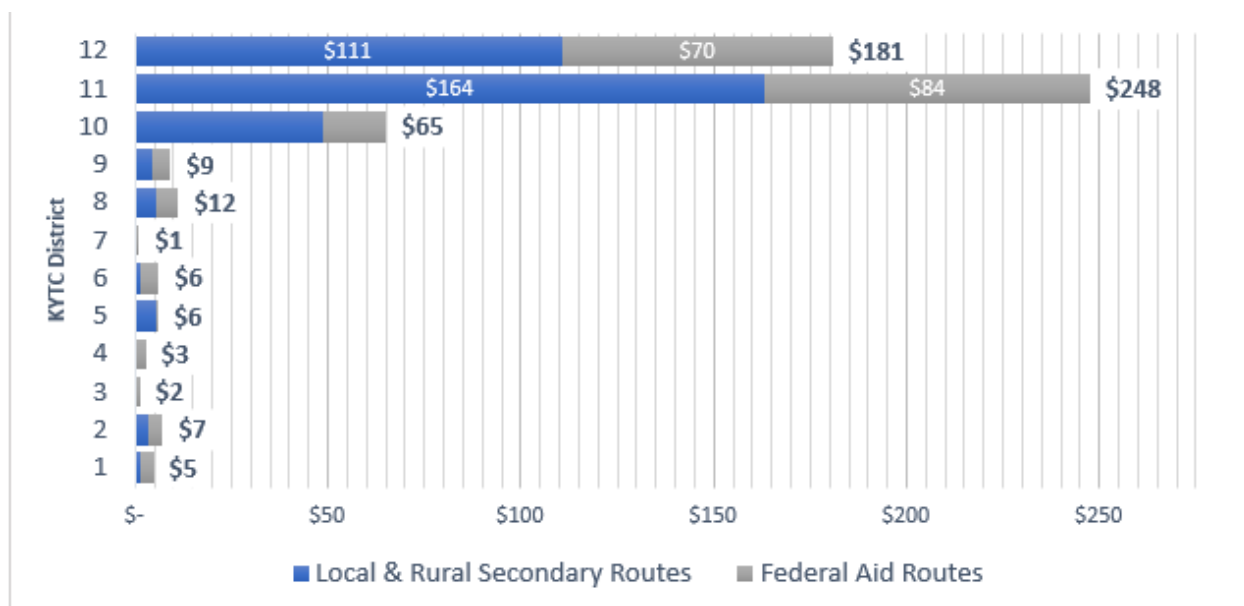


Figure 2.3 Estimated Repair and Recovery Costs By KYTC District, 2009 – 2022 (Millions of 2023 Dollars Adjusted for Inflation)

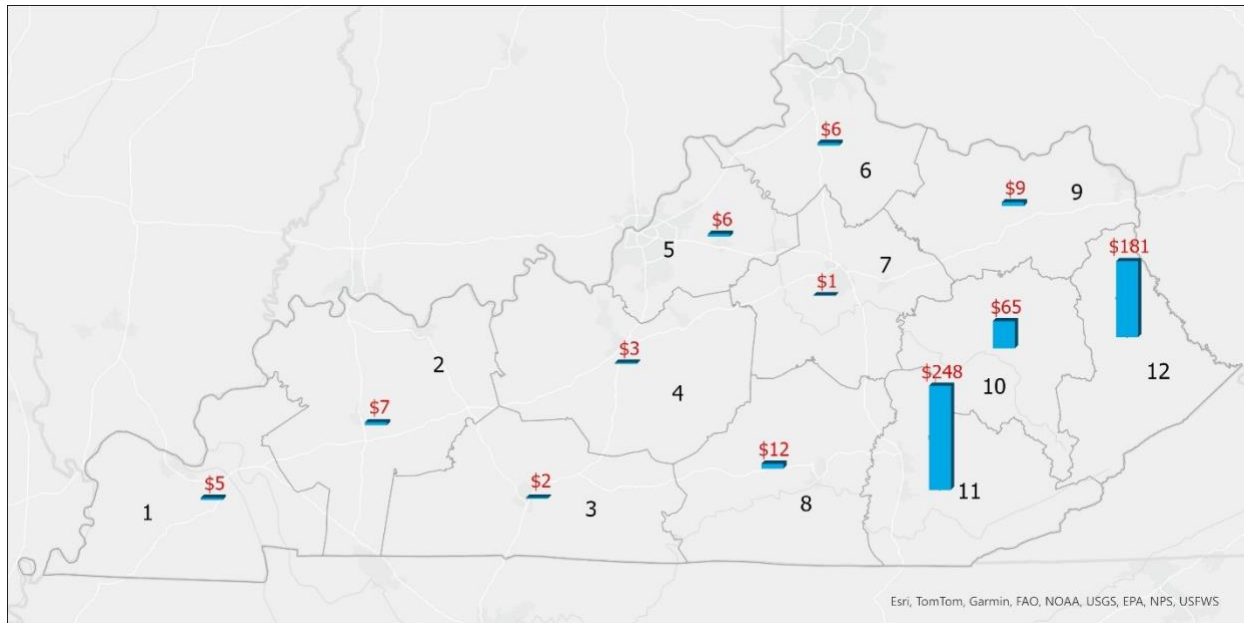


Figure 2.4 Map of Estimated Repair and Recovery Costs By KYTC District, 2009 – 2022 (Millions of 2023 Dollars Adjusted for Inflation)

With Districts 10, 11, and 12 being the most impacted, we found it valuable to identify specific roads within these districts where response and repair activities have been the most needed. Tables 2.1 – 2.3 and Figures 2.5 – 2.7 list and map the top ten most impacted roads for these districts in terms of costs, measured from 2009 and 2022.

Table 2.1 District 10 Most Impacted Routes

Rank	County	Route	Costs (2023 dollars)	Number of Events
1	Breathitt	KY 15	\$9,572,000	3
2	Perry	KY 451	\$4,718,000	7
3	Breathitt	KY 1110	\$3,014,000	7
4	Perry	KY 267	\$1,886,000	5
5	Breathitt	KY 30	\$1,821,000	6
6	Perry	KY 3351	\$1,785,000	5
7	Perry	KY 2022	\$1,772,000	5
8	Perry	KY 28	\$1,421,000	4
9	Estill	KY 499	\$1,346,000	6
10	Perry	KY 476	\$1,214,000	7

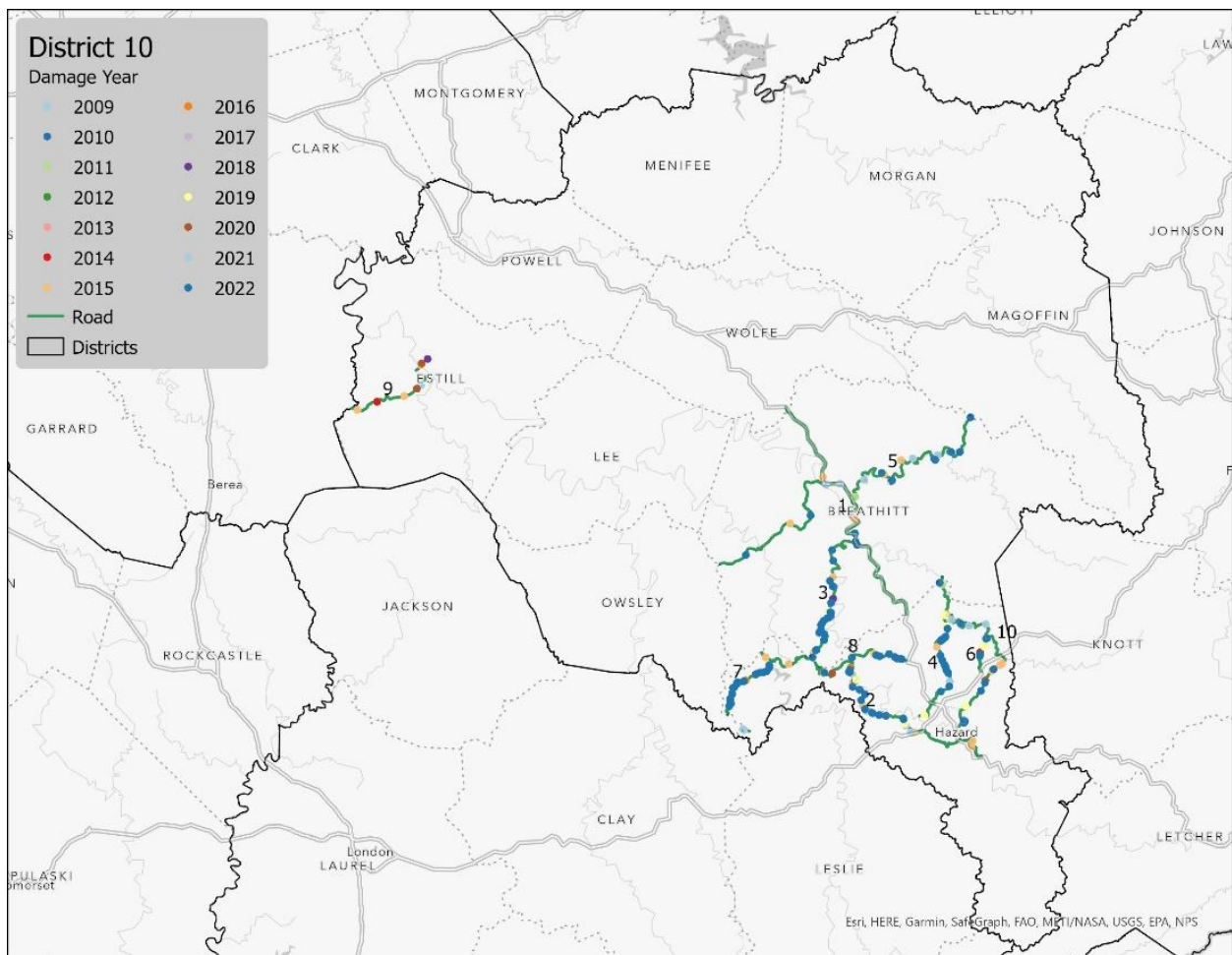


Figure 2.5 District 10 Map of the Ten Most Impacted Roads From 2009 to 2022

Table 2.2 District 11 Most Impacted Routes

Rank	County	Route	Costs (2023 dollars)	Number of Events
1	Harlan	US 421	\$9,685,000	12
2	Bell	KY 74	\$8,288,000	7
3	Clay	KY 11	\$7,592,000	7
4	Leslie	KY 2009	\$7,143,000	13
5	Clay	KY 66	\$7,107,000	8
6	Harlan	KY 179	\$6,464,000	8
7	Whitley	KY 92	\$5,986,000	10
8	Leslie	KY 257	\$5,933,000	12
9	Leslie	US 421	\$5,130,000	15
10	Knox	KY 11	\$5,049,000	8

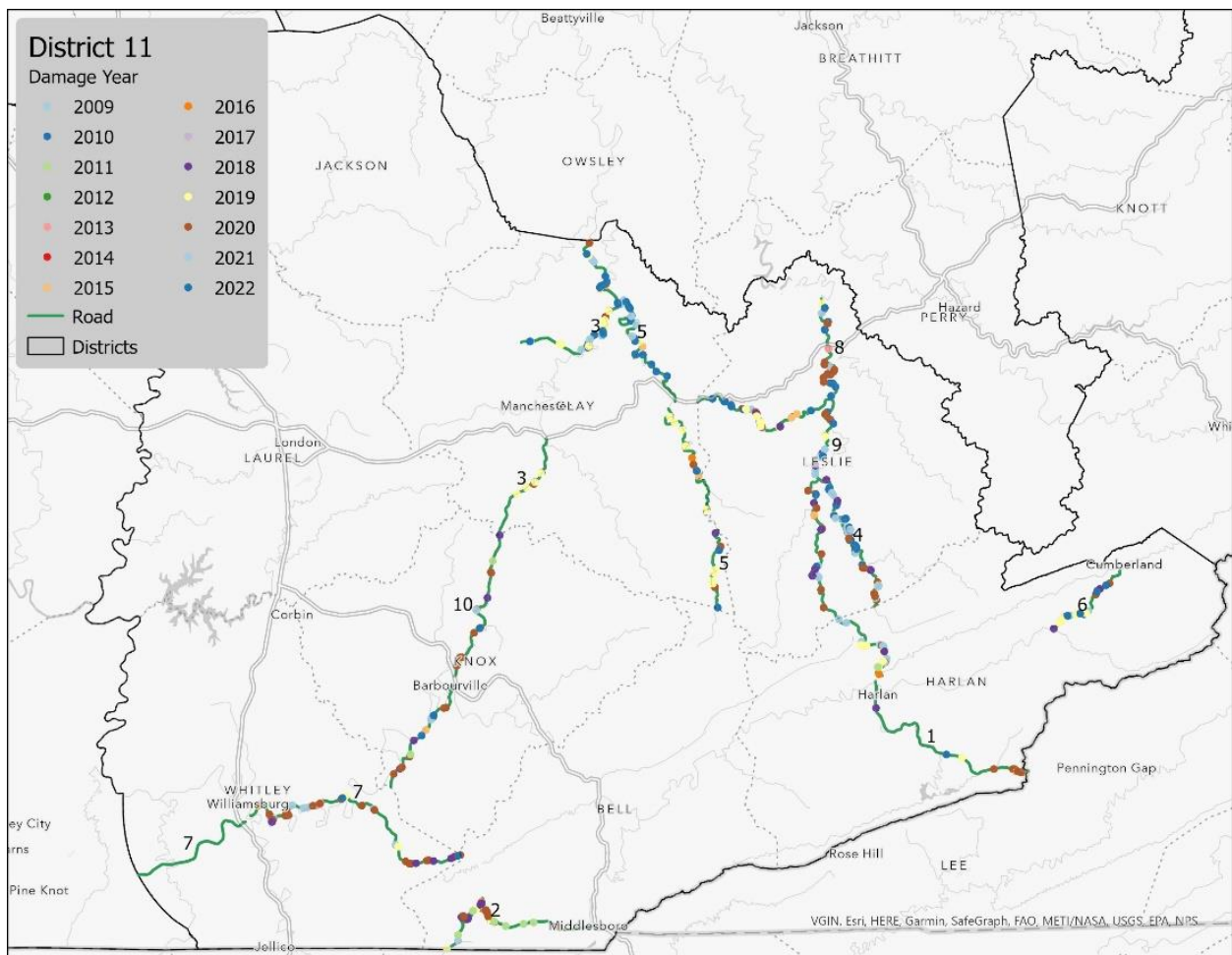
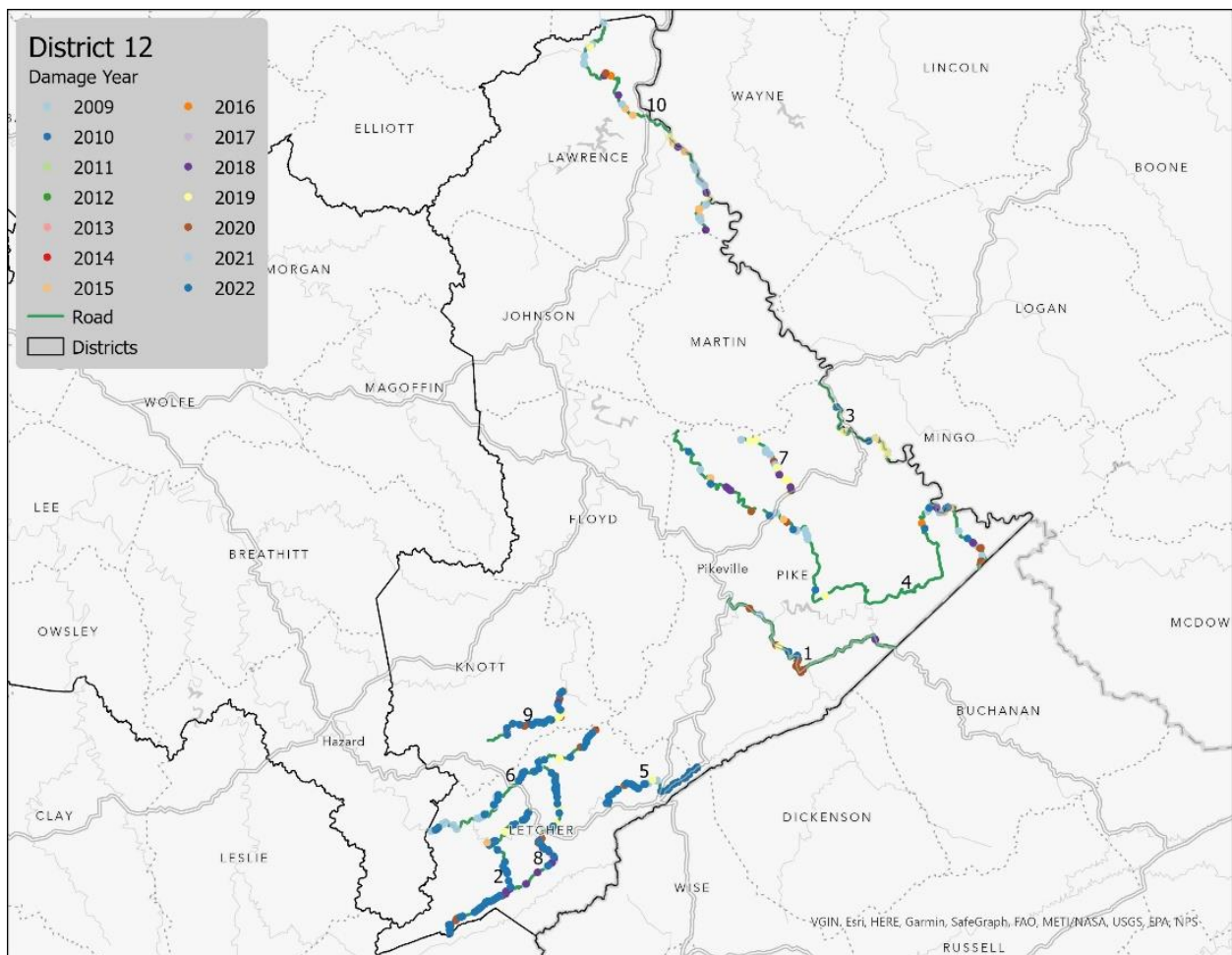


