TRC2003

Data-Driven Methods to Assess Transportation System Resilience in Arkansas

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16. Abstract
The work described in this report proposes a foundational and repeatable resiliency assessment methodology to identify the most critical and vulnerable highway infrastructure assets. This study developed resiliency metrics that measure the overall network resiliency as a combination of the probability of disruptions in one or more of the network links (threats) and the importance of the link to mobility (criticality). The research team synthesized existing studies and practices to (a) define resiliency assessment methods, (b) define resiliency indices, and (c) evaluate the current state of practices within ArDOT. The method developed by the Colorado Department of Transportation (CDOT) was adopted in this study. Briefly, the CDOT method estimates the criticality and vulnerability of each transportation network segment. Six criteria were used to estimate system criticality: traffic volume (annual average daily traffic [AADT]), roadway classification, freight output, tourism output, Social Vulnerability Index (SoVI), and redundancy. Three threat types were used to estimate system vulnerability: floods, landslides, and earthquakes. The criticality and vulnerability values were converted into intensity scores and then combined so that the highest-scoring links were considered the most critical and most vulnerable based on the underlying data and assumptions used. Crittenden, Mississippi, and Craighead counties ranked highest in terms of combined criticality and vulnerability. Across all roadway segments, five segments had the highest combined criticality and vulnerability score. For these segments, we performed a detailed benefit-cost analysis of the existing (baseline) asset conditions and possible mitigation alternatives.

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SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
		AREA		
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m^2
yd^2	square yard	0.836	square meters	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	square kilometers	km^2
		VOLUME		
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
		NOTE: volumes greater than 1000 L shall be shown in m^3		
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
		TEMPERATURE (exact degrees)		
^oF	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	^oC
		ILLUMINATION		
fc	foot-candles	10.76	lux	lx
fl	foot-Lamberts	3.426	candela/m^2	cd/m^2
		FORCE and PRESSURE or STRESS		
lbf	poundforce	4.45	newtons	N
lbf/in^2	poundforce per square inch	6.89	kilopascals	kPa

APPROXIMATE CONVERSIONS FROM SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
		AREA		
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yards	yd^2
ha	hectares	2.47	acres	ac
km^2	square kilometers	0.386	square miles	mi^2
		VOLUME		
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	cubic meters	35.314	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3
		MASS		
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg (or "t")	megagrams (or "metric ton")	1.103	short tons (2000 lb)	T
		TEMPERATURE (exact degrees)		
^oC	Celsius	1.8C+32	Fahrenheit	^oF
		ILLUMINATION		
lx	lux	0.0929	foot-candles	fc
cd/m^2	candela/m^2	0.2919	foot-Lamberts	fl
		FORCE and PRESSURE or STRESS		
N	newtons	0.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in^2

CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF ABBREVIATIONS, ACRONYMS, AND SYMBOLS

AASHTO	Association of State Highway and Transportation Officials
AADT	Annual average daily traffic
AADTT	Average annual daily truck traffic
ADOT	Arizona Department of Transportation
ADT	Average daily traffic
AGS	Arkansas Geological Survey
AHP	Analytical hierarchy process
AIJ	Aggregate individual judgments
AIP	Aggregating individual priorities
ARC	Asset replacement cost
ARDOT	Arkansas Department of Transportation
ARNOLD	All Roads Network of Linear Referenced Data
ARTDM	Arkansas Travel Demand Model
B/C	Benefit cost ratio
BIL	Bipartisan Infrastructure Law
CBC	Concrete box culvert
CDOT	Colorado Department of Transportation
CTDOT	Connecticut Department of Transportation
DEM	Digital elevation map
dTIMS	Deighton Total Infrastructure Management System
DOT	Department of Transportation
FAF4	Freight Analysis Framework Version 4
FEMA	Federal Emergency Management Agency
FHWA	Federal Highway Administration
FIRMS	FEMA Flood Insurance Rate Maps
GIS	Geographic information system
IIJA	Infrastructure Investment and Jobs Act
LoR	Loss of resiliency
LRS	Linear referencing system
MnDOT	Minnesota Department of Transportation
NBI	National Bridge Inventory
NCDOT	North Carolina Department of Transportation
NCHRP	National Cooperative Highway Research Program
NED	National Elevation Dataset
NHPP	National Highway Performance Program
PROTECT	Promoting Resilient Operations for Transformative, Efficient, and Cost-saving Transportation
R&R	Risk and resilience
RIK	Replace-in-kind

SIR	System Information and Research
SoVI	Social Vulnerability Index
STBG	Surface Transportation Block Grant Program
TAMP	Transportation Asset Management Plan
TnDOT	Tennessee Department of Transportation
TPP	Transportation Planning and Policy
USDOT	US Department of Transportation
USGS	US Geological Survey

EXECUTIVE SUMMARY

This report provides a foundational and repeatable resiliency assessment methodology to identify the most critical and vulnerable assets. This study developed resiliency metrics that measure the overall network resiliency as a combination of the probability of disruptions in one or more of the network links (threats) and the importance of the link to mobility (criticality). The research team synthesized existing studies and practices to (a) define resiliency assessment methods, (b) define resiliency indices, and (c) evaluate the current state of practices within ARDOT. The method developed by the Colorado Department of Transportation (CDOT) was adopted. Six criteria were used to estimate system criticality: traffic volume (annual average daily traffic [AADT]), roadway classification, freight output, tourism output, Social Vulnerability Index (SoVI), and redundancy. Three threat types were used to estimate system vulnerability: floods, landslides, and earthquakes. Criticality and vulnerability values were converted into intensity scores and then combined, with the highest-scoring links considered the most critical and most vulnerable.

Criteria data were gathered from the ARDOT statewide travel demand model (AADT, roadway classification, and redundancy), Federal Highway Administration (FHWA) (freight output), Arkansas Department of Parks, Heritage, and Tourism (tourism output), and the University of South Carolina Hazards and Vulnerability Research Institute (SoVI). Threat data were gathered from ARDOT GIS Office, the US Geological Survey, the Arkansas Geological Survey, and the Federal Emergency Management Agency (FEMA). The top five highest AADT, according to the statewide travel demand model, were seen in Pulaski County on Interstates 630 and 30. The top five counties ranked by freight value (million USD) include Pulaski, Washington, Crittenden, Sebastian, and Mississippi Counties. These five counties account for 47 percent of the total freight output in the state. The top five counties based on reported tourism expenditures are Pulaski, Benton, Garland, Washington, and Sebastian Counties, accounting for 81 percent of the state's total expenditures. The five most at-risk counties are Phillips, Monroe, Chicot, Baxter, and Woodruff Counties. The majority (90%) of the roadway links with estimated change in system travel time for free-flow conditions have low to no impact on the system travel time. Almost 300 (293 or 0.41%) roadway links have a redundancy score of four or five, representing high to very high impacts on system travel time. The top three locations causing the greatest disruption to the network, identified by the redundancy analysis include the Highway 7 bridge in Dardanelle, the Highway 64 bridge in Ft. Smith, and the Highway 49 bridge in Helena.

An unequal weighting scheme was applied to combine the criticality criteria in a way that reflected the importance of each criterion to ARDOT's priorities. To this end, a questionnaire survey was developed and distributed to select ARDOT staff in February 2022 for executing an analytical hierarchy process (AHP) to determine criteria weights. AHP is a multi-criteria decision-making approach in which factors are arranged in a hierarchical structure (ranked). It is an unequal weighting approach to compute a link's criticality by applying differing weights to each criterion such that the weights reflect the priorities of the decision-makers. Redundancy received the largest weight (highest rank), followed by freight (second-highest rank). AADT and roadway classification were ranked third and fourth respectively. AADT and

roadway classification are correlated in that a more heavily trafficked roadway is typically a highway or interstate roadway. This explains the closeness in the weights. SoVI and tourism were ranked fifth and sixth (last) respectively and have weights approximately five times lower than the highest ranked criterion, redundancy. The combined criticality score obtained using the weighted ranking approach (e.g., AHP method) resulted in ten roadway segments with criticality scores above 4.2 (highest possible is 6). Of the top ten, eight are in Pulaski County and one each in Sebastian County and Crittenden County.

The vulnerability of a link due to flooding is measured as the number of road closures due to flood events. The most frequent flooding events that resulted in road closures were observed in Jackson, Independence, and Lawrence Counties (northeast region) with at least 20 flood events between 2011 and 2019. The top five counties in terms of flood occurrence account for 39 percent of the total number of flood events. Sixty-two percent of the road closures due to flooding were on major collectors (low impact), with 2 percent occurring on interstates. Landslide occurrences and their impacts on the roadway are measured as the number of landslide events occurring within one mile of the roadway segment. The heaviest impacts were observed in Crawford (2,183 events, 28% of all events) and Newton (1,080, 14%) Counties. The vulnerability score for earthquake occurrence is computed based on the FEMA Hazus model. Scores are derived from the probability of extensive damage as defined by the model. Overall, the state has a 2.5 percent probability of extensive damage, and 27 of the 75 counties have a positive (non-zero) probability of extensive damage. Cross, St. Francis, Mississippi, and Crittenden (Northeast Arkansas) have average probabilities of 20 percent. Based on roadway classification, the highest probability of extensive damage (4.1%) is observed for interstates, while the lowest average probability is observed for principal arterials (2.2%). Overall, 1.2 percent (838 segments, 1.9% by mileage) of roadway segments are highly vulnerable (score >1.0) based on the combined weighting of the three threats' likelihoods.

The average combined criticality and vulnerability score is highest for interstates (3.4) and lowest for major collectors (1.9), with a statewide average score of 2.2. Based on the average combined criticality and vulnerability score and on the underlying data and assumptions used, the following three counties are ranked highest (>3.0): (1) Crittenden with an average combined criticality and vulnerability score of 3.55, (2) Mississippi with 3.42, and (3) Craighead with 3.01. The research team conducted detailed benefit/cost analyses for the five most critical and vulnerable transportation assets based on the underlying data and assumptions used. The five sites include (1) Highway 67 in Pulaski County that contains one bridge and two culverts, (2) Interstate 55 in Crittenden County that contains one bridge, (3) Interstate 40 in Crittenden County that contains one bridge, (4) Interstate 430 in Pulaski County with one bridge, and (5) Interstate 55 in Crittenden County with one bridge. For each case study site, the research team conducted a benefit/cost analysis for estimating the benefits and costs of mitigative solutions to reduce the risk of damage and increase resilience of the assets. The highest BC ratio was 3.6 for the Highway 67 culvert in Pulaski County. The lowest BC ratio was 0.006 for the I-55/Hwy 64 bridge in Crittenden County. Resilience scores for all links in the state-maintained roadway network give ArDOT a means to rank and prioritize resiliency mitigation projects across the state. The methods developed can be updated by integrating new data to maintain the relevancy of the assessment method.

CHAPTER 1: PROJECT OVERVIEW

STRUCTURE OF THE REPORT

Following the Project Overview in Chapter 1, this report is organized as follows:

- Chapter 2 reviews the state-of-the-practice and state-of-the-art methods for statewide transportation system resiliency assessment,
- Chapter 3 summarizes the metrics selected for measuring transportation system resilience,
- Chapter 4 describes the application and results of the resiliency assessment,
- Chapter 5 presents five benefit/cost analysis case studies, and
- Chapter 6 summarizes key findings, addresses limitations, and suggests avenues for future work.

BACKGROUND

The Infrastructure Investment and Jobs Act (IIJA), also known as the Bipartisan Infrastructure Law (BIL), was signed into law on November 15, 2021. For the period 2022–2026, the BIL provides $550 billion for bridges, roads, waterways, transit, and – key to this project – resilience. The BIL offers the first legal definition of resilience and establishes the Promoting Resilient Operations for Transformative, Efficient, and Cost-saving Transportation (PROTECT) program. PROTECT provides $8.7 billion over a period of five years in formula and competitive funding. PROTECT is geared at projects that "[make] existing infrastructure more resilient" (USDOT, 2022; FHWA, 2022). PROTECT's formula program offers a higher federal share for the state if the state develops a resilience improvement plan and incorporates it into its long-range transportation plan. In addition, due to the BIL, current transportation funding programs now include resiliency elements. For example, the National Highway Performance Program (NHPP) now requires consideration of resilience in lifecycle costs for asset management plans, and the Surface Transportation Block Grant (STBG) Program now includes eligible projects that add protective features to enhance resilience (FHWA, 2022). The BIL is highlighted here as a key rationale behind the need to assess resiliency of the Arkansas State–maintained roadway system. **This report provides a foundational and repeatable resiliency assessment methodology to identify the most critical and vulnerable assets.**

Motivation

Transportation is one of the most critical US infrastructure sectors because many other crucial infrastructure segments such as emergency services, food and agriculture, healthcare and public health, manufacturing, etc., depend on it for their proper functioning. However, road networks face risks from natural and human-made events such as hurricanes, floods, earthquakes, structural failure, and terrorist attacks. Events like Hurricane Katrina in New Orleans in 2008, Hurricane Sandy in the Northeastern US in 2012, flooding of Interstate 10 (I-10) in Phoenix in 2014 and Interstate 40 (I-40) in Arkansas in 2011 (Figure 1a), the Riverside County I-10 bridge washout in 2015, the Highway 23 landslide in Arkansas in 2015 (Figure 1b), and Hurricanes Harvey and Maria in 2017 have revealed how vulnerable our transportation system can be to extreme events.

(A) Flooding Closes I-40 in Arkansas in May 2011 (Ref: CNN.com)

(B) Landslide on Highway 23 in Arkansas, August 2015 (Ref: Arkansas Business)

Figure 1. Recent Arkansas Network Disruptions

The ability of transportation agencies to effectively manage, operate, and maintain a safe, reliable transportation system is being threatened by these extreme events as they have the potential to hit any geographical location with or without warning. Extreme weather events are now becoming more frequent and intense due to climate change, and long-term climatological trends are slowly but inexorably changing how transportation systems are planned, designed, operated, and maintained. A "new normal" is in the making, and state departments of transportation (DOTs) are turning their focus toward building resilient systems. Several state DOTs have initiated the process of incorporating resilience into their operations, planning, and maintained activities, according to the recent *National Cooperative Highway Research Program (NCHRP) Synthesis Report 527: Resilience in Transportation Planning, Engineering, Management, Policy and Administration* (Flannery et al. 2018). **The objective of this project was to develop and implement a framework for measuring the resilience of Arkansas's highway transportation system.**

Defining Resiliency

Resiliency, as defined by the Federal Highway Administration (FHWA), is "the ability to anticipate, prepare for, and adapt to changing conditions and withstand, respond to, and recover rapidly from disruptions" (FHWA, 2014). The American Association of State Highway and Transportation Officials (AASHTO) defines resiliency as "the ability of a system to provide and maintain an acceptable level of service or functionality in the face of major shocks or disruptions to normal operations" (TRB 2016). In the ARDOT Long Range Intermodal Transportation Plan, resilience is considered to "[imply] transformation, so not only is the infrastructure service able to survive or recover but it can adapt to a changing environment in which it operates" (ARDOT, 2017). Although different in wording, each definition concentrates on three key concepts: (1) anticipating, (2) preparing, and (3) recovering.

Resilient transportation networks are least affected by disruptions created by natural and man-made disasters and can still function at an acceptable level of service. Such networks also have the ability to return more quickly from a disrupted state to a normal functioning state. The resilience possessed by a transportation network measures the ability of the network to maintain functionality despite adverse conditions posed by disruptions as well as the ability to return quickly to normal operating conditions. Measures of resilience can be important in assessing the degree of preparedness against disasters and act as bases for making improvements or providing extra security to critical network pathways. Identifying risks is an essential step in determining the resilience of a transportation system. The National Academy of Sciences (2012) defines risk as "the potential for adverse effects [due to] the occurrence of a particular hazardous event, which is derived from the combination of physical hazards and exposure". Moreover, Moving Ahead for Progress in the 21st Century (MAP-21) requires states to develop a risk- and performance-based asset management plan to be reviewed and updated every four years for preserving and improving the condition of the national highway systems. By using risk analysis and performance-based measurement, transportation agencies are able to identify weaknesses within their respective systems to determine their potential level of resilience. Utilizing the three major components of the risk calculation (consequences, vulnerability, and threat), the anticipated annual risk based on threat and asset type as well as resilience segment can be calculated for both owner risk (ARDOT) and user risk (traveler). Understanding the risks and identifying vulnerable sections of roads will help ARDOT prioritize construction and maintenance dollars more efficiently while improving public safety and system efficiency and mitigating negative short- and long-term effects of network disruptions.

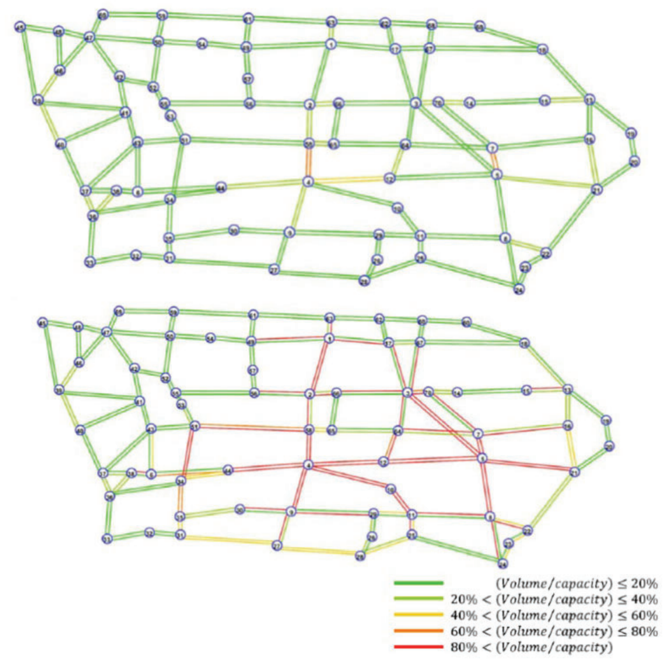


Figure 2. Comparison of Iowa's Highway Network Before (top) and After (Bottom) Network Disruption Based on Volume to Capacity (VC) Ratio as a Resilience Index; Ref: (Rahdar et al 2018)

Incorporating resiliency into the transportation infrastructure system or any infrastructure system requires developing metrics that measure the system's resiliency. Metrics provide insights about the current resiliency of the system; they enable stakeholders to determine the degree of resiliency incorporated in the system and to identify its most critical segments (see Figure 2). The metrics can also be used as indicators of improvements in the system's resiliency after the implementation of resiliency strategies, as well as being an effective tool for comparing and evaluating different mitigation options to enhance the system's resiliency. **This study developed resiliency metrics that measure the overall**

network resiliency as a combination of the probability of disruptions in one or more of the network links (threats) and the importance of the link to system wide mobility (criticality).

Network resiliency is evaluated based on the impact of threats on system performance measures such as travel time. This study modified the seven-step Risk and Resilience (R&R) for Transportation Systems process (Figure 3) as an analytical framework. Briefly, for Steps 1 and 2, the project considered bridges, culverts, and the roadway prism as assets, and earthquakes, floods, and landslides as threats. This selection was based on feedback garnered from a survey among members of the project Subcommittee. Following and adapting the Colorado DOT approach used to analyze Interstate 70 (I-70), the most critical among all assets were determined based on six criteria: roadway traffic volume (e.g., AADT), roadway functional class, freight value, tourism value, social vulnerability, and network redundancy (CDOT, 2017). Network redundancy is a measure of the potential increase in travel time across the whole network when one link is non-operational and was computed using a method developed specifically for this project. Prior studies, including the study by CDOT, did not quantify network redundancy because they were only examining single corridors, rather than statewide networks. For Steps 3, 4, and 5, the research team used the FEMA Hazus model and historical landslide and flood data to perform consequence analysis, vulnerability analysis, and threat assessment. Finally, once again using the approach outlined in the CDOT I-70 corridor resiliency assessment, the research team developed a set of case studies to demonstrate risk and resiliency quantification and mitigative action selection. The five case study locations correspond to the five most vulnerable and critical network assets. Overall, this approach helps prioritize mitigation solutions and determine potential financial impacts on transportation asset owners and their users.

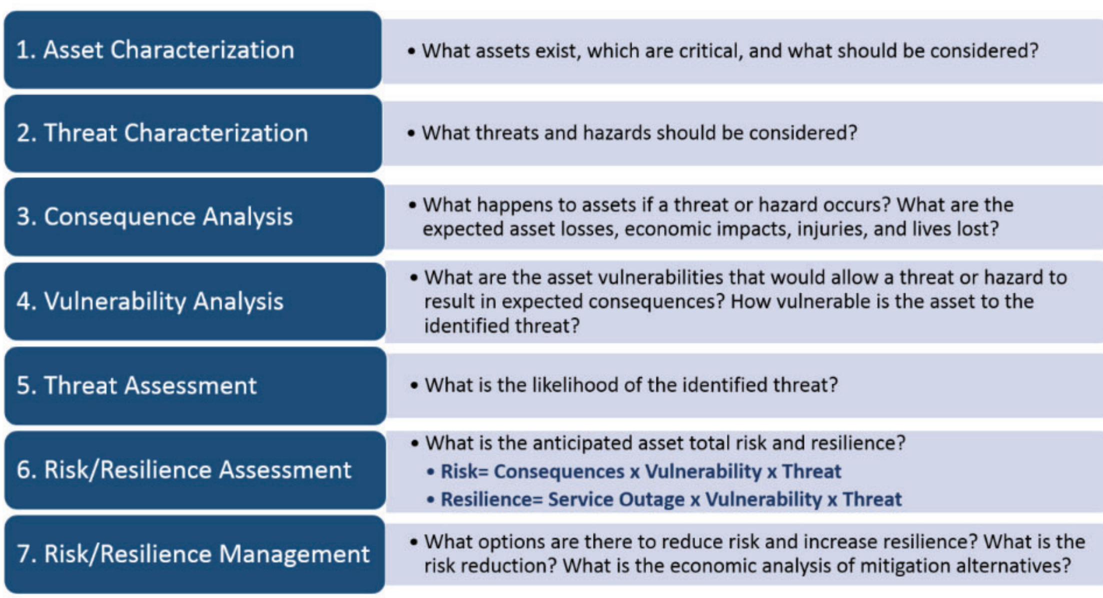


Figure 3. Risk and Resilience Processed for Critical Asset Protection; Ref: (Flannery 2017)

Benefits of the Study

Proactively measuring and addressing potential vulnerabilities in the ArDOT highway system can lead to overall cost benefits for both the agency and users. A statewide resiliency assessment also provides the data necessary to meet federal mandates and recommendations for resilience considerations (Table 1).

Table 1. Federal Laws and Regulations that Require Resilience Considerations (Dix et al. 2018)

Effective Date	Overview	Source
June 27, 2016	"(a) Each State shall carry out a continuing, cooperative, and comprehensive statewide transportation planning process that provides for consideration and implementation of projects, strategies, and services that will address the following factors: (9) improve the resiliency and reliability of the transportation system and reduce or mitigate stormwater impacts of surface transportation."	23 CFR 450.206(a)
June 27, 2016	"(b) The metropolitan transportation planning process shall be continuous, cooperative, and comprehensive, and provide for consideration and implementation of projects, strategies, and services that will address the following factors: (9) Improve the resiliency and reliability of the transportation system and reduce or mitigate stormwater impacts of surface transportation;"	23 CFR 450.306(b)
Long-range statewide transportation plan adopted after May 2018 meets requirements	"(c) The long-range statewide transportation plan shall reference, summarize, or contain any applicable short-range planning studies; strategic planning and/or policy studies; transportation needs studies; management systems reports; emergency relief and disaster preparedness plans;"	23 CFR 216 (c)
On or after May 27, 2018, an MPO meets requirements to adopt a metropolitan transportation plan	"(f) The metropolitan transportation plan shall, at a minimum, include …7) assessment of capital investment and other strategies to preserve the existing and projected future metropolitan transportation infrastructure, provide for multimodal capacity increases based on regional priorities and needs, and reduce the vulnerability of the existing transportation infrastructure to natural disasters."	23 CFR 450.324(f)(7)

Effective Date	Overview	Source
October 2, 2017	Asset Management Plan – "(c) A State DOT shall establish a process for developing a risk management plan. This process shall, at a minimum, produce the following information … (6) risk management analysis, including the results for NHS pavements and bridges, of the periodic evaluations under part 667 of this title of facilities repeated damaged by emergency event." "(h) A State DOT shall integrate its asset management plan into its transportation planning processes that lead to the STIP, to support its efforts to achieve the goals in paragraphs (f)(1) through (4) of this section."	23 CFR 515.7 (c)(6) and 515.9 (h)
Mandatory and due by November 23, 2018	State DOTs must evaluate facilities that have repeatedly been damaged in emergency events.	FAST Act 23 CFR 667
Nonbinding	The National Highway Freight Program has a goal to "improve the . . . resiliency of freight transportation in rural and urban areas". [1]	FAST Act
Nonbinding	Goals for the national transportation system include increasing safety, security, and reliability. [2]	MAP-21
Nonbinding	National Infrastructure Protection Plan aims to produce significant reductions in national risk. [3]	Department of Homeland Security
March 15, 2022	A primary goal of the 2022 Bipartisan Infrastructure Law is to increase the resiliency of the US transportation system. The law establishes the Promoting Resilient Operations for Transformative, Efficient, and Cost-saving Transportation (PROTECT) program that will provide $8.7 billion over five years to improve resiliency, and adjust formula funds to include resilience planning and mitigative activities.	Bipartisan Infrastructure Law

This study provides ARDOT with a resilience assessment method that can be incorporated into existing planning, design, construction, operations, and maintenance activities. This report describes a strategic and systematic framework for measuring resilience using data already available to ARDOT. Furthermore, this study provides ARDOT with a framework for accommodating uncertainty, incorporating a probabilistic approach to assessing risk, and for making ensuing investment decisions to increase system resilience and reduce annual risk from physical hazards. This framework considers how the system will perform under earthquake, flood, and landslide threats. The resulting resiliency metric can inform project selection, investment, maintenance, and operational decisions. Further, the quantification of resiliency as the combination of criticality and vulnerability can assist in the design process when selecting culvert and bridge capacity and determining the need for rockfall fencing. In addition, this project identified opportunities to expand the availability of existing datasets and data management practices.

To monetize the benefits of the project, a case study approach was adopted and presented in Chapter 5 titled Benefit/Cost Analysis Case Studies. To better measure the impact of resilience planning, a measure of the consequences of not improving resilience is needed. Asset improvement costs can be compared to the consequences of disruptions to the network if the assets were to fail. Consequences include owner losses and user costs. Owner losses include replace-in-kind costs of impacted assets. User costs refer to productivity losses (e.g., income) and reduced accessibility because of increased travel times resulting from impacts on individual travelers, businesses, and freight operators. This approach is followed for each of our five select case studies in Chapter 5.

In this section, we discuss the general benefits of resiliency planning by reviewing findings for other states. The benefits of vulnerability, risk, and resiliency assessment are derived from the vulnerability-reducing investments identified through this work. Vulnerability-reducing investments include prevention, repair, and restoration costs to critical transportation assets. For example, the Resilience Investment Economic Analysis program of Arizona DOT (ADOT) evaluated pavement preservation projects along State Road 191 (Flannery et al. 2018). The preliminary budget for pavement preservation along the corridor totaled $5 million. ADOT's resilience program recommended the addition of drainage structures along the corridor to mitigate risk associated with flooding (e.g., water undermining the embankment, pipe washout, etc.), leading to an additional investment of $300,000, a 6 percent increase in the overall budget. The Colorado DOT (CDOT) implemented a pilot program to measure the resilience of the I-70 corridor through Denver. A total of $170.5 million in user and owner risk was estimated along the corridor due to floods, rockfall, avalanche, landslide, high wind, and bridge vehicle strikes. Through a case study approach, high- and low-cost mitigation approaches were evaluated to develop benefit/cost (B/C) ratios. An example of one such mitigation was targeted at flooding. Mitigations for reducing flood risk include replacing culverts with concrete pipes of varied sizes. This would allow the site to handle a 50-year flood event (without mitigation, the site could only accommodate a 25-year flood event). Estimated user (traveling public) and owner (CDOT) costs, referred to as "total annualized risk", amount to $1.325 million. Owner costs include replacement cost of the culverts, and user costs include lost wages due to a predicted seven-day closure with a 140-mile detour. To mitigate risk, the replacement of the culverts with larger concrete box culverts was proposed, requiring a total cost of $1.6 million per site and an estimated annualized cost of $54,937. This mitigation was expected to reduce the risk of water overtopping the roadway during a 50-year flood, leading to reductions of $7,481 in annualized owner risk and $1.285 million in annualized total risk. The benefit/cost ratio (B/C) was calculated as the reduction in annualized risk divided by the annualized cost of the proposed mitigation. For the culvert upgrade, the B/C ratio was 0.14 (=$7,481/$54,937) for the owner and 23.4 (=$1.285 million/$54,937) for the user and owner combined. Note that the risk reduction calculations are based on the confluence of estimated consequences, vulnerability, and threats and were modeled in the CDOT study for each threat-asset pair. Thus, different mitigation solutions produce different annualized user and owner risk reduction costs, which necessitates the B/C analysis for the five case study sites (Chapter 5).

PROJECT OBJECTIVES

The central objective of this project was to develop and implement a framework for measuring the resilience of Arkansas's highway transportation system.

Objective 1: Comprehensive Review of Practice

The research team synthesized existing studies and practices to (a) define resiliency assessment methods, (b) define resiliency indices, and (c) evaluate the current state of practices within ARDOT. The method developed by the Colorado Department of Transportation (CDOT) was adopted. Briefly, the CDOT method estimates the criticality and vulnerability of each transportation network segment. Six criteria were used to estimate system criticality: traffic volume (annual average daily traffic [AADT]), roadway classification, freight output, tourism output, Social Vulnerability Index (SoVI), and redundancy. Three threat types were used to estimate system vulnerability: floods, landslides, and earthquakes. The criticality and vulnerability values were converted into intensity scores and then combined, with the highest-scoring links considered the most critical and most vulnerable.

Objective 2: Methodology Development and Application

The research team applied the CDOT methodology to assess the resiliency of the Arkansas State–maintained roadway network. Both passenger and freight networks and flows were considered within the criteria. Criteria data were gathered from the ARDOT statewide travel demand model (AADT, roadway classification, and redundancy), Federal Highway Administration (FHWA) (freight output), Arkansas Department of Parks, Heritage, and Tourism (tourism output), and the University of South Carolina Hazards and Vulnerability Research Institute (SoVI). Threat data were gathered from ARDOT GIS Office, the US Geological Survey, the Arkansas Geological Survey, and the Federal Emergency Management Agency (FEMA). Methods to estimate criticality and vulnerability scores were developed and applied to the statewide network to identify the most critical and vulnerable assets. A survey was conducted among the project Subcommittee members to rank the six criteria when estimating a combined criticality score.

Objective 3: Methodology Testing Through Case Study

The research team carried out five detailed benefit/cost analyses for most critical and vulnerable assets. The corresponding five sites are (1) Highway 67 in Pulaski County that contains one bridge and two culverts, (2) Interstate 55 in Crittenden County that contains one bridge, (3) Interstate 40 in Crittenden County that contains one bridge, (4) Interstate 430 in Pulaski County having one bridge, and (5) Interstate 55 in Crittenden County that contains one bridge. For each study site, the research team conducted a benefit/cost analysis.

Objective 4: Recommendations and Implementation

This project provides resilience scores for all links in the state-maintained roadway network. These data give ARDOT a means to rank and prioritize resiliency mitigation projects across the state. The methods developed can be updated by integrating new data to maintain the relevancy of the assessment method.

CHAPTER 2: REVIEW OF RESILIENCY ASSESSMENT METHODS

This chapter reviews state-of-the-practice (state and federal reports) and state-of-the-art (academic research) methods for quantifying the transportation system's resiliency using performance measures and other metrics. The chapter concludes by recommending the use of the Colorado DOT risk and resiliency (CDOT, 2017) methodology with adaptations to extend the approach to a statewide analysis.

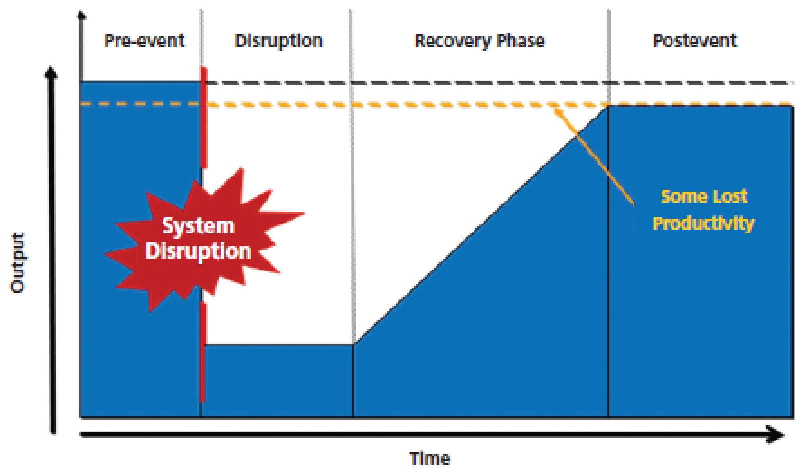
STATE-OF-THE-PRACTICE METHODS

The MAP-21 legislation enacted in 2012 required state transportation agencies to develop risk-performance-based asset management plans every four years. In accordance with that directive, the Department developed its Transportation Asset Management Plan (TAMP) in 2019 (ARDOT, 2022). As required by federal legislation, the ARDOT TAMP considered bridge and pavement assets (FHWA 2012). In line with the ARDOT TAMP, this study considered bridge (including culverts) and pavement assets for resiliency assessment. In 2014, through FHWA Order 5520, the FHWA established a policy on preparedness and resilience to climate change–induced seasonal precipitation and rain intensity (USDOT 2014). As a result of these policies, several states developed and implemented risk and resiliency measurement approaches. However, state-of-the-practice approaches to generate resiliency metrics for transportation systems are lacking according the *NCHRP Report 938: Resilience in Transportation Planning, Engineering, Management, Policy, and Administration*. In 2017, a survey of 40 state DOTs showed that most states are working toward integrating resilience practices into existing programs but that the efforts are often hindered by a lack of available practical approaches to estimate resilience. Many of the proposed methods to estimate metrics for resiliency are borrowed from existing performance measures. For example, travel time reliability can be used to measure resilience before, during, and after a disruption for depicting the deterioration and recovery curves of the resilience triangle (Figure 4).