Figure 2.6 District 11 Map of the Ten Most Impacted Roads From 2009 to 2022

Table 2.3 District 12 Most Impacted Routes

Rank	County	Route	Costs (2023 dollars)	Number of Events
1	Pike	US 460	\$7,433,000	6
2	Letcher	KY 160	\$6,065,000	4
3	Pike	KY 292	\$4,774,000	4
4	Pike	KY 194	\$4,208,000	12
5	Letcher	KY 805	\$4,030,000	4
6	Letcher	KY 7	\$3,983,000	4
7	Pike	KY 881	\$3,714,000	6
8	Letcher	KY 931	\$3,655,000	6
9	Knott	KY 582	\$3,477,000	11
10	Lawrence	KY 3	\$3,466,000	8

**Figure 2.7** District 12 Map of the Ten Most Impacted Roads From 2009 to 2022

2.3 Discussion

Each record in the database is associated with a causal event. For records associated with emergency declarations, the FEMA event number is the identifier. For those from the OMS database, the OMS emergency code is the identifier. In either case, the causal event is characterized by the type of climate and/or natural hazard that was

involved. As with emergency declarations, there can be overlap in terms of causal events, such as an event including severe storms, flooding, and landslides.

Reviewing the data reveals that 65 out of 70 of the events since 2009 involve severe storms featuring some combination of flooding, wind, and/or landslides. The remaining 5 events are winter storms featuring ice and/or snow. The 65 severe storm events account for 99.5% of the repair and recovery costs in the database.

These findings suggest that severe storms and the associated flooding, wind damage, and landslides are the primary natural hazard affecting Kentucky roadways. These impacts are felt most severely in the mountainous areas of eastern Kentucky. The combination of severe precipitation events across the rugged mountainous topography triggers hazards like flash flooding, erosion, subsidence, and landslides, all of which can cause damage to Kentucky roadways.

Subsequent stages of this research rely on the Kentucky roadway damages database as the point of reference in analyzing when, where, and how climate hazards interact with the transportation system. Because most impacts result from severe storm events, the next step seeks to model the relationship between the frequency and magnitude of climate events and eventual roadway impacts.

Chapter 3 Climate Modeling

Climate-based impacts are among the primary causes of damage and disruption to the transportation system. To better understand future impacts to Kentucky's transportation system, we obtained future climate projection data for comparison to historical climate data.

3.1 Data

Climate projection data downscaled to Kentucky was provided by the Oak Ridge National Laboratory (ORNL) Climate Change Science Institute. The downscaled data represents an ensemble average of 11 Global Climate Models (GCMs) from the Coupled Model Intercomparison Project Phase 5 (CMIP5).³ Each of the 11 GCMs use Representative Concentration Pathway 8.5 (RCP8.5), which is considered the "high emissions" scenario, in the future projections.

Historical observed data is from the ORNL Daily Surface Weather and Climatological Summaries (Daymet). Daymet data is produced by interpolating daily meteorological observations on a 1-kilometer x 1-kilometer grid. This provides estimates of weather conditions across the entire surface area even where no instrumentation exists. Historical observed data is necessary to "bias correct" the modeled data. The bias correction process addresses systematic errors that result when GCMs, which are produced on much larger grid sizes, are downscaled to a smaller localized area.⁴ For this study we used a quantile-based bias correction technique as described in Ashfaq et al, 2010.⁵

To compare and calculate changes between the historical and the future projected data, a baseline time period of 25 years was established. This period is long enough to ensure calculated changes are meaningful. The 25 years in the historical period are 1980 to 2004, and the years in the future projected period are 2026 to 2050. The modeled climate data is produced on the same 1 km x 1 km grid as the observed Daymet climate data. For this analysis, the gridded data was aggregated at the Kentucky county level, which is a scale more meaningful and easier to act on for KYTC.

3.2 Precipitation

Using the ORNL future projections and comparing them to the observed historical data, we determined the percent change and the average change in the average amount of precipitation per year between the historical period and the future projection. In addition to the percent change in the average amount of precipitation, we calculated the percent change and average change in the number of days with precipitation over certain thresholds, as these thresholds were useful in determining the likelihood of damage occurring on Kentucky's roadways.

The overall future trends for Kentucky demonstrate a generally warmer and wetter climate. For precipitation, Kentucky is projected to average 52.0 inches of rainfall in the future period compared to 50.6 in the historical period, for an increase of 1.4 inches annually. Temporally, this increase is greatest and evenly distributed across the winter,

³ Ashfaq et al., "High-Resolution Ensemble Projections of near-Term Regional Climate over the Continental U.S."; Ashfaq et al., "Near-Term Acceleration of Hydroclimatic Change in the Western U.S."; Ashfaq et al., "Influence of Climate Model Biases and Daily-Scale Temperature and Precipitation Events on Hydrological Impacts Assessment."

⁴ Smitha et al., "An Improved Bias Correction Method of Daily Rainfall Data Using a Sliding Window Technique for Climate Change Impact Assessment."

⁵ Ashfaq et al., "Influence of Climate Model Biases and Daily-Scale Temperature and Precipitation Events on Hydrological Impacts Assessment."

spring, and summer months, while autumn precipitation is projected to rise just slightly (Table 3.1). While all areas of Kentucky are projected to have increased precipitation, the highest percent change is projected in the central and northern counties (Figure 3.1).

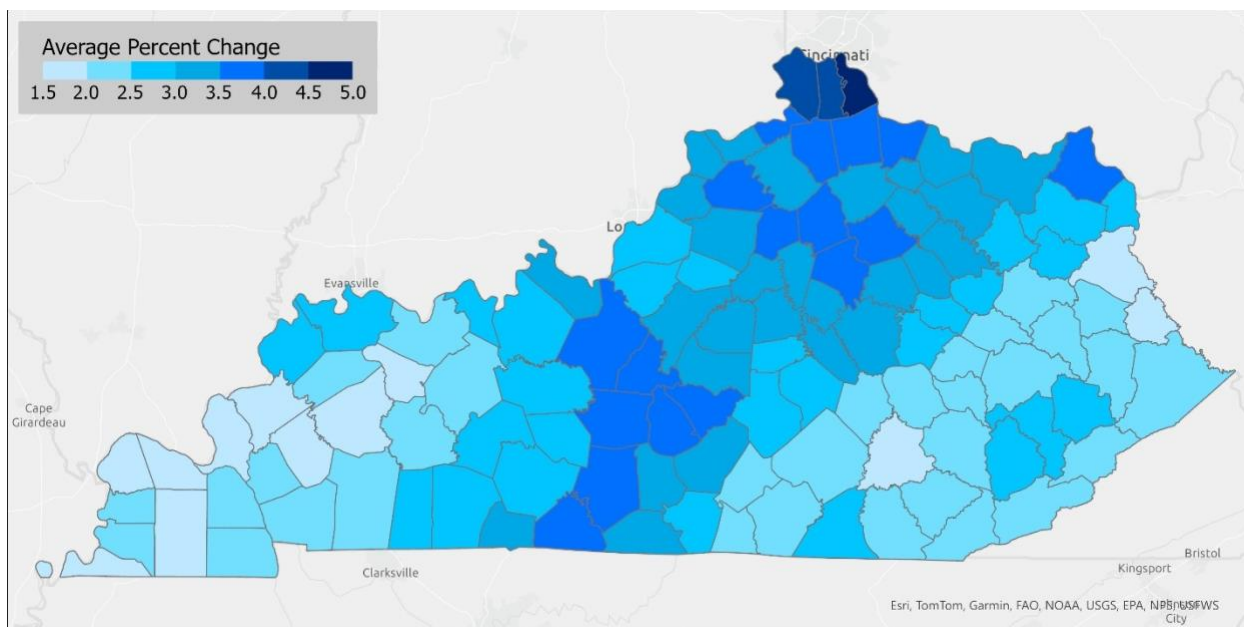


Figure 3.1 Percent Change in Average Annual Precipitation From the Historical (1980 – 2004) to Future Projected (2026 – 2050) Periods By County

In addition to an increase in overall annual precipitation, the frequency of heavy rainfall days is also projected to increase. The average annual number of days with rainfall totals greater than 1 inch, 2 inches, and 3 inches are all projected to rise, with the higher precipitation totals having the higher percentage increases (Table 3.1).

Table 3.1 Projected Change in Precipitation From the Historical Period (1980 – 2004) to the Future Period (2026 – 2050)

	Historic	Projected	% Increase
Avg annual total	50.6	52.0	2.7%
Avg winter	12.2	12.6	3.0%
Avg spring	14.6	15.0	3.3%
Avg summer	12.6	13.0	3.2%
Avg autumn	11.3	11.4	1.2%
Avg annual days >1"	10.130	10.835	7.0%
Avg annual days >2"	1.079	1.287	19.3%
Avg annual days >3"	0.146	0.200	37.2%

Figure 3.2 shows the future projected frequency by county of rain events greater than 1 inch in a calendar day. Western Kentucky will experience a higher frequency of heavy rainfall days compared to other areas of Kentucky. Eastern Kentucky will experience fewer such days, which is fortunate given the mountainous topography characterizing the area.

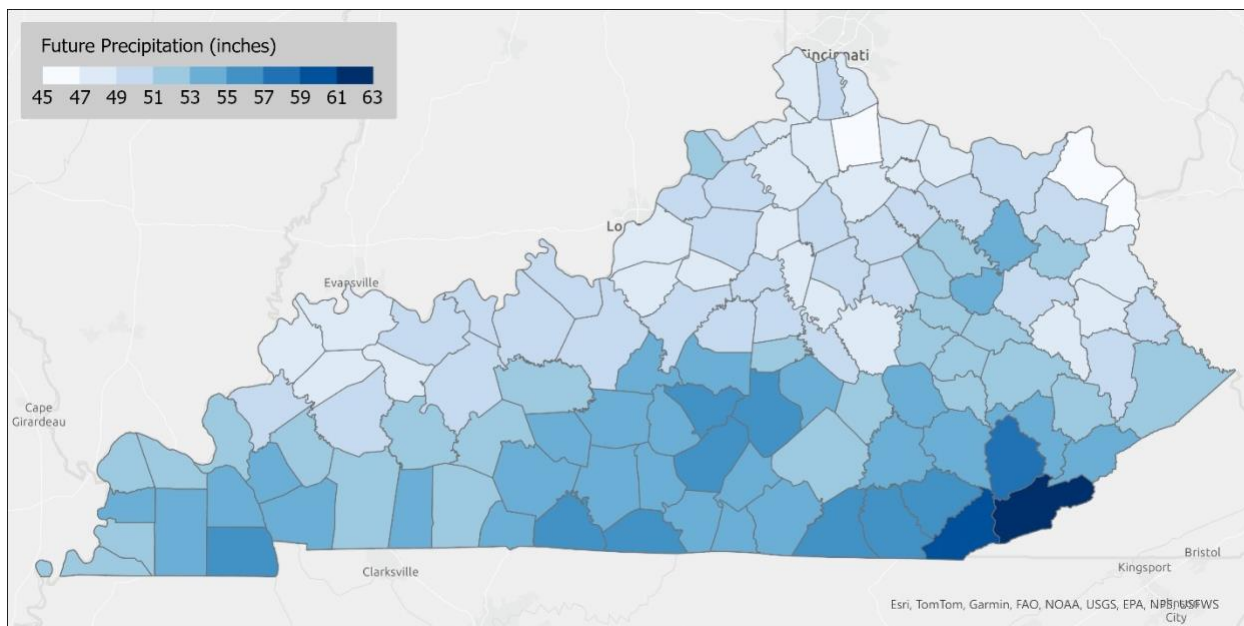


Figure 3.2 Future Projected (2026 – 2050) Total Yearly Precipitation By County

3.3 Maximum Daily Temperature

Kentucky's climate is projected to be warmer in the future period. The average daily maximum temperature is projected to rise two degrees Fahrenheit from 67°F to 69°F, and this increase is projected to extend across all four seasons in the year (Table 3.2). The average maximum yearly temperatures are similarly projected to rise from 95°F to 98°F. The rise in maximum temperature will be felt most strongly at the extremes, with Kentucky projected to experience nearly 10 days annually with temperatures above 95°F, compared to 4 in the historic period.

Table 3.2 Change in Daily Maximum Temperatures (in Degrees Fahrenheit) Between the Historical Period (1980 – 2004) and Future Period (2026 – 2050)

	Historic	Projected	% Increase
Average daily max	67°	69°	
Average winter daily max	45°	47°	
Average spring daily max	67°	69°	
Average summer daily max	85°	88°	
Average autumn daily max	69°	71°	
Average annual max	95°	98°	
Average annual days >95°	3.8	9.81	156%
Average annual days >100°	0.3	1.01	220%
Average annual days >105°	0.0001	0.03	22600%

Across Kentucky, counties in the western and northern parts of the state will experience the greatest rise in maximum temperatures (Figure 3.3). Maximum temperatures in mountainous areas of southeastern Kentucky will also rise, though to a lesser extent. This effectively means that the western areas of the state that are already the warmest will also experience the greatest increase in temperatures.

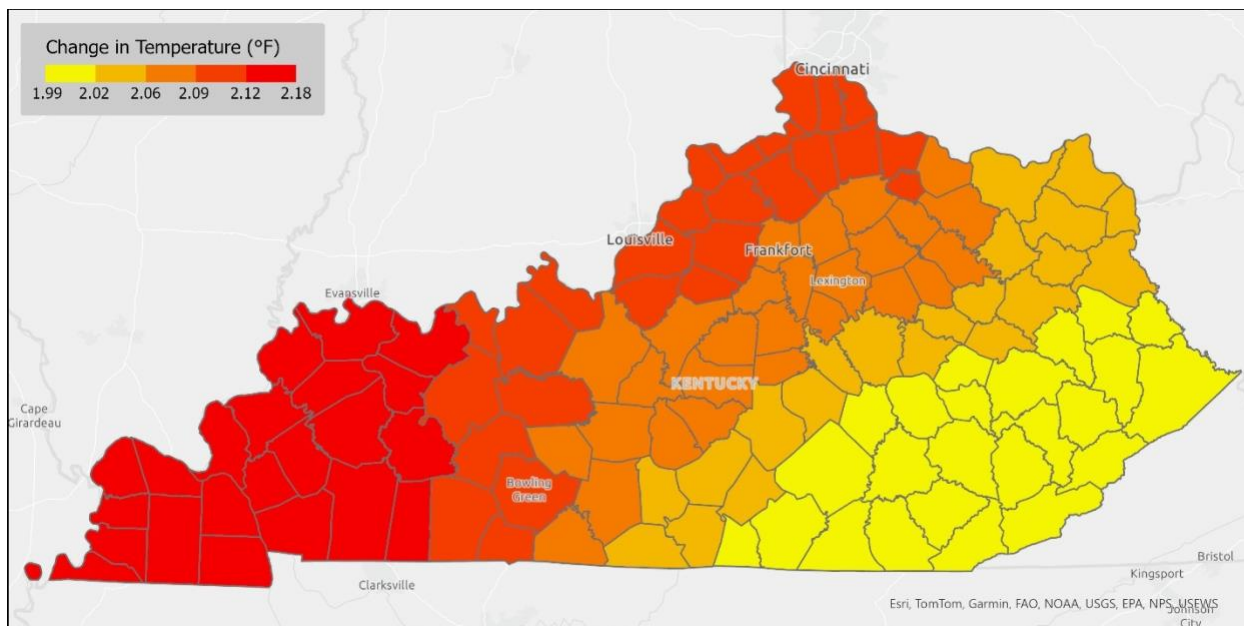


Figure 3.3 Rise in Average Daily Maximum Temperature By County From the Historical Period (1980 – 2004) to the Future Period (2026 – 2050)

Western Kentucky counties in the future period project to average more than three days per year with temperatures exceeding 100°F, and temperatures rising above 105°F once every four years (Figure 3.4).

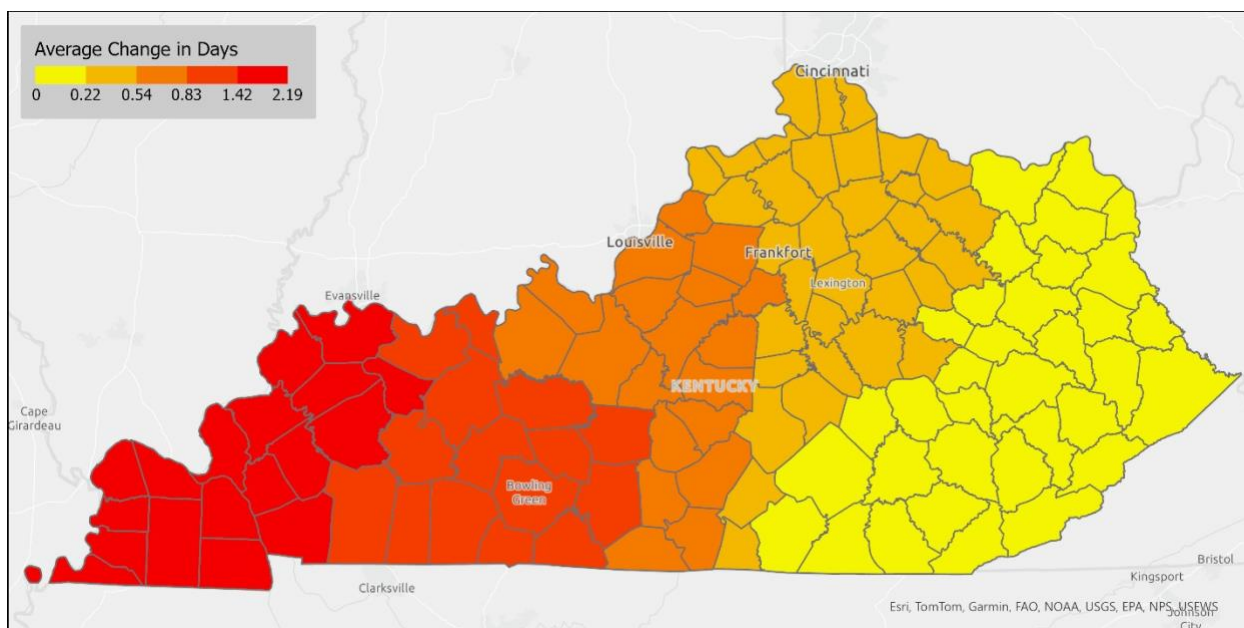


Figure 3.4 Change in the Average Number of Days Per Year With Highs Greater Than 100°F By County From the Historical Period (1980 – 2004) to the Future Period (2026 – 2050)

3.4 Minimum Daily Temperature

Increased heat can also be considered in terms of rising minimum daily temperatures. For the future projected period, the daily minimum temperature is projected to rise by three degrees Fahrenheit, from 44 to 47 (Table 3.3).

This increase is evenly distributed across the four seasons. The annual average minimum temperature in Kentucky is similarly projected to rise three degrees from -2 to 1. With these increases in daily minimum temperatures, Kentucky will average fewer days where the temperature dips below freezing: In the historic period Kentucky averaged 97.5 days annually, and in the future period this number drops by 18 percent to 80 days annually.

Table 3.3 Change in Minimum Temperatures (in Degrees Fahrenheit) Between the Historical Period (1980 – 2004) and Future Period (2026 – 2050)

	Historic	Projected	% Change
Average daily min	44°	47°	
Average winter daily min	26°	29°	
Average spring daily min	43°	46°	
Average summer daily min	63°	66°	
Average autumn daily min	45°	47°	
Average annual min	-2°	1°	
Average annual days <32°	97.45	79.85	-18%
Average annual days <15°	14.34	10.42	-27%
Average annual days <0°	1.65	0.89	-46%

When the data is analyzed by county, we uncovered that the greater increases in minimum daily temperatures will be experienced in the northern areas of Kentucky (Figure 3.5) and a decrease statewide in the average annual number of days where the temperature falls below freezing (Figure 3.6).

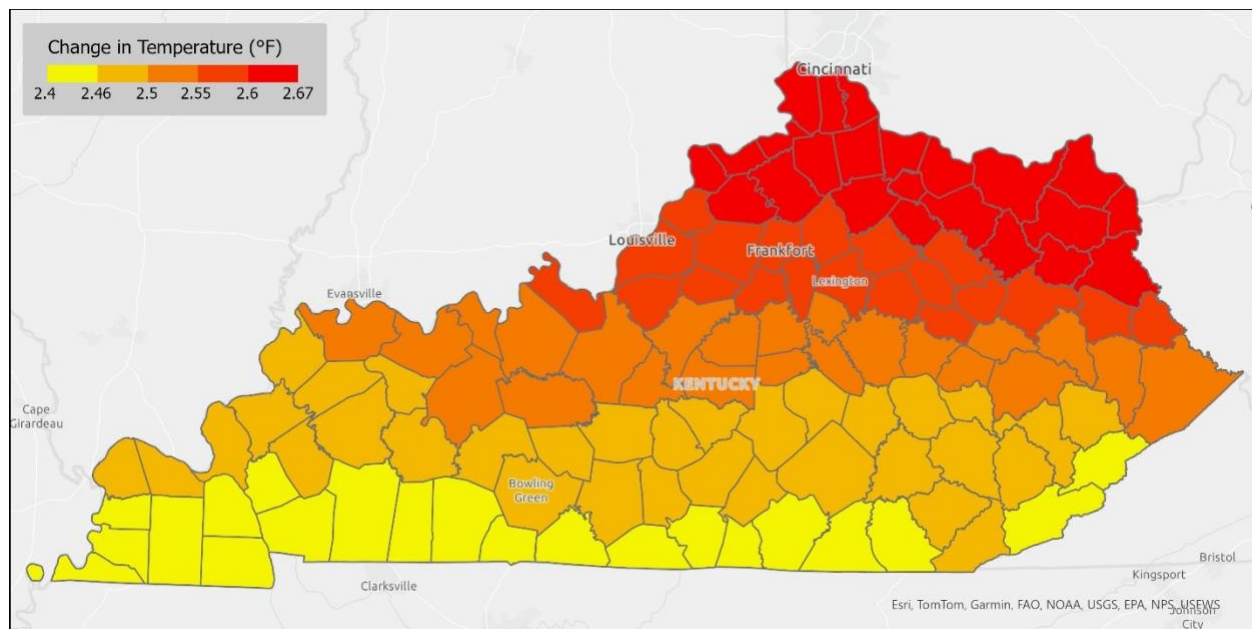


Figure 3.5 Change in Average Daily Minimum Temperature By County Between the Historical Period (1980 – 2004) and Future Period (2026 – 2050)

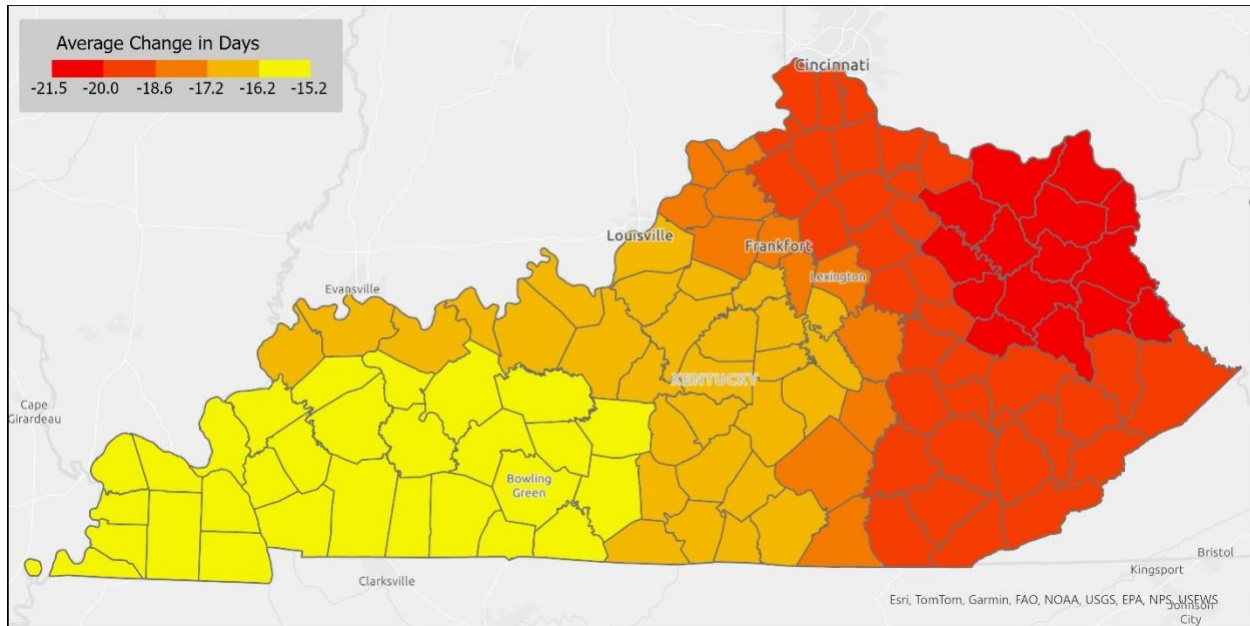


Figure 3.6 Change in Average Number of Days Per Year With Minimum Temperature Below 32°F By County Between the Historical Period (1980 – 2004) and Future Period (2026 – 2050)

3.5 Implications

As demonstrated in the previous chapter, climate events are a primary driver of transportation system impacts in Kentucky. To better understand the frequency, distribution, and magnitude of these events, we applied historical and future projected climate data downscaled to Kentucky. Analysis of this data shows that Kentucky is projected to have extreme weather events both in terms of precipitation and temperature at a higher frequency in the future period. This extends across all areas of the state. With this understanding, the next chapter will examine how these projections may manifest in terms of impacts to the transportation system.

Chapter 4 Impacts Assessment

Since the climate projection data indicates that Kentucky will experience extreme precipitation events more frequently in the future, this chapter investigates how such an increase might manifest in terms of transportation system impacts. We linked the roadway damages database to the pertinent weather data, then developed a probabilistic model that calculates the likelihood of damage occurring as the result of specific precipitation events.

We acknowledge here that the link between precipitation at a particular place and subsequent impacts to the roadway is not always immediate in either time or space. For example, widespread heavy rainfall across a region may lead to downstream riverine flooding as the water accumulates some time and distance away from where it fell from the sky. However, the damages database analysis showed that precipitation-involved impacts often occur due to flash flooding, erosion, washouts, subsidence, and landslides. These impacts tend to be more pronounced and more immediate in areas of the state with higher slopes and other susceptible physical features.

For the impacts assessment, our goal was to use climate records and the roadway damages database to calculate the probability and magnitude of impacts associated with fixed precipitation thresholds. Once these are established, the probabilities and magnitudes can be applied to historical and future projected climate data to determine the percent increase in expected impacts. Figure 4.1 is a flowchart summarizing the methods used in this analysis.

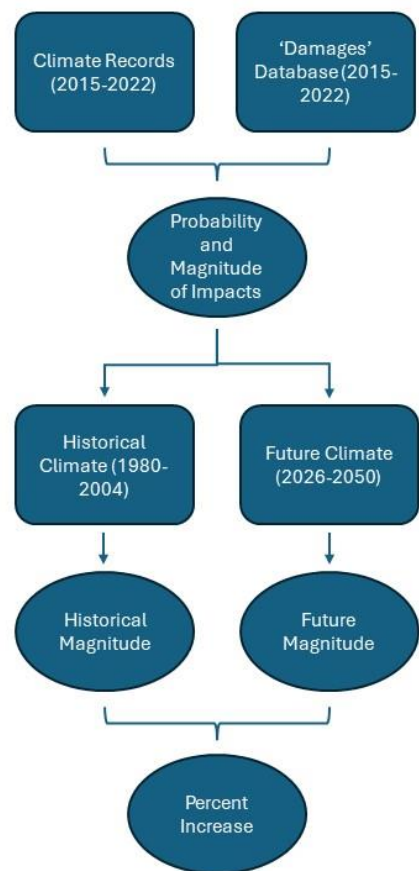


Figure 4.1 Flowchart Summarizing Methods Used to Calculate Future Climate Impacts to the Transportation System

4.1 Climate Records

To match the damages database up with specific weather events, we used the ORNL Daymet data for the years 2015 to 2022. Daily precipitation totals were extracted for each of the Kentucky grid cells in the Daymet dataset. Then, we calculated daily precipitation totals at the county level for each day by taking the maximum precipitation for any grid cell whose center point was in the county. Effectively, this yielded the maximum precipitation that fell in each county for each day from 2015 to 2022.

Using this data, we obtained a value for each county that indicated the number of days exceeding certain precipitation thresholds. Values were calculated for the following thresholds:

- >0"
- >=1"
- >=2"
- >=3"
- >=4"
- >=5"
- >=6"

Perry County, for example, yielded 1,352 days with any precipitation, 89 days with greater than 1", 6 days with greater than 2", 1 day with greater than 3", 1 day with greater than 4", 1 day with greater than 5", and 0 days with greater than 6".