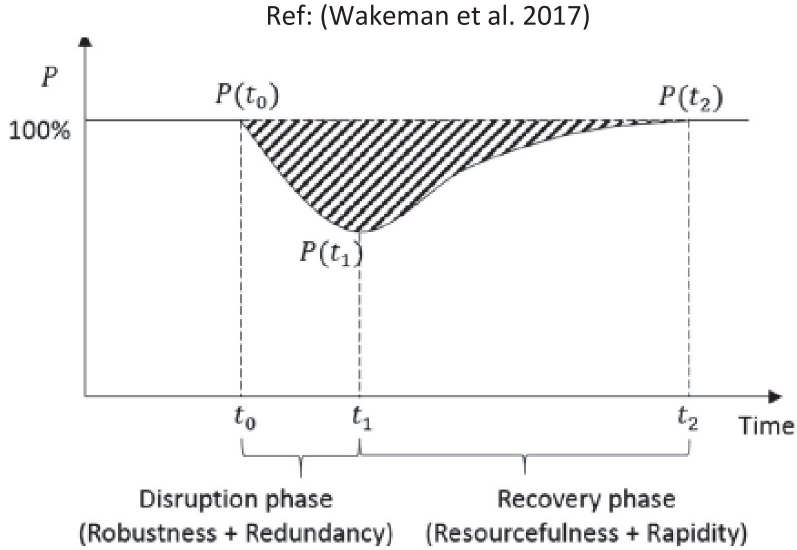
For the state-of-the-practice review in this project, we focus on existing methods used by federal and state transportation agencies to measure resilience using repeatable processes and established frameworks. Specifically, we focus on work done in states with similar threat and risk profiles to that of Arkansas. This mainly includes states that are under the threat of flooding, as opposed to hurricanes or sea-level rise. The key examples presented in this report include the work in Colorado and findings from the FHWA Climate Change Resilience pilot studies that include Connecticut, Iowa, and Minnesota. The reader is directed to *NCHRP Report 938* for a full review of policy and practice regarding resiliency assessment.

FHWA Climate Change Resilience Pilot Studies

The FHWA funded 19 climate vulnerability pilot studies aimed at examining the impacts of climate hazards on the transportation system. States received federal funds to perform vulnerability assessments for natural hazards including sea-level rise, flooding, extreme temperatures, etc. The purpose of the case studies was to help state transportation agencies enhance the resilience of their transportation systems to extreme weather and climate change. The FHWA then developed a resilience assessment and mitigation framework based on the findings of the pilot studies called the FHWA Climate Change and Extreme Weather Vulnerability Assessment Framework (FHWA, 2012). The framework includes three components (Figure 5): defining scope, assessing vulnerability, and integrating vulnerability assessments into decision-making. In this project, we developed an approach for Step 2 "Assess vulnerability" in accordance with the recommendations of the FHWA framework.



(a) Resilience Curve Showing Four Distinct Phases: Pre-Event, Disruption, Recovery, and Post-Event; Ref: (Wakeman et al. 2017)



(b) Resilience Curve Depicting Mathematical Phasing of Disruption and Recovery; Ref: (Zhou et al. 2019)

Figure 4. Resilience Curve Visualizations

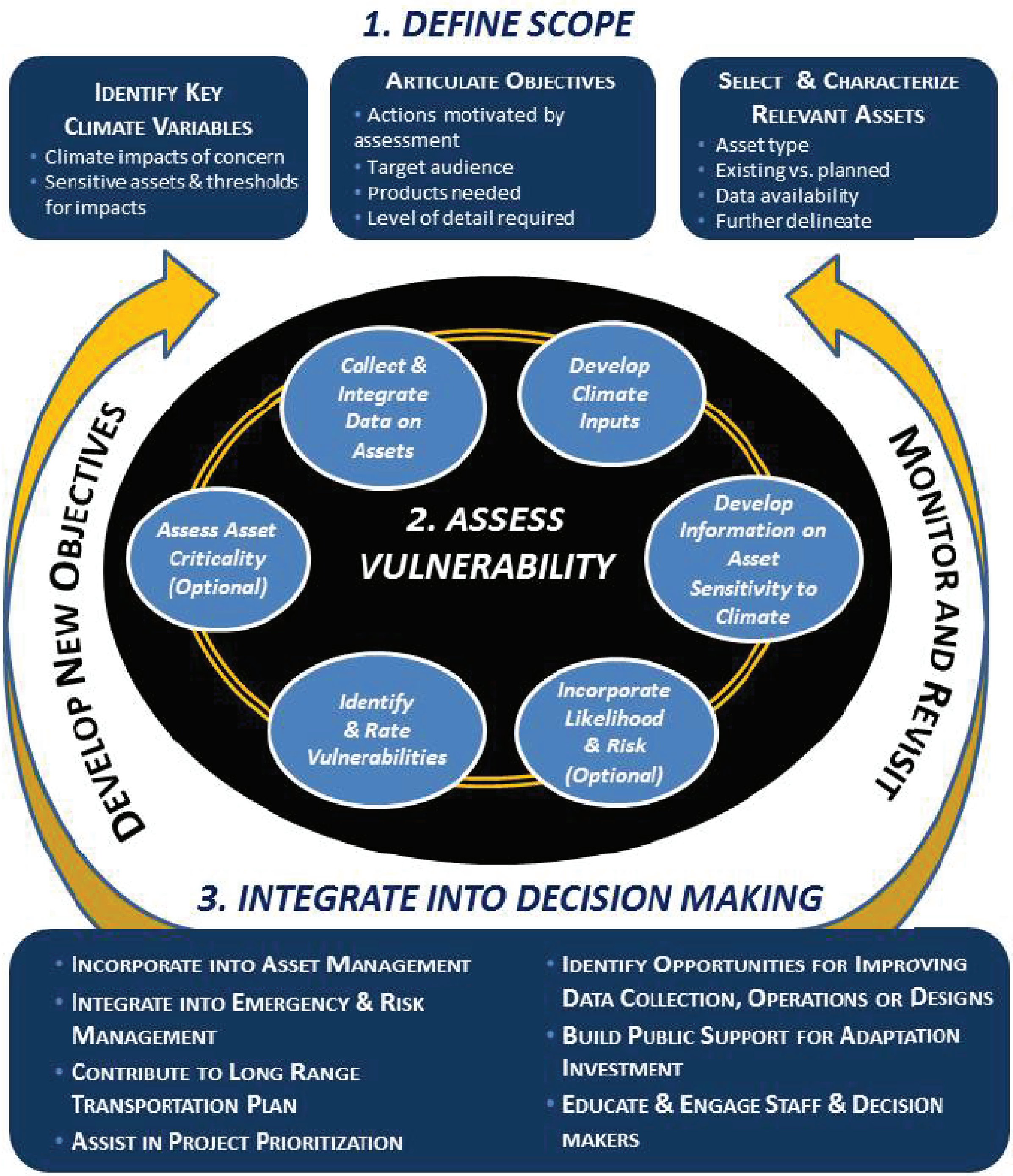


Figure 5. Climate Change and Extreme Weather Vulnerability Assessment Framework (FHWA 2017)

To assess vulnerability, the FHWA framework recommends asset criticality assessment as a structured way to identify assets that would most improve system resiliency. **The criticality of an asset is defined as its importance to the study area such that removal from operation would result in significant losses (DHS 2007).** Criticality depends on the physical characteristics of the asset and its function within the system. Criteria to measure criticality may capture one or both characteristics.

The framework suggests two approaches to assess asset criticality: desk review and stakeholder input. Desk review entails formulating criteria that identify a “broad range” of use and access using objective and quantifiable measures. Measures can include average daily traffic, functional classification, goods movement, emergency management, and expert judgment. A key challenge in this approach is the availability of data. Stakeholder input involves identifying and ranking assets based on expert knowledge gathered from stakeholders from public and private sectors, local citizens, emergency organizations, etc. Often, stakeholder input is gathered through a series of workshops. In practice, both desk review and stakeholder engagement are used to identify critical assets. For this project, we followed the framework recommendations by performing a desk review to measure asset criticality using objective measures and garnered stakeholder input to rank order each measure using a subjective voting process (For more, see Chapter 3).

Criticality serves as a filter for screening assets so that those most critical can be evaluated for vulnerability (FHWA 2011). Vulnerability, according to the FHWA, is defined by three components (FHWA 2017):

1. *Exposure* – the degree to which an asset is in an area that experiences direct impacts of disruptions
2. *Sensitivity* – the degree to which the asset fares when exposed to the disruption
3. *Adaptive capacity* – the degree to which the system can cope with non-operation of the asset

Of the 19 pilot studies (FHWA 2022b), we present three key studies in Connecticut, Tennessee, and Minnesota that are similar in scope to the project objectives of this work. We focus on flooding as a threat and perform vulnerability assessments for bridges, culverts, and roadway infrastructure.

Connecticut DOT. The CTDOT pilot study evaluated the hydraulic capacity of bridges and culverts in regions of the state with extreme rain event potential (Hogan and Lupes 2015). The analysis was based on a system-level vulnerability assessment that focused on the system’s adaptive capacity. Vulnerability was based on the assessment of the physical characteristics of the assets (e.g., structural condition rating) and environmental characteristics (e.g., precipitation expected), as well as the asset’s critically to the system (adaptive capacity). Criticality was quantified in terms of hydraulic, spatial, and social categories that included metrics such as ADT, accident count, and flood zone and flood plain location (Figure 6). Besides quantifiable metrics, the project team included stakeholder input (subjective) for a context-sensitive understanding of the system’s criticality. Of the 52 structures evaluated, 19 were rated as critical or very critical. Key recommendations from the pilot study included balancing quantitative metrics with more subjective and context-sensitive inputs from MnDOT and local agencies and emergency responders. In the current study, we used a similar matrix-based criticality assessment approach (with different metrics) and balanced the quantitative approach with subjective insights from the project Subcommittee in the form of ranking metrics.

	Very Low to Low	Moderate	Critical to Very Critical
	1 / 2 / 3	4 / 5 / 6 / 7	8 / 9 / 10
Hydraulic	High adaptive capacity	Moderate adaptive capacity	Low adaptive capacity
	No history of closure	History of periodic closures	Significant history of closure
			Scour critical
	Satisfies WSE criteria	Adjacent to scour critical structures	Does not satisfy WSE criteria
Spatial	Outside FEMA flood zones	Within 500 year FEMA flood zone	Within 100 year FEMA flood zone
	Low concentration of impervious surfaces	Moderate concentration of impermeable surfaces	High concentration of impermeable surfaces
Social	Low ADT & V/C	Moderate ADT & V/C	High ADT & V/C
	0-1 accidents	2 or more accidents	Emergency route
	Non-NHS, non-emergency route	NHS route	Emergency services cluster

Figure 6. CTDOT Criticality Matrix (FHWA 2016a)

Tennessee DOT. TnDOT performed a system-wide asset assessment across multiple modes using historical and future climate scenarios (Jones and Lupes 2016). The analysis was used to determine asset vulnerabilities and to find "hot spots" where critical assets are most prone to disruptive weather events. The results were used to adapt project priorities in the TnDOT 2040 Long Range Transportation Plan. In addition to roads, bridges, and culverts, the pilot study considered rail, navigable waterways, airports, ports, and locks, among other assets. Extreme weather impacts were determined using the National Weather Service's event database (for historical occurrence) and the USDOT's Climate Data Processing Tool (for future forecasts). The entire analysis was performed at the county level. The ranking of criticality was based on a stakeholder input survey that included 220 respondents. The survey asked respondents to evaluate the degree of damage expected to an asset based on their qualitative judgment. Stakeholder assessment of asset damage and weather event data were combined to determine the vulnerability rank of each county (Figure 7). This pilot project uniquely incorporated projections of climate change with insights from a large group of stakeholders. While the pilot project did not include site-specific adaptation analyses, it did suggest that system-wide vulnerability (and criticality) assessment is feasible through a combined quantitative and qualitative approach.

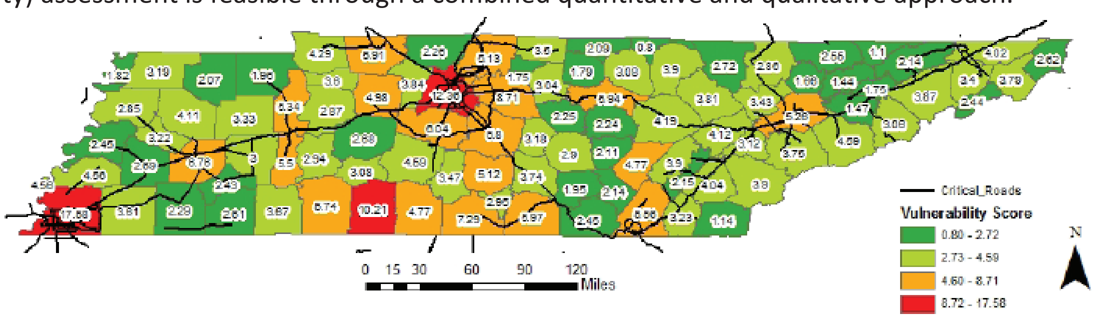


Figure 7. Vulnerability Scores for Critical Roads Estimated for the TnDOT Resiliency Pilot Study (FHWA 2016b)

Minnesota DOT. In 2012, Duluth, Minnesota experienced severe flooding causing $100 million in damage to roads and infrastructure (Parsons Brinckerhoff and Catalysis 2014). MnDOT applied the following methodology to assess the vulnerability of two key corridors and to determine cost-effective planning and design solutions to increase resiliency. The pilot study considered bridges, large culverts, pipes, and roads parallel to floodplains. To estimate criticality and vulnerability, the project considered sensitivity as the asset condition (pavement rating, scour rating, culvert condition, etc.), exposure as the flooding characteristics (stream velocity, floodplain attributes, land cover, and historical flooding issues), and adaptive capacity as AADT, average annual daily truck traffic (AADTT), and detour length. Each of the 1,819 assets was scored based on an asset-type specific set of metrics, e.g., scour was considered for bridges but not for roadways. Assets were then ranked by their vulnerability score (Figure 9).

Figure 8. Flooding in MnDOT Obstructing a Historic Bridge (Parsons Brinckerhoff and Catalysis 2014)

From the vulnerability assessment, MnDOT highlighted long-range planning actions, operations and maintenance actions, capital planning actions, and asset management actions. Some examples of action items include the following:

- *Operational*: MnDOT developed emergency action plans and real-time monitoring and warning systems for assets ranked as highly vulnerable.
- *Capital*: MnDOT incorporated vulnerability assessment scores into project prioritization at the state and district level.

Additionally, the MnDOT pilot study selected two large culverts that were ranked as highly vulnerable for detailed adaptation cost-benefit analyses. Both culverts were currently designed for 50-year flood events, and low-, mid-, and high-cost adaptations were proposed. Low-cost adaptations (approx. less than $1M) involve increasing culvert capacity to flood scenarios for the year 2100; mid- (<$2M) and high-range (>$2M) adaptations include upgrading the culverts to simple span bridges of increasing length. To estimate cost-effectiveness, the ratio of the adaptation cost to the damage costs that include the cost of repair, travel time increases due to detours, and safety impacts (injury and fatal crashes). Key conclusions from the cost-benefit analysis were the selection and prioritization of adaptive improvements.

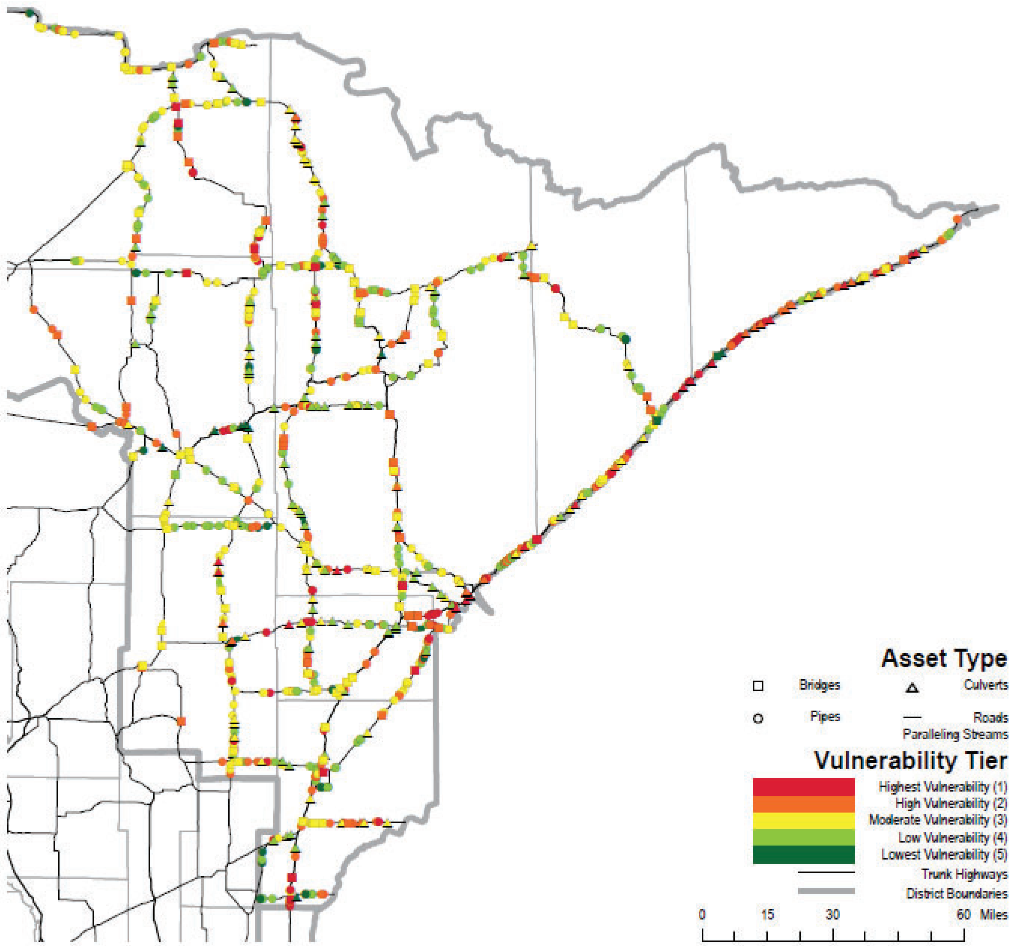


Figure 9. MnDOT Asset Vulnerability Assessment Results by Vulnerability Tier for a Study Region (MnDOT 2014)

Colorado DOT. The CDOT performed an extensive resiliency assessment of their I-70 corridor as the result of significant flooding and fires that caused loss of life and extensive travel delays (Flannery 2017). The CDOT Risk and Resilience pilot adapted the Risk Analysis and Management for Critical Asset Protection (RAMCAP) framework (see Figure 3) that involves assigning threat-asset pairs (Figure 10a), estimating criticality using quantitative metrics (referred to as asset characterization in the RAMCAP framework, Figure 10b), and ranking assets by criticality (Figure 11). The pilot concluded by suggesting a detailed method to calculate cost-benefit ratios for the mitigation of critical assets. Throughout the process, a working group provided insights and context in response to quantitative assessments.

The six criteria that comprise the criticality score were derived through a series of workshops with department experts from all divisions within CDOT including traffic, engineering and design, hydraulics, planning, maintenance, bridge, and others. Nine iterations of the model with varied criteria were considered by the department experts, and the final six (Figure 10b) were determined to best represent an objective model of asset criticality. In total, approximately 54 percent of the system assets were ranked as low, 25 percent as moderate, and 21 percent as high.

Threat/Asset	Bridge	Bridge Approach	Roadway Prism	PTCS	NBI Culverts	Minor Culverts	Wall	ITS-VMS	Control Centers
Avalanche	R&R	R&R	R&R	R&R	R&R	R&R	R&R	R&R	R&R
Flood (scour)	R&R	R&R	R&R	R&R	—	—	R&R	R&R	R&R
Flood (Overtopping/debris)	R&R	R&R	R&R	R&R	R&R	R&R	R&R	R&R	R&R
Fire (wildland)	R&R	R&R	R&R	R&R	R&R	R&R	R&R	R&R	R&R
Landslide	R&R	R&R	R&R	R&R	R&R	R&R	R&R	R&R	R&R
Rockslide	R&R	R&R	R&R	R&R	R&R	R&R	R&R	R&R	R&R
High Wind (CO. special wind zone)	R&R	R&R	R&R	R&R	R&R	R&R	R&R	R&R	R&R
Tornado	R&R	R&R	R&R	R&R	R&R	R&R	R&R	R&R	R&R
Bridge Strike	R&R	—	—	—	—	—	—	—	—

(a) Threat-Asset Pairs Included in the CDOT Risk and Resilience Pilot (the symbol R&R denotes that the threat and asset were related according to the workshop participants)

Criteria	Criticality Score					
	1 Very Low Impact	2 Low Impact	3 Moderate Impact	4 High Impact	5 Very High Impact	Weight
AADT	40 - 720	721 - 1,900	1,901 - 4,600	4,601 - 15,000	>15,000	1/6
AASHTO Roadway Classification	Minor Collectors	Major Collectors	Minor Arterial	Principal Arterial	Interstate Freeway Expressway	1/6
Freight ($M)	<=4,422	6,423 - 6,513	6,514 - 6,685	6,686 - 8,806	>8,806	1/6
Tourism ($M)	<152	153 - 479	480 - 1,050	1,051 - 3,414	>3,414	1/6
SoVI	(-9.69) - (-2.93)	(-2.92) - (-1.24)	(-1.23) - 0.67	0.68 - 2.51	2.52 - 6.23	1/6
Redundancy (CDOT 2015v)	4.51 - 50.5	3.01 - 4.5	2.01 - 3	1.51 - 2.0	1.0 - 1.5	1/6

(b) Asset Criticality Model for System Resilience

Figure 10. CDOT Risk and Resilience Pilot Key Steps (CDOT 2017)

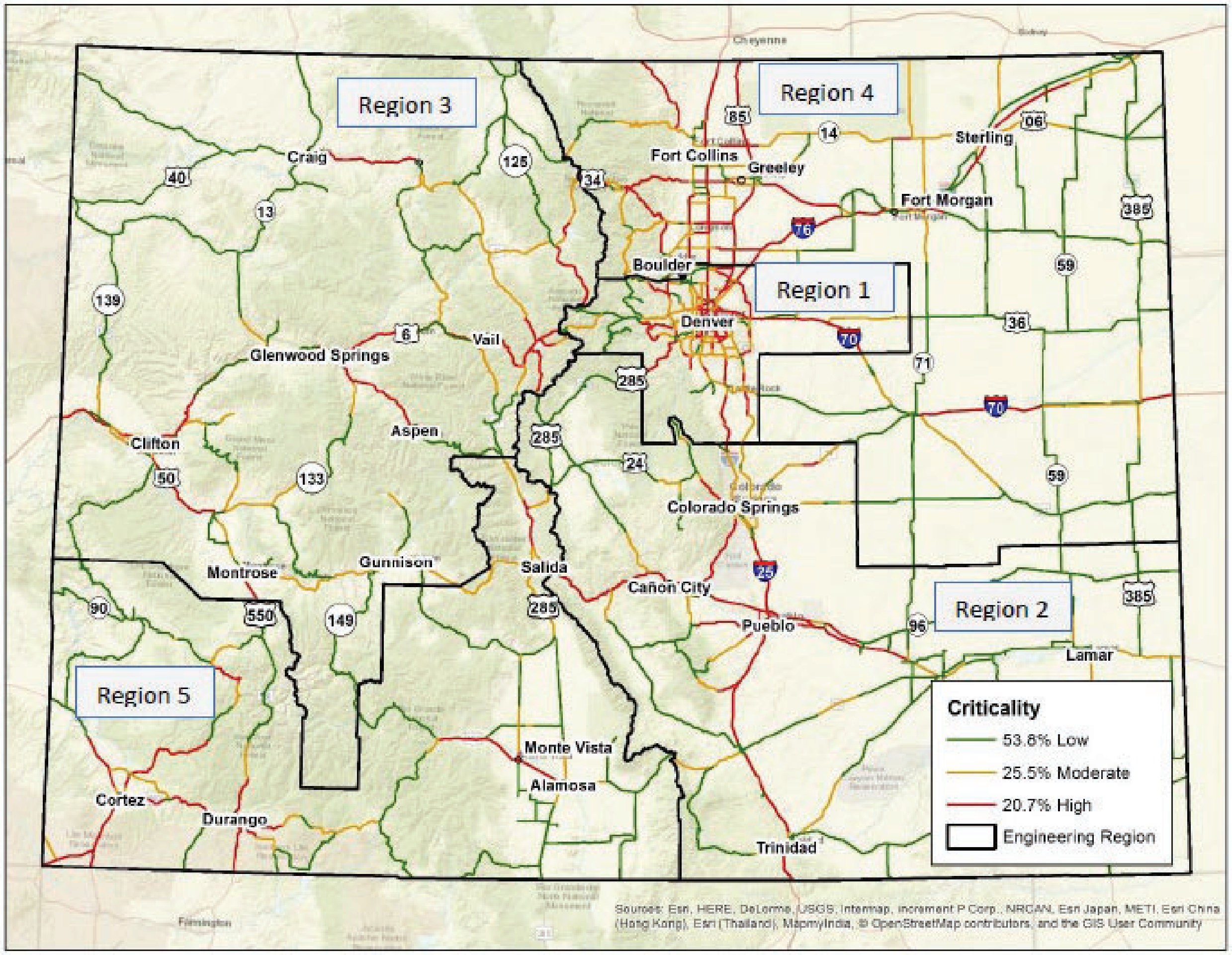


Figure 11. CDOT Asset Criticality Map for System Resilience (CDOT 2017)

In addition to the robust and validated method to estimate criticality, the CDOT study provided an extensive methodology for estimating the consequences of disruption for critical assets. Such a method is needed to calculate benefit-cost ratios to evaluate options for mitigative action for critical assets. A detailed review of the method is provided in Chapter 5. A brief overview is provided here.

First, consequences are estimated in terms of human impacts, user costs, and owner costs that would likely arise if the asset in question were to be non-operational. Human impacts include loss of life and injury from accidents. User costs include vehicle running costs and lost wages, while owner costs include asset damage and loss-associated costs. User costs are estimated based on the length and assumed delays associated with the detour around the damaged asset. In the CDOT study, detours are restricted to CDOT owned and operated facilities as per the recommendation of the stakeholder group. Owner costs are replace-in-kind (RIK) costs and based on bid-item costs in the CDOT database. Second, risk to an asset is calculated by combining the consequence cost with the vulnerability (probability of the estimated consequences occurring) and threat likelihood (probability of the threat occurring). Lastly, reduced risk is calculated by re-estimating risk after applying a mitigative adaptation (increasing culvert size, for example). Then, the benefit-cost ratio is expressed as the difference in pre- and post-mitigative adaptation cost divided by the difference in pre- and post-mitigative action consequence. As an example, one of the pilot study sites in the CDOT study included a flood risk to a set of corrugated metal pipe culverts with 25-year hydraulic capacity on I-70. Mitigation options included upgrading to larger concrete pipe culverts with 50-year hydraulic capacity (low-cost alternative, $1M for the site) and to larger box culverts with 100-year hydraulic capacity (high-cost alternative, $1.6M for the site). The total annualized consequence to owners and users resulting from damage to the asset was approximately $1.3M. The concrete pipe option potentially reduced annual total risk by $1.22M, while the box culvert option represented an $1.28M reduction, leading to B/C ratios of 25.6 and 23.4 respectively.

The methods developed by the CDOT are detailed, repeatable, and provide a balance between quantitative and qualitative assessment. The approach is easy to adopt in other regions and states as it uses data commonly available to state transportation agencies. The work in Colorado is heavily cited in other state resilience assessment reports as well as national studies and pilot projects. For these reasons, the research team highly recommended that the ARDOT resiliency assessment apply the CDOT approach with minor modification. The CDOT methodology was applied to a single corridor, e.g., I-70, while the current study was applied statewide. Thus, while criticality criteria such as AADT and freight value are easy to gather statewide, the redundancy criteria present a computationally intensive metric to gather at a statewide scale. Thus, the research team developed a method to estimate redundancy, which is detailed in Chapter 3.

STATE-OF-THE-ART METHODS

Following the state-of-the-practice review, the research team evaluated methods to estimate network-level features that represent asset criticality. Specifically, the research team sought state-of-the-art methods to calculate network redundancy measures. State-of-the-art methods to measure system resilience (not just redundancy) can be categorized into topological, attribute-based, performance-based, and multi-criteria metrics. The reader is directed to Zhou at el. (2019) for a comprehensive list of references related to the measurement for transportation systems' resilience. The metrics are briefly defined as follows.

Topological

Topological metrics capture network connectivity and disregard the system's dynamic use. A network with higher connectivity is more resilient than one with lower connectivity since the former connectivity possesses more alternate routes. Topological measures of resiliency include network diameter, average shortest paths, average node degree, redundancy, and cyclicity (Schintler et al. 2007; Berche et al. 2009; Testa et al. 2015; Zhang and Miller-Hooks 2015). A commonly used topological metric is the average shortest path (Schintler et al. 2001). The average shortest path captures the connection strength or connectivity of the network. A benefit of topological methods in estimating resiliency is that they do not require data beyond network geography. Nonetheless, they have two key limitations. First, topological measures can be computationally expensive for large networks. Most related examples are small case studies on hypothetical networks. Second, topological measures do not consider dynamic performance (although they offer the advantage of not requiring dynamic data).

Attribute-Based

Attribute-based measures of resiliency consider the performance of structures constituting the transportation system and traffic that use those structures during specific time periods, e.g., either during the disruption phase or the recovery phase but not both (Figure 4). Examples include recovery speed, recovery efficiency, travel time index, and adaptive capacity (Murray-Tuite 2006; Beiler et al. 2013; Yoo and Yeo 2016). Two measures are more commonly used: recovery speed and recovery efficiency. Recovery speed describes the time needed for the transportation system to return to a steady-state condition after a disruption. Recovery efficiency contextualizes recovery speed by considering the amount of resources necessary to reach steady-state conditions over a specific period. The advantage of attribute-based measures over topological measures is that the former considers the infrastructure's dynamic use. Meanwhile, the main disadvantage of attribute-based measures is that they do not consider the relative effect of pre- to post-disaster period performance.

Performance-Based

Performance-based measures of resiliency capture the spatiotemporal changes in the performance of the system during and after a disaster (example in Figure 4). Unlike attribute-based approaches, performance-based approaches consider the whole period affected by the disruptions in a single metric, e.g., from the onset of the disruption to the end of the recovery phase. For instance, travel time can be measured before and after a disaster to then compute a ratio (e.g., travel time reliability ratio) to be used as a metric for measuring system resilience with the goal of obtaining a ratio of one or less (Omer et al 2012; Faturechi and Miller-Hooks 2014). Other examples of performance-based metrics include loss of resiliency (LoR) and slope of the recovery rate diagram (Zhu et al. 2017). In general, performance-based approaches are favored over attribute-based approaches, and both are preferred over topological approaches because topological approaches do not capture dynamic behaviors. A key benefit of performance-based metrics is that they consider the entirety of the disruption period including onset and recovery. Meanwhile, a limitation of their use is the need to capture dynamic conditions during disruptions, which can be a challenge when assessing statewide networks.

Multi-Criteria

Multi-criteria metrics present a composite measure consisting of indicators that capture a wide range of system impact areas. For example, the CDOT used traffic volume, roadway classification, tourism value, freight value, and Social Vulnerability Index within their multi-criteria resiliency metric (CDOT 2017). Serulle et al. (2011) created a multi-criteria metric that considered nine factors including road capacity, road density, alternate route proximity, intermodality (availability of other modes), delay, speed reduction, transportation cost (user cost), commercial transportation cost, and network management. Frekleton et al. (2012) developed a sixteen-criteria metric consisting of several more unique criteria such as food and medicine access index, goods and materials access index, fuel and energy access, emergency response, and disaster response availability. A key benefit of multi-criteria approaches is the diversity of system performance aspects that are captured in a single measure. The main challenge in implementing multi-criteria measures is the scale and scope of data required for computation. Moreover, much of the necessary data are not available from transportation agencies and must be gathered from outside sources.

SUMMARY OF FINDINGS AND RECOMMENDATIONS

Based on the literature reviewed, the research team recommended a multi-criteria approach that includes topological redundancy measures in addition to the multi-dimensional metrics included in the CDOT work. Although topological measures are less preferred than attribute- or performance-based metrics, the data needed for the latter are likely unavailable to the department or would require extensive assumptions of disruptive event characteristics. For instance, for any of the performance-based metrics, data on or assumptions of traffic volumes, roadway capacity, system degradation rate, system recovery rate, and the duration of the disruption are necessary. Moreover, the state-of-the-art attribute- and performance-based methods for resilience measurement do not scale to regional or statewide analysis both from a data availability and computational capacity perspective. Among the many topological measures, redundancy metrics are most common and are scalable (with adaptations) to large and complex networks.

The recommendation to use a multi-criteria approach along with a measure of redundancy is made under the assumption that the department has ready access to the necessary data for a multi-criteria approach.

CHAPTER 3: METRICS FOR STATEWIDE RESILIENCY ASSESSMENT

This chapter presents the methodology developed to estimate and assess the resiliency of the Arkansas highway system. This includes a survey among members of the project Subcommittee to identify threats, assets, and context for the assessment, review of the criticality metrics, summary of data needs and sources, and an overview of the process to rank order criticality metrics based on a second survey among the project research committee members.

SURVEY OF ARDOT PRACTICES

An online survey aimed at gauging the current state of resiliency practice within ARDOT in terms of definitions, performance metrics, and resiliency assessment implementation was developed and distributed among select ARDOT staff in July 2020. Staff from Construction, System Information and Research (SIR), Planning, Engineering, and Environmental were invited to participate in the survey through an e-mail invitation sent on July 29, 2020. Fourteen responses were collected as of August 18, 2020, when the survey was closed. The questions in the survey questionnaire were divided into five broad categories with various multiple-select and open-response formats. The full survey is provided in Appendix A. The five general categories were as follows:

1. General background questions
2. Risk and vulnerability assessments
3. Transportation resilience
4. Long-term investment and funding
5. Wrap-up questions

Response Results

The survey resulted in 14 responses. The respondents could select more than one response, so the total number of responses exceeded the total number of respondents. In the first question of the survey questionnaire, respondents were asked to describe their current role at ARDOT. “Engineer” was the most frequent, and “Manager” and “Supervisor” were also common in the responses. The respondents were asked to select their “division” within ARDOT, and they could select multiple “divisions”. The respondents were divided into six groups: Planning, Engineering, System Information & Research (SIR), Multiple divisions, Construction, and Environment (Table 2).

Table 2. Respondents to the ARDOT State-of-the-Practice Survey

Respondent Division	Number of Responses
Planning	5
Engineering	4
Systems Information and Research (SIR)	2
Construction	1
Environmental	1
Multiple Divisions	1
TOTAL	***14***

Definitions of Transportation Resilience

The respondents were asked to define resilience in a sentence or two as it pertains to their role within ARDOT. Overall, 12 responses were recorded. The most frequent words used to define resiliency were "ability", "basic operations", and "disruptive events". The respondents were also asked to select keywords (from provided options) to define transportation resilience. The options "Withstand Disruptions", "Recover rapidly", and "Maintain level of service" were most commonly chosen. Defining resilience using the provided options, respondents from the Planning staff selected "Withstand Disruptions" and "Recover rapidly", while those from the Engineering staff chose "Maintain level of service". Furthermore, the respondents were asked to select all the performance measures that their staff used to assess system resilience. In this case, "volume", "capacity", and "volume/capacity (v/c)" were the most frequently reported by the ARDOT staff.