4.2 Linking Climate Records to Damages Database

Records from the roadway damages database were then linked to the daily precipitation data. To do this, first the damage records were consolidated by county and by event. This process was conducted for 8,992 roadway damage records pertaining to 50 storm events from 2015 to 2022. Appendix B lists each of the storm events and provides the number of damage records, number of counties impacted, and total estimated dollars associated with each.

Consolidation of the roadway damage records by county and event resulted in 920 records for analysis. We then linked these consolidated records to the highest daily precipitation total within the event span in the county where the damage occurred. Though each roadway damages record is linked to a storm event that occurred, many of the events took place across multiple days in Kentucky. For example, FEMA emergency declaration 4358-DR pertains to severe storms, flooding, landslides, and mudslides that occurred between February 9th and February 14th, 2018. Using FEMA 4358-DR as an example event, the highest daily precipitation total in Bell County during this event was 2.2 inches of rainfall, and so this precipitation total was linked to all Bell County roadway damages associated with this event. Once this process was completed for all county and event records, a count was produced for each county indicating how many times during the study period damage resulted when precipitation exceeded each of the thresholds (i.e. >0", >=1", etc.).

4.3 Probability and Magnitude of Impacts

To calculate the probability of impacts occurring, the count of damages occurring in each county for each precipitation threshold was divided by the respective number of days each county experienced precipitation above the thresholds. While this was calculated for each county, the relatively large number of Kentucky counties (120) compared to the number of county/event records (920) resulted in too small a sample size to be meaningful. However, when these records are aggregated to the 12 KYTC districts, the probabilities have greater significance.

Table 4.1 shows, by district, the probability that damages were incurred after daily precipitation totals exceeded the given thresholds. Two patterns in the table are evident: first, that damage is more likely after greater daily rainfall and, second, that higher numbered districts tend to have higher probabilities of impacts after heavy precipitation events. Both trends match the expected results: The higher numbered districts are located in mountainous areas of eastern Kentucky where impacts are both more likely to occur and more likely to be severe.

Table 4.1 Roadway Damage Probabilities By District for Each Daily Precipitation Threshold

District	>0"	>1"	>2"	>3"	>4"	>5"
1	0.6%	4.4%	17.6%	25.0%	33.3%	100.0%
2	0.9%	5.9%	13.6%	42.9%	100.0%	
3	0.8%	4.6%	22.0%	40.0%	75.0%	100.0%
4	0.5%	3.7%	13.7%	33.3%	0.0%	
5	0.9%	6.8%	17.5%	42.9%	66.7%	
6	0.8%	8.7%	37.0%	71.4%	100.0%	
7	0.6%	4.1%	22.0%	25.0%	100.0%	
8	1.0%	6.5%	29.0%	50.0%		
9	0.9%	9.1%	37.5%	66.7%	100.0%	
10	1.8%	13.7%	45.2%	85.7%	100.0%	100.0%
11	1.0%	10.9%	43.5%	100.0%	100.0%	
12	0.9%	11.4%	60.0%	100.0%	100.0%	

Table 4.1 does, however, reveal some anomalies in the data that are likely a result of the small sample size. For example, in District 4 the probability of 3" of precipitation is 33.38% but then drops to 0% at 4". This is because there are no records of damage occurring in District 4 after four inches of rainfall, but also there is only one instance during this time of District 4 experiencing that much rainfall in a day. It is reasonable to expect that a larger sample size than 1 would yield a more expected probability of damage.

With the district-level probabilities established, we then sought to determine a measure of magnitude associated with these impacts. Several different measures of magnitude were considered, including the number of sites impacted, the total lane miles impacted, and the associated costs in dollars from the impacts. Each of these potential measures presents a challenge. There is not a consistent way in which a site is reported in the data. For example, some records might indicate pavement buckling on KY 40 at milepoints 2.2, 2.4, 2.7, and 2.9. This would then count as four records. Elsewhere, the data may be recorded as a single record of pavement buckling along KY 40 from milepoint 4.2 to 4.9. This inconsistency made the number of records and the number of lane miles too problematic for consideration.

Instead, magnitude was calculated in terms of dollars associated with the impacts. For records originating from the FHWA-ER and the FEMA database, these dollars generally represent funds requested for reimbursement. For records originating from the OMS database, these dollars represent costs for each emergency code associated with responding to events and repairing damages. We emphasize that the specific dollar totals are not considered to be exact, but rather are intended to represent a level of magnitude for comparing across events.

To determine magnitude, the county/event records were further consolidated to the district/event level. Doing this resulted in 193 consolidated records for analysis. Table 4.2 demonstrates how magnitudes were calculated from these records. We grouped the 193 records based on precipitation thresholds, then determined the number of

events and the total number of dollars associated for each of them. Dividing the total dollars by the number of events for each of the precipitation thresholds yields an average total of dollars per event.

Table 4.2 shows statewide how the magnitude of impacts increases as the precipitation levels increase. Statewide, the average costs of a disaster resulting from five inches of rain in a day are over \$12 million per event, compared to just \$707 thousand for a disaster resulting from one to two inches of rain in a day. Table 5 also calls attention to the fact that higher precipitation totals lead to a greater magnitude of impacts, as rainfall totals of 1 to 2 inches accounted for 42 percent of all events but only 11 percent of the total dollars in impacts, whereas 4 to 5 inches of rainfall accounted for 5 percent of all events but 18 percent of the total dollars in impacts.

Table 4.2 Estimated Impacts Associated With Each Precipitation Event That Resulted in Damages (in Thousands of Dollars)

All Districts	0-1"	1-2"	2-3"	3-4"	4-5"	>5"
# of Events	4	82	72	22	10	3
% of Events	2%	42%	37%	11%	5%	2%
Dollars	\$9	\$57,990	\$240,238	\$88,209	\$91,070	\$37,214
% Dollars	0%	11%	47%	17%	18%	7%
\$\$ per Event	\$2	\$707	\$3,337	\$4,009	\$9,107	\$12,405

The magnitude of these impacts, however, varies considerably across the state. For instance, a three-inch rainfall in the mountains of eastern Kentucky is much more impactful than the same weather in western Kentucky. But again, due to the small sample size in this analysis, calculating these variations across the state results in anomalies, even at the district level. For this reason, it is useful to group the districts according to how impactful the precipitation events are to the transportation system. This is largely a function of the relative topography of the districts. For this analysis, districts are grouped according to the average slope across the district, where:

- Districts 1, 2, 3 – average slope of 6 to 11 percent
- Districts 4, 5, 7 – average slope of 12 to 15 percent
- Districts 6, 8, 9 – average slope of 16 to 23 percent
- Districts 10, 11, 12 – average slope greater than 30 percent

Table 4.3 shows the average magnitude of impacts for each precipitation threshold across the KYTC grouped districts. Here, the importance of slope to the magnitude of impacts is apparent, as districts with the highest slope average over \$36 million in impacts after five inches of rain in a day, whereas for the lowest slope districts this average is only \$174 thousand. This pattern largely holds true across all the precipitation thresholds. Even with the data aggregated at this level, there are some anomalies apparent. For example, in KYTC districts 4, 5, and 7 the average magnitude of impacts for 3 to 4 inches of rain is \$985 million, whereas for 4 to 5 inches of rain it drops to \$93 million. This is again a product of the small sample size. Continued gathering of data on precipitation events and ensuing impacts to the transportation system would be expected to resolve these anomalies.

Table 4.3 Magnitudes Per Grouped Districts and Precipitation Thresholds (In Thousands Of Dollars)

Districts	0-1"	1-2"	2-3"	3-4"	4-5"	>5"
1,2,3	\$0	\$82	\$533	\$30	\$50	\$174
4,5,7	\$0	\$53	\$286	\$985	\$93	\$93
6,8,9	\$2	\$236	\$668	\$353	\$691	\$691

Districts	0-1"	1-2"	2-3"	3-4"	4-5"	>5"
10,11,12	\$2	\$1,353	\$11,224	\$10,254	\$44,630	\$36,866

This analysis establishes an approximation of how historic precipitation events have impacted the transportation system in Kentucky. These figures can be combined with the probability of impacts data (Table 4.1) for the years 2015 to 2022 to determine both probability and magnitude. These calculations rely on eight years of climate and associated roadway damages data, which is a limited sample size. Continued collection of data will broaden the sample size and further refine these numbers.

4.4 Comparing Historical to Future

If we carry over the probability of impacts data across all years, then probabilities and magnitudes can be extrapolated to other time periods. To do so, we need annual counts of climate events that fall in the precipitation thresholds for all KYTC districts. This data can be produced from the climate modeling effort described in the previous chapter for both a historic period (1980 to 2004) and future period (2026 to 2050). Combining the annual counts of precipitation events with the probabilities data (Table 4.1) yields an expected number of events resulting in impacts. These new impacts can then be combined with the magnitude data in Table 4.2 to determine a future magnitude and impacts in comparison to the modeled historical magnitude and impacts. Thus, we consider three climate data periods:

- Historical (observed): 1980 to 2004
- Recent (observed and linked to damage database): 2015 to 2022
- Future (projected): 2026 to 2050

For all three time periods, we have data indicating the frequency with which each KYTC district has or will experience precipitation events within the thresholds. Applying the same likelihood of impacts associated with these precipitation events across all three time periods yields a count of how many times damage-causing events would or will have occurred for each of the precipitation thresholds across all twelve districts. These counts can then be multiplied by the magnitude values from Table 4.2 to yield historically modeled (based off observed climate data) and future projected (based of modeled future climate data) to calculate the difference in damages from the historic period to the future period. Table 4.4 shows these values for each of the twelve districts. The future model predicts an average of \$71 million in damages annually compared to \$54 million historically, which represents a 31 percent increase.

Table 4.4 Projected Increase in Precipitation-Induced Annual Impacts to the Transportation System (in Thousands of 2023 Dollars)

District	Historic	Projected	% Increase
1	\$481	\$540	12%
2	\$416	\$488	17%
3	\$436	\$526	21%
4	\$362	\$527	46%
5	\$230	\$284	23%
6	\$382	\$480	26%
7	\$408	\$658	61%
8	\$1,222	\$1,426	17%
9	\$690	\$883	28%

District	Historic	Projected	% Increase
10	\$17,109	\$21,789	27%
11	\$20,768	\$28,335	36%
12	\$11,888	\$15,074	27%
ALL	\$54,392	\$71,009	31%

4.5 Discussion

The results from Table 4.4 demonstrate the significance of how a wetter future climate will lead to higher repair and recovery costs for KYTC. All twelve districts show a double-figure percent increase in average annual costs, with the already hardest-hit District 11 showing a 36 percent increase to \$28,335 annually.

It should be noted that this analysis relied on three periods of climate data, 1980 – 2004, 2009 – 2022, and the projected years of 2026 – 2050. The observed and projected climate data from these years support the scientific prediction of a wetter climate for Kentucky as it moves forward. Precipitation observations from the earliest time period are the driest, the “middle years” were observed to be wetter than the earliest period, and the future years are projected to be even wetter than the middle years. Climate scientists continue to advance the state of the practice for climate modeling, and there remains uncertainty in terms of how a wetter overall climate may manifest in specific weather events. There is some concern, for example, that models are underestimating the likelihood of extreme precipitation events in the future. Even so, the methodology and results in this chapter sufficiently summarize the challenges we face as the climate trends warmer and wetter.

Chapter 5 Other Impacts

We began this research by examining all types of extreme weather and all types of transportation-related impacts, but overwhelmingly found that precipitation is the major driver of impacts in Kentucky. This chapter summarizes the work we did in the early project stages to reach that conclusion. It catalogs the main transportation assets in Kentucky, other types of extreme weather to which Kentucky may be vulnerable, and their impacts. The research within this chapter is less comprehensive than the research on precipitation impacts, though it still provides value in understanding the state's overall weather patterns and vulnerabilities. Accordingly, this chapter is meant to support and supplement the main research but can be bypassed if the reader's primary interest is precipitation impacts.

5.1 Transportation Asset Inventory

The research has primarily focused on roads and bridges which are the asset types for which we have the best available data on historical impacts from natural hazards. Kentucky's transportation system consists of more than just roads and bridges, though, and includes other modes of transportation that move both people and goods. A truly resilient network relies on all modes of transport operating effectively and accounts for the interconnectedness of these systems.

To understand the future climate and natural hazard impacts on Kentucky's transportation infrastructure, we collected and summarized geospatial data on the state's essential transportation assets. Table 5.1 summarizes the extent of each critical infrastructure asset and provides the source of the data. Using geospatial data, we were able to see how projected changes in climate in different parts of the state would affect the regions surrounding critical assets in different regions.

Table 5.1 Summary of Transportation Asset Classes

Asset Class	Summary Stats	Source
Roads	89,134 miles	KYTC DataMart
North American Rail Network	3,583 miles	Bureau of Transportation Statistics
Rail Switchyards	80 switchyards, 153,838,149 sq. feet	Bureau of Transportation Statistics
Commercially Navigable Rivers	1,160 miles	Bureau of Transportation Statistics
Major Ports	7 ports	Bureau of Transportation Statistics
Waterway Locks	23 locks	Bureau of Transportation Statistics
Bridges	18,801 bridges	KYTC DataMart
Dams	1,084 dams	Bureau of Transportation Statistics
FAA Airport Runways	59 runways, 162,125,010 sq. feet	Bureau of Transportation Statistics
Pipelines	Natural Gas, Petroleum, Liquid Natural Gas	Bureau of Transportation Statistics
Intermodal Freight Air to Truck	12 intermodal connections	Bureau of Transportation Statistics

Asset Class	Summary Stats	Source
Intermodal Freight Rail	4 intermodal connections	Bureau of Transportation Statistics
Transit Agencies	4 agencies	KYTC DataMart
Bicycle and Pedestrian Facilities	4,786 miles	KYTC DataMart

Much of this report has focused on precipitation impacts to roads and bridges, whether those impacts are in the form of flooding, landslides, or other precipitation induced events. Other asset classes are also vulnerable to extreme precipitation, though typically the severity is less impactful. In the event of major riverine flooding, locks and dams can be closed to freight traffic until the water levels recede. Transit, airline, and freight operations can experience interruption due to extreme precipitation.

Understanding these vulnerabilities and mitigating the risk is particularly beneficial toward preparing for times of crisis. For example, in the event of a major earthquake, multiple transportation modes would be required to move emergency personnel and supplies to impacted communities. Regional airports and grounds would be valuable emergency response assets for the staging of equipment and supplies. Maintaining multiple points of access, where possible, to airport facilities would bolster system resilience. Rail and waterways can be used to move supplies in bulk to hard-hit communities when other modes of transportation are disrupted. Accessibility to port and intermodal facilities is critical. Although each of these assets plays an important role in Kentucky's transportation infrastructure, many are privately owned or otherwise not managed by the state. Resilience improvements in this regard require coordination with the various owners and administrative agencies. The next sections provide a brief description of some of the other hazards that may affect transportation system operations and performance.

5.2 Earthquake

Western Kentucky lies near the New Madrid Fault, a seismic zone along the Mississippi River in Kentucky, Missouri, Arkansas, and Tennessee. Major earthquakes emanating from New Madrid were last felt in 1811-12, when a series of earthquakes with an estimated magnitude greater than 7.0 magnitude occurred. Since that time, seismic activity has been sporadic, and there is considerable uncertainty regarding the potential for future events.

Despite the uncertainty, the threat remains of a major earthquake occurring that would cause considerable damage to the Kentucky communities.⁶ KGS estimates losses from a New Madrid earthquake to be in the range of \$10 to \$50 billion.⁷ Among transportation assets, bridges and bridge embankments demonstrate the highest vulnerability.⁸

⁶ Wang et al., "Seismic-Hazard Maps and Time Histories for the Commonwealth of Kentucky."

⁷ Orton et al., "Earthquake Hazard Mitigation in the New Madrid Seismic Zone."

⁸ Zatar, Harik, and Sutterer, "Seismic Vulnerability of Highway Bridge Embankments."

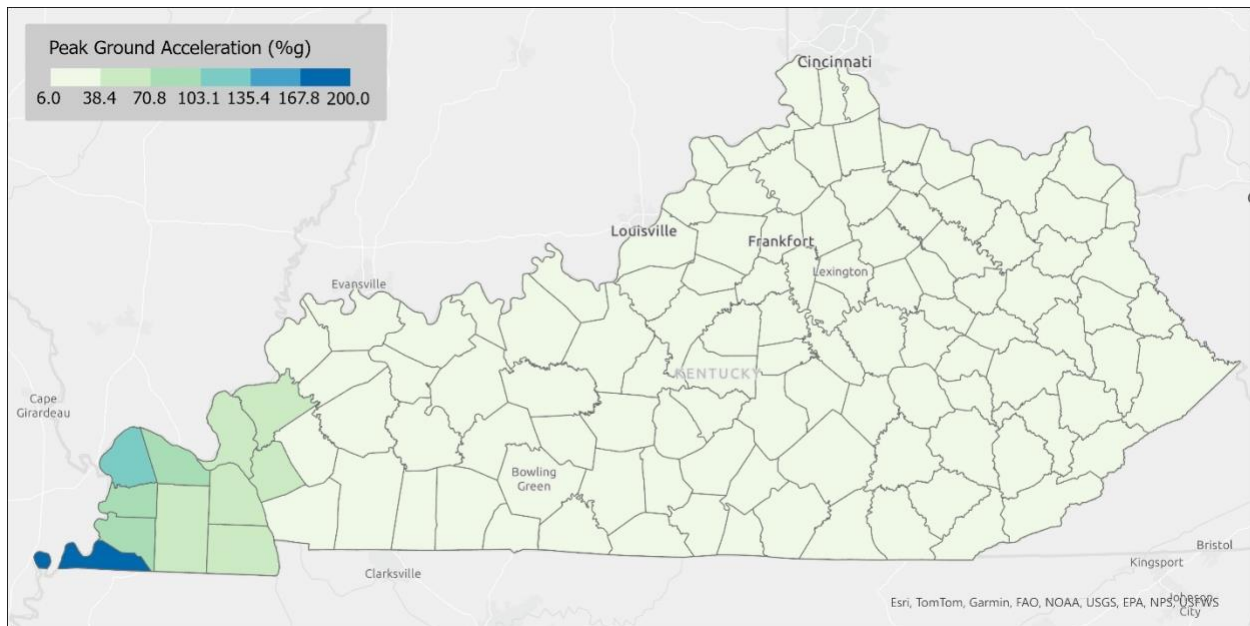


Figure 5.1 Maximum Peak Ground Acceleration With 2% Probability of Exceedance in 50 Years Per County
Peak Acceleration Expressed As A Percent Of Gravity (%G)⁹

5.3 Wind

Kentucky experienced a severe tornado outbreak in December 2021 that killed dozens and cost billions in recovery efforts. Direct impacts to the transportation system from this outbreak were minimal, though. Severe wind can damage signage and signals and require debris clearance to keep roads open. Kentucky typically experiences severe wind from tornadoes, straight line winds associated with severe storms, tropical storm remnants as they move inland, or derechos.

5.4 Extreme Heat

Kentucky is projected to experience warmer temperatures in the coming years. This includes warmer temperatures in the winter, with fewer days below freezing and fewer freeze/thaw cycles, and also warmer temperatures in the summer, with more days of extreme heat and higher average nighttime temperatures. While Chapter 4 of this report provides an analysis of projected temperatures changes in Kentucky, this section discusses how the changes may impact Kentucky's transportation system. In extreme circumstances, heat can negatively impact roadway infrastructure.

Asphalt is susceptible to softening in sustained extreme heat, which can lead to rutting and shoving. When extreme heat is combined with dry conditions, concrete pavements are susceptible to cracking.¹⁰ Pavement binder exhibits sensitivity when exposed to temperatures above 108°F, especially on roads with heavy truck loads.¹¹ The type of aggregate used for asphalt pavements affects the sensitivity to heat, with more angular aggregates demonstrating

⁹ USGS, "PGA 2% in 50 Yrs."

¹⁰ FHWA, "Vulnerability Assessment Scoring Tool (VAST)."

¹¹ FHWA.

increasing resistance to rutting.¹² Extreme heat can also impact bridges, with thermal expansion of steel placing stress on expansion joints.¹³

Transportation maintenance activities are also susceptible to extreme heat. Extreme conditions may both increase the need for maintenance work while also restricting the ability of crews to perform the work. Sustained extreme heat poses a threat to worker health and safety and may limit the number of daytime hours during which maintenance crews can work. High temperatures can also stress equipment and engines.

Figure 5.2 shows which counties in Kentucky are projected to have the highest annual number of days with the maximum temperature at or above 100°F. Western counties in Kentucky are projected to average over three days per year with the temperature above 100 degrees.

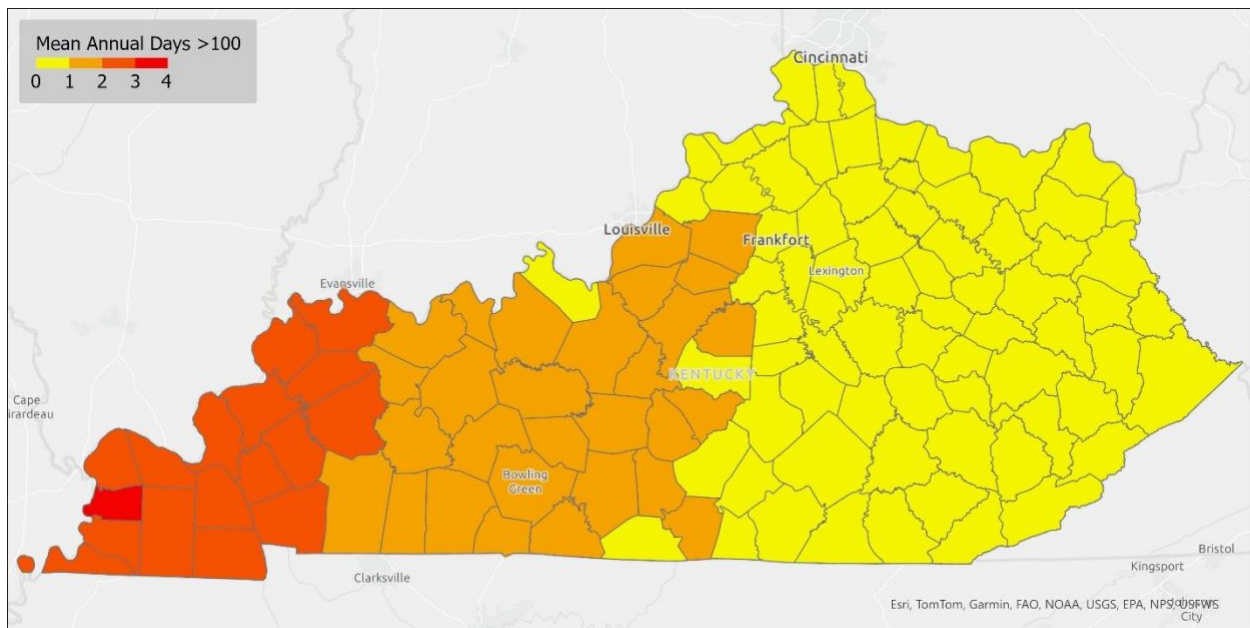


Figure 5.2 Average Annual Number of Days By County With Maximum Temperature at or Above 100°F

5.5 Wildfire

Wildfire in Kentucky has not historically been a source of impact to the transportation system, though there have been several instances of federally declared emergencies due to wildfire. These include the years 1999, 2000, 2001, and 2016. Typically, wildfires in Kentucky causes disruptions to service due to smoke and fire. Other impacts may include damage to guardrails, signage, signals, and landscaping.¹⁴ Figure 5.3 shows the total acres burned due to wildfire in Kentucky since 2000. The forested and mountainous areas of eastern Kentucky are the most susceptible to wildfire.

¹² Anderson, Youtcheff, and Zupanick, "Asphalt Binders."

¹³ Meyer et al., "Volume 2: Climate Change, Extreme Weather Events, and the Highway System: Practitioner's Guide and Research Report."

¹⁴ Diaz, "Economic Impacts of Wildfire."

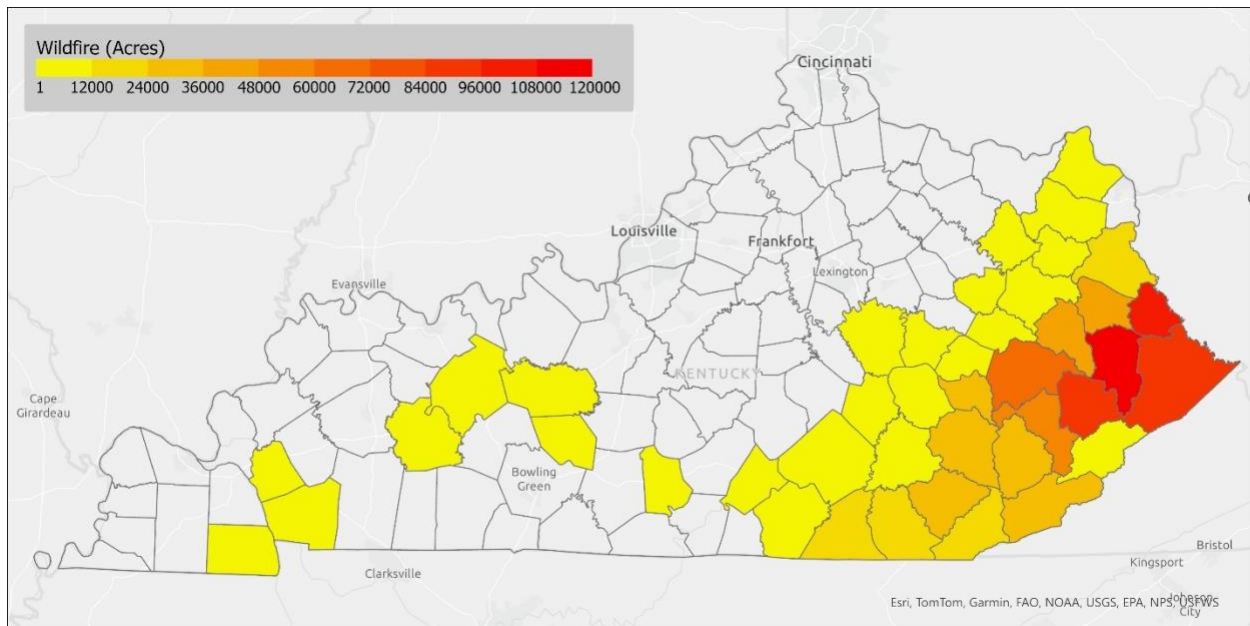


Figure 5.3 Total Acres Burned Due to Wildfire.¹⁵

5.6 Sinkholes

Perhaps the most infamous instance of sinkholes and transportation in Kentucky involves not roadways but rather a museum. In 2014 a thirty-foot sinkhole opened under the Skydome of the National Corvette Museum, swallowing and damaging eight rare Corvettes on display. Fortunately, no one was hurt, but the event was captured on nighttime security cameras and has since become an attraction in and of itself.

The Museum is located in Bowling Green, Kentucky, which is the area of the state most vulnerable to sinkhole formations (Figure 5.4). More typical sinkhole impacts to the transportation system include roadway subsidence, pavement damage, and intermittent flooding caused by changing karst drainage patterns.¹⁶

¹⁵ NIFC, "NIFC Open Data Site."

¹⁶ Moore and Beck, "Karst Terrane and Transportation Issues."

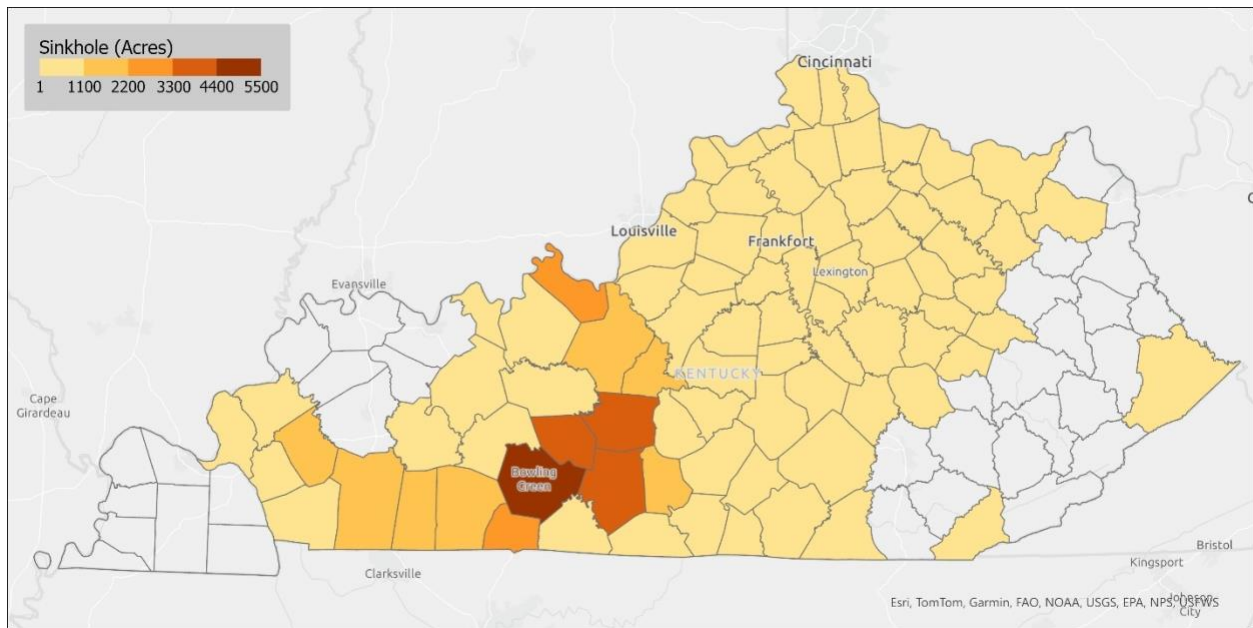


Figure 5.4 Total Acres Per County of Sinkhole Formations¹⁷

¹⁷ Paylor et al., "GIS Sinkhole Database."

Chapter 6 Cost of Inaction

6.1 Kentucky's Vulnerabilities

This research has revealed that extreme weather events pose a threat to the safety, reliability, effectiveness, and sustainability of transportation infrastructure and operations. Examination of historical data provided a snapshot of the high cost of weather events in the last several decades. The findings are underscored by recent severe weather events in eastern Kentucky and the associated high cost of damage. Unfortunately, this may become increasingly common. Climate projections indicate that severe weather will continue to affect the state and its transportation infrastructure.

A resilient system can combat the forces of extreme weather and make us less vulnerable to emergency situations. Investment in resiliency is expensive and can be difficult to justify, especially when it is preemptive. However, in the future, the costs associated with non-resilient roadways will be greater than the initial investment. Early action to incorporate resiliency into transportation infrastructure is critical.

Based on historical data, predictions can be made about weather impacts and what assets will be most vulnerable. Kentucky is especially vulnerable to extreme precipitation, which can impact a variety of transportation assets. For highly vulnerable transportation asset classes, we must consider how to improve their resiliency. On a practical level, this means deciding between simply “building back” the asset and “building back better.” For example, an agency can consider if it is worth repairing the specific damage to a bridge or building the bridge to withstand greater forces in the future. Resiliency does not just refer to reinforcing or hardening infrastructure. Instead, it focuses on extensibility, adaptability, and flexibility.