The respondents were asked about the incorporation of resilience practices into their existing programs, practices, or policies. Only five respondents (out of 14) replied "Yes". All four respondents from the Engineering staff replied "no". Three respondents did not respond. Respondents from the Planning, SIR, and Maintenance staff all reported incorporating resilience practices into existing programs, practices, and policies to some extent. Respondents from the Engineering staff reported that resilience practices have not yet been incorporated into their existing programs, practices, and policies.

The respondents were asked to select the models or software (from the listed options) that their staff uses to incorporate or evaluate system resilience. Although most responses indicated "None of the above", two respondents from the SIR staff reported using "Deighton Total Infrastructure Management System (dTIMS)". The "Transportation Asset Management Plan (TAMP)", "Statewide Long-Range Intermodal Transportation Plan", and "Design-Build Guidelines and Procedures" were noted as documents and programs that consider resilience.

Awareness of Risk and Vulnerability Assessments in Practice

The definitions of resilience, risk assessment, and vulnerability assessment were provided to the respondents before proceeding with the questions so that they understood the basic concepts of resilience, risk, and vulnerability assessments. The respondents were asked to select the levels at which they were aware of resilience, vulnerability, and risk assessments performed within their staff. They were also asked to select the hazards and assets (from the listed options) considered in resilience, vulnerability, and risk assessments. The respondents noted that assessments of resilience, risk, and vulnerability were conducted at site-specific or asset level and system-wide levels (e.g., statewide or region-wide etc.). Flooding, earthquakes, and ice storms were identified as the main hazards to be considered when performing resilience, vulnerability, and risk assessments (Figure 12). Bridge, culvert, and roadway prism (pavement and embankment) were the most common responses for asset types in both risk and vulnerability assessments (Figure 13).

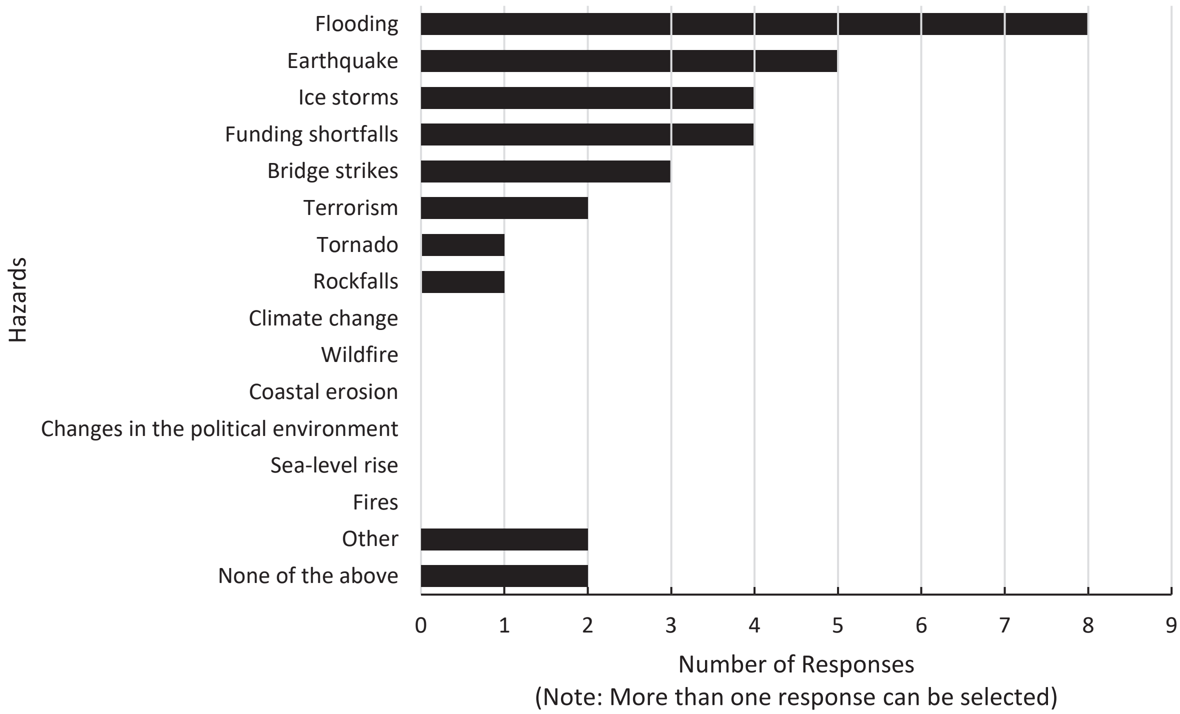


Figure 12. Hazards Considered in Resilience, Vulnerability, and Risk Assessments

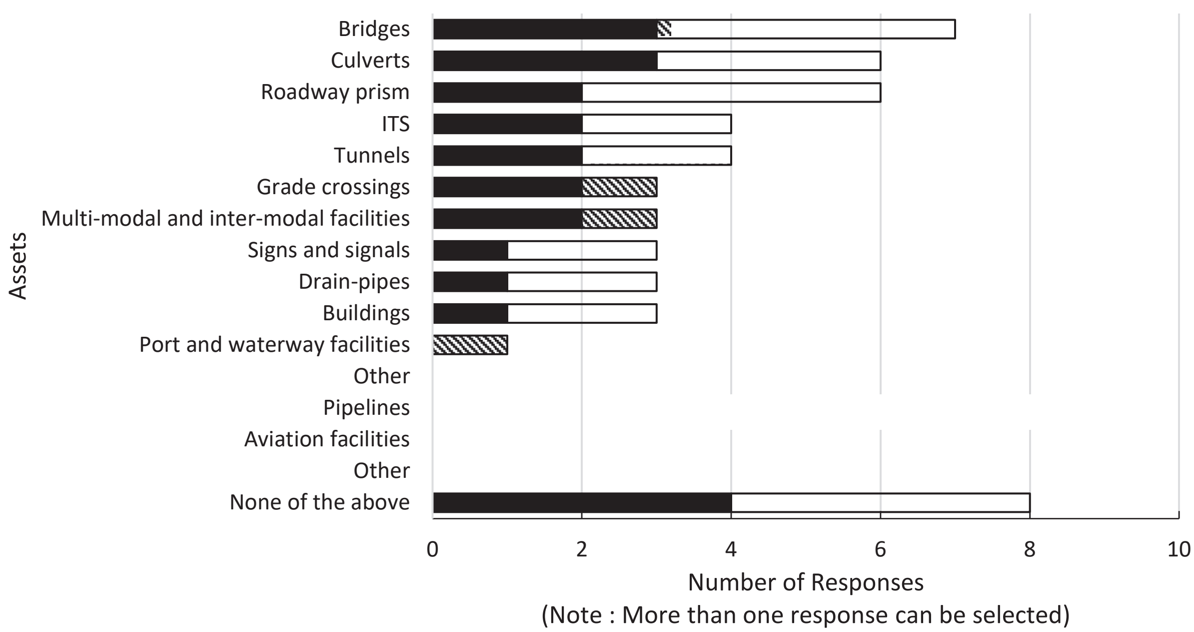


Figure 13. Assets Considered in Vulnerability and Risk Assessments

Long-term Investment and Funding

The respondents were asked about funding allocated to improve transportation resilience. They were also asked about their ability to share general data with the research team to complete a resiliency assessment of the Arkansas highway network. Responses show that some funds have been allocated to the planning and operation areas and have improved transportation resilience. Respondents from Planning noted that geospatial location, user cost, and asset inventory data were available within their staff. Respondents from SIR noted that asset conditions, capital cost, deterioration curves, and asset performance metrics data were available within their staff, and those from Construction noted that original construction cost and possible material information were available within their staff.

Benefits of Resiliency Assessment

The respondents were asked to select all the elements of a resiliency assessment that they find helpful to support other ongoing programs, policies, and practices. Finally, they were asked to indicate the overall strength of their current resiliency planning. The respondents suggested that “Identification of critical highway assets”, “Measurement of user impacts from hazardous events”, “Identification of alternative routes for emergency routing”, “Cost estimated for improving the resilience of the transportation system”, and “Estimation of system performance metrics in response to different hazards” are elements of resiliency assessment that would be helpful to support other ongoing programs, policies and practices. Respondents from Engineering reported that considerations of hydraulic design, traffic flow optimization, and safety during the construction phase would strengthen their current resiliency planning. Respondents from SIR noted that incorporating flexibility into resource allocation and providing means to adjust scheduled projects would benefit their current resiliency planning, while those from the Environmental staff noted that considerations for wetland and stream mitigation and the native roadside plant program would support resiliency planning efforts.

Summary of Findings

In defining transportation resilience, respondents reporting as “Planners” suggested defining resilience as the ability to “withstand disruptions and recover rapidly”. Respondents reporting as “Engineers” suggested defining resilience as the ability to “maintain level of service”. The respondents conveyed the use of measures such as volume, capacity, volume/capacity (v/c), travel time, and speed to assess system resilience. They reported that the Planning, SIR, and Maintenance staff have incorporated resilience practices into their existing programs, practices, and policies to some extent. For example, the SIR staff reported the use of the “Deighton Total Infrastructure Management System (dTIMS)” to evaluate system resilience. However, respondents from the Engineering staff reported that they have not yet incorporated resiliency practices into their plans or programs. Among all threats and hazards, the respondents indicated that flooding, earthquake, and ice storms are the main hazards to be considered when performing resilience, vulnerability, and risk assessments. To assess risk and vulnerability, the respondents recommended considering bridge, culvert, and roadway prism (pavement and embankment) assets. Furthermore, they reported that some funds have been allocated to support transportation resilience in terms of planning and operations.

CRITICALITY ANALYSIS

The approach adopted in this project is to calculate a numeric criticality value ("metric") for each transportation network link operated by ARDOT. This is a comprehensive approach unlike what has been explored in prior studies where the focus is on a single corridor rather than a state-wide network. Further, this project's approach is comprehensive because it combines measures of link performance like travel time with multi-criteria measures that capture the importance of the link in the context of daily traffic volume, tourism, freight, social vulnerability, and network structure.

Criticality Metrics

Based on a review of the literature, the research team adopted the criticality assessment metrics outlined in the CDOT I-70 resiliency study (Table 3). The annual average daily traffic (AADT), roadway classification, freight, tourism, and Social Vulnerability Index (SoVI) criteria definitions were adapted from the CDOT study. The redundancy metric in the CDOT study was unsuitable for a state-wide analysis; rather, it was appropriate for a corridor-level study. Thus, we developed a new redundancy metric based on methods found in the literature. Brief explanations for the criteria are as follows.

Annual Average Daily Traffic (AADT). AADT data were gathered from the "alternate assignment" procedure that is part of the TransCAD travel demand model and corresponds to the base year 2010. According to the Arkansas Travel Demand Model (ARTDM) documentation, the alternate assignment is estimated as follows: "Instead of running a full assignment (by purpose, income group, and mode), the trip tables are collapsed into broader categories in the alternative assignment: passenger vehicle, commercial trucks, and heavy trucks. …The alternate assignment reduces the assignment run time and hard drive space, which allows users to assess model results more conveniently if no further details, such as a full assignment, are necessary for the analysis" (ARDOT 2005). For divided highways, the AADT is reported as a directional volume. For undivided highways, the AADT is reported as the sum of both directions. The AADT reported in this study is directly from the ARTDM base year model, and may be either one-way or two-way volumes, according to respective link attributes. It should also be noted that highway mileages used in this study may differ from those reported in the ARDOT *Road and Street Data* reports. This is due to the differing characterization of roadway types, as well as the reference year (ARTDM was last updated in 2009) between the ARTDM and the Road and Street Data report.

Roadway Classification. Roadway classification data were gathered from the transportation network used in the TransCAD model with the same base year as the 2010 AADT data. AADT and roadway classification are defined for each link, i.e., the resolution is link level as indicated in Table 3.

Freight Value. Freight value is expressed as the total value of imports and exports by county estimated by the national freight travel demand model called the Freight Analysis Framework Version 4 (FAF4). FAF4 gathers freight value data from the Commodity Flow Survey. Freight value data used for this project's criticality analysis are from 2017. Freight value is defined for each county. Higher resolution level, e.g., census tracts, links, etc., is not available from any public source.

Table 3. Criticality Criteria Summary

Criteria	Definition	Data Source	Resolution
Annual Average Daily Traffic (AADT)	Daily traffic volume for each roadway link.	Travel Demand Model (TransCAD) for the base year 2010	Link
Roadway Classification	Functional class of roadway link: Interstate, Freeways & Expressways, Principal Arterials, Minor Arterials, and Major Collectors	Travel Demand Model (TransCAD) network	Link
Freight	Freight value in Millions of US dollars by county for the year 2017	US Department of Transportation, Bureau of Transportation Statistics and Federal Highway Administration, Freight Analysis Framework, Version 4.5, 2019	County
Tourism	Tourism value expressed as total county expenditures in millions of US dollars by county	2019 Arkansas Tourism Economic Impact Report, Arkansas Department of Parks, Heritage, and Tourism (AR Tourism, 2022)	County
Social Vulnerability Index (SoVI)	SoVI measures the social vulnerability of US counties to environmental hazards. It is an indicator comprised of 29 socioeconomic variables that contribute to a county's ability to prepare for, respond to, and recover from hazards.	University of South Carolina Hazards & Vulnerability Research Institute, 2010–2014	County
Redundancy	The amount of additional travel time added to the network when a link is non-operational	Derived for this project using the statewide Travel Demand Model network and open-source computing tools	Link

Tourism. Tourism data were gathered from the *Arkansas Tourism Economic Impact Report* for the year 2019 and represent the total expenditures for tourism in the county for that year. For this project, tourism value is defined at the county level. Although tourism value may be available at a finer geography, e.g., sub-county level, it was not publicly available at the time of this project. Future work should consider estimating tourism expenditures at a sub-county level.

Social Vulnerability Index (SoVI). Social vulnerability data were gathered from the University of South Carolina's Hazards and Vulnerability Research Institute, which produces the Social Vulnerability

Index or SoVI. SoVI is a computed, comparative index comprised of 29 socio-demographic variables among eight categories and represents a region's level of social vulnerability (Cutter et al. 2003). The eight categories grouped in the model include wealth, race (black) and social status, age, ethnicity and lack of health insurance, special needs populations, service sector employment, race (Native American), and gender (female).

SoVI scores greater than 1.5 standard deviations above the mean (positive) are considered the most socially vulnerable, while counties with scores below 1.5 standard deviations of the mean (negative) are the least vulnerable. SoVI values should only be used for relative comparisons across a state or to compare counties within a state to others in the US. For this project, SoVI is defined at the county level relative to the state average. Finer resolution was not available publicly at the time of this project. Future work may obtain SoVI at the sub-county level, e.g., census tract, available from the Center for Disease Control (Agency for Toxic Substances and Disease Registry 2022).

Redundancy. The redundancy metric chosen for this project leverages the network model contained within the Arkansas Travel Demand Model (ARTDM) implemented in TransCAD. The redundancy metric captures the increase in overall system-wide travel time as a result of a complete link closure. To compute redundancy, we simulate the closing of a link, run a network assignment, and then compute the total system travel time under the closed link scenario. This is repeated for each link in the network. When comparing the closure scenario of each link to a baseline in which all links were operational, we can determine the effect of a link closure on the network. Links that increase system-wide travel time when closed are more critical than those that cause only a minimal change in system-wide travel time when closed. We consider this a measure of redundancy since a link with many alternate routes of similar distance and travel time would have minimal impact on the overall system travel time. On the other hand, a link with few to no alternate routes or alternate routes that are much longer would have a higher impact on the overall system travel time. The network modeling efforts developed in this project to calculate redundancy are provided in Chapter 4. Redundancy is defined at the link level.

Criticality Metric Scoring

This section describes the method to produce a scaled "score" for each criticality metric for combining the metrics using a weighted average approach with equal and unequal weighting. Each criticality metric is divided into levels based on the divisions outlined in the CDOT procedure and modified when necessary to accommodate the range of values for that criterion in Arkansas. Table 4 provides the proposed ranges for each level of the criteria. The levels of each criterion are specifically defined for Arkansas. Ranges for the criterion corresponding to each score are based on natural breaks and distributions of the data. Using the same criterion ranges as the CDOT study is not advisable as Colorado's geography and population characteristics and magnitudes differ greatly from those in Arkansas. Each criterion is assigned a numerical level. The numerical levels can then be combined or averaged to estimate the overall criticality of a link.

Table 4. Criteria Levels for Criticality Metrics

Criteria	Criticality Score					Weight
	1 Very Low Impact	**2** Low Impact	**3** Moderate Impact	**4** High Impact	**5** Very High Impact	
AADT (vehicles per day)	<=720	721–1900	1901–4600	4601–15000	>15000	1/6
Roadway Classification	Major Collector	Minor Arterial	Principal Arterial	Freeway Expressway	Interstate	1/6
Freight ($M)	<=800	801–2085	2086–3898	3899–12250	>12250	1/6
Tourism ($M)	<=85	86–270	271–567	568–928	>928	1/6
SoVI	-4.49–-2.92	-2.93–-1.23	-1.24–0.67	0.68–2.51	2.52–5.40	1/6
Redundancy (vehicle-hours)	<=200	201–788	789–1870	1871–7500	>7500	1/6

Criticality Metric Ranking

The six criteria for the criticality metric can be combined in two ways: (1) equally weighted and (2) unequally weighted.

Equal Weighting. The CDOT study used an equal weighting approach such that each criterion is weighted 1/6 with respect to the total. The equal-weighted approach assumes that each criterion is of equal consideration in assessing the criticality of a link. For example, consider the following levels of the criteria that are estimated for a single link:

1. AADT is 500 vehicles per day and assigned Level 1.
2. Roadway class is a minor arterial and assigned Level 2.
3. Freight value is $1000M and assigned Level 2.
4. Tourism value is $2M and assigned Level 1.
5. SoVI is estimated to be 1.55 and assigned Level 4.
6. Redundancy is estimated to be 1600 vehicle-hours and assigned Level 3.

The equally weighted average is calculated as follows:

$$\boldsymbol{Criticality_i} = \sum_{n=1}^{N}(\boldsymbol{w_i}) \times \boldsymbol{c_{i,n}} \qquad \textbf{Equation 1}$$

Where

$Criticality_i$ is the combined criticality score for each link i

$w_{i,n}$ is the weight assigned to each criterion, n, e.g., 1/6 is the equal weight of six criteria

$c_{i,n}$ is the score of the criterion, n, for each link i

N is the number of criteria, e.g., $N = 6$

$$Criticality = \left(\frac{1}{6}\right) \times 1 + \left(\frac{1}{6}\right) \times 2 + \left(\frac{1}{6}\right) \times 2 + \left(\frac{1}{6}\right) \times 1 + \left(\frac{1}{6}\right) \times 4 + \left(\frac{1}{6}\right) \times 3 = 2.17$$

If the estimated criticality of the link is 2.17, then it would be less critical than a link that has a criticality rating of 3.00, for example.

Ranked Weighting (Analytical Hierarchy Process). An unequal weighting scheme would more appropriately reflect the importance of each criterion to ARDOT's priorities. For example, mobility is a top priority for ARDOT, and criteria related to traffic volume (AADT) would be weighted more than those related to tourism when combining criteria to estimate a single score for a segment.

To this purpose, a survey questionnaire was developed and distributed among select ARDOT staff in February 2022 to execute an analytical hierarchy process (AHP) for determining criteria weights. AHP is a multi-criteria decision-making approach in which factors are arranged in a hierarchical (ranked) structure (see Figure 14 and survey questionnaire in Appendix C). It is an unequal weighting approach to compute the criticality of a link by applying differing weights to each criterion such that the weights reflect the priorities of the decision-makers. Through pairwise comparisons, the AHP generates a reciprocal decision matrix by allowing the evaluator to focus on the comparison of only two criteria at a time. As compared with weighting by ranking (ranking criteria directly by relative importance), which loses explanatory power as the number of criteria increases, the AHP method provides a consistent and effective approach for prioritizing and ranking criteria. The steps of the AHP used for this task were as follows:

1. Collect the input data by pairwise comparisons of the criteria through the questionnaire survey
2. Calculate consistency ratios from the individuals' set of judgments and aggregate individual judgments (AIJ) for each set of pairwise comparisons into an "aggregate hierarchy" using the geometric mean method
3. Compute the overall criteria weights

For the first step of the AHP, a questionnaire was developed and distributed among ARDOT representatives from Program Management, System Information and Research (SIR), Maintenance, and Transportation Planning and Policy. The questions in the survey questionnaire asked participants to compare the relative importance of the six criteria and provide their judgments through pairwise comparisons. The initial survey was sent via e-mail on February 15, 2022. Five responses were collected as of March 10, 2022, when the survey was closed. Next, the consistencies of each individual set of judgments were determined to ensure that the consistency ratios were within the acceptable and tolerable ranges to be included in the synthesis. The resulting reciprocal matrix from the individual pairwise comparisons obtained from the questionnaire survey were then synthesized using the geometric mean to form a single matrix. This approach is known as aggregating individual judgments (AIJ). Finally, the overall criteria weights were computed from the single matrix generated through the aggregation using the AHPy library in Python.

From the five responses to the survey, we were able to calculate the weights for each criterion, and the final weights are shown in the last column of Table 5. The table is organized by weight ranking.

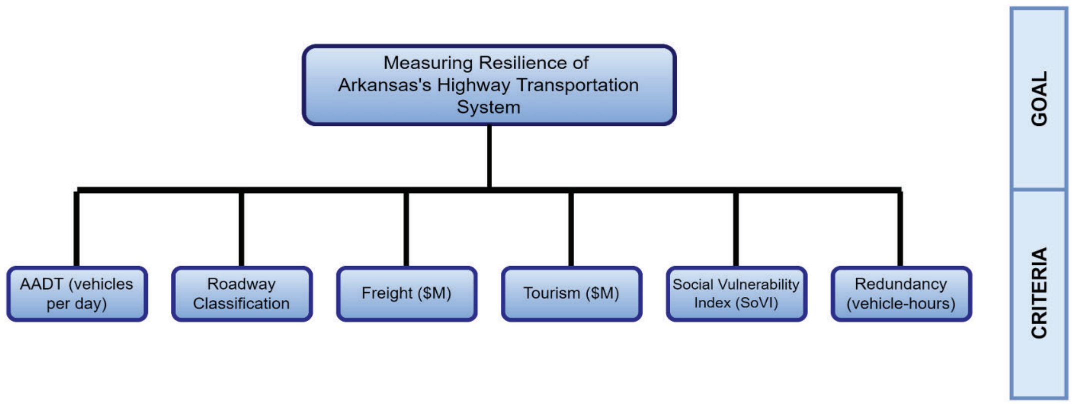


Figure 14. Analytical Hierarchy Process Schematic for Criteria Weighting

Table 5. Criterial Levels and Weights Derived from the Analytical Hierarchy Process (AHP) Method

Criteria	Criticality Score					Weight
	1 Very Low Impact	**2 Low Impact**	**3 Moderate Impact**	**4 High Impact**	**5 Very High Impact**	
Redundancy	<=200	201–788	789–1870	1871–7500	>7500	**0.333**
Freight	<=800	801–2085	2086–3898	3899–12250	>12250	**0.235**
Annual Average Daily Traffic (AADT)	<=720	721–1900	1901–4600	4601–15000	>15000	**0.177**
Roadway Classification	Major Collector	Minor Arterial	Principal Arterial	Freeway Expressway	Interstate	**0.146**
Social Vulnerability Index (SoVI)	-4.49– -2.92	-2.93– -1.23	-1.24–0.67	0.68–2.51	2.52-5.40	**0.060**
Tourism	<=85	86–270	271–567	568–928	>928	**0.049**

Redundancy received the largest weight (highest rank). Redundancy is a measure of how well the transportation network performs in terms of travel time when a link is non-operational. Freight obtained the second-largest weight (second-highest rank). The freight criterion represents the dollar amount of freight originating and destined for the county in which the transportation network link is located. AADT and roadway classification were ranked third and fourth respectively. They both are correlated in that typically a more heavily trafficked roadway is a highway or interstate roadway. This can explain the closeness in their weights. SoVI and tourism were ranked fifth and sixth (last) respectively and have weights approximately five times lower than the highest ranked criterion, redundancy. This reflects the relative indifference of these measures among the six criteria.

Another method to aggregate the individual responses is synthesizing the individual hierarchies and aggregating the resulting priorities using either the geometric or arithmetic mean. This is known as aggregating individual priorities (AIP). In this approach, the individual results and ranking of the criteria as well as the consistency ratios are computed. The AIP approach allows us to see how individuals ranked each of the criteria, thus helping to illuminate different rankings and priorities by various staff within ARDOT. For the criticality weights in this project, the AIP approach produces the same ranking results as the AIJ approach and only slightly different weights (e.g., 0.330 vs 0.333) for the weight assigned to redundancy.

A total of five responses were received from various ARDOT staff. Using the tolerable range of less than 0.2, four individual judgments passed the consistency ratio test and were included in the overall computation. Freight was ranked first by the respondents from Transportation Planning and Policy (TPP) and was placed second, third, and fourth by the remaining respondents. The respondent from System Information and Research (SIR) ranked annual average daily traffic (AADT) first, while it was ranked second, third, and fourth by respondents from Program Management (PM), TPP, and Maintenance, respectively. The ranking of roadway classification varied widely, ranking second, third, fourth and sixth across the four individual judgments. The highest ranking assigned to Social Vulnerability Index (SoVI) was third and was assigned this rank by only one respondent from SIR. Tourism, which was ranked sixth (last) in the overall ranking was ranked fifth and sixth twice by the respondents.

From the individual responses (Table 6), it is evident that assigning a high priority for a criterion by a single respondent has a significant effect on the final and overall priority after aggregation. This can be attributed to variations in priorities across ARDOT staff and differing interpretations of the criteria in the various responses as well as the consistency ratios. For example, looking at the redundancy criterion, even though the other two judgments had scores of 0.179 and 0.137, the priority scores of 0.528 and 0.451 from Maintenance and PM had a greater impact on the overall score of 0.330.

Take the following as an example of how the weights are applied to estimate the total criticality of each link in the transportation network. Each criterion is weighted based on the weights obtained from the AHP method using the geometric mean (Table 5). For example, consider the following levels of the criteria that are estimated for a single link (following the same example values from the prior section):

1. AADT is 500 vehicles per day and assigned Level 1.
2. Roadway class is a minor arterial and assigned Level 2.
3. Freight value is $1000M and assigned Level 2.
4. Tourism value is $2M and assigned Level 1.
5. SoVI is estimated to be 1.55 and assigned Level 4.
6. Redundancy is estimated to be 1600 vehicle-hours and assigned Level 3.

The equally weighted average is calculated as follows:

$$\boldsymbol{Criticality_i = \sum_{n=1}^{N}(w_i) \times c_{i,n}} \qquad \textbf{Equation 2}$$

Where

$Criticality_i$ is the combined criticality score for each link i
$w_{i,n}$ is the weight assigned to each criterion, n, e.g., AHP deduced weighted
$c_{i,n}$ is the score of the criterion, n, for each link i
N is the number of criteria, e.g., $N = 6$.

$Criticality = 0.177 \times 1 + 0.146 \times 2 + 0.235 \times 2 + 0.049 \times 1 + 0.060 \times 4 + 0.333 \times 3 = 2.23$

If the estimated criticality of the link is 2.23, then it would be less critical than a link that has a criticality rating of 3.00, for example. As reference, for the same example values of the criteria, using the equally weighted approach, the criticality of the link was estimated to be 2.17.

Table 6. Aggregation of Individual Priorities (AIP) Using Geometric Mean

Criteria (Rows)/ Respondent (Columns)	SIR	Maintenance	TPP	PM	*Mean*	*Normalized Weight*	*Ranking*
Redundancy	0.179	0.528	0.137	0.451	*0.28*	***0.330***	***1st***
Freight	0.220	0.124	0.556	0.115	*0.204*	***0.243***	***2nd***
Annual Average Daily Traffic (AADT)	0.238	0.071	0.127	0.196	*0.143*	***0.171***	***3rd***
Roadway Classification	0.054	0.216	0.118	0.173	*0.124*	***0.148***	***4th***
Social Vulnerability Index (SoVI)	0.179	0.03	0.032	0.043	*0.052*	***0.062***	***5th***
Tourism	0.129	0.03	0.031	0.022	*0.041*	***0.048***	***6th***
Consistency Ratio	*0.033*	*0.094*	*0.153*	*0.2*			

VULNERABILTY ANALYSIS

Although an asset may be critical according to the criticality index, it may not be particularly vulnerable to identified threats. In this report, we consider flooding, earthquakes, and landslides as threats in accordance with the feedback from the project Subcommittee via the state-of-the-practice survey (see Section 3.1). Vulnerable links are considered as those most likely to be exposed to the defined threats.

Vulnerability Metrics

All measures of threat likelihood were derived at the link-level for floods, landslides, and earthquakes (Table 7). Data sources include the Department's GIS office, the US and AR Geological Surveys, and the FEMA Hazus Model.

Table 7. Natural Hazard Threats Summary

Threat	Data Source	Data Description
Flood	ARDOT GIS Office	Historical (2011–2019) geospatial road closure due to flooding. Range from 48 to 214 unique occurrences by year (see table in appendix for more detail). Probability of flooding estimated from frequency of occurrence.
Landslide	ARDOT GIS Office, US Geological Survey (USGS), and Arkansas Geological Survey (AGS)	Historical (dates unknown, latest is 2016) geospatial landslide occurrence data. Includes 765 landslides. Landslides are represented in the geospatial file as point locations, and the point locations were matched to the transportation network using a spatial buffer to associate their possible damage to a transportation network link. Of all landslides, 25 were within 1 mile of a network link, 23 within 0.5 mile, and 19 within 0.25 mile. Probability of landslide estimated based on frequency of occurrence.
Earthquake	Federal Emergency Management Agency (FEMA) Hazus Model; AR GIS Digital Elevation Map (DEM), and AR Geologic Map Data (USGS 2022)	Predicted earthquake impacts from the New Madrid seismic zone (NE AR/SW MO). Predictions include the physical damage to bridge and road infrastructure including predicted economic losses. Probability of damage estimated for various damage categories, e.g., "complete" to "no damage".

Flooding. Historical data on road closures due to flooding events were used to determine the likelihood that a link experiences frequent flooding. The data indicating road closures due to floods were obtained from the ARDOT GIS and Mapping Office. We estimated the probability of a flood event by counting the number of times a link was closed between 2011 and 2019. Approximately 4,161 roadways were closed due to flooding over the eight-year data period with the number of flood events per road ranging from one to twenty-six events. In total, 10,691 road closures occurred due to flooding, and 200 roadways were closed due to flooding at least 11 times over the eight-year period.

Landslide. Historical data on landslide occurrences were used to determine the likelihood that a link experiences landslide events. These were obtained from the Arkansas Geological Survey. The time period of the data is unknown, but the list of landslide events provided to the research team dates back to at least 2017, although some of the records may be from before 2017. The landslides were mapped to the closest roadway link within 0.25, 0.50, and 1.0 mile of a link. In total, 7,795 roadway segments were affected by at least one landslide within a one-mile area around the roadway. The number of landslides affecting roadway segments ranged from one to twenty-five events over the time period of the data. Overall, 109 links experienced at least 11 landslide events within a one-mile distance from the roadway that may have impacted the link.

Earthquake. Earthquake damage estimates were modeled using Hazus. Hazus is a nationally standardized model for earthquake risk assessment developed and maintained by the Federal Emergency Management Agency (FEMA). It predicts physical damage, economic loss, and social impacts of earthquakes. The Hazus model contains infrastructure inventory including bridges, buildings, and roadways. The model requires the following inputs: (1) ground failure maps including landslide, liquefaction, and soil data and (2) user-provided asset, transportation, and building data to enhance the Hazus model's output accuracy.

The landslide ground failure map was created using digital elevation models (DEM) provided by the Arkansas GIS Office. The DEM contained the National Elevation Dataset (NED) data in the form of one-meter tiles that provided the bare earth elevation data for the entire state of Arkansas. ArcMap's spatial analysis tool, Slope, was used to determine the slope of each tile of the DEM. Those slopes were used to assign landslide susceptibility for areas of the state based on rock and soil types as well as water table depth. Water table depth data were not available, so we assumed the worst-case scenario of "wet" conditions (groundwater at surface level). The liquefaction ground failure map was created using a digitized version of an existing liquefaction susceptibility map from the Arkansas Geological Survey (AGS 2022). Soils data maps were obtained from USGS ShakeMap. ShakeMap is a product of the USGS Earthquake Hazards Program and contains near-real-time ground motion and shaking maps. Regional soils data are built into the ShakeMap development process and thus did not have to be sourced outside of Hazus.

The Hazus asset map includes 13,000 bridges, culverts, and tunnels, and the transportation network includes 72,000 links. For this study, we consider only the assets located along the transportation network. We mapped all assets to their respective transportation link, and damages were reported by asset and roadway link.

The main outputs of the Hazus model include (1) damage maps, (2) damage probability estimates, and (3) economic loss predictions. If there were a 7.7 magnitude earthquake along the New Madrid seismic zone (the default simulation in Hazus), we can anticipate that the most damaged assets would be concentrated in Northeast Arkansas in Mississippi County, with more minor damage extending as far east as Pulaski County and as south as Lincoln and Desha Counties. Damage is represented as the probability of extensive damage. Damage predictions can be tied to economic losses by assuming the replacement value for each asset. For roadway links, the replacement cost is based on the functional class of the roadway.

Vulnerability Metric Scoring and Ranking

Three approaches were considered to estimate the overall vulnerability of a link analyzing (*Approach 1*) the set of all links that experience flooding, landslides, and earthquakes, (*Approach 2*) the top 25 links that experience either flooding, landslides, or earthquakes, and (*Approach 3*) a weighted combination of threats each categorized by frequency of occurrence.

For *Approach 1*, flooding, landslide, and earthquake occurrence probabilities were combined with equal weighting to determine the overall vulnerability of a transportation network link. The set of earthquake-impacted links only considers the links with the possibility of complete damage. The combined vulnerability map following *Approach 1* results in a set of 50 links (17.4 miles).

For *Approach 2*, flooding, landslide, and earthquake occurrence probabilities were combined by considering the 25 most affected (highest likelihood of threat occurrence) for each threat separately. By definition, this includes 75 links covering 45.7 miles.