The decision to build back or build back better is one that should be made on an individual project level and will require a nuanced approach. A cost-benefit analysis can be utilized, but it should include precise definitions of what metrics are being examined. Furthermore, decision-makers will have to consider both the project itself and how it relates to the entire state’s infrastructure system. This chapter serves as a starting point to inform the approach and make decisions.

6.1 Conceptualizing a Cost-Benefit Analysis of Resilience

6.1.1 A System of Systems

Our initial approach to resiliency research relied on the theory of a “system of systems.” By its very nature, transportation infrastructure is highly connected. One asset cannot be analyzed or adapted without considering its influence on other assets as well as its effect on the system as a whole.

Likewise, the “system of systems” approach can also guide resiliency improvements. Here, the meaning is adapted to refer to systems of complimentary investments: investments into infrastructure must be paired with investments into social capital (e.g. educating the public about disaster preparedness, communication) and natural capital (e.g. floodplains, ecosystems).

The concept of resilience is intrinsically imprecise. Any meaningful analysis of resilience must respect that. Decision-makers should be careful not to divide investment choices into infinitesimally small levels. Instead, examine systems, connections, and overarching themes.

6.1.2 Data-Driven Cost-Benefit Analysis

Assessing risk is one of the first steps in a resiliency improvement plan. Risk assessment incorporates the concept of vulnerability and provides some measure of the costs (monetary and otherwise) associated with damages and performance interruptions. The objective of a risk assessment is to facilitate the comparison of various strategies. On the individual project level, a cost-benefit analysis is typically the most common approach.

Data can inform the analysis at multiple stages. In the case of resilience updates, cost-benefit analyses should consider both direct and indirect costs. Direct costs may include infrastructure damage and build-back costs. This can be measured via project costs, including design, materials, and labor. Focusing solely on direct costs is straightforward, but it will not provide a complete picture. It risks creating solutions that focus on “hardening” infrastructure. Hardened infrastructure may be more robust, but it is not more resilient.

Considering indirect costs will support the creation of a more resilient system. Indirect costs may include travel metrics (consider the Value of Travel Time Savings [VTTs], Level of Service [LOS], and safety), the ability to support the economy (consider the creation or dissolution of jobs, access to major employers, GDP, or commodity flow), and the health of citizens (consider isolation versus access, vehicle emissions, and behavior effects). Overall, it requires considering each alternative within the frame of its adaptability to threats. This approach addresses flexibility and agility, two of the most important components of a resilient transportation system.

The timeframe for cost-benefit calculations should reflect the expected lifespan of the asset. For instance, road alignment is a fairly permanent choice while the choice of pavement marking materials may be more of a short-term decision. If a route encompasses a bridge, the cost-benefit analysis should reflect the expected lifespan of the bridge. These projected costs should be adjusted for inflation appropriately to the time scale, too.

No matter what metrics are chosen, it is crucial to tailor a vulnerability assessment and subsequent resiliency improvement plans to the overall goals of the program. As much as possible, it is valuable to quantify each evaluation criteria. However, it is vital to remember the “system of systems” approach that guides big-picture resiliency improvements.

6.2 Case Study: US 421 in Harlan County

6.2.1 Historical Vulnerability

Looking at historical data is a helpful place to start when considering resiliency improvements. Historical data highlights where vulnerable assets are located in the state. Often, after a disaster, these assets have been “built back.” That is, they were replaced to withstand the same force or weather event as before. When subsequent storms hit, these assets succumbed to the same type of damage again. Alternatively, we can consider the idea of “building back better.” Building a more resilient version may result in lower costs over an extended period.

According to the roadway damages database, US 421 in Harlan County (District 11) experienced over \$9 million worth of damage between 2012 and 2022. This 27-mile stretch of road experienced the highest weather-related cost in the state. There were twelve contributing storms over the 10-year period. Additionally, projections indicate that Harlan County will continue to receive the highest amount of rainfall in the state, making it susceptible to more damage. Figure 6.1 highlights the route; points show the specific damaged areas from each storm. Because it has been exposed to repeated damage, the route is a candidate for resilience-informed improvements. In order to determine whether resiliency improvements will be worth it, agencies can analyze the cost of building a more resilient route against the cost associated with sustaining continued storm damage.

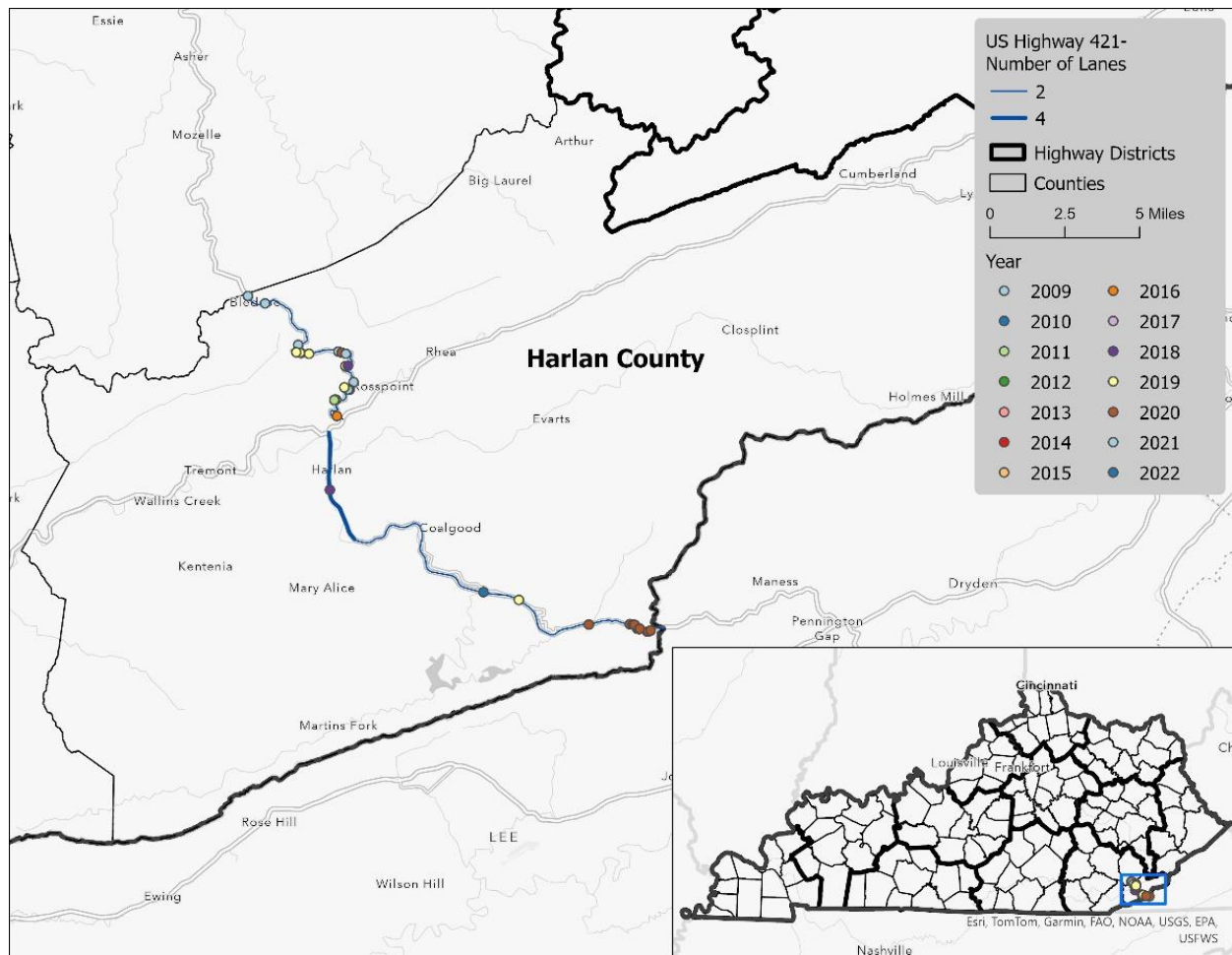


Figure 6.1 Map of US 421 in Harlan County

6.2.2 General Steps of a Resilience-Focused Cost-Benefit Analysis

The cost-benefit analysis for a project like this one will follow these general steps:

1. Consider the current environment and what aspects contribute to this route's vulnerability.
2. Consider alternative solutions that would build resilience into the system. Remember that resilience can mean increasing flexibility as well as strengthening.
3. Consider direct costs: the expenses undertaken to repair assets after damage or to create new resilient systems.
4. Consider the indirect impacts of improving this route.

An example of how these steps can be applied to Harlan County's US 421 follows.

1. Consider the current environment and what aspects contribute to this route's vulnerability.
 - a. Examine the roadway itself and the nature of the location:
 - US 421 is a rural route that travels generally north-south and passes through several small towns in southeastern Kentucky. It consists of 2-lane, 3-lane, and 4-lane segments.
 - Generally, the 2-lane segments traverse the mountains, while the wider segments are in towns. The majority of historical damage has occurred on the 2-lane segments.

- The road winds its way around mountains and streams. There are steep slopes on either shoulder (both up and down).
 - Because of its geography, the route is at risk of landslides that wash debris onto the road or wash out the road itself.
 - With dense woods on either side of the road, trees are likely to fall across the road and block traffic.
 - There is often no shoulder and very little room to maneuver if any part of the road is blocked.
 - There is potential for drainage issues because of how the road is situated in some areas. Insufficient drainage can lead to pavement degradation over time.
 - Much of the road is on a steep grade as it passes through and around mountainous terrain. There is minimal warning signage. This presents two potential issues. First, vertical curvature is associated with reduced safety, especially in inclement weather. Second, asphalt pavement wears faster on grades, with the potential for cracking, distortion, and associated repair costs.
 - For photos of the route's current environment, see Figures 6.1 through 6.10.
- b. Identify vulnerable assets:
- This route consists of numerous bridges. Some are large and span a significant body of water; many others are small and cross a small creek. In many cases, this route is the only available way to cross a body of water. In the actual project's cost-benefit analysis, a comprehensive force analysis of the bridges should be included.
 - Much of US 421 follows the flow of streams and creeks. There are stretches where a body of water is directly next to and nearly level with the road. Any increase in water levels will immediately affect the road. For this reason, there is a flood wall in downtown Harlan. Practitioners are encouraged to evaluate the flood wall's capabilities. Consideration could also be given to expanding it or adding flood walls in more locations along the route.
 - This route is closely associated with railways. Railways can be a key asset during emergency situations, so it is important to protect them from road-related damage when possible. This route is at risk of damaging nearby rail assets; there are rail crossings at grade and multiple bridges that go over railway. Strengthening portions of the road associated with rail corridors could be a strategic way to prioritize improvements.
 - For example, photos of the route's vulnerable assets, see Figures 6.11 through 6.14.
- c. Assess the function of the route overall:
- US 421 is one of the primary north-south routes through eastern Kentucky. The area is mountainous; most cities and towns have poor connectivity between them because they are separated by mountains and valleys. US 421 serves as a vital connection for many of the small towns in Harlan County. In emergency situations, losing this one route has an outsized effect because of its criticality.
 - The largest city along US 421 in this county is the city of Harlan, which has a population of about 2000. Harlan is located in a narrow mountain valley and has limited outside access due to its geography.
 - This road supplies traffic to much of the local economy, including a quarry directly on US 421 as well as other large businesses and employers nearby.
 - Some essential emergency services, such as police departments and fire stations, are located along US 421.
 - This route provides access to several schools. Schools are often utilized as shelters in emergency situations, so access is crucial.
 - US 421 is the primary route that exits the state to the southeast. It provides access to Virginia and Tennessee. Inter-state connectivity and evacuation routes could be affected if this road suffers damage.

- Refer to Figures 6.15 through 6.17.
2. Consider the alternative solutions that would build resilience into the system. Remember that resilience can mean increasing flexibility as well as strengthening.
 - Rerouting US 421 through less vulnerable terrain could be one potential solution. Recognizing that much of eastern Kentucky is mountainous, this idea may not be realistic nor particularly desirable to the residents that consider the landscape part of the area's appeal.
 - Another potential solution is creating route redundancy. Right now, US 421 is the main north-south route through southeastern Kentucky. Many of the area's small towns are only accessible via US 421. Adding other connection points would provide residents with other mobility options if the main route were impaired. Redundancy in the transportation system supports flexibility and adaptability, two core tenants of resiliency.
 - Some segments of the road could benefit from wider shoulders and an increased right-of-way. The current design of the two-lane segments consists of narrow lanes, very minimal shoulders, and steep slopes up and down. Wider shoulders could mitigate roadside hazards such as trees and cliffs, allowing more room to maneuver while driving and more available width to utilize in case of partial road closures.
 - Hillside stabilization would enhance the resilience of steep corridors. In past extreme weather events, portions of the road have been washed away when a downslope collapses and other portions have been covered in debris falling onto the road from higher elevations. Either of these issues could be prevented or minimized with hillside stabilization techniques.
 - Because bridges are an extremely vulnerable asset class, one potential solution is altering the way bridges are constructed. The area is susceptible to flash flooding and shifting terrain. To create resilience, bridges could be constructed with a greater factor of safety. This may include increasing the height of bridges, lengthening the approach, and/or providing reinforcement methods.
 - Debris is an unavoidable side effect of severe weather and can cause extensive damage to infrastructure. To protect against these vulnerabilities, practitioners can consider ways to control debris. This may include physical solutions such as filters, dams, or flood walls. It may also include public education campaigns regarding the dangers of loose debris and the importance of securing belongings before a storm.
 - Many of these solutions can be combined with one another. In a case study like this, with almost 30 miles of roadway to consider, it will benefit the practitioner to adopt a broad view approach and a flexible mindset.
 3. Consider direct costs.
 - The direct costs refer to the quantifiable expenses undertaken to repair assets after damage from weather events.
 - The calculations for direct costs will be straightforward. It will encompass the cost of route improvement or asset repair projects.
 - For lifecycle costs, the timeframe should reflect the expected life of the asset and costs should be adjusted for inflation appropriately to the time scale.
 - However, practitioners should consider that repair projects will likely be repeated every few years, in accordance with future climate trend predictions.
 4. Consider the indirect impacts of improving this route.
 - Indirect impacts are more difficult to quantify, but nonetheless important. Generally, the indirect impact of route improvements will be improved resilience. Since resilience cannot be measured directly, it must be

put in terms that can be measured. The choice of which indirect impacts to measure is that of the evaluation teams, but it should be informed by the functions and vulnerabilities identified in Step 1.

- The solutions that were generated in Step 2 will also inform this step. They were selected because they can mitigate risk; that is, reduce the likelihood of or lessen the consequences of severe weather or other emergencies. If likelihood or consequences can be quantified or measured in any way, that should be the initial phase of the operation. Other examples follow.
- In analyzing transportation systems, two of the most common measurements are reliability and safety. For transportation practitioners, this is a familiar paradigm of using quantifiable metrics to evaluate a more abstract concept. Reliability can be measured via level of service or travel time. Safety can be measured via crash data or safety performance functions. It will be valuable to compare these metrics across three situations: current standard measurements, emergency/impact data, and the predicted values after making resilience improvements.
- In addition to transportation system improvements, improved resilience can create a more secure economy. In this case study, the local economy relies heavily on coal, timber, and mining, with support from transportation (rail and automotive). Many significant companies are located directly on US 421. A closed route and collapsed businesses can have far-reaching economic implications. A previous study from the Army Corps of Engineers quantified the economic impacts of transportation networks in terms of Gross Domestic Product (GDP) and commodity flow. Other ways to quantify a local economy may include employment or consumer spending.
- Reduced risk is associated with less expensive insurance premiums, which would be a great benefit to local residents. Over one third of Harlan County's population is below the poverty line, so cost savings to residents could be a substantial selling point. Practitioners should consider if securing access to homes can reduce home insurance and how reducing impacts to the transportation system can reduce auto insurance.
- The safety of residents is hard to measure but may be a significant indirect impact of resilient systems. In Harlan County, 20 percent of households have someone living alone. Severe weather and other emergencies can become more catastrophic when people are isolated from services they need. In cases like this one, where community access is heavily dependent on just one route, it is advisable to evaluate the impacts that system resilience may have on community safety and wellbeing.

6.3 Conclusions

Building and evaluating resilience is an inexact science and one with which many transportation practitioners are unfamiliar. However, by putting risk and resilience into measurable quantitative metrics, it is possible to objectively evaluate the influence of improved system resilience. Consideration should be given to both direct and indirect costs, which may include values that define reliability, safety, economic strength, and community wellbeing. Practitioners should make an effort to quantify as much as possible, while not losing sight of the overall goals of the resiliency improvement program.

Kentucky's Harlan County case study serves as a good starting point for future analyses. With its wide variety of cross-sections and interplay of multiple asset types, US 421 is a prime example of a "system of systems" within a transportation network. A brief analysis of the route illustrates the far-reaching effects that resiliency improvements may have on the area.

Statewide, the need for a resilient transportation system is apparent. The current system is vulnerable to extreme weather and may not respond well to emergencies. Resiliency improvements will allow Kentucky to maintain the safety, reliability, and effectiveness of transportation operations. While these improvements can be expensive, they will be valuable investments for the future.



Figure 6.2 US 421 Steep Slopes



Figure 6.3 US 421 Steep Cliff, Curve



Figure 6.4 US 421 Limited Space and Right of Way



Figure 6.5 US 421 Steep Grade, Unsigned, Poor Visibility



Figure 6.6 US 421 Narrow Lanes, No Shoulder



Figure 6.7 US 421 Mountains, No Shoulder



Figure 6.8 US 421 Curve, No Shoulder, Limited Visibility, Trees Fall Across Roadway

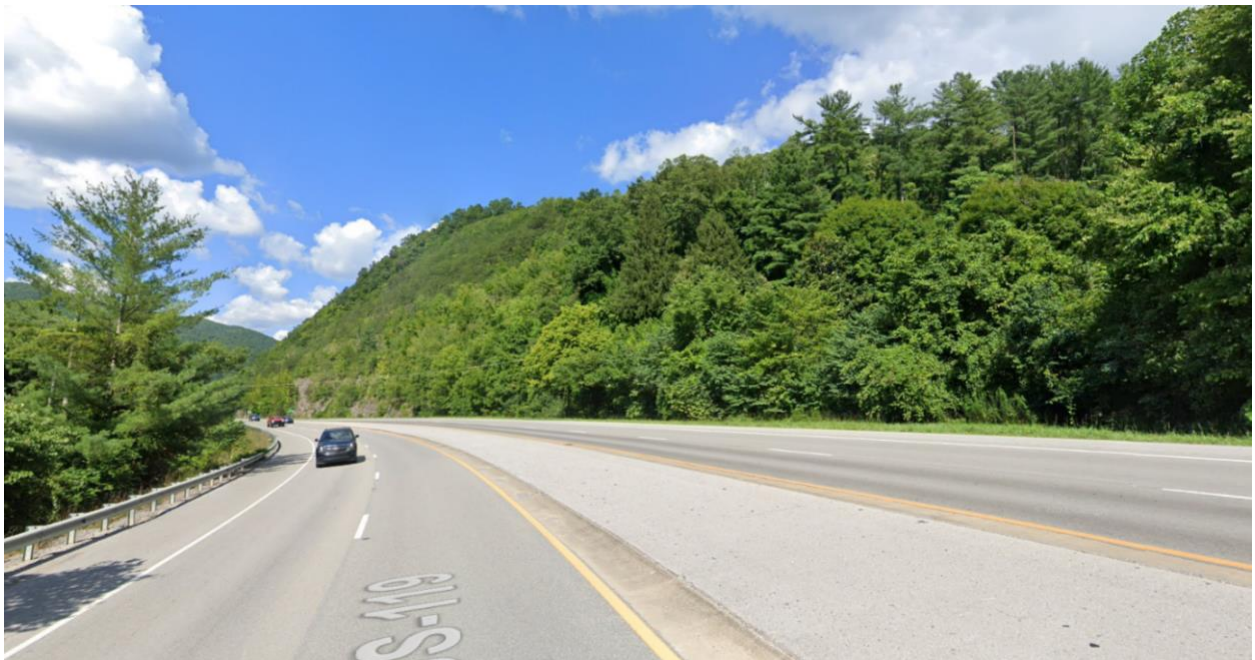


Figure 6.9 US 421 Wider Right of Way, Four-Lane Sections With Median in Less Rural Areas



Figure 6.10 US 421 Wider Right of Way and Shoulders, Cut Through Mountain



Figure 6.11 US 421 Landslide/Washout



Figure 6.12 US 421 Bridge Crossing Water



Figure 6.13 US 421 Bridge Crossing Railroad



Figure 6.14 US 421 Flood Wall in Harlan



Figure 6.15 US 421 Quarry



Figure 6.16 US 421 Flatter Terrain Toward Virginia, Possible Evacuation Route



Figure 6.17 US 421 Emergency Services

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Appendix A Expanded Literature Review

A literature review was conducted to assist in the early development of a Resiliency Improvement Plan. Literature sources focused on federal guidance about resiliency plans and FHWA's resiliency pilot program series. Researchers also investigated how other DOTs and transportation agencies have approached building resiliency into their programs. There were some similar notable actions and accomplishments from emergency management and other non-transportation specific agencies. Lastly, a review of academic literature uncovered several resiliency-related studies within the fields of engineering, transportation, geography, planning, and environmental science. To unify these sources and their information, four main objectives for the literature review were established. The objectives are:

- To define vulnerability, risk, and resiliency; and to understand the concept of resiliency improvement plans.
- To recognize why Kentucky needs a resiliency improvement plan.
- To synthesize the federal guidance for creating a plan and find other recommendations from similar studies.
- To learn from other state DOTs, especially those with robust resiliency plans and/or those with similar climates to Kentucky.

Objective 1: Defining Vulnerability, Risk, and Resiliency.

A Vital But Vulnerable Transportation System

The Nation's transportation system is crucial to the U.S. economy and the population's quality of life. Within the past few decades, transportation infrastructure has become progressively more complex and interconnected, resulting in improved productivity and efficiency. Increasingly intertwined infrastructure underscores the need for a system that is safe, secure, reliable, and efficient. Research suggests the changing climate will result in an increase in extreme weather events, which will challenge the strength and reliability of the current transportation system.¹⁸ Unfortunately, today's transportation infrastructure is largely inflexible to changes in utilization and external conditions. Assets are often used well past their intended lifetime under conditions that may have not been explicitly planned for.¹⁹ Most transportation agencies currently operate under a "patch and repair" mentality, addressing problems and making improvements only when necessary and with minimal cost. It is imperative to move past that mentality and move forward with a focus on increasing investment in a fundamentally resilient transportation system.

Resilient Infrastructure

Resiliency is defined as the ability to reduce the magnitude or duration of disruptive events, which is accomplished by anticipating, absorbing, adapting to, or rapidly recovering from the disruption. In simplest terms, resilient systems can maintain critical functions during a disruption and require less time and fewer resources to recover functions that have failed. Negative consequences of failure can include effects on public safety, asset damage, or service interruption. Planners can increase resiliency by either reducing the sensitivity of the assets to extreme events or by enhancing the adaptive capacity of the assets or both.²⁰

¹⁸ Baylis et al., "Transportation Sector Resilience."

¹⁹ Markolf et al., "Transportation Resilience to Climate Change and Extreme Weather Events – Beyond Risk and Robustness."

²⁰ Kilgore et al., "Highways in the River Environment - Floodplains, Extreme Events, Risk, and Resilience."

A statewide resiliency improvement plan focuses on reducing vulnerability. In the transportation context, extreme weather vulnerability is a function of an asset's exposure to climate effects, sensitivity to climate effects, and adaptive capacity. Exposure refers to whether an asset or system is located in an area experiencing direct effects of extreme weather; sensitivity refers to how the asset or system fares when exposed to a climate variable; and adaptive capacity refers to the system's ability to cope with existing climate variability or future climate impacts. Increasing resiliency, therefore, can mean either hazard mitigation or adaptability.²¹

Quantifying and Analyzing Risk

In conjunction with the objective of increasing resiliency, it is important to understand the concept of risk. Risk is the probability of an event occurring multiplied by the potential consequences of that event. Analyzing risk will be one of the first steps in a resiliency improvement plan. Risk analysis or assessment incorporates the concept of vulnerability and provides some measure of the costs (monetary and otherwise) associated with damages and performance interruptions. The objective of a risk assessment is to facilitate the comparison of various strategies. Some risks are too unpredictable and difficult to plan around. In these cases, network-wide management is more appropriate than location-specific solutions, which is why a resiliency improvement plan should focus on the "system of systems" that is a transportation network.

Robustness Versus Resiliency

One way to think of the strength of a transportation asset or transportation system is its robustness. Robustness is defined as the capacity to prevent disruptions from occurring by emphasizing control, armoring, and strengthening. However, a robust asset is not necessarily analogous to a resilient one. Resilience is comprised of many non-mutually exclusive regimes, and adaptive capacity is the ability to move between these regimes. In addition to robustness, examples of other resilience regimes include rebound – the ability to restore conditions and systems that have been damaged by extreme events; graceful extensibility – the ability to extend performance and mitigate the consequences of surprising events to avoid sudden and catastrophic failure; and sustained adaptability – the ability to transform, balance, and trade off multiple system dimensions in response to evolving system and environmental conditions over the long term. The flexibility within the definition of resilient highlights the need for flexible thinking when developing a resiliency improvement plan.

The Economic Cost of Non-Resiliency

The US Army Corps of Engineers conducted a study about the grave socioeconomic implications if the need to build resiliency is ignored. They acknowledge that investment in resiliency is expensive and can be difficult to justify, especially when it is preemptive. However, in the future, the costs associated with non-resilient roadways will be greater than the initial investment. When road networks are not resilient, unpredictable events can cause significant delays that may not be proportional to the extent of the disruption.

The economic study from the US Army Corps of Engineers utilized a model of urban transportation network performance that quantified resilience and then integrated it into a microeconomic transportation planning model called REMI TranSight. Their study's independent variable encompassed any transportation disruption (defined as any mechanism by which mobility is reduced or the cost to maintain desired levels of mobility drastically increases), and their dependent variable was the affected area's gross domestic product (GDP.) Results showed that GDP losses are significant following a disruption and can continue to affect economic output for a full year following the event.

²¹ Filosa et al., "Vulnerability Assessment and Adaptation Framework, 3rd Edition."

While this research quantifies disruption in terms of GDP, they note that in general resilience should be quantified in terms compatible with standard practice. An alternative to GDP may be commodity flow; in that case, if goods can be transported via multiple modes, then disruptions may be less significant than what is indicated by the state of the asset itself. Many current practices involve evaluating road performance by level of service or travel time. While marginally useful, this only scratches the surface of a true cost/benefit analysis. If a practitioner utilizes this type of evaluation, they must define the value of reliability and the value of time. Neither is capable of accounting for unpredictability or large variance. No matter what metrics are chosen, it is crucially important to tailor a vulnerability assessment and subsequent resiliency improvement plans to the overall goals of the program.²²

Objective 2: Recognize Kentucky’s Need for a Resiliency Improvement Plan

Federal Infrastructure Improvement Within a Changing Climate

In February 2013, the Presidential Policy Directive 21 formalized the call to enhance the nation’s critical infrastructure and resilience, including transportation systems. It is important to highlight the transportation system specifically because every critical infrastructure sector depends on a resilient transportation system that is safe, secure, reliable and efficient. Without the ability to move people and goods, most critical services cease to function.

A Transport Policy journal article titled “Transportation resilience to climate change and extreme weather events – Beyond risk and robustness” reports that transportation systems have largely been designed and operated for historical climate conditions, but those historical climate conditions are often exceeded in the present environment. The engineering community is in the emerging stages of understanding how climate change might affect transportation systems. Climate change is likely to disrupt transportation systems both acutely through extreme weather events and chronically through gradual changes. Hazards are numerous: coastal and urban flooding, heat, cold, drought, and wind, to name a few. In Kentucky, the most likely climate issues are extreme heat and precipitation; the most critical natural hazards are earthquakes, floods, landslides, and sinkholes.²³

Flexibility Over Hardness

When extreme weather events occur, there are direct and indirect “pathways of disruption.” Direct pathways of disruption consist of abrupt impacts to physical infrastructure and non-physical factors such as human health, behavior, and decision-making. Indirect pathways of disruption result from interconnections with other critical infrastructure and social systems. The authors (Markolf et al) emphasize the idea of adaptability and flexibility in addition to robustness in resiliency. Currently there is more focus on direct pathways of disruption, which usually involves “hardening” infrastructure (increasing robustness), but indirect pathways of disruption are also important and are less amenable to robustness-based approaches. In building resiliency improvement plans, practitioners should supplement the focus on robustness by addressing flexibility and agility.

FHWA’s report titled “Synthesis of Approaches for Addressing Resiliency in Project Development” supports Markolf’s assertion of the importance of indirect pathways of disruption. The document stresses that diverse climate stressors have nonlinear effects and may interact with each other, so it is important to consider the relational aspect between them. For example, in Kentucky a fire (extreme heat) in a watershed will impact how a future storm (extreme precipitation) affects the topography and landslide potential. Climate change does not necessarily mean design

²² Kurth et al., “Lack of Resilience in Transportation Networks.”

²³ Blandford, Schurman, and Wallace, “Assessing Transportation Assets for Vulnerability to Extreme Weather and Other Natural Hazards.”

standards should change. Design standards are based on risk tolerance, which should not change over time. Instead, practitioners need to consider how to meet the standard given the fact that the causes and effects of risks may change.²⁴

Data-Driven Resiliency

Although necessary to rebuild in the short-term, the money available through disaster relief has hampered long-term resiliency efforts. From 2003 to 2017, there was almost 10 billion dollars in federal assistance for transportation. The availability of funds for restoration discourages efforts to reduce loss. However, mitigating these disasters is proven to reduce losses and speed up recovery time. Thorough data and versatile metrics will be needed to demonstrate the value of building resiliency.

In Kentucky, this data will come from a variety of sources. Data on historic natural disasters in Kentucky from the Federal and State declared emergencies list, state roadway damage and repair database, National Oceanic and Atmospheric Administration (NOAA) Storm Events Database, and Kentucky Transportation Cabinet (KYTC) Operation Management System (OMS) offer statistics about climate and its effects in Kentucky while also highlighting the need for a resiliency plan. In addition to historic data on climate and natural disasters, projections of temperature and precipitation changes in Kentucky from Oak Ridge National Laboratory (ORNL) and results from the First Street Foundation Flood Model can predict flooding. Moving forward, successful prioritization of stressors and adaptation strategies will require detailed regional knowledge of the climate, condition of the infrastructure, state of the broader transportation system, budgetary constraints, and the timescale of analysis. Using this data, a formal resiliency improvement plan can be built, which will greatly benefit Kentucky.