For *Approach 3*, flooding, landslide, and earthquake occurrence probabilities were categorized according to natural breaks in the quantitative data for each threat separately and then combined as an average assuming equal weighting for each category. This is the same approach followed in link criticality assessment.

Table 8 shows the range of values for each category for each threat and their assigned category level. First, for each link, the individual score is determined for each threat. Then, the individual scores are combined using a weighted average calculation with the weights shown in the last column of Table 8. The combined vulnerability scores are stratified representing low, moderate, and high vulnerability based on natural breaks found in the data.

Of the three approaches, the research team recommends *Approach 3* as it comprehensively captures the spatial distribution of threats while uniquely considering the levels of likelihood relative to each threat. The equally weighted average is calculated as follows:

$$\boldsymbol{Vulnerability_i = \sum_{n=1}^{N}(w_i) \times v_{i,n}} \quad \textbf{Equation 3}$$

Where,

$Vulnerability_i$ is the combined vulnerability score for each link i

$w_{i,n}$ is the weight assigned to each threat score, n, e.g., 1/3 is the equal weight of three threats
$v_{i,n}$ is the score of the threat, n, for each link i
N is the number of criteria, e.g., $N = 3$

As an example, consider the following threat likelihoods that are estimated for a single link:

1. Flood events occurred near the link three times over the period of historical data and the threat likelihood is assigned level 1 and score of 1.
2. No landslide events occurred on the link over the period of historical data and the threat likelihood is assigned a score of zero.
3. Earthquake probability of extensive damage for the link is 10 percent and is assigned level 2 and a score of 2.

$$Vulnerability_{\ i} = \left(\frac{1}{3}\right) \times 1 + \left(\frac{1}{3}\right) \times 0 + \left(\frac{1}{3}\right) \times 2 \ = \ 1.00$$

If the estimated vulnerability of the link is 1.00, then it would be less vulnerable than a link that has a vulnerability rating of 2.00, for example.

Table 8. Combined Vulnerability Score for Landslide, Flood, and Earthquake Events

	Vulnerability Score			
Criteria	1 Low Vulnerability	2 Moderate Vulnerability	3 High Vulnerability	Weight
Flood Events (number of road closures)	1-3	4-10	11-26	1/3
Landslide Events (number of landslides)	1-3	4-10	11-25	1/3
Earthquake (probability of extensive damage)	1%-9.66%	9.83%-25.71%	25.87%-33.81%	1/3

COMBINED CRITICALITY AND VULNERABILITY

The combined criticality and vulnerability score is calculated as follows:

$$Critical_i = Criticality_i + Vulnerability_i, \quad \textbf{Equation 3}$$

Where,

$Critical_i$ is the combined score for each link i,
$Criticality_i$ is the combined criticality score for each link i, and
$Vulnerability_i$ is the combined vulnerability score for each link i.

As an example, consider the following criticality and threat likelihoods that are estimated for a single link following the prior examples:

1. Criticality score of 2.17
2. Vulnerability score of 1.00

$$Critical_i = 2.17 + 1.00 \quad = 3.17$$

If the estimated critical score of the link is 3.17, then it would be more critical than a link that has a critical score rating of 2.00, for example.

CHAPTER 4: RESILIENCY ASSESSMENT APPLICATION AND RESULTS

This chapter shows the results, as maps and descriptions, from estimating the criticality and vulnerability metrics for the Arkansas State–maintained roadway network. Section 4.1 discusses necessary updates to the modeled network. Sections 4.2 and 4.3 present the results from the critically and vulnerability analyses respectively. Section 4.4 provides the critical location maps developed by combining the criticality and vulnerability scores and concludes with the list of five most critical sites in Arkansas.

NETWORK MODELING

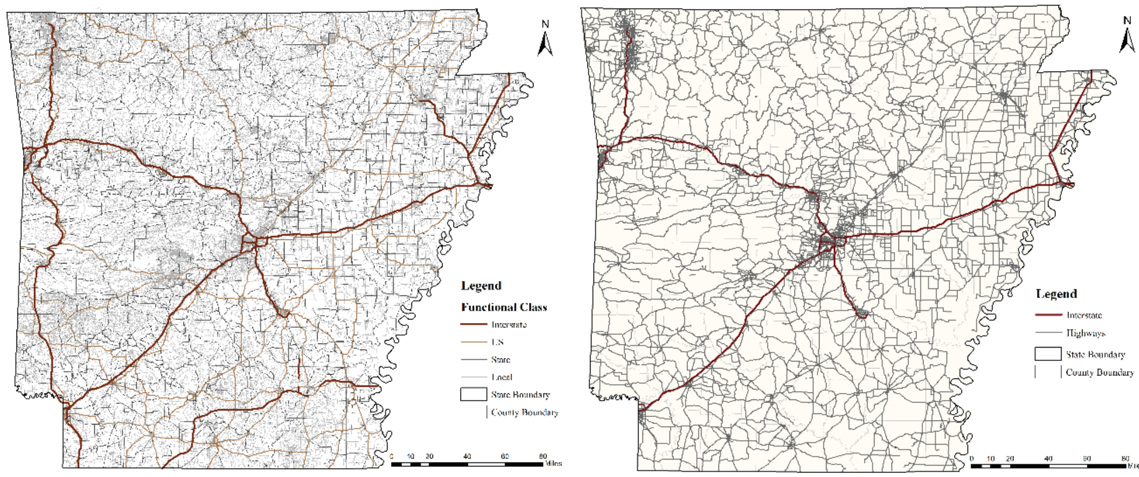
Based on the recommendations of the project Subcommittee, the All Roads Network Of Linear referenced Data (ARNOLD) network files were used in this project. ARNOLD is the name given to the Linear Reference System (LRS) data submitted to the FHWA as a requirement for inventory of all public roads. In short, the ARNOLD network contains all public road geometry and is available as a file compatible with Geographical Information System (GIS) software, e.g., a .SHP file and geodatabase. At the time of this project, the ARNOLD network was available but was not complete. It was incomplete in that it contained duplicate and missing geometry and was not designed to be a routable network. A routable network is one in which given an origin and destination, an algorithm can be used to find a complete and connected path between that origin and destination such that the path is represented by links and nodes in the network.

To calculate the redundancy metric, a complete and routable network was needed. Therefore, the research team combined the ARNOLD LRS with the network represented in the ARTDM. The ARTDM network is a routable network with abstract geometric representation. It is not complete in that despite representing all state-maintained highways it lacks the geometry for local and other non-state roads. The following section details the procedure to combine the ARNOLD and ARTDM roadway network representations to produce a complete and routable network file for this project.

Network Updates Overview

The ARNOLD network data were provided by ARDOT and consists of centerline geometry, road identification number, functional class, road design, road length, and others (Table 9, Figure 15(a)). The network is presented in “segmented” form, that is, if two lines intersect, each of them is broken at the intersection, or segmented. It details one-way streets and turn restrictions at intersections, which are important characteristics for vehicle routing and emergency response. The ARNOLD network is geometrically representative of roadway segments and is the most updated and complete road network inventory available.

The ARTDM network data was collected from the ARTDM implemented in TransCAD, a proprietary travel demand modeling software. The model was developed in 2009. The network considers only interstates and highways and no local roads (Figure 15(b)). The network data consists of road name, year built, posted speed, directional number of lanes, terrain type, functional class, and annual average daily traffic (AADT). The ARTDM network is a geometric abstraction of roadways and is outdated.



(a) **(b)**

Figure 15. Road network (a) ARNOLD (b) ARTDM

Table 9. Network Comparison

ARNOLD	ARTDM
Contains all roads including local roads and is geometrically representative	Contains interstates and highways only and provides abstract geometry and locations
68,515 segments of highways and interstates	70,928 segments of highways and interstates
63,373 nodes and 68,515 links	68,054 nodes and 70,928 links
18,723.939 miles of highways and interstates in total	21,316.356 miles of highways and interstates in total
Attributes: City, zip, functional class, length, and surface type	*Attributes*: Road name, year built, posted speed, directional number of lanes, terrain type, functional class, and AADT
Does not provide posted speeds	Provides posted speeds
More recent, modified in 2020	Outdated, developed in 2009/2010
Needs modifications to make it useful for travel demand modeling	Already used in 2015 travel demand modeling

Hybrid Network Development

A unique benefit of the ARTDM network is that it is routable and was already applied in the 2010 statewide travel demand model. ARNOLD is richer in terms of representation since it includes every road in Arkansas and is updated with new links that do not appear in the older ARTDM network, including proposed roads and roads that are newly built. However, ARNOLD is not a routable network. The goal for TRC2003 was to make a hybrid network from these two networks. To accomplish this, we first merged the two networks. Treating ARTDM as our base network, we omitted the overlapped links from the ARNOLD network. Then we compared and identified non-overlapping links, e.g., links in one map but not in the other. There were 1,473 new links totaling 697.40 miles including 68 new proposed links on Interstate 49 (I-49), Interstate 69 (I-69), and Hwy. 29.

The first problem encountered in combining the networks was that their links and nodes do not overlap. Therefore, we manually reviewed the hybrid network to find and remove the topology errors that appeared after the merging. Using ArcGIS tools, we identified the topology errors to ensure the new links from ARNOLD snapped to the old links and created a continuous link (routable). A total of 1,720 “dangling ends” (unconnected links) were found. We conducted spot checks to make sure the “dangling errors” were fixed, and routes are continuous. The whole state was divided into five regions (central, north-east, north-west, south-east, south-west), and three counties (total 15 counties) were randomly selected from each to ensure there were no errors in the hybrid network. The final network with highlighted additions is shown in Figure 16. Further details are provided in Appendix B.

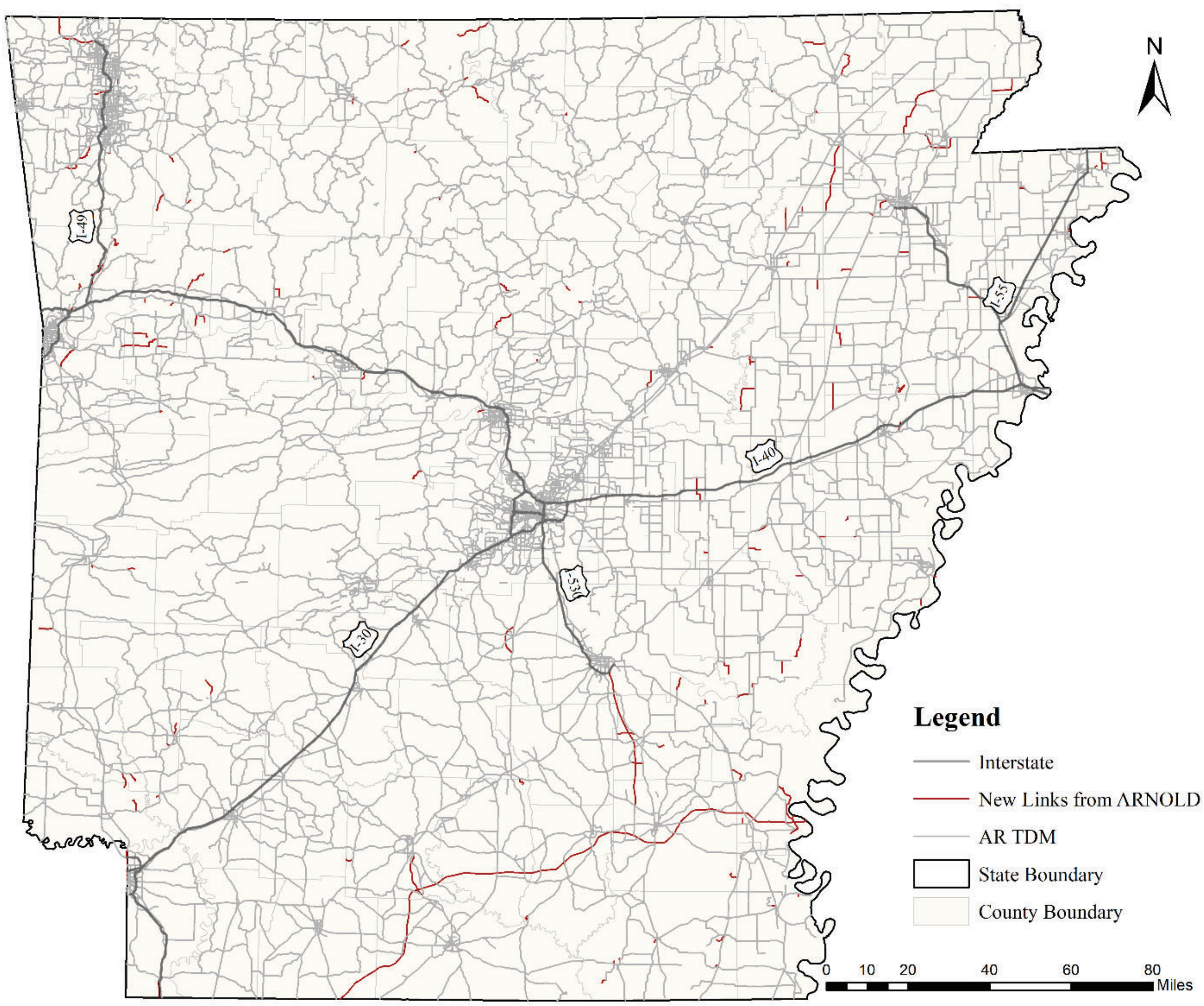


Figure 16. Hybrid Network with Red Links Showing Links Added to the Original ARTDM Network

Table 10. Summary Table of Network Edits

Discrepancies	Details
New links	1,473 links totaling to 697.40 miles were integrated to the base ARTDM network.
Proposed links	Of the new links, 68 new links and 458.61 miles of roadways including proposed I-49, I-69, and Hwy. 29 links were integrated to the base ARTDM network.
Fixed Dangling Errors	1,720 dangling ends (unconnected links) were fixed.

CRITICALITY ASSESSMENT RESULTS

The application of the link-based metrics involved acquiring the listed data and ensuring the data were available for each link in the network. For the county-based metrics, the application involved acquiring data for the county and assigning them to all links in the county. The maps presented in this section depict each of the criteria according to the levels defined for the criticality assessment.

Annual Average Daily Traffic (AADT)

AADT data were extracted from the ARTDM model and correspond to free-flow traffic conditions. The highest AADT is seen for Interstates and in Central, West-central, and Northwest Arkansas (Figure 17). The top five highest AADT (>60,000 vehicles per day, according to the ARTDM model) is seen in Pulaski County on Interstates 630 and 30 (Figure 18).

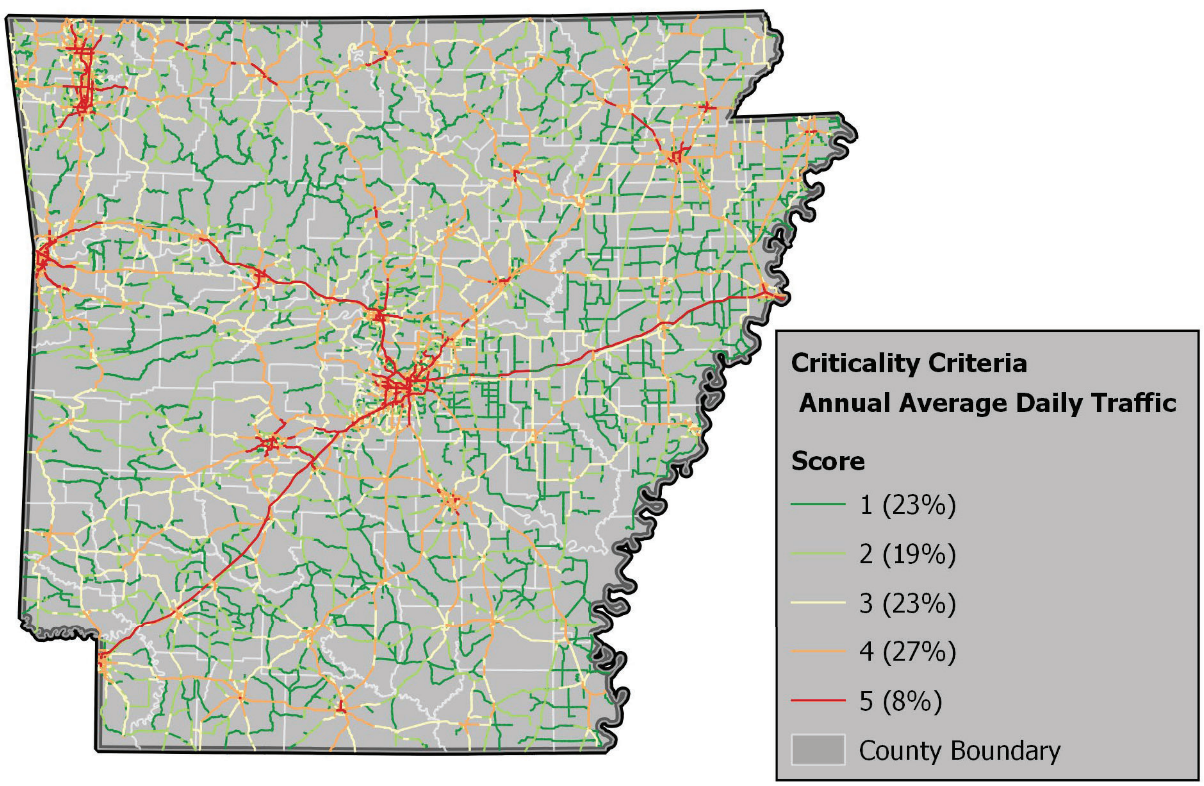


Figure 17. Annual Average Daily Traffic (AADT), Base year 2010, Extracted from the Statewide Travel Demand Model Using Alternative Assignment

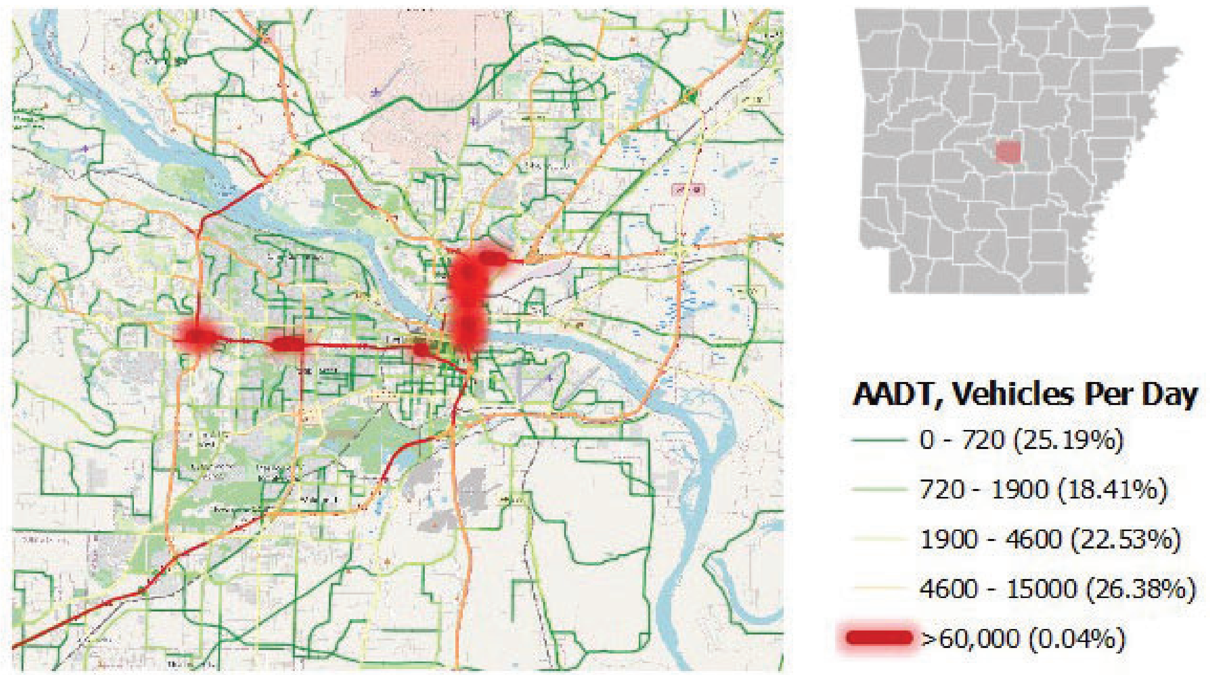


Figure 18. Annual Average Daily Traffic (AADT), Top Five Locations

Roadway Classification

Roadway classification is presented in Figure 19. Based on the criteria, interstates are given the highest score of 5, while major collectors are given the lowest score of 1 (Table 11). Note that the roadway classification and mileage are derived from the hybrid network created for this project and may not reflect the exact values that ARDOT reports for federal programs.

Table 11. Summary of Roadway Class by Length and Number of Segments

Roadway Classification Score	Total Roadway Mileage (miles)	Percent of Length by Score
1: Major Collectors	11,880	57%
2: Minor Arterial	4,166	20%
3: Principal Arterial	2,879	14%
4: Freeway/Expressway	523	2.5%
5: Interstate	1,394	6.7%
Total	***20,845***	***100.00%***

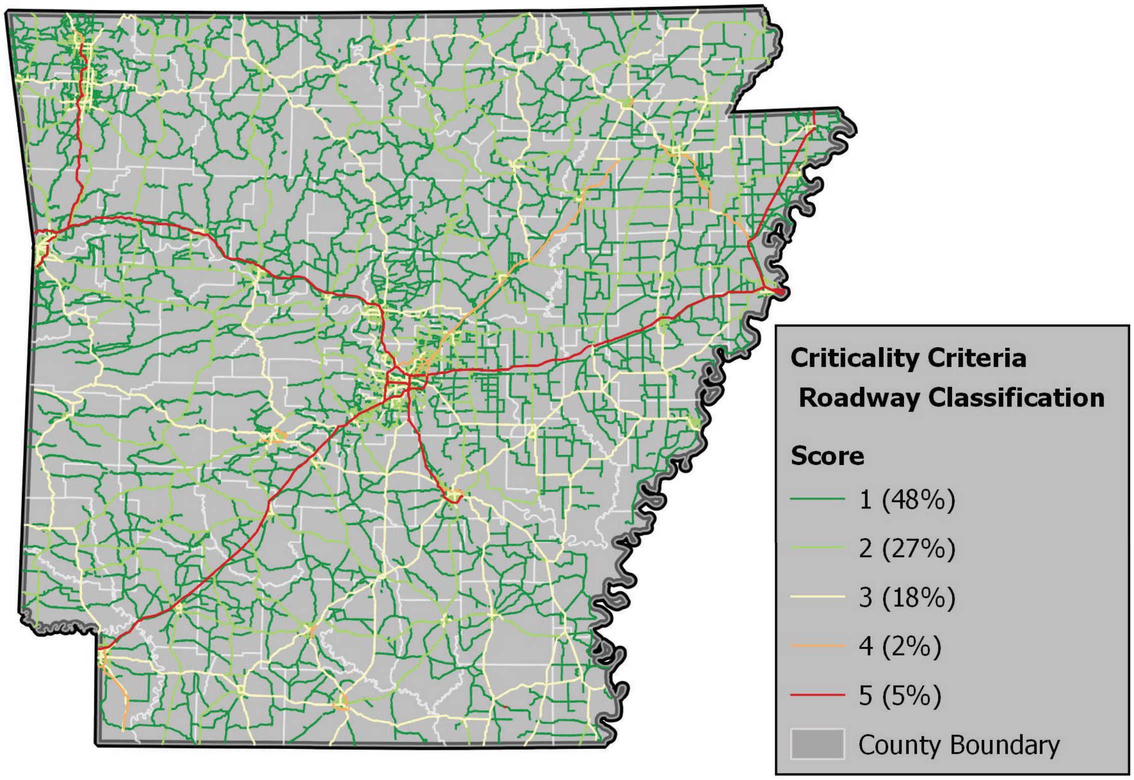


Figure 19. Roadway Class, Base year 2010, Extracted from the Statewide Travel Demand Model

Freight Value

The freight value for a county is assigned to each link in the county (Figure 20). In a few cases, the beginning and ending points of the link are in different counties. In this case, the link is assigned the value for the county that contains the majority of the link length. The top five counties ranked by freight value (in million US dollars) include Pulaski, Washington, Crittenden, Sebastian, and Mississippi counties (Table 12). These five counties account for 47 percent of the total freight output in the state.

Table 12. Summary of Freight Value by County for the Top Five Counties

County	Freight Value (Million $)	Percent of Total
Pulaski	22,679	16%
Washington	12,432	9%
Crittenden	11,331	8%
Sebastian	10,796	8%
Mississippi	9,392	7%
Total for all 75 Counties	***141,998***	***100%***

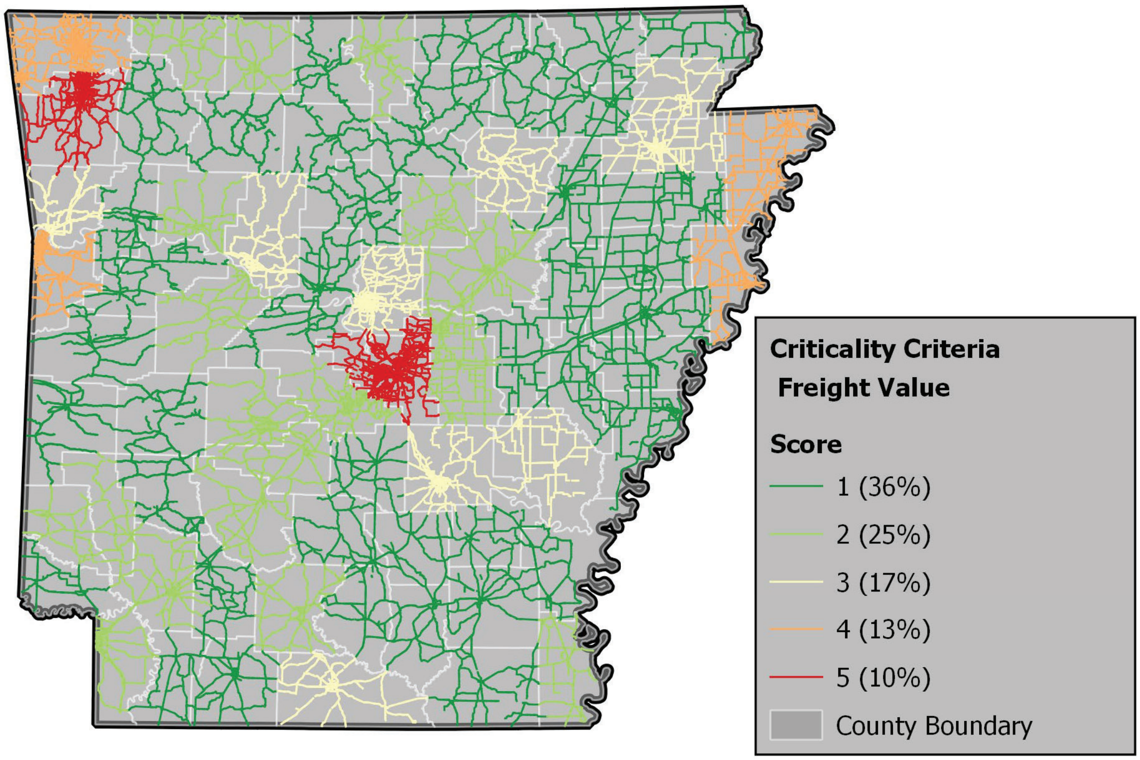


Figure 20. Freight by County, Assigned to Links Within the County, Data from 2017

Tourism Value

Tourism value is expressed as expenditures (in million US dollars) by county (Figure 21). All roadways in the county are assigned the tourism value for the county. If a roadway spans two counties, it is assigned the value for the county that contains the majority of the link. The top five counties based on reported tourism expenditures are Pulaski, Benton, Garland, Washington, and Sebastian (Table 13). These five counties account for 81 percent of the total expenditures for the state.

Table 13. Summary of Tourism Value by County for the Top Five Counties

County	Tourism (Million $)	Percent of Total
Pulaski	1,898	47%
Benton	928	12%
Garland	717	8%
Washington	566	7%
Sebastian	329	7%
Total for all 75 Counties	***7,675***	***100%***

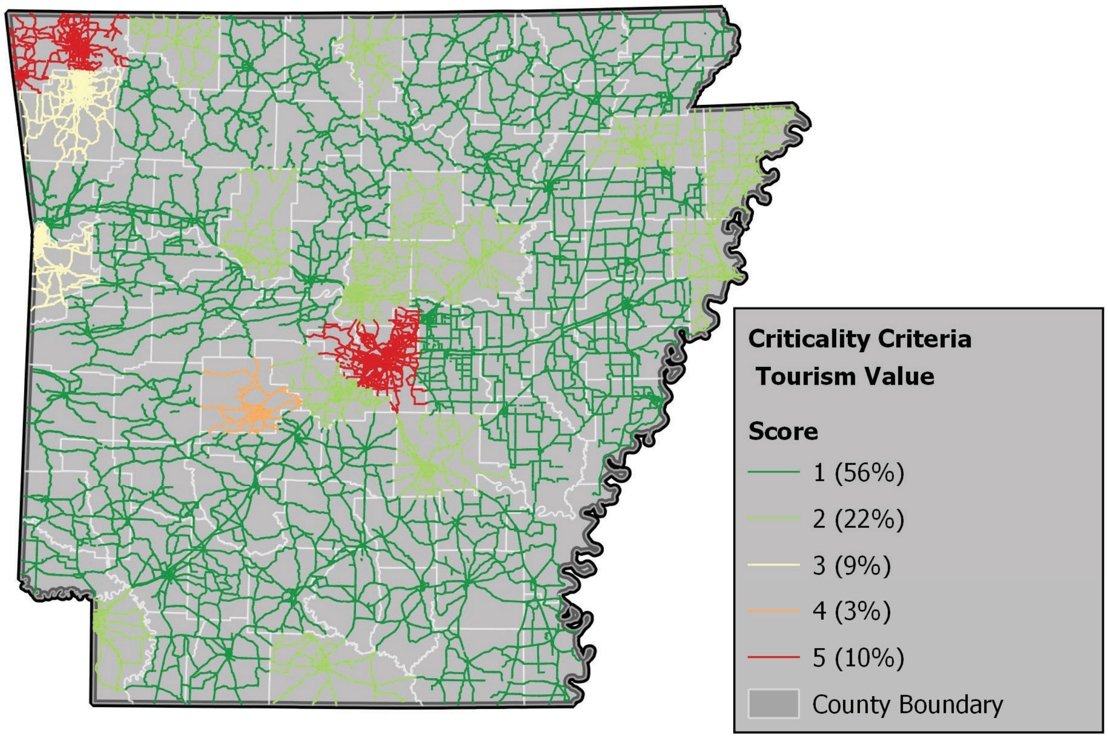


Figure 21. Tourism by County, Assigned to Links Within the County, Data (represented as millions of US dollars) from 2019

Social Vulnerability Index (SoVI)

For this project, the SoVI index was obtained at the county level (Table 14, Figure 22). The SoVI values for the county were assigned to all roadways in the county. If a roadway spanned two counties, it was assigned the value for the county that contained the majority of the link. The SoVI is expressed as a relative value, specifically, the quartile relative to the state average. The top five most at-risk counties are Phillips, Monroe, Chicot, Baxter, and Woodruff (Table 15).

Table 14. Summary of Counties by SoVI Score

SoVI Score	Number of Counties
1: Very Low Impact	1
2: Low Impact	11
3: Moderate Impact	20
4: High Impact	30
5: Very High Impact	13
Total	***75***

Table 15. Summary of SoVI by County for the Top Five Counties

County	SoVI Quartile Relative to the State
Phillips	5.40
Monroe	4.71
Chicot	4.22
Baxter	4.18
Woodruff	4.16
Percent of At-Risk Counties[1]	***35% (26 counties)***

1. At-risk counties are considered to be 1.5 standard deviations above the mean, with positive SoVI values.

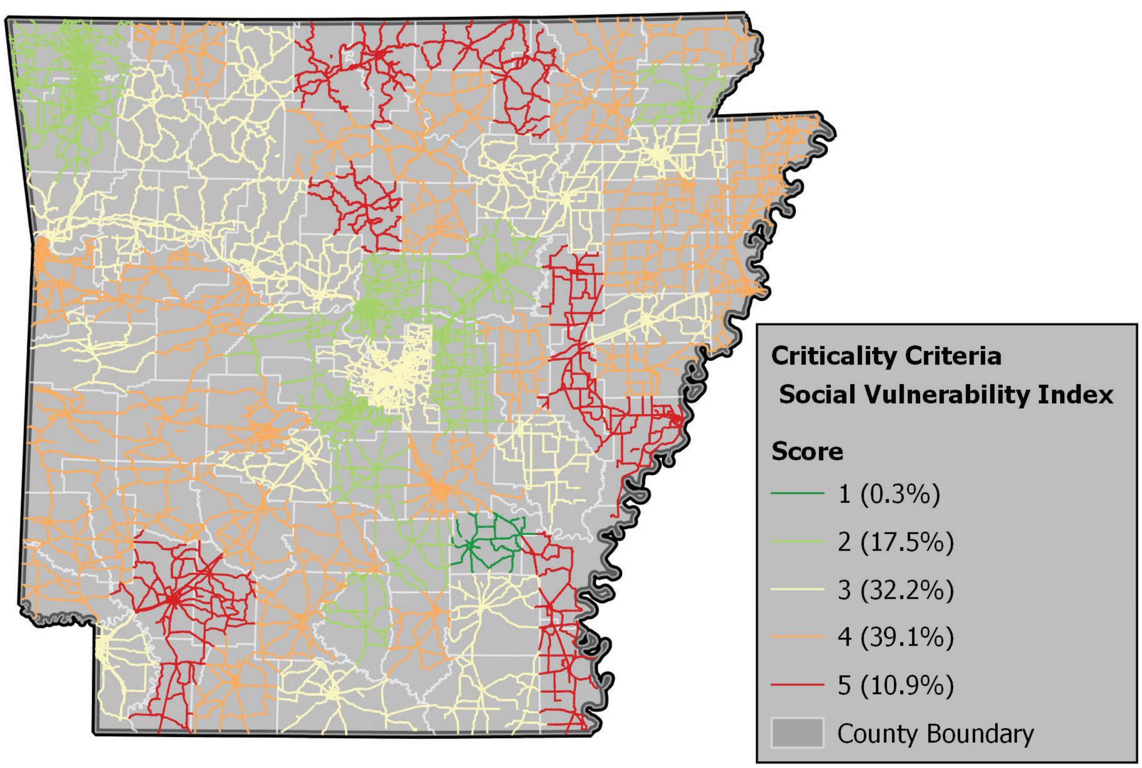


Figure 22. Social Vulnerability Index (SoVI) by County, Ranked by Quartile Relative to the State, Data from 2014

Redundancy

Redundancy is represented as the impact of a roadway closure on system-wide travel times. Higher redundancy means that there are many alternate routes within the vicinity of a closed roadway that can accommodate the offset traffic from the closed roadway. Lower redundancy means that there are few or no alternate routes in the vicinity of a closed roadway, resulting in increased travel times on the network as drivers have to follow longer detour routes and may experience higher congestion.

For the redundancy metric, the application was as follows. The redundancy metric calculation requires each link to be "closed" (made non-operational) and then a full traffic assignment algorithm to be executed. There are 69,846 links in the network and three time periods of analysis – the AM peak, the PM peak, and the midday time period. Thus, the process of calculating redundancy for each link becomes intensive in terms of computation and time. A specialized computer code (script) was written to execute the procedure. To minimize computational time, first, the redundancy metric was calculated for all links for the AM peak period. Then, the procedure was repeated but only for the links with "higher" redundancy (a greater increase in the total system travel time resulting from that link being closed). We used the free-flow redundancy measure. The free-flow measure does not consider congestion effects but rather performs an all-or-nothing assignment of flow each time a link is made non-operational.

For the redundancy measure, two types of data unavailability can occur. These relate to (1) disconnected trips and (2) lack of convergence of the model. Disconnected trips occur when a link closure results in a subset of the links becoming inaccessible. For example, consider a park entrance with a single entrance link. If the entrance link were to be non-operational (closed), then all trips in and out of the neighborhood would be disconnected from the network (Figure 23). This scenario is possible and highly undesirable in real life. From a modeling perspective, the estimated total system travel time may decrease as a result of the link closure because the disconnected trips no longer access the network to cause an increase in travel time (congestion). In total, 146 roadway links (0.21% of all roadway links), when closed, resulted in a situation of disconnected trips. These links were manually examined and deemed to be not significant to overall network resiliency and were thus removed from further analysis. There can be a lack of model convergence when no feasible traffic assignment solution can be reached in a predetermined computational time limit. This is a limit of the computational capabilities of the approach and not necessarily a product of the network characteristics. In total, 125 roadway links (0.18% of all roadway links), when closed, resulted in a situation of failed model convergence. These links were manually examined and deemed to be not significant to overall network resiliency and were thus removed from further analysis.

The majority (90%) of the roadway links with estimated change in system travel time for free-flow conditions have low to no impact on the system travel time (Table 16). Almost 300 (293 or 0.41%) roadway links have a redundancy score of four or five, representing high to very high impacts on system travel time (Figure 24).

Table 16. Summary of Redundancy Score by Roadway Links and Mileage

Redundancy Score	Number of Links
1: Very Low Impact	63,448
2: Low Impact	4,860
3: Moderate Impact	1,323
4: High Impact	282
5: Very High Impact	11
Total	***69,924***

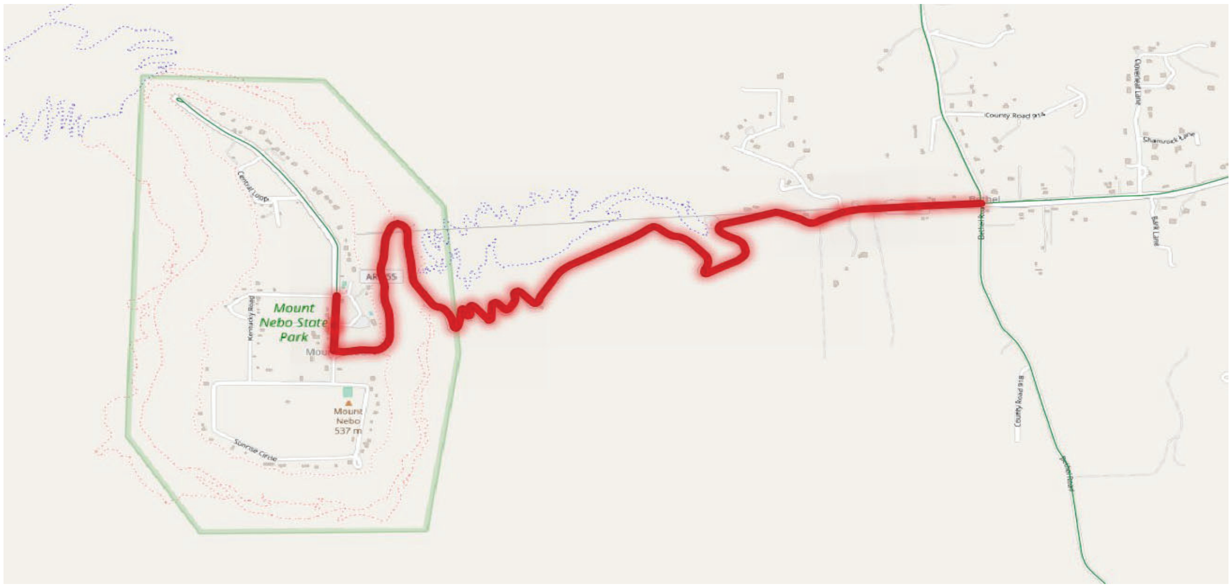


Figure 23. Example of Disconnected Trips Resulting from Redundancy Analysis

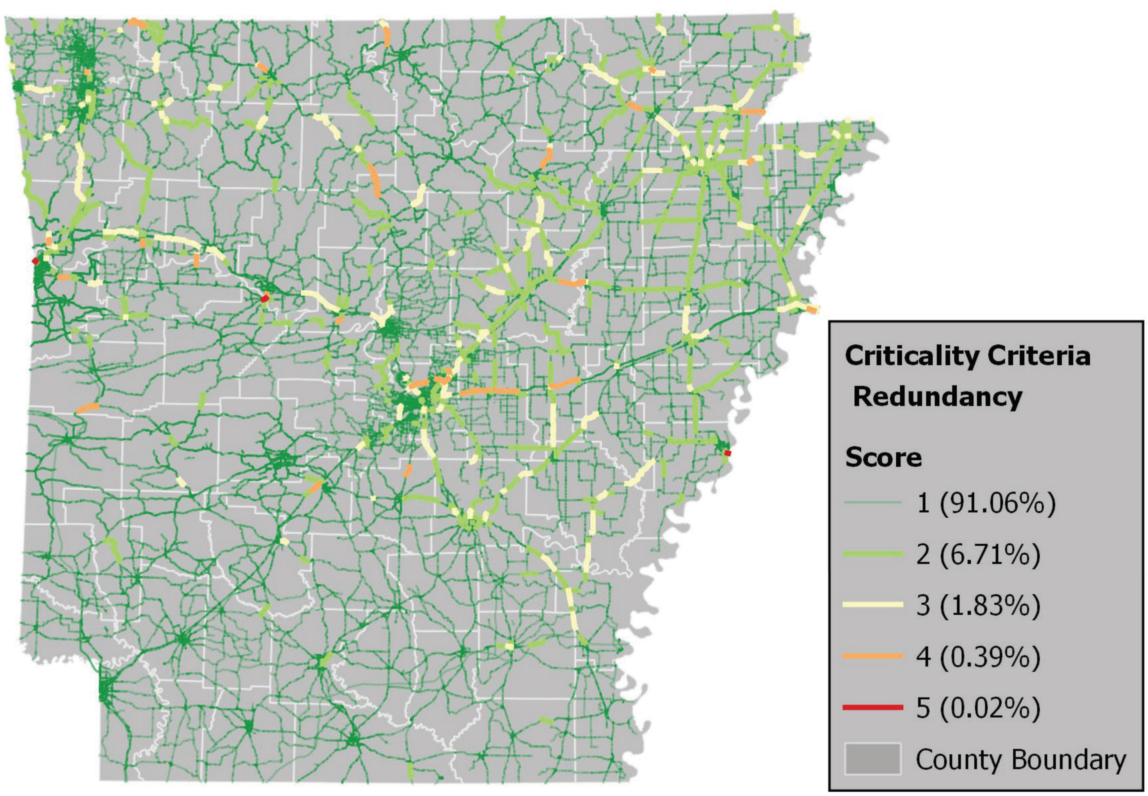


Figure 24. Redundancy by Link Represented as the Change in Overall System Travel Time Resulting from the Link Closure, Base Year 2010

The top three locations that cause the greatest disruption to the network identified by the redundancy analysis include:

1. Highway 7 bridge over the Arkansas River in Dardanelle separating Yell and Pope Counties that results in an estimated 23,671 vehicle-hours of travel time to the system when closed (Figure 25),
2. Highway 64 bridge over the Arkansas River in Fort Smith separating Arkansas's Sebastian County from Oklahoma's Sequoyah County that results in an estimated 8,109 vehicle-hours of travel time to the system when closed (Figure 26), and
3. Highway 49 bridge over the Mississippi River in Helena separating Arkansas's Phillips County from Mississippi's Coahoma County that results in an estimated 12,928 vehicle-hours of travel time to the system when closed (Figure 27).

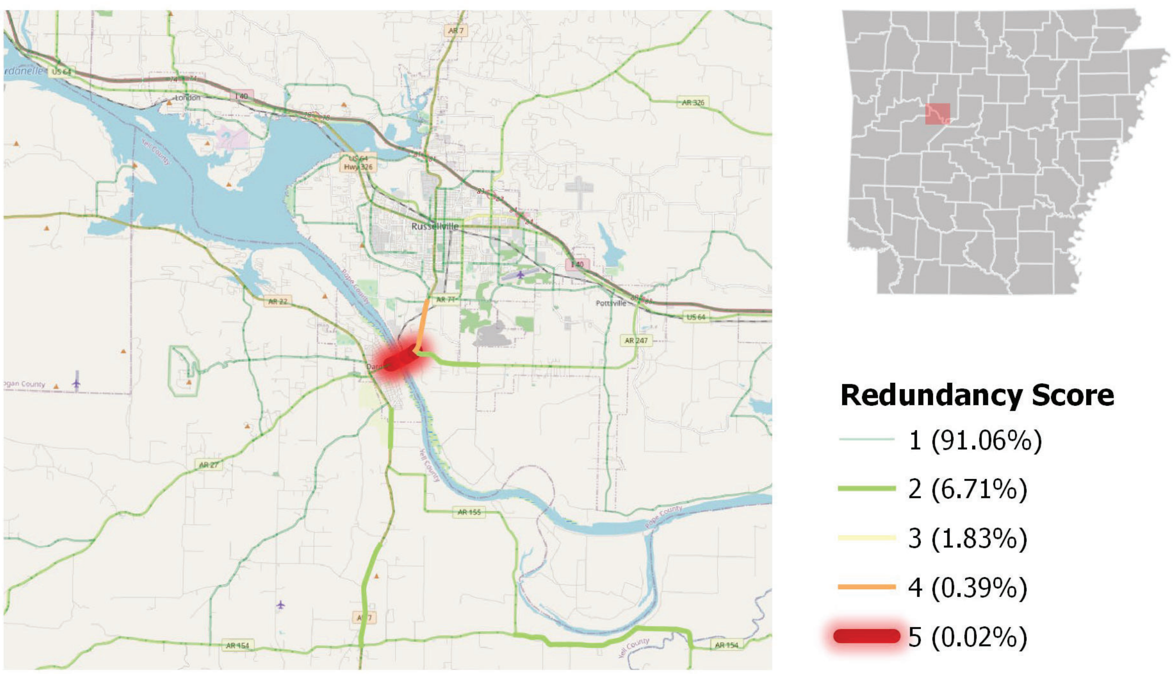


Figure 25. Highway 7 Bridge Over Arkansas River in Dardanelle, Top Redundancy Metric Score

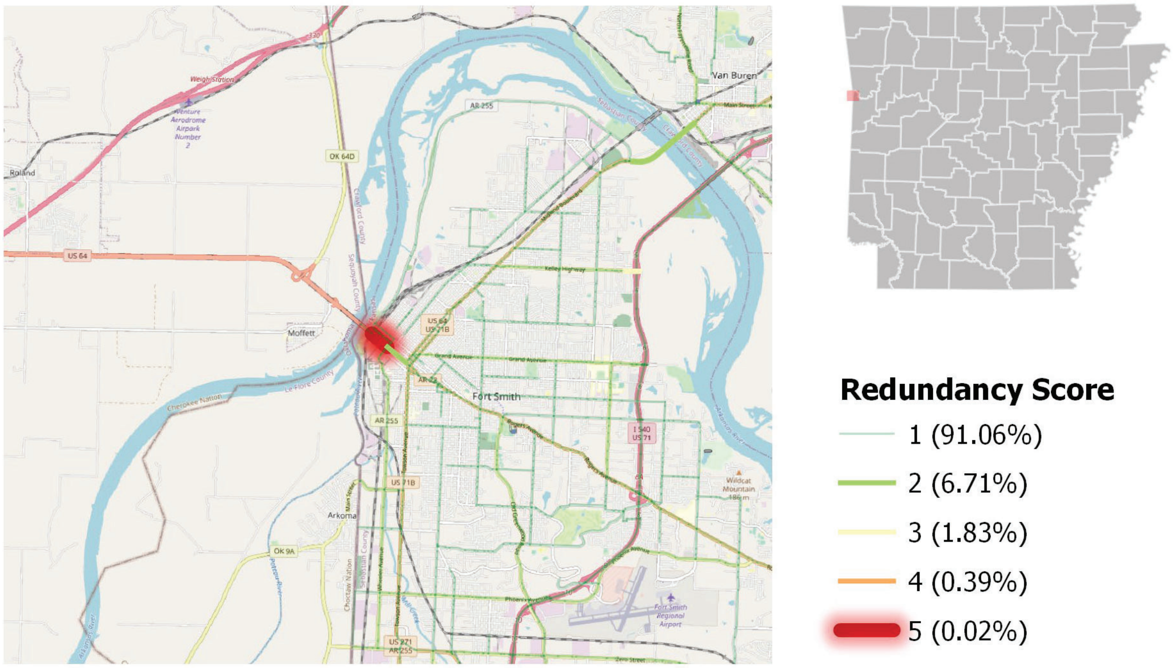


Figure 26. US Highway 64 Bridge over Arkansas River in Fort Smith, Top Redundancy Metric Score

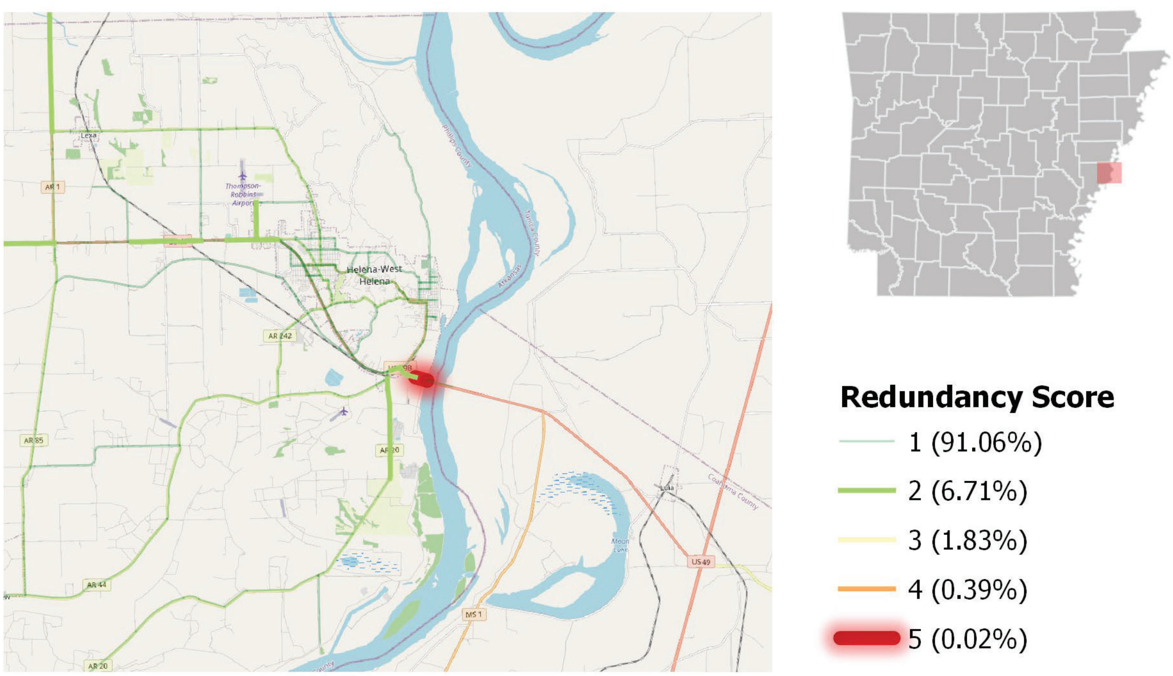


Figure 27. US Highway 49 Bridge over Mississippi River in Helena, Top Redundancy Metric Score

Combined Criticality

The following sections present the results of the criticality assessment based on the equal and unequal criteria weighting approaches.

Equal Weighting of Criticality Criteria. To better visualize the criticality map, the combined criteria (with equal weights) were divided into low, moderate, and high criticality (Figure 28). The stratification of criticality values was chosen based on approximately 55 percent of the links being classified as having low criticality, 25 percent as having moderate criticality, and 20 percent as having high criticality. This approach was adopted from the CDOT study. A heavy concentration of high criticality links based on the underlying data and assumptions used was found in Northwest Arkansas, Fort Smith/Van Buren, Little Rock, West Memphis, Hot Springs, and Pine Bluff areas. The length of Interstate 30 (I-30) between Texarkana and Benton areas is of high criticality as is the length of I-40 between Alma and Conway.

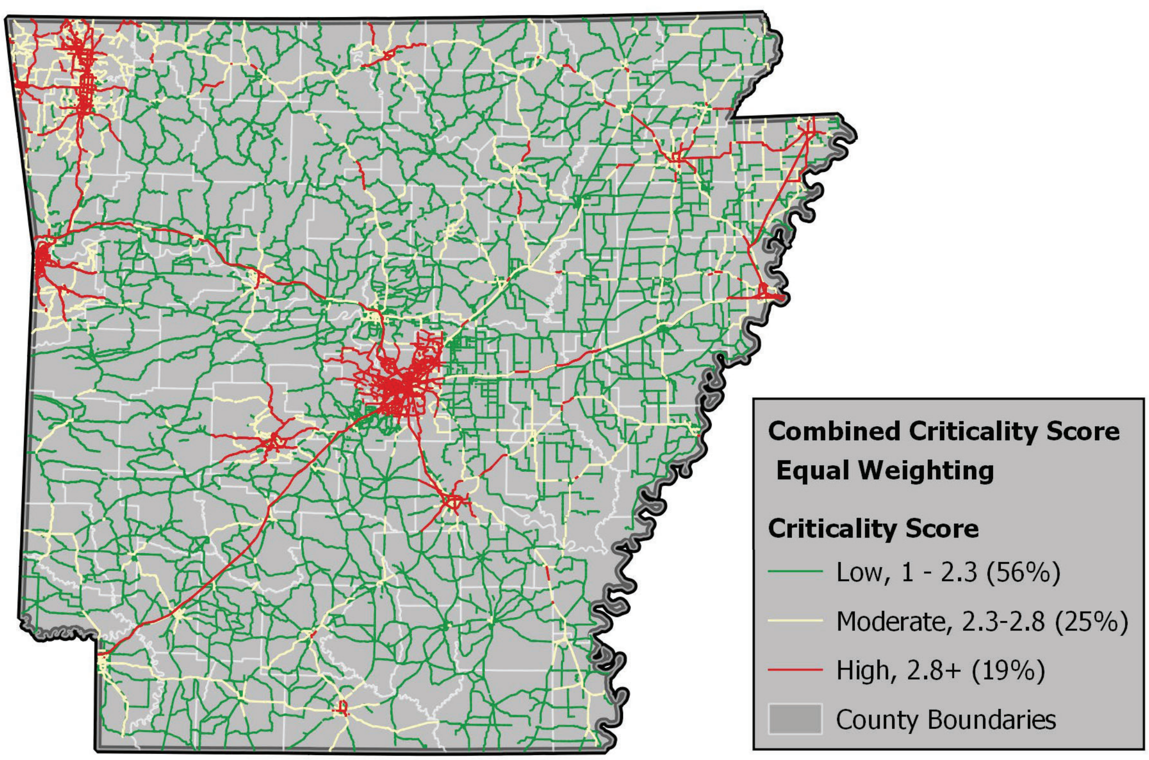


Figure 28. Combined Criticality Score Using the Equal Weighting Approach

Unequal Weighting of Criticality Criteria. When using the AHP method to rank the criticality criterion, there is a shift in the number of locations marked as highly critical roadways (Figure 29). For ease of identifying locations undergoing the most change, we present the percent difference in the equal and unequal (AHP) approaches calculated as the percent difference relative to the equal weighting approach (Figure 30). The three largest percent differences were seen in Garland (west-central region), Lafayette (south-west region), and Woodruff (east-central region) counties each with an average of 22 percent difference. This is attributed to the lower ranking of the SoVI criterion (0.166 or 1/6 in the equal approach to 0.06, or ranked second to last in the AHP approach) and the tourism criterion (0.166–0.049, or last-ranked). For absolute difference, the largest differences were seen for Pulaski, Sebastian, and Garland Counties. On average, the criticality of roadways in Pulaski County increased by 0.40 units, by 0.33 units in Sebastian, and by 0.60 units in Garland. This is attributed to the higher ranking of the freight (0.166 in the equal ranking and 0.235 in the AHP ranking) and AADT (0.166 in the equal ranking and 0.177 in the AHP ranking) criteria in the AHP ranking. Redundancy was ranked as the highest priority, with a weight of 0.333 in the AHP ranking, representing double the weight assumed for equally weighted criteria. On average, the total criticality of roadways scoring 5 for redundancy saw an increase of 10 percent in their overall criticality score. Overall, relative to the scores of the most critical sites, the differing ranking of criteria does affect the topmost critical sites.

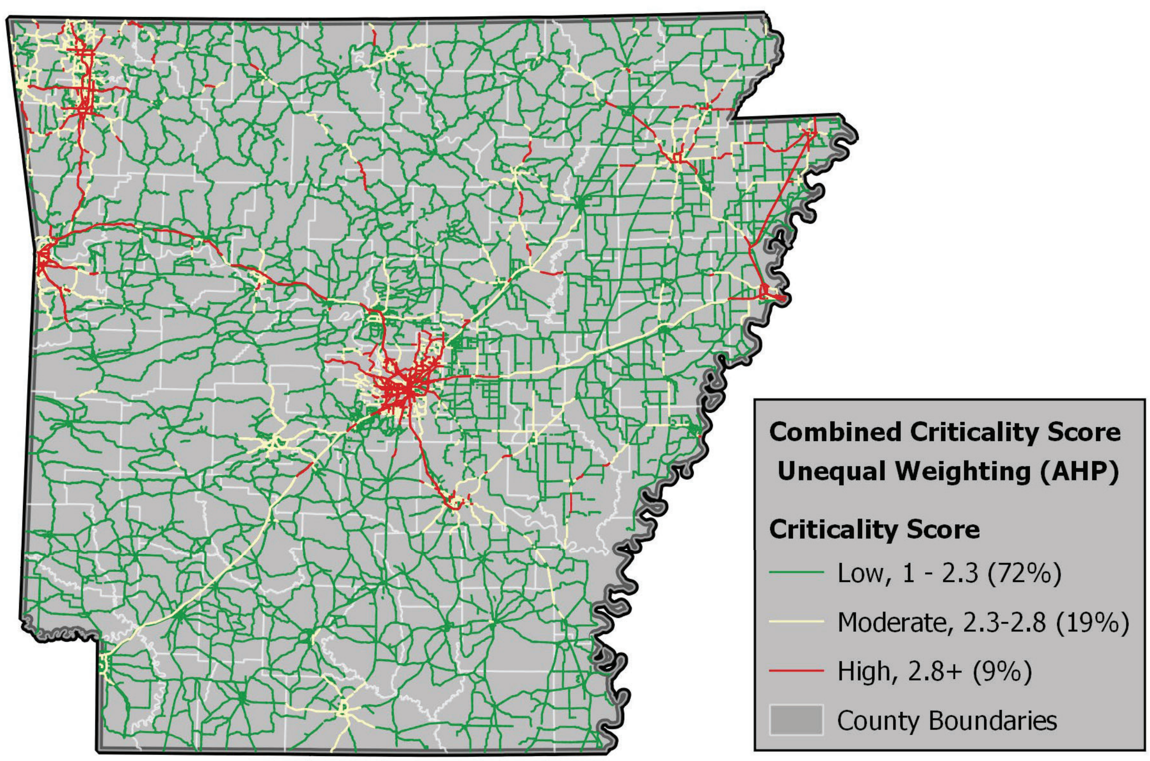


Figure 29. Combined Criticality Score Using the Unequal (AHP) Weighting Approach

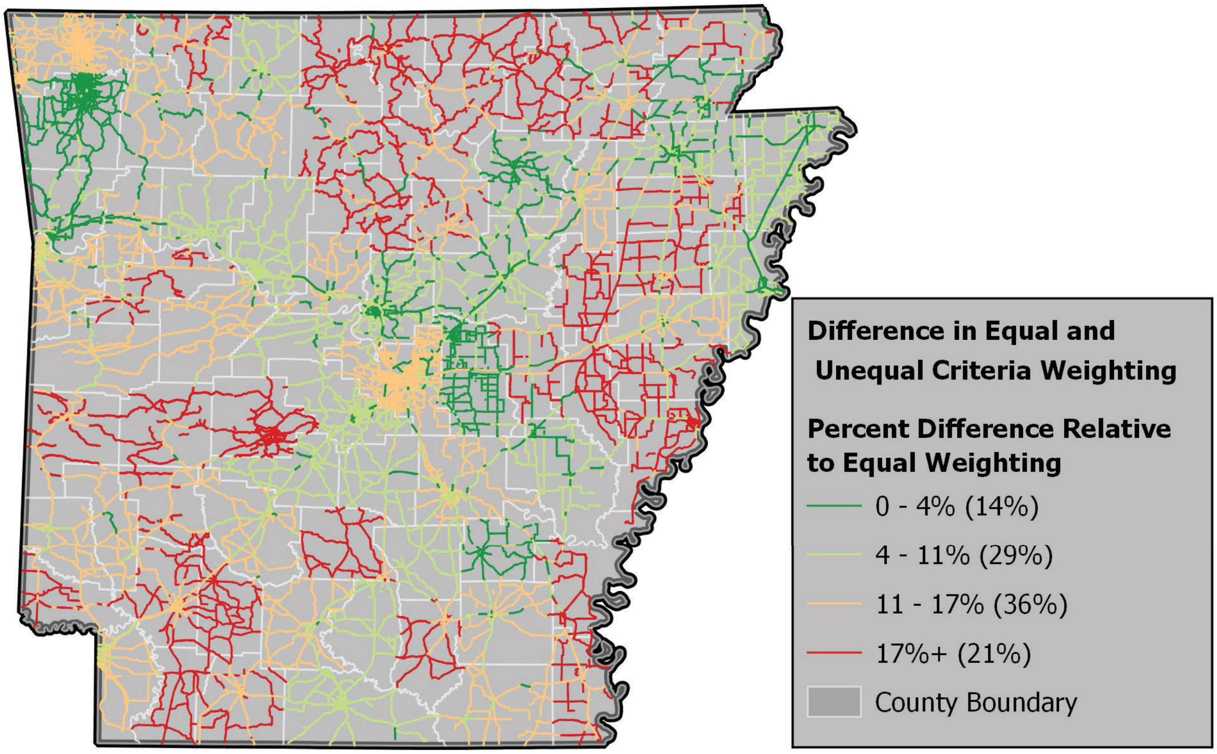


Figure 30. Percent Difference Between Equal and Unequal (AHP) Criticality Criteria Weighting Approaches Expressed as the Absolute Difference Relative to the Equal Weighting Approach

Based on the unequal weighting method (e.g., AHP), the following locations rank among the ten most critical sites with criticality scores greater than 4.2 based on the underlying data and assumptions used (Figure 31, Figure 32, Figure 33):

1. Hwy 67/167 from Hwy 440 to South Redmond Road, *Pulaski County*, score: 4.401
2. Garrison Avenue, *Sebastian County*, score: 4.315
3. I-55 from Hwy 70 to the I-55 Memphis-Arkansas Bridge, *Crittenden County*, score: 4.225
4. I-430 from S. Shackleford Road to Stagecoach Road and from the I-40 to Crystal Hill Road (Hwy 100) interchange, *Pulaski County*, score: 4.214
5. I-40 from Crystal Hill Road to West Military Drive, *Pulaski County*, score: 4.214
6. I-40 from Hwy 440 to Hwy 391, *Pulaski County*, criticality score: 4.214
7. I-30 from Hwy 365 to I-530/I-440 interchange, *Pulaski County*, score: 4.214 (Figure 31)
8. I-530 from 145th/Pratt Road to E. Bingham Road, *Pulaski County*, score: 4.214
9. I-440 from Fourche Dam Pike to Hwy 165, *Pulaski County*, score: 4.214
10. I-40 from the I-430 interchange to Crystal Hill Road, *Pulaski County*, score: 4.214

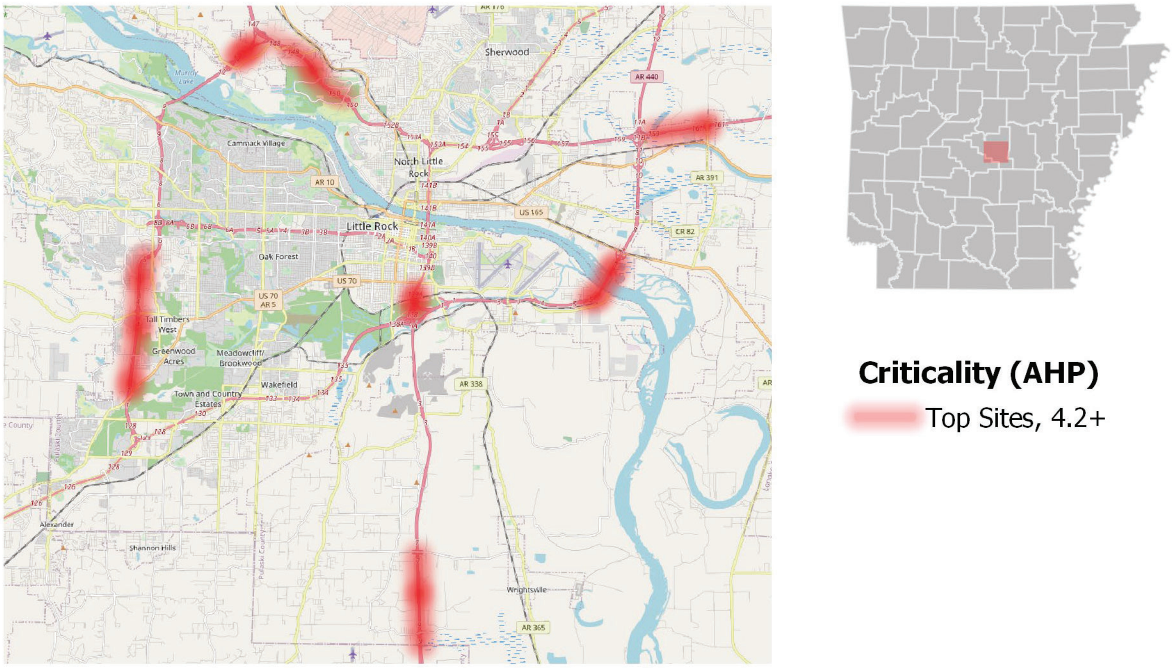


Figure 31. Pulaski County, Top Ranked Site by Criticality

Figure 32. Garrison Avenue, Sebastian County, Top Ranked Site by Criticality

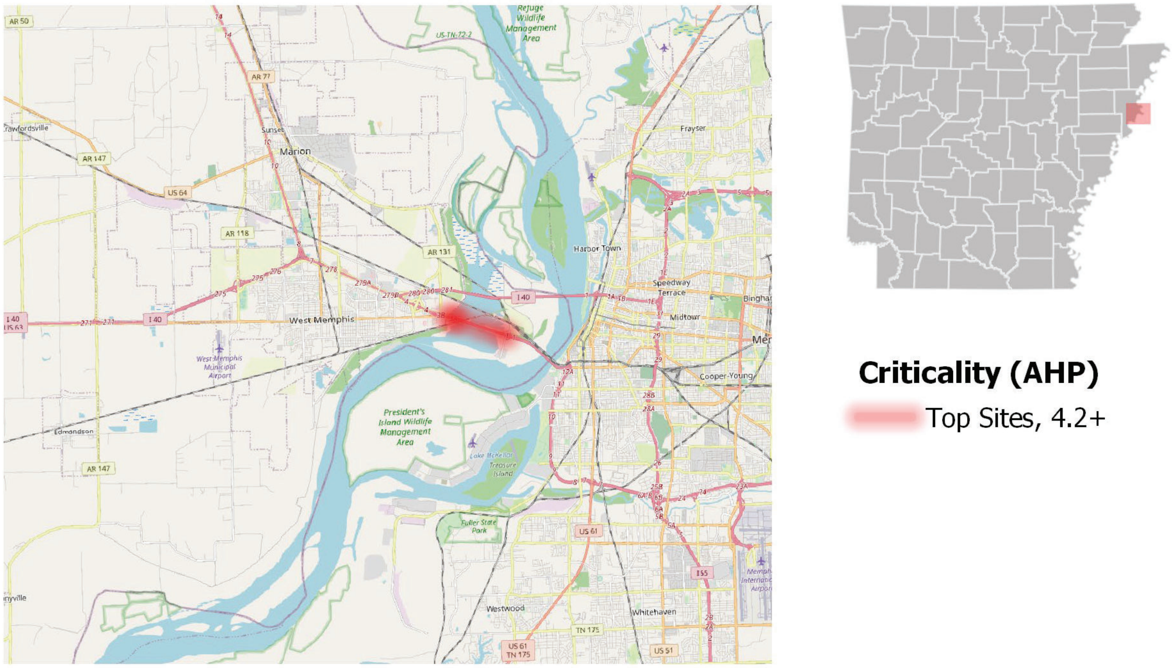


Figure 33. I-55, Crittenden County, Top Ranked Site by Criticality

VULNERABILITY ASSESSMENT RESULTS

This section presents the results of the vulnerability analysis including the estimation of the vulnerability score.