Objective 3: Synthesize Federal Guidance and Other Academic Literature About Resiliency Improvement Plans

NIAC's Transportation Sector Resilience

Although the concept of resiliency improvement plans is relatively new, there is some federal guidance for developing these plans. A transportation agency involved in the creation of a resiliency improvement plan can utilize the National Infrastructure Advisory Council's (NIAC) report on Transportation Sector Resilience.¹ This report examines the common challenges of building resiliency into a transportation system and provides general recommended strategies. According to the authors, it is imperative that our nation's transportation system moves beyond the "patch and repair" mentality and instead focus on fundamental changes. Their recommended approach consists of three steps:

- First, baseline current risks. Conduct a quadrennial review (QR) that assesses systemic risks, including quantitative estimates of the likelihood and magnitude of different types of risk. Existing key datasets and tools should be identified early. In addition, this step should determine funding requirements and measure the risks associated with underfunding. Authors point to United Kingdom's National Infrastructure Plan 2014 as a successful example of this phase.¹ This plan utilized £460 billion public and private investments and explicitly prioritized infrastructure, policy framework, and the supply chain, recognizing that strong fundamentals create a sustainable and resilient future.²⁵
- Next, develop the analytical tools, models, and exercises to better understand and plan for emerging risks and interdependencies. In the context of transportation infrastructure, this means developing models that can

²⁴ Choate et al., "Synthesis of Approaches for Addressing Resilience in Project Development."

²⁵ *National Infrastructure Plan 2014*.

simulate transportation disruption scenarios as well as revising design standards and practices such that they expressly incorporate resilience attributes into planning, construction, and operation.

- Lastly, use results to operationalize resilience by increasing funding and implementing effective federal practices, procedures, and procurement processes. The knowledge gained in prior phases must be translated into guidance, programmatic practices and procedures, funding criteria, and procurement processes to help cultivate a culture of resilience.

FHWA's Vulnerability Assessment and Adaptation Framework

Within the creation of a resiliency improvement plan, a critical early step is evaluating a transportation system's vulnerability to climate change. FHWA's Vulnerability Assessment and Adaptation Framework provides a structured process for building climate adaptations into transportation infrastructure. Of particular relevance to Kentucky's objective were chapters 4 and 5, which feature vulnerability assessments and adaptation options, respectively.

Chapter 4 of the Framework details how to assess the vulnerability of a transportation asset or system. Agencies can utilize stakeholder input, which is an empirical qualitative approach, or indicator-based review, which is more analytical and quantitative. Either of these approaches can be used for systems-level or area-level analyses. For specific assets, agencies should use a hybrid "engineering-informed assessment" that combines the quantitative aspects of indicator-based reviews with the qualitative aspects of empirical stakeholder reviews. The text provides a few examples of each type of approach, which were subsequently examined within the process of this literature review. The manual emphasizes that the three types of assessments are not mutually exclusive (and indeed, several cases obtained during the literature search proved that a hybrid approach is often sensible.)

During the assessment, risk should be thought of as the consequence(s) of projected changes or impacts. Practitioners should consider both extreme and incremental changes. There are many ways to appraise risk: agencies should consider the level of use of an asset, the degree of redundancy in the system, and/or the value of an asset in terms of cost of replacement, economic loss, environmental impacts, cultural values, or loss of life.

Following a vulnerability assessment, agencies will identify, analyze, and prioritize adaptation options. Chapter 5 of the Framework manual offers guidance on how to approach this step. Any number of adaptation solutions can be considered; they can be natural, structural, or policy based. Strategies may include engineering new assets, retrofitting existing ones, improving maintenance practices, increasing redundancy of the system, and relocating assets or systems. The guide cautions that too broad of a strategy may undermine the value of creating a plan. Instead, agencies should focus on developing a list of fewer but more detailed adaptation strategies for a subset of assets or vulnerabilities.

Once the adaptations are identified, there are two methods to evaluate them: multi-criteria analysis and economic analysis. A multi-criteria analysis compares adaptation options across range of qualitative and quantitative criteria, allowing consideration of aspects that cannot easily be quantified or put into monetary terms. Economic analysis clarifies the potential long-term costs and benefits in a more exact and measurable way. Economic analyses are often preferred but there are pitfalls. Most importantly, the measures used in an economic analysis must be tailored to suit the decision it is intended to inform. An economic analysis need not include every measurable criterion that can be found. Indeed, it is better to use pertinent qualifiable data than irrelevant quantifiable data. Moreover, the level of detail must be scaled appropriately. More comprehensive assessments are possible for individual assets, while entire regional networks will require an economic analysis that relies on aggregate descriptions. The level of detail that can be provided will affect the precision of cost and benefit estimates.

FHWA's Synthesis of Approaches for Addressing Resilience in Project Development

Choate et al. integrates these themes from FHWA's Framework in "Synthesis of Approaches for Addressing Resilience in Project Development." The paper describes how to conduct economic analyses and complete engineering assessments and design in the fields of coastal hydraulics, riverine flooding, pavement and soils, and mechanical and electrical systems. It synthesizes lessons learned from a variety of recent FHWA pilots, with the intent to understand why, where, and how to integrate climate considerations into the project development process.

The authors learned that adaptation studies are best conducted early in the project development process. Practitioners should use downscaled CMIP3 and CMIP5 climate and hydrology predictions. Any climate projection data that is used within an adaptation study is surrounded by some level of uncertainty. However, the authors point out that there is also uncertainty in many of the most used datasets for transportation practitioners so incorporating uncertainty should not be a deterrent. Continual usage of these datasets will allow more informed applications over time.

There are many adaptation options; the paper summarizes the five main adaptation strategies that may be implemented stepwise over time as needed. They are:

1. Maintain existing infrastructure for optimal performance and manage the response to extreme events through advanced preparation.
2. Increase redundancy: services provided by infrastructure can be supplied in other ways.
3. Protect infrastructure: reduce or eliminate damage by providing physical barriers.
4. Modify or redesign for better performance in future climate-stressed environment.
5. Relocate infrastructure away from the climate stressor.

To evaluate these adaptation options, the authors provide a summary of economic analyses that may be performed. These include benefit-cost analysis, net present value, lifecycle cost analysis, and economic impact analysis. Economic analyses performed to identify efficient adaptation options can be considered enhancements of traditional lifecycle cost analyses. These enhanced analyses consider repair costs as well as socioeconomic; they also account for uncertainties or risks inherent in the assumptions of future climate scenarios. Lastly, the authors caution that practitioners must consider the big picture to know when regional solutions may be more effective than asset-based interventions. This will ensure that adaptation islands are not created (for example, a bridge being strengthened to withstand more stress while approach roads are still flooding.)

Seismic Vulnerability Study as a Model for Vulnerability Assessments

In addition to federal guidance, some individual entities have created similar resiliency-focused plans or made related improvements. In July 2021, researchers in Norway and Italy teamed up to evaluate vulnerability to earthquakes across the developing world. While much of their research was specific to earthquakes and masonry buildings, some of the methods used in the seismic vulnerability assessment can be applied in general terms towards Kentucky's objective of creating a transportation asset vulnerability assessment.

Perhaps most helpful was the team's explanation of how to choose an appropriate level of detail for these studies. As discussed previously, there are three main ways to assess vulnerability: empirical, analytical, and hybrid methods. The research team used a simplified analytical method by defining a damage probability matrix or fragility curve. They noted that empirical methods limited the data validity and resulted in overly regionally specific datasets. Strictly analytical methods attempted to quantify and calibrate all physical characteristics of the structures they were evaluating, which was prohibitively time-consuming, required high computational effort, and did not allow for

diversity of structures. This team's utilization of a simplified analytical method retained the advantages of quantitative data while acknowledging that extremely specific data hinders development of a comprehensive but versatile improvement plan.

In development of Kentucky's forthcoming plan, it will be important to realize that, while site visits to each and every asset is unrealistic, physical visits will help address specific uncertainties and it will be critically important to involve local personnel with intimate understanding of the assets. This study also emphasized the importance of including multiple metrics to measure vulnerability. In a transportation context, this means that a strong resiliency improvement plan must include capacity and demand as well as susceptibility to damage.²⁶

Designing Highways in the River Environment

FHWA has also published guidance that more specifically addresses Kentucky's propensity for extreme precipitation. In the Hydraulic Engineering Circular (HEC) 17, the FHWA Office of Bridges and Structures and the Office of the Natural Environment provide a manual on how to assess vulnerability of transportation systems to climate change, specifically in areas surrounding rivers. The manual's focus is on quantifying exposure to extreme flood events considering climate change.

When planning and designing, the main priority of the transportation community is to ensure public safety, followed by the preservation of the asset itself. Transportation asset managers should craft operational and maintenance strategies with the intent of increasing resilience by resisting damage where possible and anticipating it where it is not possible to resist. Preparing to address damage quickly and effectively where and when it does occur is of equal importance to the design of new features and the management of existing ones.

The authors of the HEC-17 manual approach resiliency by treating future climate projections as "design events." Design events (for example, a 100-year flood) are used by bridge and culvert engineers to forecast what capacity the asset should be able to withstand. Precipitation projections allow asset managers to specify a certain event that they are designing for, and thereby more accurately calculate and balance risks, costs, and benefits. Often, a design event based on future climate projects is simply an increase in the probability that an event will occur. What was once a 100-year flood may become a 25-year flood. Extending the probability of exceeding a design event increases the probability that managing the consequences of exceedances will be required over the design life of the project. The longer the design life, the greater the risk of an extreme event occurring during the design life. It is necessary to consider the remaining service life of a transportation asset before deciding whether to adapt or start new.

The life-cycle cost of a transportation asset consists of several parts. The most visible and evident costs are the design and construction costs. Other costs that are harder to quantify at design are maintenance costs, potential costs to the public in the event of interruption of service, reduction in the value of adjacent land in cases of increased base flood elevation, repair or replacement cost for the structure in the event of damage due to flooding, and repair costs to the adjacent roadway in the event of damage due to flooding. Whereas design and construction costs are certain to be incurred and reasonably predictable in magnitude, many other costs are not only uncertain in magnitude, but uncertain in likelihood.

²⁶ Shabani, Kioumars, and Zucconi, "State of the Art of Simplified Analytical Methods for Seismic Vulnerability Assessment of Unreinforced Masonry Buildings."

When specifying and planning for a design event, the HEC-17 manual suggests considering the nature of the facility and whether that is likely to change. For example, rural and urban roads are surrounded by different land uses which can uniquely influence the effects of a precipitation event. Planners also must consider whether the nature of the facility is likely to change, thereby affecting land usage or traffic volumes. Sometimes after consideration of future changes and the remaining service life of an asset, it will be more judicious to build new rather than adapt the current design.

A general framework is provided for levels of analysis when performing risk and vulnerability assessments. Note that the framework builds upon itself such that an agency should include all data and expertise within the level itself and the previous level(s).

- Level 1: Apply historical data. In order to perform any kind of assessment, utilizing accurate quantitative data will be necessary.
- Level 2: Qualitatively consider future changes in land use and climate, and quantitatively estimate ranges or confidence limits of the historical data from Level.
- Level 3: Quantitatively estimate projected changes in precipitation for project area.
- Level 4: Develop projected land use and climate data and utilize them within models or projections.
- Level 5: Expand the team to include site-specific expertise in climate science or land use planning.

Recognize that different plans and projects will merit unique levels of analysis. For a statewide resiliency improvement plan, it is likely that the priority will necessarily be on broader levels of analysis; however, more specific quantitative data and/or expertise should be incorporated when possible.

Lastly, the HEC-17 manual emphasizes the importance of embracing uncertainty. Designing bridges and other hydraulic structures already relies on the relative uncertainty of design events that may or may not occur within the asset's lifespan; designing for future design events is simply projecting those calculations one step further. Therefore, when possible, asset managers should explicitly consider a wide range of feasible outcomes

Appendix B Storm Events in Roadway Damages Database (2015 – 2022)

FEMA # / OMS Code	Event Description	Year	# Damage Records	# Counties Impacted	Dollar Estimates
D15C	#MULTIVALUE	2015	472	45	\$29,942
D15D	April 2015 Flooding Emergency	2015	403	55	\$3,491
D16A	#MULTIVALUE	2015	327	34	\$194,338
D16D	Storms 2/2/16	2016	6	5	\$1,621,043
D16E	Storms 5/2/16	2016	52	15	\$0
D17A	July 5 thru 7 Storms	2016	339	22	\$2,078,386
D16B	Flooding Dec and Jan 2016	2016	7	3	\$11,426
D17C	Storms Feb 28 and March 1	2017	34	14	\$7,739
D17E	Storms April 5th	2017	1	1	\$25,669
D17F	Flooding April 21st	2017	29	6	\$312,471
D17G	Storms May 4 - 7, 2017	2017	2	2	\$422,995
D17H	Storms June 23 - 25	2017	12	5	\$8,543
D18A	#MULTIVALUE	2017	86	4	\$70,488
D18B	Storms Aug. 31- Sept 2017	2017	7	2	\$888
D18D	Rain Dec 23-Dec 31 2017	2017	3	1	\$37,414
D18E	Storms January 11 thru 15, 2018	2018	4	2	\$2,570
D18F	#MULTIVALUE	2018	291	16	\$47,150
FEMA-4358-DR	Severe Storms, Flooding, Landslides, and Mudslides	2018	492	17	\$134,453
D18G	#MULTIVALUE	2018	369	42	\$1,175,714
FEMA-4361-DR	Severe Storms, Tornadoes, Flooding, Landslides, and Mudslides	2018	118	33	\$129,884
D18H	April - May 2018 Storms	2018	2	1	\$789
D19A	July 20, 2018, Storms	2018	15	9	\$808
D19B	Sept. 8-9, 2018, Storms	2018	27	9	\$4,095
D19E	Storms Sept. 21-28 2018	2018	15	7	\$3,398,808
D19F	Storms Feb. 2019	2019	622	49	\$51,434,475
FEMA-4428-DR	Severe Storms, Straight-line Winds, Flooding, Landslides, and Mudslides	2019	1003	55	\$4,712,251
D19G	Storms June. 2019	2019	42	11	\$746,896
D20A	Storms Feb 4, 2020	2020	381	20	\$14,833,534
FEMA-4540-DR	Severe Storms, Flooding, Landslides, and Mudslides	2020	835	22	\$5,474
D20C	Storms March 2020	2020	3	3	\$32,907,263
D20D	Storms April 2020	2020	49	8	\$570,821
D20E	Storms May 2020	2020	74	9	\$4,543,234
D21A	#MULTIVALUE	2020	43	11	\$5,391
D21B	Hurricane Laura Aug 2020	2020	5	2	\$9,779
D21C	Storms Sept. 2020	2020	23	5	\$43,842

FEMA # / OMS Code	Event Description	Year	# Damage Records	# Counties Impacted	Dollar Estimates
D21D	Winter February 2021	2021	42	12	\$57,172
D21E	Flooding February - March 2021	2021	518	51	\$7,040,563
FEMA-4595/4592-DR	Severe Storms, Flooding, Landslides, and Mudslides	2021	709	29	\$754
D21F	March Storms 25-31, 2021	2021	33	5	\$97,387,580
D21G	May 4, 2021, Storms	2021	57	12	\$45,585
D22A	July 29, 2021, Storms	2021	15	5	\$3,552,772
D22B	August 2021 FLOOD	2021	10	6	\$93,296,028
D22C	August/Sept 2021 FLOOD	2021	7	3	\$8,859
D22D	Dec. 10, 2021, Storms	2021	71	13	\$215,341
D22E	Dec. 28, 2021, Storms	2022	110	10	\$39,491
FEMA-4643-DR	Severe Storms, Straight-line Winds, Tornadoes, Flooding, Landslides, and Mudslides	2022	69	5	\$29,404
D22G	Feb 2 Storms	2022	14	7	\$1,340
D22F	Mid Jan. 2022 Storms	2022	1	1	\$84,123
D22H	Feb 23-24 Storms	2022	19	5	\$247,009
FEMA-4663-DR	Severe Storms, Flooding, Landslides, and Mudslides	2022	1124	18	\$134,402,603