Flooding

The vulnerability of a link due to flooding is calculated based on the number of road closures due to flood events. The most frequent flood events that resulted in road closures were observed in Jackson, Independence, and Lawrence Counties (northeast region) with at least 20 flood events occurring over the eight-year period between 2011 and 2019 (Figure 34). The top five counties by flood occurrence account for 39 percent of the total number of flood events (Table 17). Across the state, 98.9 percent of roadway links did not face road closures due to flooding. Sixty-two percent of the road closures due to flooding were on major collectors (low impact) with 2 percent occurring on interstates (Table 18). The relative proportion of road closures due to flooding and mileage by roadway class was largest (0.56) for major collectors and lowest for interstates (0.17) with a statewide total ratio of 0.52 closures per mile. The five most closures due to flood events occurred on the following roadway segments:

1. Hwy 18 from Hwy 37 east to the county line, Jackson County, 26 flood events
2. Hwy 367 (Arlington Street) from the Hwy 14 intersection east to the county line, Jackson County, 23 flood events
3. Hwy 37 from Hwy 14 north to Hwy 18, Jackson County, 22 flood events
4. Hwy 37 from Hwy 122 south towards the county line, Independence County, 21 flood events
5. Hwy 226 from Hwy 367 to Hwy 224, Jackson County, 21 flood events

Table 17. Top Five Counties by Flood Count

County	Number of Road Closure Events	Percent of all Road Closures
Jackson	1,206	11%
Independence	955	9%
Randolph	716	7%
Pulaski	643	6%
Lawrence	610	6%
Total of All Counties	***10,691***	***100%***

Table 18. Road closures due to flooding by roadway classification

Roadway Classification	Road Closure due to Flood (Percent of All Closures)	Total Mileage (Percent of Total Mileage)	Ratio of Closures to Mileage
1: Major Collectors	6,663 (62%)	11,880 (57%)	0.56
2: Minor Arterials	2,285 (21%)	4,167 (20%)	0.54
3: Principal Arterials	1,072 (10%)	2,880 (14%)	0.37
4: Freeway/Expressway	422 (4%)	523 (3%)	0.81
5: Interstate	249 (2%)	1,395 (7%)	0.17
Total	***10,691***	***20,845***	***0.52***

Landslide

Landslide occurrences and their impacts on the roadway are calculated based on the number of landslides occurring within one mile of the roadway segment. In total, 3,289 roadway links were affected by landslides, and a total of 7,795 landslide events occurred. The heaviest impacts were observed in Crawford (2,183 events, 28% of all events) and Newton (1,080, 14%) Counties (Figure 35). Forty-four percent of all landslides occurred within one-mile of major arterials representing the highest ratio (0.82) of landslide occurrence to miles of that roadway class (Table 19). Only 627 landslide events occurred within one mile of interstate roadways, representing eight percent of all landslides and a ratio of landslide to mileage of 0.45. The statewide average ratio of landslides to mileage was 0.37. The locations with the highest (>16) landslide activity include the following:

1. Hwy 71 (various sections), around the Lake Sheppard Spring Dam on Lake Fort Smith, Crawford County, 16–25 landslides within a one-mile buffer.
2. Hwy 7, from Hwy 74 to Hwy 374, Newton County, 16–24 landslides within a one-mile buffer.
3. Wyman Road, between Hwy 45 and Hwy 16, Washington County, 19 landslides within a one-mile buffer.
4. Hwy 74 (various sections), from County Road 20 east to Hwy 327, Newton County, 12–14 landslides within a one-mile buffer.
5. Hwy 23 between HWY 215 and the Franklin/Madison County border, Franklin County, 11 landslides within a one-mile buffer.

6. Hwy 59, from the Washington/Crawford County border north to Hwy 156, Washington County, 11 landslides within a one-mile buffer.

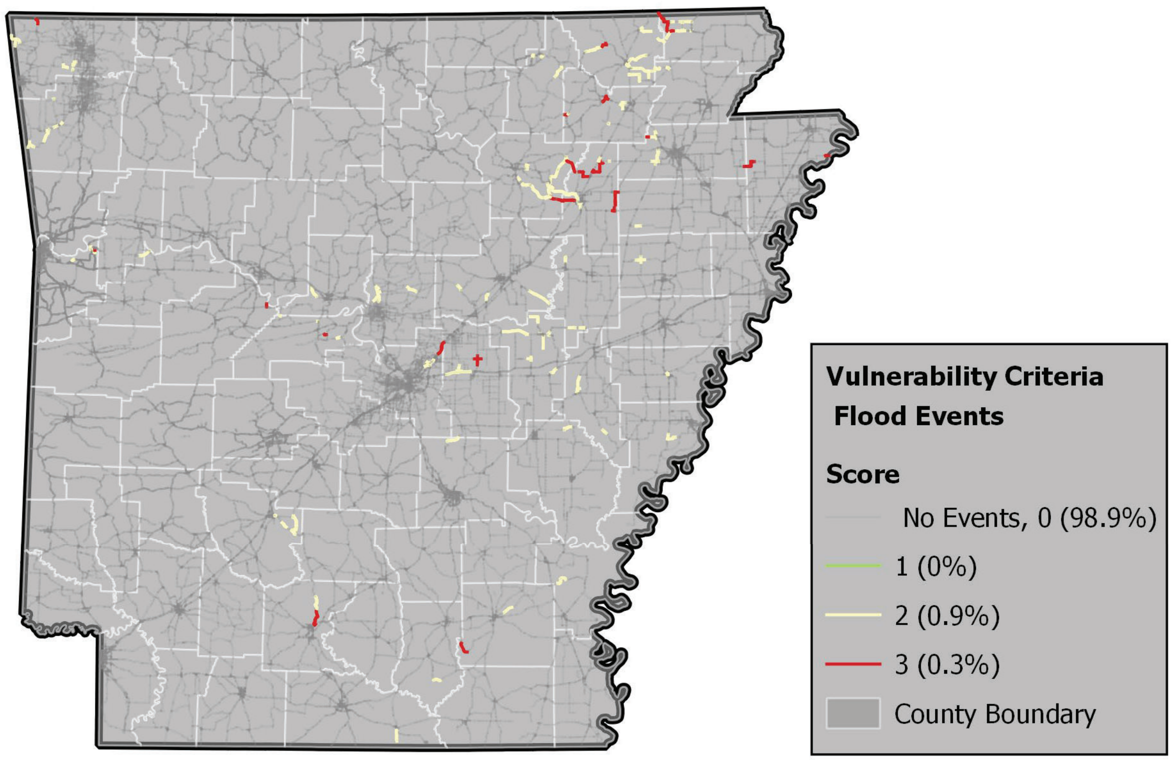


Figure 34. Road Closures due to Flooding Events in Arkansas. Data from the ARDOT GIS and Mapping Office. Floods between 2011 and 2019.

Table 19. Landslides within a One-Mile Buffer by Roadway Classification

Roadway Class	Landslides Within a One-Mile Buffer (percent of all landslides)	Total Mileage	Ratio of Closures to Mileage (closures per mile)
1: Major Collectors	3,045 (39%)	11,880 (57%)	0.26
2: Minor Arterials	3,420 (44%)	4,167 (20%)	0.82
3: Principal Arterials	602 (8%)	2,880 (14%)	0.21
4: Freeway/Expressway	101 (1%)	524 (3%)	0.19
5: Interstate	627 (8%)	1,395 (7%)	0.45
Grand Total	***7,795***	***20,845***	***0.37***

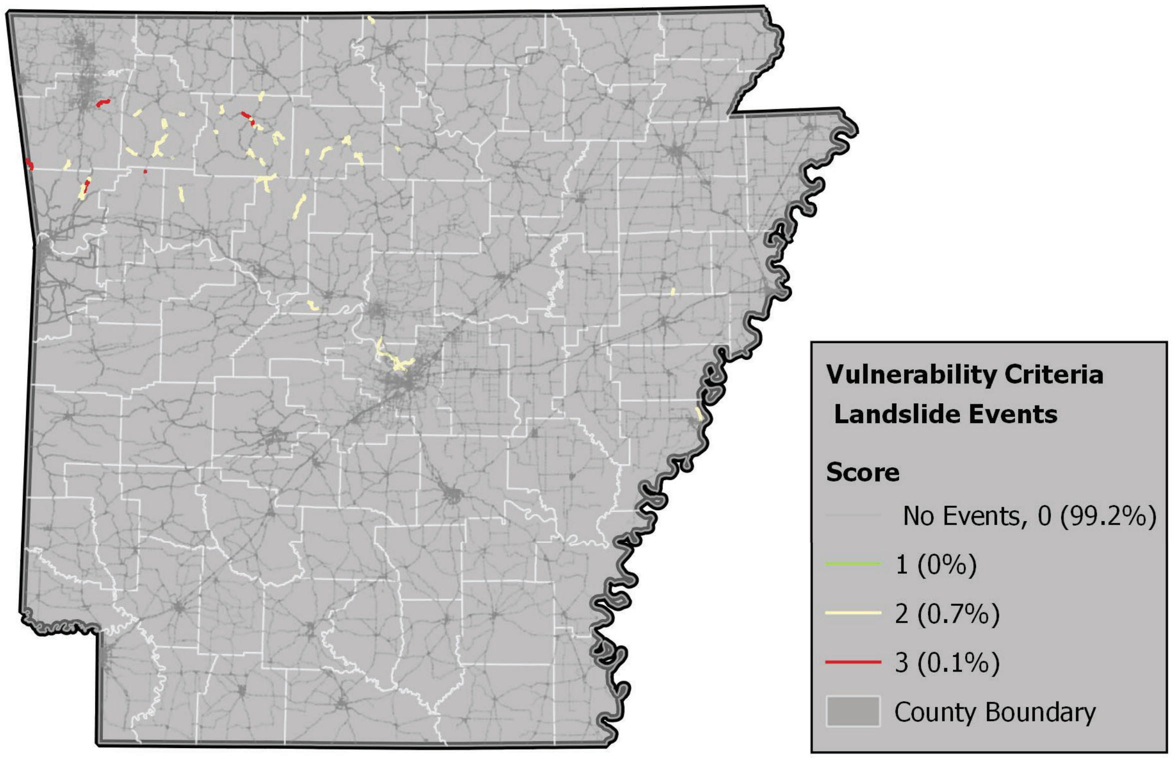


Figure 35. Landslide Occurrences in Arkansas. Data from the Arkansas Geological Survey. (Landslides mapped to the closest transportation link within one mile)

Earthquake

The nearest active seismic zone to Arkansas capable of producing an earthquake with non-negligible effects is the New Madrid Seismic Zone (NMSZ) (Hendricks 2019). This fault line stretches approximately 150 miles from Arkansas into Missouri and Illinois. The New Madrid Seismic Zone (NMSZ) was responsible for some of the most violent earthquakes in the history of the continental United States in 1811–1812 (Hendricks 2019). The 1811–1812 earthquakes measured over a magnitude of 7.5 and destroyed buildings, shaped the land due to liquefaction, and produced shaking felt all the way in New England and Canada (AGS 2019).

The Federal Emergency Management Agency (FEMA) created “Hazards United States-Multi Hazard”, commonly referred to as “Hazus-MH” or just “Hazus”, as a free and open-sourced program. Hazus combines information systems (GIS) with engineering, science, and mathematical models (Nastev and Todorov 2013). This simulation tool determines the potential losses associated with floods, earthquakes, tsunamis, and hurricanes. It operates by associating mathematical models in the form of graphs like fragility curves (for road damages), capacity curves (for building destruction), and restoration curves (to determine functionality after an amount of time) (FEMA(b) 2020). Hazus was chosen for this thesis because of its ability to incorporate user data alongside a large array of nationally acquired information to create more accurate analyses. Furthermore, this approach to hazard modeling was chosen because it allows for running multiple scenarios related to geographical features like soil types and water levels, roadway infrastructure, and cost models. Finally, it enables data visualization and quantification through widely available GIS programs like ArcGIS and QGIS.

A basic earthquake analysis can be performed with Hazus using FEMA's provided collection of inventory databases in conjunction with the USGS ShakeMap website. The USGS ShakeMap scenarios provided are useful in Hazus simulations because they contain ground acceleration data as well as soil information (FEMA 2020). Using these data, alongside FEMA's default facility information, basic analyses can be performed to produce initial earthquake estimates. To generate losses for infrastructure such as roads, liquefaction and landslide susceptibility maps for a study region must be developed in addition to the USGS-provided soil map as Hazus does not consider ground shaking alone as a factor for determining road damage (FEMA 2021). In fact, it considers ground failure (related to landslides and liquefaction) as the main risk factor in predicting road damages (FEMA 2021). Bridges and tunnels, on the other hand, can be affected just by ground-shaking and experience damage.

The landslide map was created using a digital elevation model provided by the Arkansas GIS Office and ArcMap. The DEM contained National Elevation Dataset (NED) data in the form of one-meter tiles that provided the bare earth elevation data for the entire state of Arkansas (Arkansas GIS Office, 2018). ArcMap's spatial analysis tool, aptly named "Slope", was used to determine the slope of each tile of the DEM (ESRI 2020). Those slopes were used to assign a landslide susceptibility for areas of the state based on rock and soil types as well as groundwater level. For two groundwater conditions: a) dry (groundwater below level of sliding) and b) wet (groundwater at level of ground surface), two different landslide susceptibility maps may be created (FEMA 2020). Wet conditions may yield the most conservative losses and were used in this analysis. Apart from hazard maps, updates to Hazus' default data can be made as well. Users can import and replace the data that comes with Hazus. Road network information comes from the National Highway Planning Network created by the Federal Highway Administration in 2005 (FEMA 2021). This information is updated every three to six years, and the most recent data are from 2019 (FEMA 2021). Users may choose to add their own road networks and other facility data, based on their research needs and priorities.

The vulnerability score for earthquake occurrence is based on the FEMA Hazus model. The FEMA Hazus model scores are derived from the probability of extensive damage as defined by the model. The model uses the New Madrid Seismic Zone as the epicenter for a 7.7 magnitude earthquake to estimate damage probability to roadways and transportation structures like bridges and culverts. Using the Hazus model, we estimate the probability of extensive damage to each roadway link in the network (Figure 36). Results from this analysis showed that an earthquake with a magnitude of 7.7 from the New Madrid Seismic Zone would produce more than $3 billion dollars in damage to the transportation system and affect over 23,000 miles of road. Nearly 300 assets have a probability of complete damage of above 40%—meaning little to no functionality—in the case of a large earthquake according to the Hazus model results. Full details of the Hazus model development can be found in Rothwell (2022).

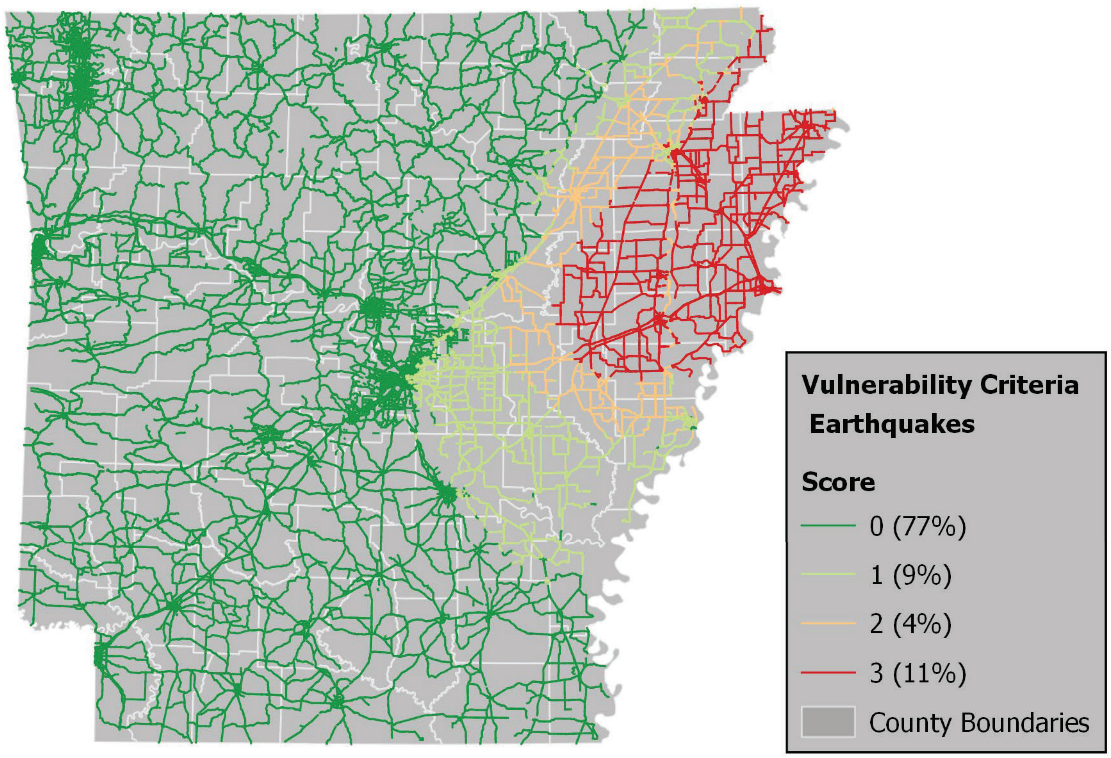


Figure 36. Estimated Probability of Extensive Damage to Highway Assets Using the FEMA Hazus Model to Simulate a 7.7 Magnitude Earthquake Along the New Madrid Seismic Zone

For the state as a whole, there is a 2.5 percent probability of extensive damage, and 27 of the 75 counties have a positive (non-zero) probability of extensive damage. Cross, St. Francis, Mississippi, and Crittenden Counties (Northeast Arkansas) have average probabilities of 20 percent. By roadway classification, the highest probability of extensive damage (4.1%, average score of 0.69) is observed for interstates, while the lowest average probability is observed for principal arterials (2.2%, average score of 0.44) (Table 20). Translating the probability of extensive damage to an earthquake vulnerability score, 77 percent of the roadway links are expected to have zero probability of extensive damage (score of zero), while 11 percent of the links have a probability between 25 and 34 percent of extensive damage (score of 3).

Combined Vulnerability

The vulnerability scores for each threat (flood, landslide, and earthquake) were combined using an equal-weighted average to estimate the combined vulnerability (Figure 37). The combined vulnerability score was then categorized as low, moderate, and high based on natural breaks in the data and the goal of having around 1 percent of the roadway segments qualify as highly vulnerable. Overall, 1.2 percent (838 segments, 1.9% by mileage) of roadway segments were considered to be highly vulnerable (score >1.0) based on the underlying data and assumptions used (Table 21).

Table 20. Probability of Extensive Damage from Earthquake by Roadway Classification

Roadway Class	Average Probability of Extensive Damage	Average Vulnerability Score
1: Major Collectors	2.6%	0.50
2: Minor Arterials	2.4%	0.45
3: Principal Arterials	2.2%	0.44
4: Freeway/Expressway	3.7%	0.80
5: Interstate	4.1%	0.69
Grand Total	***2.6%***	***0.49***

Table 21. Summary of Roadway Segments and Mileage by Vulnerability Score

Vulnerability Score	Number of Roadway Segments (percent of segments)	Total Mileage (miles) (percent of miles)
0: None	48,400 (69.2%)	13,457 (64.6%)
0-0.5: Low	9,386 (13.4%)	3,111 (14.9%)
0.5-1: Moderate	11,313 (16.2%)	3,890 (18.7%)
1.0-2: High	838 (1.2%)	387 (1.9%)
Total	***69,937***	***20,845***

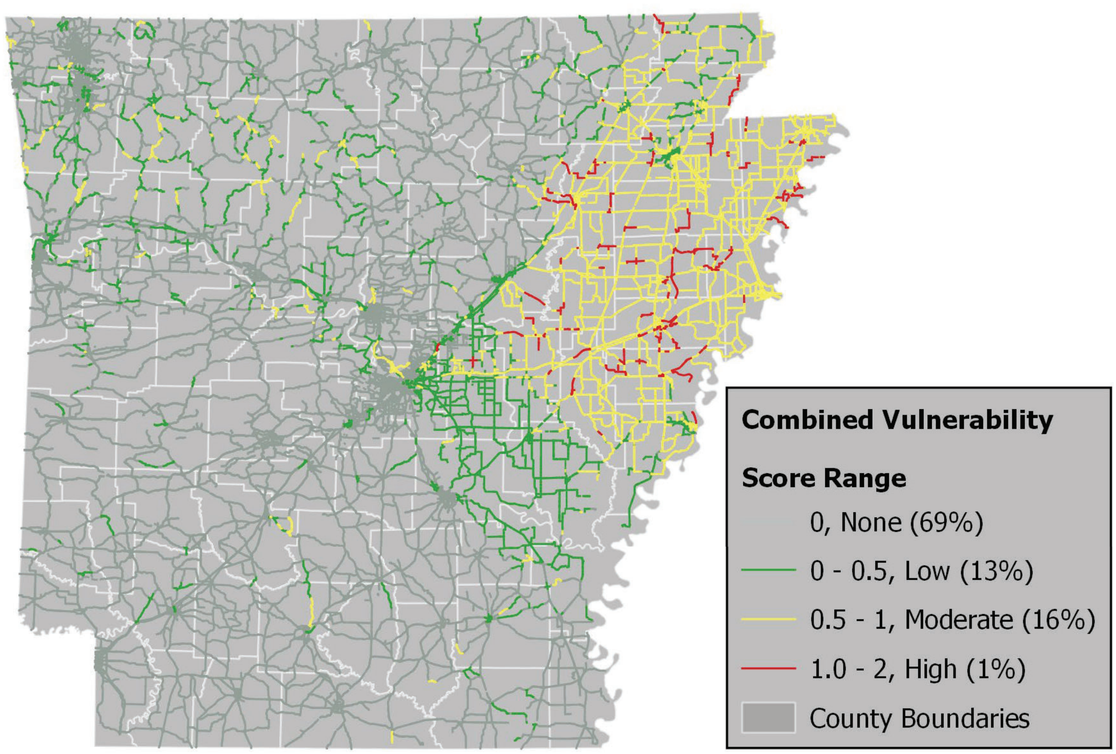


Figure 37. Combined Vulnerability Map Showing the Links with Flood, Landslide, and/or Earthquake Events combined with Equally Weighted Average Ranking

By average vulnerability score across all segments in the county, the following counties rank as having high vulnerability with scores above 1.0 and are all located in east-central Arkansas based on the underlying data and assumptions used: St. Francis (average vulnerability score: 1.04), Cross (1.03), Mississippi (1.03), and Crittenden (1.01). Their ranking is largely dependent on their high scores for earthquake damage. By roadway class, the second-highest average vulnerability of the interstates is 0.29, while the lowest average score of 0.17 is seen for principal arterials (Table 22).

Table 22. Average Vulnerability Score by Roadway Class

Roadway Class	Average Vulnerability Score
1: Major Collectors	0.21
2: Minor Arterials	0.20
3: Principal Arterials	0.17
4: Freeway/Expressway	0.32
5: Interstates	0.29
Statewide Average	***0.20***

COMBINED CRITICALITY AND VULNERABILITY

The approach outlined in Chapter 3 was applied to combine criticality and vulnerability to identify the ranking of critical network links (Figure 38). The following analysis and figures correspond to the unequal weighting of criticality criteria based on the application of the AHP method to rank order criticality criteria. The designation of segments by combined criticality and vulnerability as low (<=2), moderate (<=3), high (<=4), and priority (>4) are based on the goal of including 1 percent of the links in the priority category. Sixteen roadway segments totaling approximately 7.2 miles have a combined criticality and vulnerability score above 5.0. These segments are in Pulaski and Crittenden Counties. Based on the average combined criticality and vulnerability score, the following three counties are ranked highest (>3.0) based on the underlying data and assumptions used:

1. Crittenden with an average combined criticality and vulnerability score of 3.55
2. Mississippi with 3.42
3. Craighead with 3.01

By roadway class, the average combined criticality and vulnerability score is highest for interstates (3.4) and lowest for major collectors (1.9), with a statewide average of score of 2.2 (Table 23).

Table 23. Combined Criticality and Vulnerability by Roadway Class

Roadway Class	Average Combined Criticality and Vulnerability
1: Major Collectors	1.9
2: Minor Arterials	2.3
3: Principal Arterials	2.6
4: Freeway/Expressway	2.9
5: Interstates	3.4
Statewide Average	***2.2***

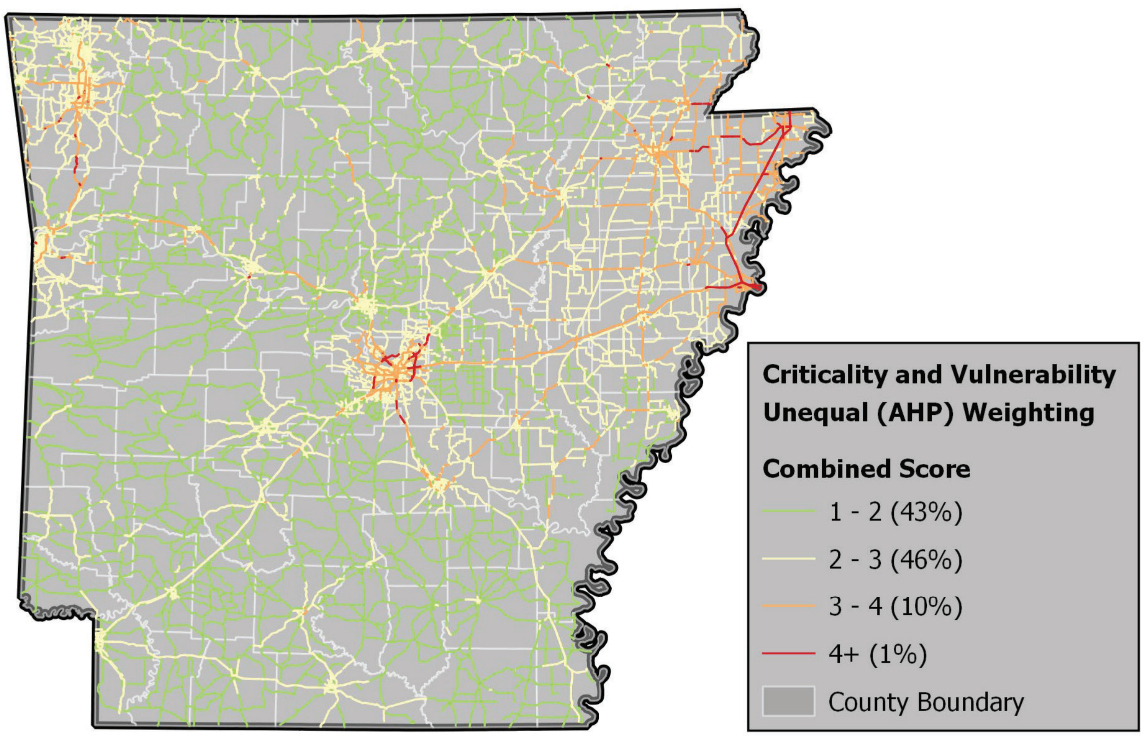


Figure 38. Combined Scoring of Vulnerable and Critical Links on the Arkansas Highway Network Using the Unequal (AHP) Weighting Approach for Criticality

Top-Ranked Sites

To combine vulnerability and criticality, we summed the vulnerability score and the criticality score. This produced a combined score such that a higher value was assigned when a link was both highly critical and highly vulnerable. Many of the top-ranked links are part of the same corridor or segment. For this reason, we combined adjacent links into longer study segments. The top five segments (most critical and most vulnerable) based on the underlying data and assumptions used include (Figure 39):

1. Highway 67: Pulaski County (20 links, 9.58 miles)
2. Interstate 55 (Highway 64): Crittenden County (8 links, 1.68 miles)
3. Interstate 40: Crittenden County (12 links, 5.2 miles)
4. Interstate 430: Pulaski County (6 links, 1.78 miles)
5. Interstate 55 (Highway 63): Crittenden County (3 links, 3.1 miles)

Two of the five most critical and vulnerable links are located in Pulaski County (Figure 40), and the remaining three are in Crittenden County (Figure 41). The sites in Pulaski County on Highway 67 are not continuous but are considered as one study segment since they are along the same highway and would affect the same traffic flows.

The top links being present in only two counties is partly due to the equal weighting of criticality factors. Recall that criticality is calculated by combining six criteria: (1) roadway classification, (2) annual average daily traffic, (3) tourism expenditures, (4) freight value, (5) Social Vulnerability Index (SoVI), and (6) link redundancy. The criteria for tourism, freight, and SoVI are estimated for the county, and thus all links in the county are attributed the same value. The criticality score for Pulaski County is 5 (high) for freight and tourism. This pushes links in Pulaski County to the top of the list for most critical links. Adjusting the weights of the criteria when calculating the criticality and/or vulnerability measures can have a moderate effect on the overall ranking of the most critical and vulnerable links.

These five links are recommended as case study locations. For the case studies, we estimate the costs to improve the link and/or asset and compare them to the estimated costs of not improving the link and/or asset. In Chapter 5, we detail the suggested types of improvements and include appropriate detour routes to follow if the link and/or asset were to become non-operational.

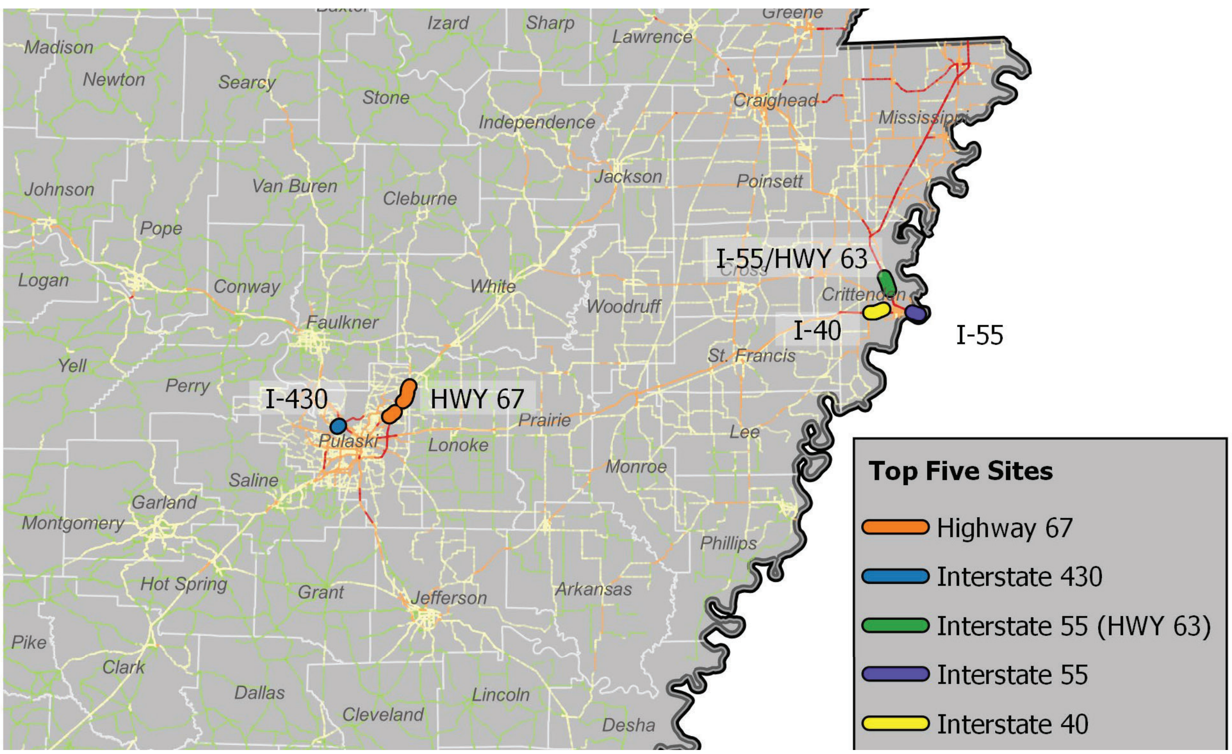


Figure 39. Locations of the Five Most Vulnerable and Critical Segments

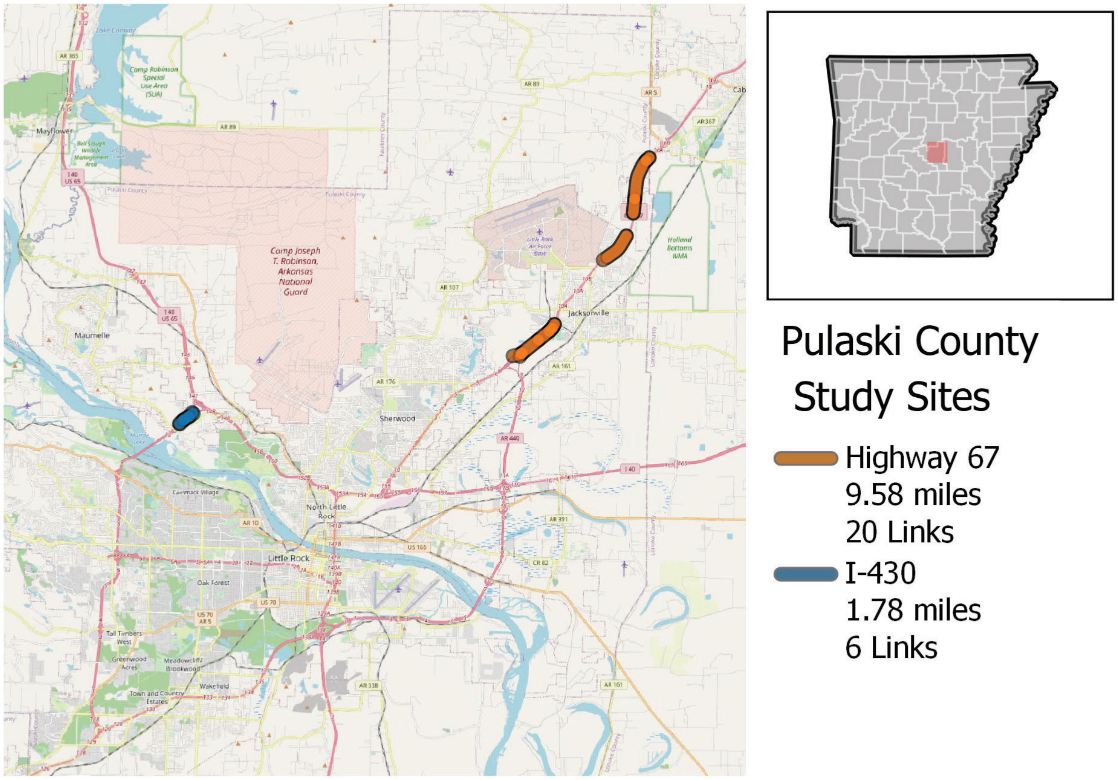


Figure 40. Pulaski County Study Sites

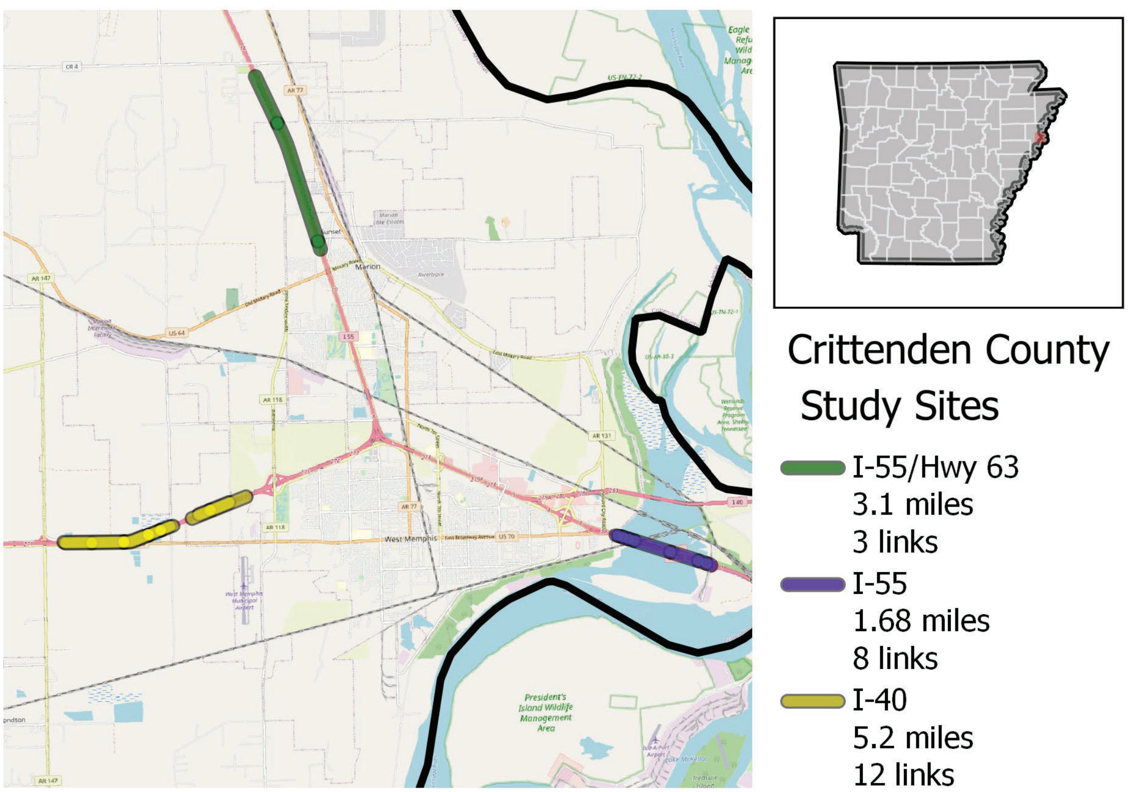


Figure 41. Crittenden County Study Sites

CHAPTER 5: BENEFIT/COST ANALYSIS CASE STUDIES

This chapter provides an overview of the benefit-cost methodology applied to estimate the benefit-cost ratios for mitigative actions at each of the five most critical and vulnerable study segments. The full benefit-cost analyses can be found in Appendix D.

OVERVIEW OF BENEFIT-COST METHODOLOGY

Benefit-cost analyses are used to compare cost-effective asset mitigation and/or protection solutions for addressing system vulnerabilities of the most critical links. The quantitative method applied in this work estimates: (1) the potential loss of an asset resulting from impacts by physical threats like floods, landslides, and earthquakes, (2) the loss of service of the asset and its impacts on the travelling public, and (3) the cost of improvements to the asset that would strengthen the asset to withstand disruptive events in the future. The approach is probabilistic, monetarily quantifiable, and a function of consequences, hazard frequency or likelihood, and the vulnerability of an asset to an identified threat or event. In particular, we follow the procedures outlined in the risk and resilience procedure developed for the Colorado DOT (CDOT 2020) (Figure 42).

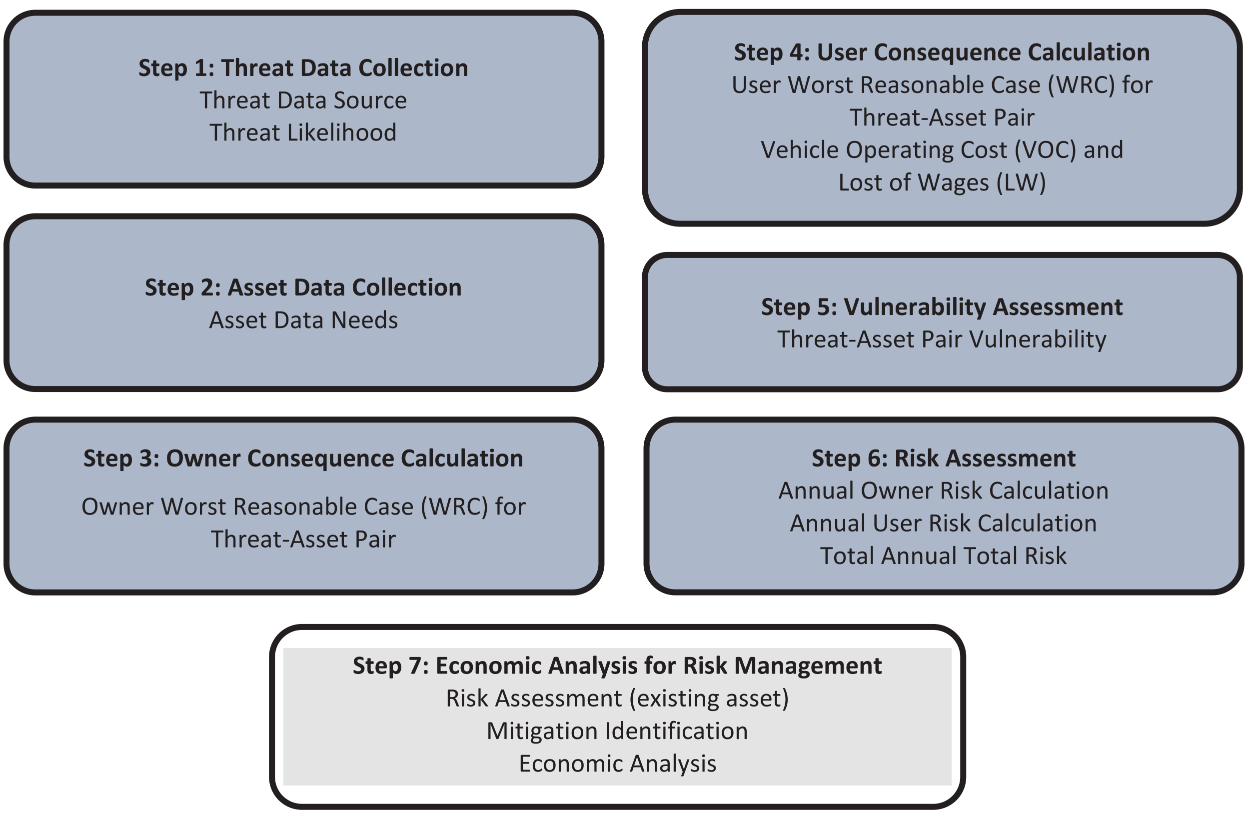


Figure 42. Overview of the Benefit-Cost Analysis procedure; adapted from (CDOT 2020)

Threat Data Collection

In Step 1, the threat source and history of occurrence are used to estimate threat likelihood. In this project, we considered floods, landslides, and earthquakes. Floods and landslides were considered based on historical data gathered from ArDOT and the Arkansas Geological Survey. Earthquake damage potential was estimated from the FEMA Hazus model. Threat likelihoods for floods were based on flood recurrence, e.g., 100-yr flood, when considering bridges, roadways, and major culverts (Table 24). Threat likelihoods for landslides relied on assumptions of landslide size in terms of area, slope, and land cover. The CDOT study approach included detailed modeling on landslide activity for each of their study locations. As an approximation, in this study, we assumed a moderately sized landslide area and topography to estimate threat likelihood for a small, medium, and large landslide occurrence (Table 25). Threat likelihoods for earthquakes were based on predicted activity probabilities for the New Madrid Seismic Zone provided by the USGS (Frankel et al. 2009) (Table 26). The USGS Fact Sheet states, "Based on this history of past earthquakes, the USGS estimates the chance of having an earthquake similar to one of the 1811–12 sequence in the next 50 years is about 7 to 10 percent, and the chance of having a magnitude 6 or larger earthquake in 50 years is 25 to 40 percent". The Hazus model estimated damage probabilities based on a 7.7 magnitude earthquake. Thus, applying the USGS guidance, we assumed a two percent chance of an earthquake of that magnitude occurring over the next 50 years.

Table 24. Flood Recurrence Threat Likelihood

Recurrence Interval (Years)	Threat Likelihood
1	1/1
2	1/2
5	1/5
10	1/10
25	1/25
50	1/50
100	1/100
500	1/500

Table 25. Landslide Threat Likelihood

Category	Threat Likelihood
T_{small}	0.20
T_{Medium}	0.05
T_{Large}	0.01

Table 26. Earthquake Threat Likelihood

Category	Threat Likelihood
T_{50}	0.0004

Asset Data Collection

In Step 2, data on the asset characteristics (e.g., width, length, etc.), condition, and use (e.g., AADT, etc.) were collected. Asset replacement costs were gathered from Hazus, and those unavailable were estimated using unit cost (Table 28). The FHWA National Bridge Inventory (NBI) database was used for bridge size and condition (FHWAc, 2022). When specific asset characteristics were not available directly from ARDOT, measurements were approximated from Google Earth or referenced from the CDOT study where appropriate. The following details were gathered or estimated for each asset:

1. *Type of culvert*, e.g., concrete box culvert (CBC): gathered from ARDOT asset database
2. *Width*: gathered from ARDOT asset database and cross-referenced with NBI database
3. *Length*: gathered from ARDOT asset database and cross-referenced with NBI database
4. *Height*: 15 ft assumed from CDOT study (for culverts)
5. *Condition*: gathered from NBI database
6. *Hydraulic capacity*: baseline value of 50-yr assumed from CDOT study

The following details were gathered or estimated for the area surrounding each asset:

1. *Drainage basin land cover*: observed using Google Earth
2. *Slope of surrounding area*: approximated from Google Earth
3. *Landslide area*: assumed to be categorized as "large" based on CDOT study
4. *Frequency of movement (landslide)*: assumed to be moderate based on CDOT study

Owner Consequence Calculation

In Step 3, owner consequences of asset damage or non-operation are calculated in terms of costs of asset replacement and clean-up. For bridges and culverts, the cost of replacement and clean-up due to flood is 100 percent of the asset replacement cost (ARC) and $5,000 for clean-up (Table 27). The ARDOT asset database and the Hazus inventory contain data on ARC. When the ARC was not directly available from the ARDOT asset database or the Hazus inventory, per unit costs (e.g., per sq foot for bridges and per cubic foot for culverts) were used to estimate the replacement cost (Table 28). Cost for culvert ARC were based on square footage following the example in the CDOT study referenced previously. At the time of this study, square footage estimates were based on the length and width measurements provided by the ARDOT and NBI databases and an assumed height gathered from the CDOT study. In future work, if more accurate ARC are available, they can be used in place of the estimated values described in this section of the report.

Table 27. Asset Replacement and Clean-up Costs for Owner Consequence Calculation (CDOT 2020)

Asset	Threat			
	Debris Flow	Flood	Scour	Rockfall
Bridge	N/A	100% ARC + $5,000 Cleanup	100% ARC + $5,000 Cleanup	100% ARC + $200,000 if length <100 ft, else $2.5 million
Culvert	100% ARC + $5,000 Cleanup	100% ARC + $5,000 Cleanup	N/A	N/A
Roadway	100% ARC + $5,000 Cleanup	100% ARC + $5,000 Cleanup	N/A	100% ARC of 100 ft section + $200,000 Cleanup

Table 28. Unit Costs for Asset Replacement Cost

Asset	Units	Unit Cost
Bridge	sq ft	$600
Culvert	cu ft	$55
Road Prism (Asphalt)	sq yds	$150
Road Prism (Concrete)	sq yds	$350

User Consequence Calculation

In Step 4, "User Consequences" are estimated. These generally include the cost incurred by travelers due to delays and detours resulting from full and partial closure periods in terms of vehicle operating and running costs and their personal time. User consequences are estimated for partial and full closure situations (Equation 4). Full closures correspond to bridge and culvert damage scenarios where the entire roadway would be closed to traffic as a result of damage and reconstruction. Partial closures correspond to roadway damage from floods or landslides that may not close the entire roadway facility and may leave one or more travel lanes operational.

$$\boldsymbol{Total\ User\ Consequences = User\ Consequence_{FC} + User\ Consequence_{PC}} \quad \textbf{Equation 4}$$

Where

$User\ Consequence_{FC}$ = User consequences due to full closure

$User\ Consequence_{PC}$ = User consequences due to partial closure

User consequence for full and partial closures are based on estimated vehicle operating costs (VOC) and lost wages (LW) (Equation 5).

$$\boldsymbol{User\ Consequence_{s} = VOC_{s} + LW_{s}} \quad \textbf{Equation 5}$$

Where,

VOC_s = Vehicle operating costs incurred due to scenario *s* = [full closure (FC), partial closure (PC)]

LW_s = Lost wages/truck revenue incurred due to scenario *s* = [full closure (FC), partial closure (PC)]

VOC for full closures is a function of vehicle running costs for passenger vehicles and trucks, and their respective traffic volumes expressed as AADT, the difference in miles between the detour and the original route, and the number of days of the full closure (Equation 6). VOC for partial closures is a function of work zone characteristics (length, speed limit, and speed limit reduction), traffic volumes for passenger vehicles and trucks and their respective running costs, and the number of days of the partial closure (Equation 7). In this study, AADT is derived from the ARTDM. AADT used in Equation 6 and elsewhere for Benefit/Cost ratio calculations follows the convention of one- and two-way volumes for divided and undivided highways as provided in the ARTDM. There may be instances in the network contained in the ARTDM that do not follow the general convention of divided or undivided highways as one- or two-way volumes, respectively. In these cases, no correction was made to the volume. Instead, the volumes of the ARTDM are directly used. It should also be noted that AADT volumes used in this study may differ from those reported in the ARDOT *Road and Street Data* reports. This is due to the differing characterization of roadway types and directional volumes, as well as the reference year (ARTDM was last updated in 2009) between the ARTDM and the Road and Street Data report.

$$VOC_{FC} = \left((C2 \times AADT_{Vehicle}) + (C3 \times AADT_{Truck})\right) \times d_{FC} \times C7$$ **Equation 6**

Where

C2 = Vehicle running cost ($/vehicle-mile)

C3 = Freight running cost ($/truck-mile)

C7 = Difference in distance between detour and original route (mile)

$AADT_{Vehicle}$ = Average annual daily traffic (non-truck)

$AADT_{Truck}$ = Average annual daily truck traffic

d_{FC} = Number of full closure days (days)

$$VOC_{pc} = \left[\left(\frac{1}{\left(\frac{1}{WL}\right)(WZS - WZSR)} - \frac{1}{\left(\frac{1}{WL}\right)WZS}\right) \times \left((C8 \times AADT_{Vehicle}) + (C9 \times AADT_{Truck})\right)\right] \times d_{pc}$$

Equation 7

Where

WL = Work zone length (miles)

WZS = Work zone speed limit (mph)

WZSR = Work zone speed limit reduction (mph)

C8 = Vehicle running cost ($/vehicle-hour)

C9 = Freight running cost ($/truck-hour)

d_{PC} = Number of days of partial closure (days)

Lost wages for full closures are a function of the driver's value of time, vehicle occupancy, traffic volumes for passenger vehicles and trucks, extra travel time on the detour, and the number of days of the full closure (Equation 8). Lost wages for partial closures are a function of work zone characteristics, the driver's value of time, vehicle occupancy, traffic volumes for passenger vehicles and trucks, and the number of days of the full closure (Equation 9).

$$LW_{FC} = ((C4 \times O \times AADT_{Vehicle}) + (C5 \times AADT_{Truck})) \times d_{FC} \times \left(\frac{D_t}{60}\right)$$ **Equation 8**

$$LW_{pc} = \left[\left(\frac{1}{\left(\frac{1}{WL}\right)(WZS - WZSR)} - \frac{1}{\left(\frac{1}{WL}\right)WZS}\right) \times \left((C4 \times AADT_{Vehicle} \times O) + (C5 \times AADT_{Truck})\right)\right] \times d_{pc}$$

Equation 9

Where

$C4$ = Average value of time ($/adult-hour)
O = Average occupancy (adult/vehicle)
$C5$ = Average value of freight time ($/truck-hour)
D_t = Extra travel time on detour (minutes)
Other terms have been defined previously.

Values for most of the variables listed above were gathered from *Benefit-Cost Analysis Guidance for Discretionary Grant Programs* (USDOT, 2021) and are provided in 2019 US dollars (Table 29 and Table 30). Variables C8 and C9, vehicle and truck running costs per hour, respectively, were taken from the CDOT study. The variable for average occupancy (O) was gathered from the ARTDM and references to a base year of 2009.

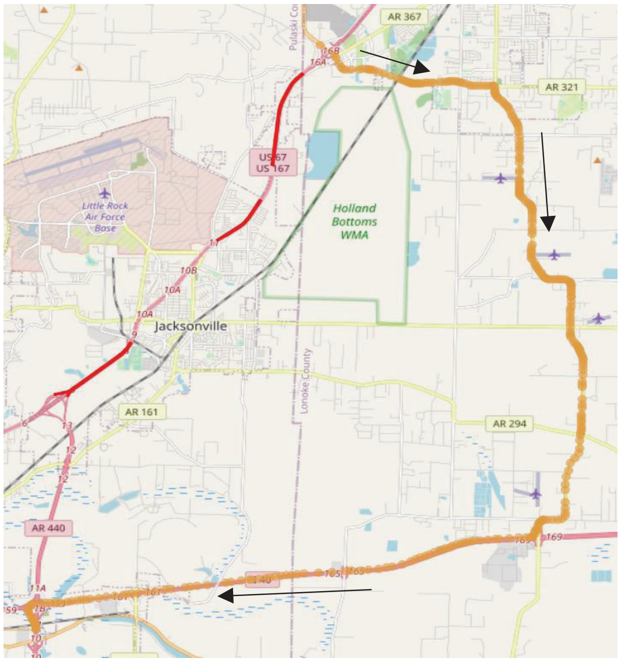
Detour length in distance and time was used to estimate user consequences. In our analysis, we included detour travel time and length based on the shortest route around the damaged asset using ARDOT-maintained roadways. As a point of reference, we also estimated the detours along (1) the path that avoids high flood risk zones and (2) the path of lowest vulnerability (using the estimated vulnerability score). For (1), the FEMA Flood Insurance Rate Maps (FIRMS) were used to determine regions of flood activity when deciding detour routes. In all cases, the speed limits were determined from the ARDOT "Speed Limits" GIS files found on the ARDOT Featured Maps and Apps webpage. Distances for the detours were estimated using QGIS's Measure tool and referenced to the Open StreetMap GIS layer. The following maps demonstrate how detours were estimated for the Highway 67 study site (Pulaski County) (Figure 43). In this example, the detour on ARDOT roadways is approximately 25 miles (27 minutes), 64 miles (70 minutes) around the floodplain regions, and 64 miles (70 minutes) on links having low vulnerability.

Table 29. Values of Variables Used in User Consequence Calculations

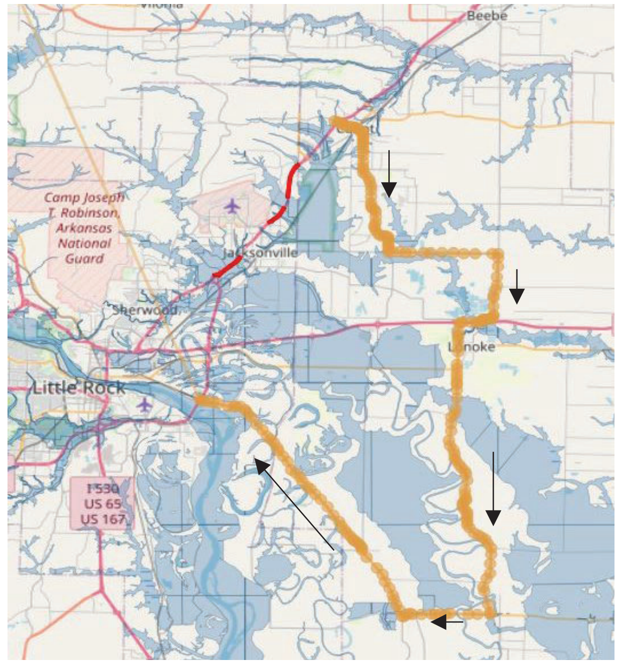
User Cost Terms	Variable	Value
Average Vehicle Occupancy	O	1.67
Car Running Cost per Mile	C2	$0.43
Truck Running Cost per Mile	C3	$0.93
Average Value of Time per Adult per Hour	C4	$17.90
Average Value of Freight Driver Cost per Hour	C5	$30.80
Car Running Cost per Hour	C8	$26.52
Truck Running Cost per Hour	C9	$44.24

Table 30. Values Used for Estimated Full and Partial Closure Days by Threat and Asset (CDOT 2020)

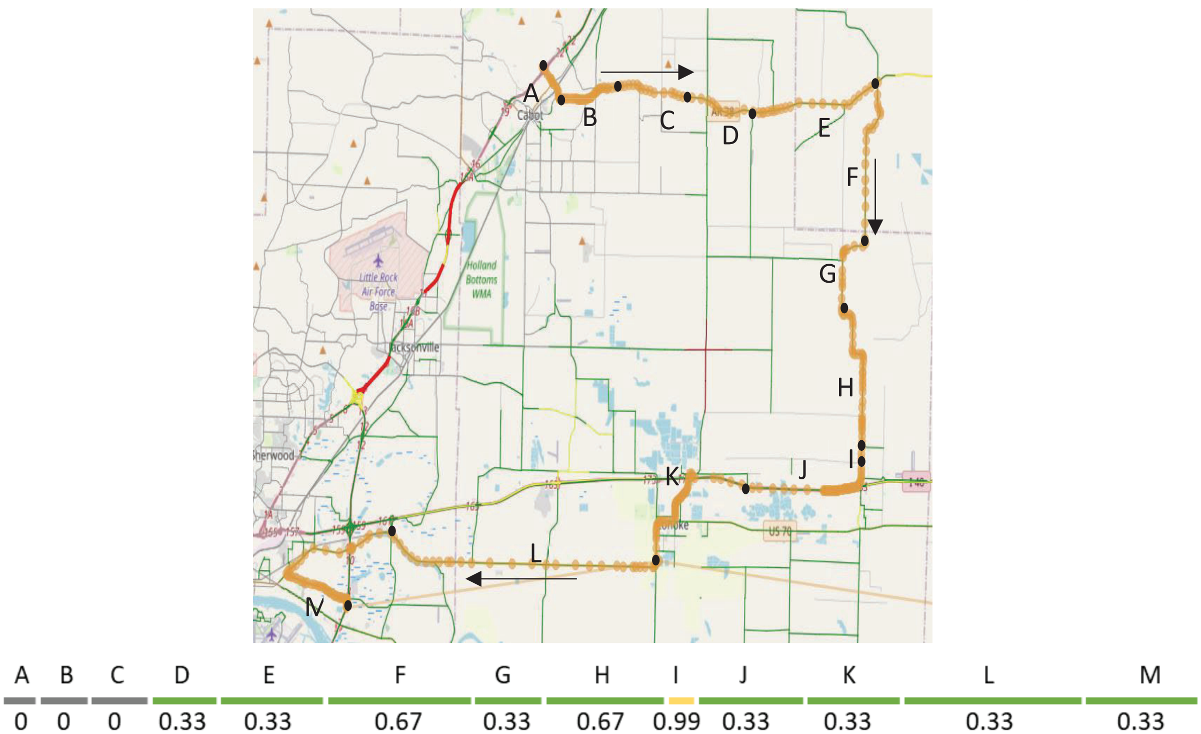
Asset	Threat	Full Closure Days (d_{FC})	Partial Closure Days (d_{PC})
Bridge	Flood	180	0
Bridge	Landslide	25	25
Bridge	Earthquake	180	0
Culvert (major)	Flood	30	0
Culvert (minor)	Flood	3	0



(a) Detour on ARDOT Roadways



(b) Detour Around Floodplain



(c) Detour on Low Vulnerability Roadways

Figure 43. Detour Routing Examples, Highway 67 Study Site

Vulnerability Assessment

In Step 5, the vulnerability of each asset to threats is estimated as a probability between zero (not vulnerable) and one (highly vulnerable). This estimate is based on the probability of the worst reasonable case occurring due to a threat occurring and is dependent on the threat and asset pair. We use the vulnerability estimates generated in CDOT (2020), based on judgments from subject matter experts. The vulnerability of culverts due to flooding depends on flood magnitude, hydraulic capacity, culvert condition, channel condition, and debris potential (Table 31, shown for the 100-yr flood event). Debris potential is a function of land cover and slope (Table 32). The vulnerability of bridges due to flooding depends on hydraulic capacity, scour, superstructure and substructure condition, span length, and debris potential (Table 33, shown for 100-yr flood event). The vulnerability of culverts and bridges due to landslides are generalized from the vulnerability values from CDOT (2017) and are dependent on site characteristics (Table 34). Vulnerability due to earthquakes are gathered from the Hazus model for the link on which the asset resides and are specific to the asset (Table 35).

Table 31. Culvert Vulnerability Look-Up Table (CDOT 2020)

Flood Event Magnitude	Hydraulic Capacity	Culvert Condition	Channel and Channel Protection	Debris Potential				
				Very Low	Low	Moderate	High	Very High
100-yr	100-yr	7-9	7-9	0.001	0.001	0.004	0.01	0.02
			4-6	0.001	0.001	0.007	0.01	0.03
			0-3	0.002	0.002	0.004	0.02	0.04
		4-6	7-9	0.001	0.002	0.005	0.02	0.03
			4-6	0.001	0.002	0.007	0.02	0.04
			0-3	0.002	0.003	0.01	0.04	0.07
		0-3	7-9	0.003	0.004	0.01	0.05	0.09
			4-6	0.004	0.005	0.02	0.06	0.11
			0-3	0.007	0.009	0.03	0.10	0.18
	50-yr	7-9	7-9	0.03	0.04	0.12	0.40	0.73
			4-6	0.03	0.04	0.15	0.49	0.90
			0-3	0.05	0.07	0.24	0.81	0.99
		4-6	7-9	0.04	0.05	0.18	0.60	0.99
			4-6	0.05	0.07	0.22	0.73	0.99
			0-3	0.08	0.11	0.36	0.99	0.99
		0-3	7-9	0.11	0.15	0.49	0.99	0.99
			4-6	0.13	0.18	0.60	0.99	0.99
			0-3	0.22	0.30	0.99	0.99	0.99

Table 32. Debris Potential Look-Up Table for Culvert Vulnerability Calculations (CDOT 2020)

Mean Basin Site Slope	Land cover of Drainage Area: Water and Snow	Urban	Shrubs	Trees
Low (0–8%)	Very Low	Low	Moderate	Moderate
Moderate (9–16%)	Very Low	Moderate	High	High
High (>16%)	Very Low	High	High	Very High

Table 33. Bridge Vulnerability Look-Up Table for 100-Yr Flood Event (CDOT 2020)

				Superstructure Condition								
				7–9 Substructure Condition			5–6 Substructure Condition			0–4 Substructure Condition		
Hydraulic Capacity	Debris Potential	Scour Condition	Span Length	7–9	5–6	0–4	7–9	5–6	0–4	7–9	5–6	0–4
100-yr	Very Low	4–9	> 30 ft	0.001	0.003	0.015	0.002	0.005	0.028	0.006	0.016	0.085
			< 30 ft	0.001	0.004	0.02	0.003	0.007	0.038	0.008	0.021	0.117
		0–3	> 30ft	0.206	0.5	0.5	0.386	0.5	0.5	0.5	0.5	0.5
			<30ft	0.282	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5
	Low	4–9	> 30 ft	0.001	0.003	0.017	0.002	0.006	0.031	0.007	0.018	0.097
			< 30 ft	0.002	0.004	0.023	0.003	0.008	0.043	0.009	0.024	0.133
		0–3	> 30 ft	0.233	0.5	0.5	0.437	0.5	0.5	0.5	0.5	0.5
			< 30 ft	0.32	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5
	Moderate	4–9	> 30 ft	0.001	0.003	0.019	0.003	0.007	0.035	0.008	0.02	0.11
			< 30 ft	0.002	0.005	0.026	0.003	0.009	0.049	0.011	0.028	0.15
		0–3	> 30ft	0.265	0.5	0.5	0.496	0.5	0.5	0.5	0.5	0.5
			< 30 ft	0.362	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5
	High	4–9	> 30ft	0.002	0.004	0.021	0.003	0.007	0.04	0.009	0.023	0.125
			< 30 ft	0.002	0.005	0.029	0.004	0.01	0.055	0.012	0.031	0.171
		0–3	> 30 ft	0.3	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5
			<30 ft	0.411	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5
	Very High	4–9	> 30ft	0.002	0.005	0.028	0.004	0.009	0.052	0.011	0.029	0.16
			< 30 ft	0.003	0.007	0.038	0.005	0.013	0.071	0.016	0.04	0.219
		0–3	> 30 ft	0.386	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5
			< 30 ft	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5

Table 34. Landslide Vulnerability for Existing and Improved (Mitigation) Conditions

Variable	Existing	Mitigation
V_{Low}	0.02	0.01
$V_{Moderate}$	0.15	0.02
V_{High}	0.75	0.03

Table 35. Vulnerability of Earthquake Damage

Site	Vulnerability	Value
I-40, Crittenden *(Link 52234)*	$V_{no\ damage}$	0.7531
	$V_{extensive}$	0.1974
	$V_{complete}$	0.0493
I-55/HWY 64, Crittenden *(Link 74473)*	$V_{no\ damage}$	0.7546
	$V_{extensive}$	0.1962
	$V_{complete}$	0.049
I-55/HWY 63, Crittenden *(Link 52084)*	$V_{no\ damage}$	0.7522
	$V_{extensive}$	0.1981
	$V_{complete}$	0.0496

Risk Assessment

In Step 6, the total risk to the asset is calculated. Risk is the multiplicative estimate of consequences, vulnerability, and threat likelihood, and it is annualized for owner and user consequences (Equations 10 and 11). Consequence estimates for owners and users are calculated in Steps 3 and 4 respectively. Vulnerability values for each event are selected in Step 5, while threat likelihood is selected in Step 1. The number of events refers to scenarios of future threat events, for example, both 100- and 500-year flood event probabilities are included in the calculation of risk. Total annual risk is the summation of the annual user and owner risks (Equation 12).

$$\sum_{i=1}^{n} \textit{Annual User Risk}_i = \textit{Consequence} \times \textit{Vulnerability}_i \times \textit{Threat Likelihood}_i$$

Equation 10

$$\sum_{i=1}^{n} \textit{Annual Owner Risk}_i = \textit{Consequence} \times \textit{Vulnerability}_i \times \textit{Threat Likelihood}_i$$

Equation 11

$$\textit{Total Annual Risk} = \sum_{i=1}^{n} \textit{Annual Owner Risk} + \sum_{i=1}^{n} \textit{Annual User Risk}$$

Equation 12

Where

n = number of events.

All other terms have been specified previously.

Economic Analysis for Risk Management

After Step 6, we arrive at an estimate of total risk to the existing asset. To continue toward a calculation of benefit-cost ratios for mitigation (risk management), we apply three additional steps. In Step 7, we identify possible mitigation alternatives that are dependent on the particular asset. For culverts in the case of flood events, the mitigation alternative is to upgrade the hydraulic capacity of the culvert by increasing the culvert size. For bridges in the case of earthquakes the mitigation alternative is to add cross culverts to low points on the roadway in the vicinity of the bridge. For earthquakes for bridges, the mitigation measure is to perform a seismic retrofit of the bridge. Seismic retrofit cost estimates are based on general factors provided in the *Seismic Retrofitting Manual for Highway Structures: Part 1 – Bridges* (Table 36) (FHWA 2006). In this work, we assume an average cost and that only the superstructure will be retrofit. The factors are multiplied by the bridge replace-in-kind cost.

Table 36. Seismic Retrofit Cost Estimate Factors

Cost Range	**Retrofit Strategy**		
	Superstructure Only	Superstructure and Substructure	Superstructure, Substructure and Foundations
Low	1.3	0.7	2.3
Average	3.1	15.4	28.8
High	13.2	64.8	232.9

Note: Reprinted from Seismic Retrofitting Manual for Highway Structures: Part 1 – Bridges

Next, we follow Steps 1–6 to estimate the risk for the mitigation alternative and annualize the cost of the mitigation (Equation 13). To estimate risk, we consider a reduced vulnerability due to the improvement at the site. For floods, the hydraulic capacity of the culvert and bridge increases, e.g., 50-yr to 100-yr, which reduces the vulnerability as indicated in the look-up tables. For earthquakes, we assume that the improvement will reduce the vulnerability of the asset by lowering the probability of extensive and complete damage to zero, thus only leaving a probability of no damage. Subsequently, the annualized mitigation benefit is calculated as the difference between the annual risk of the existing asset and the annual risk of the alternative (Equation 14). Finally, we estimate the benefit-cost ratio as the annualized mitigation benefit relative to the annualized mitigation cost (Equation 15).

$$\boldsymbol{Mitigation\ Annual\ Cost = Mitigation\ Present\ Cost \times \frac{i\times(1+i)^n}{(1+i)^n-1}}$$ **Equation 13**

$$\boldsymbol{Mitigation\ Benefit = Total\ Annual\ risk_{Baseline} - Total\ Annual\ Risk_{Mitigation}}$$
Equation 14

$$\boldsymbol{\frac{B}{C} = \frac{Mitigation\ Benefit}{Annual\ Cost\ of\ Mitigation}}$$ **Equation 15**

Where

$Total\ Annual\ risk_{Baseline}$ = annualized total risk for existing conditions of the asset

$Total\ Annual\ Risk_{Mitigation}$ = annualized total risk for the alternative (improved) conditions of the asset

i = Discount rate (7% used in accordance with USDOT Benefit-Cost Analysis Guidance for Discretionary Grant Programs) (USDOT 2021)

n = life expectancy of mitigation

CASE STUDY SUMMARIES

The five most critical and vulnerable roadway segments based on the underlying data and assumptions used were selected following the procedures outlined in Chapter 3 (Table 37). The threat that contributed most to the vulnerability score that is most apparent based on the asset's environmental setting is used for the analysis of mitigative action costs. For example, the Highway 67 segment in Pulaski County was most impacted by floods with some of the comprising segments experiencing 11 road closure events due to flooding. We also consider only the asset on the roadway segment that was identified in the criticality and vulnerability analysis. Although it is likely that a threat would equally affect both directions of a roadway, we limit the benefit-cost analysis to only one direction, i.e., the direction of the roadway identified in the criticality and vulnerability analysis.

In this section, we present an overview of the benefit-cost analyses for each of the five study sites. It is important to note that the data used for characterizing assets are based on NBI and ARDOT asset inventories and aerial imagery. In several cases, the asset characteristics were reported differently in the NBI and ARDOT databases. In such cases, the research team defaulted to the measurement that was more logical, given aerial imagery. Also, characteristics unavailable in the ARDOT or NBI databases, such as hydraulic capacity, were assumed at the lower reasonable value (50-yr capacity in all cases) for a conservative estimate of risk. All mitigation alternative costs were based on CDOT study examples in lieu of recommendations from ARDOT. At the time of this study, recommendations from ARDOT could not be gathered due to the ongoing COVID-19 pandemic. Future works should aim to produce more accurate cost analyses. Full details for the BC analyses are provided in Appendix D.

Table 37. Top Five Study Sites Based on the Underlying Data and Assumptions Used

Site	Segment Length	County	Threat	Asset
1. Hwy 67	9.58 miles	Pulaski	Flood	Culvert, Bridge
2. I-430	1.78 miles	Pulaski	Flood	Bridge
3. I-40	5.20 miles	Crittenden	Earthquake	Bridge
4. I-55 (Hwy 63)	3.10 miles	Crittenden	Earthquake	Bridge
5. I-55 (Hwy 64)	1.68 miles	Crittenden	Earthquake	Bridge

The estimated detours for the top five study sites range from 2 to 195 miles (Table 38). Generally, detours increase as the restraining conditions on routes are tightened with avoidance of the flood zones having the tightest restrictions. The longest detours are seen for Site 5: I-55 (Hwy 64) where the detour route for the low vulnerability and flood zone routes are restricted by the Mississippi River, requiring rerouting to the Caruthersville Bridge in Missouri.

Table 38. Estimated Detour Routes for Study Sites

Site	Local links		Low vulnerable Links		Avoiding flood zone	
	Distance	Time	Distance	Time	Distance	Time
1. Hwy 67	25 miles	27 min	64 miles	70 min	64 miles	70 min
2. I-430	2 miles	3 min	18 miles	20 min	20 miles	22 min
3. I-40	11 miles	12 min	15 miles	16 min	15 miles	16 min
4. I-55 (Hwy 63)	18 miles	20 min	18 miles	20 min	9 miles	10 min
5. I-55 (Hwy 64)	8 miles	9 min	121 miles	132 min	195 miles	212 min

It should be noted that the following analyses are meant to be illustrative and are not definitive. Several assumptions and estimates were necessary to carry out the analysis. The key assumptions are as follows. First, the existing conditions and measurement characteristics for each asset were based on the National Bridge Inventory (NBI) database and the ARDOT Asset Inventory database provided by the project Subcommittee. When asset condition and/or characteristics were not found in these two databases, reasonable assumptions were made as stated in the Asset Data Collection section of this report. Second, truck traffic volumes ($AADT_{Truck}$ as per Equations 6-9 used for the user consequence calculation) were assumed as 10% for all sites except the I-55/Highway 64 site where the assumption was 20% truck traffic. A discussion on the sensitivity of the BC calculations related to truck traffic can be found in Chapter 6.

The proposed asset mitigation alternatives for each site are summarized in Table 39. For culverts in response to flood threats, the mitigation measure includes increasing the culvert's hydraulic capacity, i.e., from 50-yr to 100-yr hydraulic capacity. For bridges in response to flood threats, the mitigation measure includes adding flow-relief structures (cross culverts) to low points on the highway. For bridges in response to earthquakes, the mitigation measure includes retrofitting the bridge with restrainer cables or high-strength bars (Table 39).

A Benefit-cost ratio greater than one represents a higher benefit than cost, while a ratio less than one represents a lower benefit than cost. Projects with benefit-cost ratios greater than one are more favorable. The benefit-cost ratios range from 0.006 (no benefit relative to cost) to 3.64 (high benefit relative to cost) (Table 40). Total annual risk for the baseline conditions (owner and user) ranged from $65,000 for the Interstate 430 (I-430) bridge in Pulaski County to $142,000 for the Hwy 67 culvert in Pulaski County. The total annual risk (owner and user) as a result of the mitigative alternative ranged from $10,880 for the Hwy 67 culvert in Pulaski County to $80,000 for the I-55/Hwy 64 bridge in Crittenden County (Figure 44). Among a number of factors, the analysis is dependent on the asset costs gathered from the ARDOT asset database and the assumed costs for mitigation alternatives. We adopted the general costs for mitigative actions from the CDOT study (2017). Further analysis is required to determine more exact mitigative action costs.

Table 39. Summary of Existing Asset and Mitigation Proposed

Site	Asset Name	Existing Asset Basic Characteristics	Proposed Mitigation
1. Hwy 67	*Culvert "Branch Jacks Bayou"*	Concrete box culvert (CBC), 70 by 21.5 ft and assumed height of 15 ft; culvert condition = 9; channel condition = 8; assumed hydraulic capacity = 50-yr	Replace with larger CBC; proposed hydraulic capacity = 100-yr
	Bridge "Bayou Meto" (SB)	842 ft length by 67 ft width with max span length of 50 ft SB; superstructure condition = 7; substructure condition = 8; scour condition = 5; channel condition = 7; assumed hydraulic capacity = 50-yr	Add flow-relief structures (cross culverts) at low points on highway; hydraulic capacity = 100-yrs
2. I-430	*Bridge "White Oak Bayou" (NB)*	288 ft length by 62 ft width with max span length of 61 ft; superstructure condition = 7; substructure condition = 7; scour condition = 5; channel condition = 7	Add flow-relief structures (cross culverts) at low points on highway; hydraulic capacity = 100-yrs
3. I-40	*Bridge "Ditch No. 9" (EB)*	57 ft length by 43 ft width with max span length of 55 ft; superstructure condition = 8; substructure condition = 8; scour condition = 5; channel condition = 8	Seismic retrofit (restrainer cables or high-strength bars at hinges)
4. I-55 (Hwy 63)	*Bridge "15 Mile Bayou" (SB)*	81 ft length by 43 ft width with max span length of 29 ft; superstructure condition = 7; substructure condition = 7; scour condition = 5; channel condition = 8	Seismic retrofit (restrainer cables or high-strength bars at hinges)
5. I-55 (Hwy 64)	*Bridge "CR 314 CRI&P RR & Creek" (SB)*	3,476 ft length by 43 ft width with max span length of 107 ft; superstructure condition = 6; substructure condition = 7; scour condition = 5; and channel condition = 8	Seismic retrofit (restrainer cables or high-strength bars at hinges)

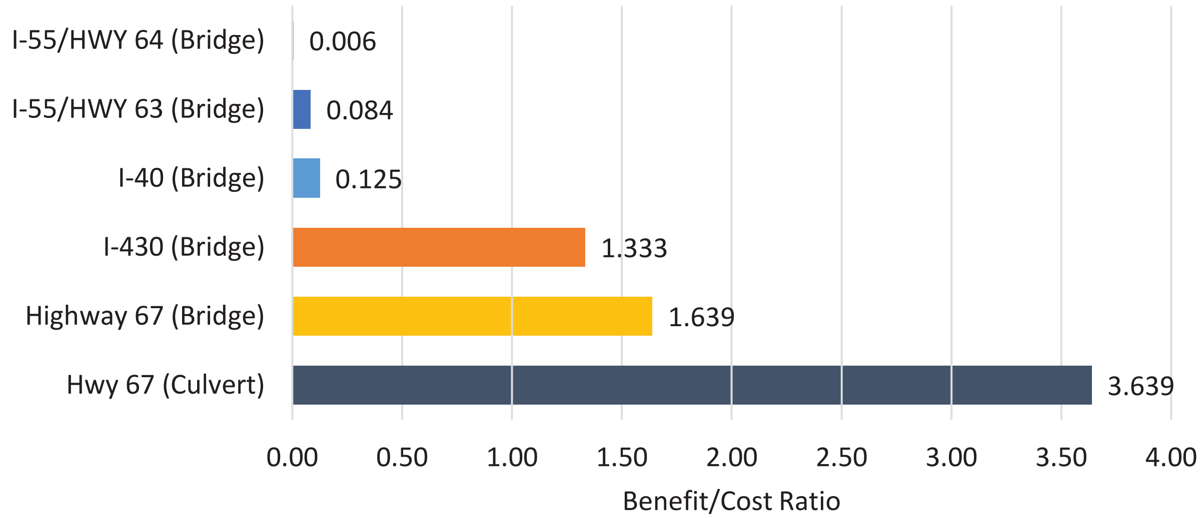


Figure 44. Summary of Benefit-Cost Analysis by Study Site

Table 40. Summary of Benefit-Cost Calculations for Five Most Critical and Vulnerable Road Segments

County	Site	Asset	Threat	Existing Asset (Baseline)			Alternative			Mitigation		B-C Ratio
				Annual Owner Risk	Annual User Risk	Total Risk	Annual Owner Risk	Annual User Risk	Total Risk	Annual Benefit	Annual Cost	
Pulaski	**Hwy 67**	Culvert	Flood	$5,000	$137,000	$142,000	$130	$10,750	$10,880	$131,000	$36,000	3.639
Pulaski	**Hwy 67**	Bridge	Flood	$3,000	$73,000	$76,000	$30	$17,000	$17,000	$59,000	$36,000	1.639
Pulaski	**I-430**	Bridge	Flood	$1,000	$64,000	$65,000	$30	$16,000	$17,000	$48,000	$36,000	1.333
Crittenden	**I-40**	Bridge	Earthquake	$1,000	$87,000	$88,000	$1,000	$65,000	$66,000	$22,000	$176,000	0.125
Crittenden	**I-55/ Hwy 63**	Bridge	Earthquake	$1,000	$87,000	$88,000	$2,000	$66,000	$67,000	$21,000	$250,000	0.084
Crittenden	**I-55/ Hwy 64**	Bridge	Earthquake	$16,000	$86,000	$102,000	$16,000	$65,000	$80,000	$22,000	$3,550,000	0.006

CHAPTER 6: KEY FINDINGS AND RECOMMENDATIONS

This study provides a foundational assessment of the Arkansas highway transportation system's resiliency. This section summarizes the developed methodologies, key findings, limitations, and future research directions.

Methodological Contributions

The assessment includes estimation of roadway segment criticality and vulnerability. Following from the work by CDOT (202), we used six criteria to estimate the criticality of each roadway segment: (1) annual average daily traffic (AADT), (2) roadway classification, (3) freight value, (4) tourism value, (5) Social Vulnerability Index, and (6) redundancy. Redundancy is a measure of the amount of travel time that will be added to the transportation network when a link is non-operational (closed). An algorithm to estimate redundancy was developed specifically for this project. The six criteria were individually scored from one to five, with one denoting low criticality and five suggesting high criticality. Then the six criteria were combined into a single metric using a weighted-average approach. Weights were based on the ranking of the criteria by the project Subcommittee. Redundancy was ranked first, followed by freight value. Once averaged, criticality was categorized as low, moderate, and high. Based on a survey of the project Subcommittee members, vulnerability was estimated for three threats: (1) floods, (2) landslides, and (3) earthquakes. The threat likelihood for floods and landslides was based on the frequency of occurrence of historical events. The threat likelihood for earthquakes was based on the FEMA Hazus model, which predicts the probability of damage, given a 7.7 magnitude earthquake on the New Madid Seismic zone. Flood, landslide, and earthquake threats were individually scored and combined. Roadway segment criticality and vulnerability were combined and scored as low, moderate, and high.

Key Findings

Crittenden, Mississippi, and Craighead Counties ranked highest in terms of combined criticality and vulnerability based on the underlying data and assumptions used. This is due to their high likelihood of extensive damage due to earthquakes. Of all roadway classes, interstates had the highest combined criticality and vulnerability score (3.4 on average). Across all roadway segments, five segments had the highest combined criticality and vulnerability score based on the underlying data and assumptions used. For these segments, we performed a benefit-cost analysis of the existing (baseline) asset conditions and possible mitigation alternatives. The benefit-cost analysis considers annualized owner and user risk as the function of threat likelihood, vulnerability, and cost consequence. Examples of mitigative actions include increasing hydraulic capacity for culverts, adding culverts at low points for bridges prone to flooding, and seismic retrofitting for bridges with earthquake vulnerability. The estimated benefit-cost ratios are above one (positive benefit relative to cost) for the selected study sites of Highway 67 culvert and bridge as well as the I-430 culvert sites in Pulaski County. All other study sites including the I-40 bridge, the I-55 (Hwy 63) bridge, and the I-55 (Hwy 64) bridge sites in Crittenden County had benefit-cost ratios less than one (Table 41).

Table 41. Summary of Benefit-Cost Analysis for the Five Most Critical and Vulnerable Roadways

Study Site	Asset Description	Mitigation Alternative	Benefit-Cost Ratio
Hwy 67	"Branch Jacks Bayou" Culvert	Upgrade culvert with increased hydraulic capacity	3.639
	"Bayou Meto" Bridge (SB)	Add flow-relief structures (cross culvert)	1.639
I-430	"White Oak Bayou" Bridge (NB)	Add flow-relief structures (cross culvert)	1.333
I-40	Ditch No. 9 Bridge (EB)	Seismic retrofit	0.125
I-55 (Hwy 63)	15 Mile Bayou Bridge (SB)	Seismic retrofit	0.084
I-55 (Hwy 64)	"CR 314 CRI&P RR & Creek" Bridge (SB)	Seismic retrofit	0.006

Limitations and Future Research

This project relied heavily on accurate, consistent, complete, and up-to-date data from several sources to estimate roadway resiliency in terms of criticality and vulnerability. Data collected from ARDOT included the following: AADT, roadway classification, freight value, landslide occurrence, flood occurrence, and asset inventory and characteristics. Data collected from other agencies and references included Social Vulnerability Index, additional asset characteristics, additional data on landslide occurrence, cost data on assets and mitigative alternatives, among others.

First, a limitation of the study was the inconsistency and lack of detail in data on floods and landslides. Flood events were found in the ARDOT road closure database, which contained the date and location of the flood but lacked other details such as the level of water (inches) on the roadway. This would have been helpful in ranking flood severity as part of the vulnerability assessment. For landslides, data were gathered from the Arkansas Geological Survey (AGS) and ARDOT. The database did not have information on whether the landslide affected a roadway, so we performed a spatial analysis to locate roadways within one mile of the location of the landslide and assumed that the landslide could affect the roadway. This process could be improved if road closure history due to landslide occurrence was available. The ARDOT project subcommittee provided the team with the list of emergency repair (ER) sites between 2004 and 2019 for comparison with the vulnerability sites found in our work. Based on a cursory review, we found minimal correlation between the locations of ER sites and sites denoted as moderately to highly vulnerable. More work is thus needed to develop a methodology of estimating vulnerability from historical ER sites as the ER data would be a direct indication of roadway vulnerability.

Second, a major data limitation in the benefit-cost analysis was the assumed costs for asset replacement and cost of alternatives. The ARDOT asset database supplied cost estimates for current assets, but some assets did not contain information on asset characteristics like length or width. Further, information gathered from the NBI sometimes conflicted with that from the ARDOT database. Moreover, for site mitigation alternatives, site-specific estimates were not used. Instead, assumptions based on the CDOT studies (2017, 2020) were used.

Third, AADT is used as a criticality metric and in the calculation of user consequence costs needed to estimate benefit-cost ratios. To maintain consistency between the criticality assessment and the benefit-cost calculations, measures for AADT were gathered from the ARTDM for total traffic volumes (passenger cars and truck volumes). However, since the user consequence calculations require truck volumes to be considered separately from total traffic volumes, a truck percentage was assumed for each of the study segments. Alternately, the truck percentage may be pulled from the most current ARDOT Interactive Average Daily Traffic (ADT) maps provided publicly online. Specifically, from count stations with classification counts. If a truck percent is not available within the study segment, the closest and most related truck percent could be used. For four of the study segments, the assumed truck percent was 10% and 20% for the remaining site (I-55 Hwy 64 bridge). The resulting cost estimates are sensitive to the truck percentage. For example, the I-40 bridge site in Crittenden County has an estimated truck volume of 10% assumed in the cost calculation contained in this report. Under that assumption, the estimated user consequence cost was approximately $215M with a BC ratio of 0.125. If the truck percent increased to 55%, the estimated user consequence cost would be approximately $242M, increasing the BC ratio to 0.136. Due to this sensitivity, future work should look to refine the estimated truck volumes at each of the study sites.

Besides expanding data sources, future extensions of this work should add safety as a metric to criticality criteria and include additional topological features to the redundancy criticality metric. In this study, the vulnerability of a roadway segment to disruptions considered only natural threats (floods, landslides, and earthquakes). Future works should examine how man-made disruptions affect roadway vulnerability. Specifically, crash occurrence data can be used to estimate the likelihood of a disruption due to smaller but more common disruptions like crashes. A link with a high crash rate can create significant system disruptions and could be improved with safety countermeasures. Such an evaluation should be considered in future works. Second, network structure, or topology, plays a significant role in how a system will perform when disrupted in terms of the availability of alternate routes for detours. In this work, we used a redundancy measure that considers how the travel time for the system will change when a roadway segment is non-operational. Although redundancy estimations were computationally intensive, they provided key insights into the network structure. Future works should consider easy-to-calculate topographical characteristics like node degree to measure connectivity.

Updates to the data used in the model for estimating criticality and vulnerability should be made as newer data become available. The Implementation Report outlines the data files that should be updated. A reasonable timeline for major updates coincides with updates to ARDOT's Statewide Travel Demand Model. The current ARSTRM is based on estimated AADT for the year 2010. When this model is updated, new estimates of AADT will be available and should be integrated into the criticality metrics. The current model network includes planned extensions for several major highways and Interstates in Arkansas including the Bella Vista Bypass (I-49 in NW Arkansas) and the I-49 extension south from Ft.

Smith to Texarkana. In the current model, volume assigned to the planned extensions are zero and the extension segments were not considered in the redundancy metric calculations. However, the geometry of these links is included in the network files to make it easier to update in the future. Additionally, if the freight module of the ARTDM is updated then criticality measures for freight value by county should also be updated.

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APPENDIX A: ARDOT STATE-OF-THE-PRACTICE SURVEY

EXPLANATION OF RESEARCH

Project Title: Data Driven Methods to Assess Transportation System Resilience in Arkansas
Principal Investigator: Sarah Hernandez, PhD, PE
Co-Principal Investigator: Suman Kumar Mitra, PhD; and Ashlea Milburn, PhD
Student Researchers: Sharif Mahmud, Farzana Mehzabin Tuli

Sponsor: Arkansas Department of Transportation (TRC2003)

Version Date: May 8, 2020

Purpose: You are being asked to take part in a research study. The purpose of this research study is to review the internal process of measuring, managing, and implementing resiliency assessment and proactively addressing the vulnerabilities in the ARDOT highway system.

Activities: The study activities include the administration of a survey designed to understand the current resiliency planning and practices within ARDOT.

Time: Your participation in this study will last about 10 minutes.

Confidentiality: It is possible that others could learn that you participated in this study, but the information you provide will be kept confidential to the extent permitted by law. The data will be shared with the research team at the University of Arkansas.

Risks: The security and confidentiality of the information collected from participants online cannot be guaranteed. Confidentially will be kept to the extent permitted by the technology being used. Information collected from online can be intercepted, corrupted, lost, destroyed, arrive late or incomplete, or contain viruses.

Benefits: There are no direct benefits to participants; however, the research has the potential to improve resiliency planning in Arkansas to mitigate the impacts of future events.

Voluntary: Participation in this study is voluntary. If you choose to participate, you can decide to skip questions; however, for your results to be included in the research, all questions must be answered.

Study contacts: If you have any questions about this research project, please contact: Dr. Sarah Hernandez at sarahvh@uark.edu

Name of the Respondent

____

E-mail:

____

A. General Background Questions

A1. Which of the following best describes your current role at ARDOT? (Select all areas that apply)

- ☐ Engineer
- ☐ Planner
- ☐ Manager
- ☐ Other, please specify all that apply

A2. In your current role at ARDOT, in which division(s) do you work? (Select all areas that apply)

- ☐ Planning
- ☐ Engineering
- ☐ Asset Management
- ☐ Policy
- ☐ Maintenance
- ☐ Administration
- ☐ Operation
- ☐ Emergency and Event Response
- ☐ Construction
- ☐ Other, please specify all that apply

A3. In your current role at ARDOT, which of the following sector(s) outside of ARDOT do you interact with when dealing with transportation engineering, planning, and investment decisions, practices, and/or policies? (Select all areas that apply)

- ☐ Neighboring governments and jurisdictions
- ☐ Hospital systems
- ☐ Educational systems
- ☐ Private-sector companies
- ☐ First responder organizations (e.g., police departments, fire services, ambulance, etc.)
- ☐ Other, please specify all that apply

B. Risk and Vulnerability Assessments

B1. Vulnerability refers to the potential and susceptibility of an asset to damage that can be assessed in terms of exposure, sensitivity, and adaptive capacity.
Risk assessments are undertaken for the most vulnerable assets to identify the level of risk from the expected hazards.
In general, resilience, vulnerability, and/or risk assessments are considered to be any study, policy, program, report, or other form of practice that has the potential to mitigate adverse effects of hazardous events. According to this general definition, are you aware of any resiliency, vulnerability, and/or risk assessments within your division?

- ○ Yes
- ○ No

B2. At what level does your division perform these resilience, vulnerability, and risk assessments? (Select all areas that apply)

- ☐ System-wide level (e.g., statewide or region-wide)
- ☐ Site-specific or asset level
- ☐ Facility level (e.g., Traffic Management Center)
- ☐ The modal level (e.g., a bus-rapid transit system)
- ☐ Other, please specify all that apply

B3. Which of the following hazards do your resilience, vulnerability, and risk assessments consider? (Select all areas that apply)

- ☐ Climate change
- ☐ Flooding
- ☐ Earthquakes
- ☐ Tornado
- ☐ Ice storms
- ☐ Wildfire
- ☐ Coastal erosion
- ☐ Funding shortfalls
- ☐ Changes in the political environment
- ☐ Terrorism
- ☐ Sea-level rise
- ☐ Fires
- ☐ Rockfalls
- ☐ Bridge strikes
- ☐ Other, please specify all that apply

B4. Which of the following assets does your division(s) consider within its vulnerability and risk assessments? (Select all areas that apply)

	Vulnerability Assessments (1)	Risk Assessments (2)
Pipelines	☐	○
Multi-modal and inter-modal facilities	☐	☐
Aviation facilities	☐	☐
Port and waterway facilities	☐	☐
Grade crossings	☐	☐
Tunnels	☐	☐
ITS (intelligent transportation system)	☐	☐
Signs and signals	☐	☐
Buildings	☐	☐
Drain-pipes	☐	☐
Culverts	☐	☐
Roadway prism (pavement and embankment)	☐	☐
Bridges	☐	☐
Other, please specify	☐	☐

C. Transportation Resilience

C1.

In a sentence or two, how would you define resilience as it pertains to your division within ARDOT?

C2.

As a representative of your division within ARDOT, what keywords would you use to define transportation resilience? (Select all areas that apply)

- ☐ Withstand disruptions
- ☐ Recover rapidly
- ☐ Absorb shocks
- ☐ Respond rapidly
- ☐ Sustain shocks
- ☐ Cope with change
- ☐ Adapt to long-term stresses
- ☐ Adapt to adverse stress
- ☐ Maintain level of service
- ☐ Other, please specify all that apply

C3. Currently, does your division use any specific performance measure related to resilience?

- ○ Yes
- ○ No

C4. Which of the following performance measures has your division used to assess system resilience? (Select all areas that apply)

- ☐ Travel Time
- ☐ Volume
- ☐ Capacity
- ☐ Roadway Density
- ☐ Volume/Capacity (V/C)
- ☐ Cost/Benefit
- ☐ Speed
- ☐ Level of Service
- ☐ Vehicle Miles Traveled (VMT)
- ☐ Vehicle Hour Traveled (VHT)
- ☐ Other, please specify all that apply

C5. Has your division incorporated resilience practices into existing programs, practices, policies, etc.?

- ○ Yes, please specify the program(s); list all that apply

- ○ No

C6. Does your division use any specialized models/software to incorporate and/or evaluate system resilience, risk, and/or vulnerability?

- ○ Yes
- ○ No

C7. Which of the following specialized models/software does your division use to incorporate and/or evaluate system resilience? (Select all areas that apply)

- ☐ Sea-level risk sketch planning tool based on the US Army Corps of Engineers (USACE)
- ☐ The FHWA Vulnerability Assessment Scoring Tool
- ☐ The Risk and Resilience Analysis based on RAMCAP Plus framework
- ☐ The CalFIRE Wildfire Model
- ☐ Deighton Total Infrastructure Management System (dTIMS)
- ☐ Other, please specify all that apply

C8. Are you aware of any federal or state guidance or procedures in place to incorporate consideration of resilience assessment into planning, project development, and engineering design?

- ○ Yes, please specify the policy document title(s)

- ○ No

D. Long-term Investment and Funding

D1. Does your division allocate or set aside funding to improve transportation resilience for any of the following general areas? (Select all areas that apply)

- ☐ Maintenance
- ☐ Operations
- ☐ Planning
- ☐ Design
- ☐ Construction
- ☐ Other, please specify all that apply

D2. To complete a resiliency assessment for the Arkansas highway network, we are looking for data of different types and from various sources. Which of the following general data would your division be able to share with the research team for resiliency assessment? (Select all areas that apply)

- ☐ Asset Inventory
- ☐ Asset Conditions
- ☐ Geo-spatial Location and Asset
- ☐ User Costs
- ☐ Maintenance Costs
- ☐ Capital Costs
- ☐ Anticipated Risks from Multiple Hazards
- ☐ Asset Performance Metrics
- ☐ Deterioration Curves or Models
- ☐ Asset Vulnerability
- ☐ Expected Benefits from Mitigation
- ☐ System, Site, and/or Asset Criticality Assessment
- ☐ Resilience Metrics and Assessment Methods
- ☐ Other, please specify all that apply

E. Wrap-up Questions

E1. Select all of the following elements of a resiliency assessment that you find to be helpful to support other ongoing programs, policies and practices within your division at ARDOT.

- ☐ Identification of critical highway assets
- ☐ Measurement of user impacts (travel time, cost, etc.) from hazardous events
- ☐ Identification of alternate routes for emergency routing
- ☐ Cost estimates for improving the resilience of the transportation system
- ☐ Estimation of system performance metrics in response to different hazards
- ☐ Other, please specify all that apply

E2. Within your division at ARDOT, what do you consider are the overall strengths of your current resiliency planning?

APPENDIX B: NETWORK MODELING TOPOLOGY ERROR EXAMPLES

CATEGORY 1: MISSING LINKS

Count: After merging the ARTDM and ARNOLD maps, 83 missing links remained in the hybrid network.

Action: Existing links were extended to make continuous links.

Figure 45. Missing Link Examples

CATEGORY 2: REDUNDANT LINKS

Count: After merging the ARTDM and ARNOLD maps, 57 redundant links existed in the hybrid network.

Action: Redundant links were removed from the hybrid network.

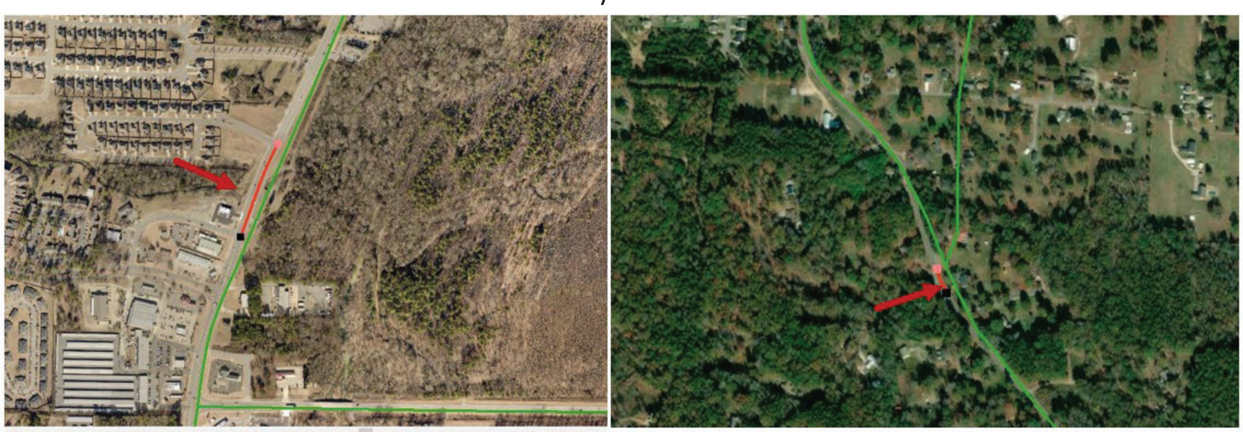


Figure 46. Redundant Link Editing

CATEGORY 3: ISOLATED LINKS

Count: After merging the ARTDM and ARNOLD maps, 27 isolated links were identified in the hybrid network.

Action: Isolated links were removed from the hybrid network.

Figure 47. Isolated Links

CATEGORY 4: BROKEN LINKS

Count: After merging the ARTDM and ARNOLD maps, eight diverged links were identified in the hybrid network.

Action: Broken links were corrected by realigning the link geometry to match the existing links.

Figure 48. Broken Links

CATEGORY 5: DEAD ENDS

Count: After merging the ARTDM and ARNOLD maps, 1191 dead-end links were identified in the hybrid network.

Action: Dead-end links that were not observed to be “dangling ends” were ignored. If a dead-end was identified to be a dangling end, it was connected to existing links.

Figure 49. Dead-End Links

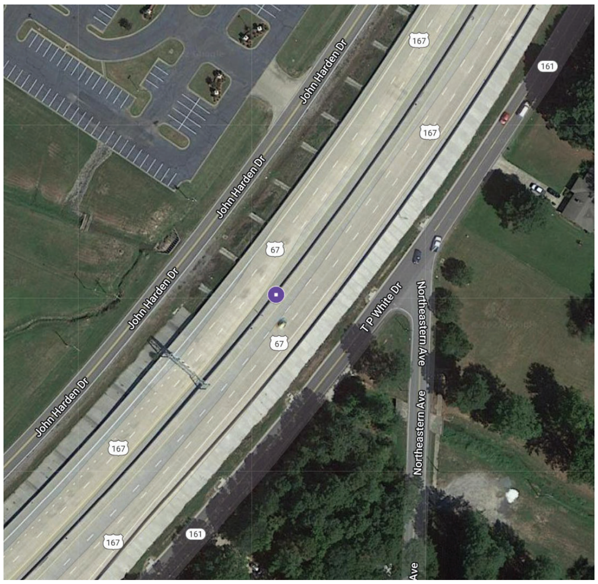
APPENDIX C: ANALYTICAL HIERARCHY PROCESS SURVEY QUESTIONAIRRE

With respect to goal**: MEASURING RESILIENCE OF ARKANSAS HIGHWAY TRANSPORTATION SYSTEM**
Using the scale from 1 to 9 (where 9 is extremely and 1 is equally important),
please indicate (X) the relative importance of options **A** (left column) to options **B** (right column).

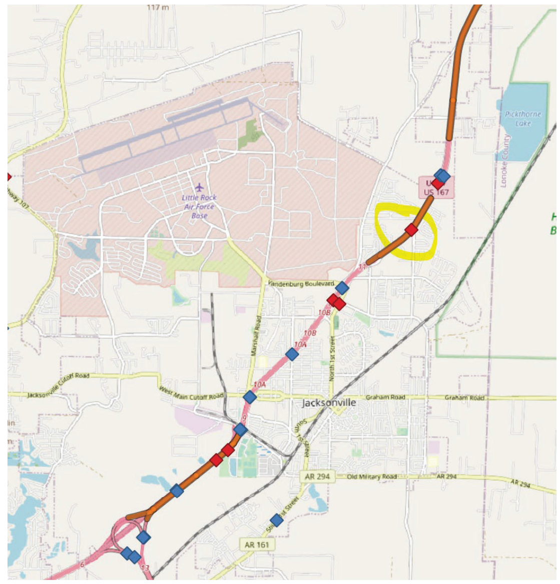
A Options	Extremely		Very Strongly		Strongly		Moderately		Equally		Moderately		Strongly		Very Strongly		Extremely	**B** Options
Annual Average Daily Traffic (AADT)	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	**Roadway Classification**
Annual Average Daily Traffic (AADT)	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	**Freight**
Annual Average Daily Traffic (AADT)	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	**Tourism**
Annual Average Daily Traffic (AADT)	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	**Social Vulnerability Index (SoVI)**
Annual Average Daily Traffic (AADT)	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	**Redundancy**
Roadway Classification	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	**Freight**
Roadway Classification	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	**Tourism**
Roadway Classification	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	**Social Vulnerability Index (SoVI)**
Roadway Classification	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	**Redundancy**
Freight	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	**Tourism**
Freight	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	**Social Vulnerability Index (SoVI)**
Freight	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	**Redundancy**
Tourism	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	**Social Vulnerability Index (SoVI)**
Tourism	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	**Redundancy**
Social Vulnerability Index (SoVI)	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	**Redundancy**

APPENDIX D: CASE STUDY BENEFIT COST ANALYSES

SITE 1A: HIGHWAY 67 CULVERT, PULASKI COUNTY



(A) Aerial Image



(B) Location (Open Street Map)

Figure 50. Highway 67 Culvert Study Site

Table 42. Site Summary for Highway 67 Culvert Site

Category	Site Characteristic	Information	Units
Site Location	Location	Highway 67, Pulaski County	
	Lat/Long	34.89777	-92.09143
	Asset ID (NBI, ArDOT)	0000000000X1518	X1518
	Lane	Six-lane (three lanes in each direction)	
	Direction	Southbound	
	Replacement cost	$1,255,150	
Site Characteristics	Type	Major Culvert	Concrete Box Culvert
	Name	"Branch Jacks Bayou"	
	Width	70	ft
	Length	21.5	ft
	Height	15	ft
	Hydraulic capacity	50 yr	
Site Condition	Culvert condition	9	
	Channel and channel protection condition	8	
	Drainage basin land cover type	Trees	
	Slope	Low	%
Site Traffic	AADT vehicle	51,321	vehicles per day
	AADT truck	5,132	trucks per day
Detour and Work Zone	Detour length (C7)	25	miles
	Extra travel time on detour (Dt)	27	minutes
	Number of days of full closure (dfc)	30	days
	Number of days of partial closure (dpc)	0	days
Mitigation Alternative	Solution	Larger Culvert, 100-yr hydraulic capacity	
	Cost	$500,000	
	Life (n)	100	years

Existing Asset Risk Assessment

Owner Consequences	*Asset Cost*	*Cleanup Cost*	*Owner Consequence*	*Rounded*
C_{owner}	$ 1,255,150	$5,000	**$1,260,150**	**$1,261,000**

User Consequences	*Cost*	*Variable*	*Estimate*	*Rounded*
Full Closure	Vehicle Operating Costs	VOC_FC	$20,130,662	$20,131,000
	Lost Wages	LW_FC	$22,844,799	$22,845,000
Partial Closure	Vehicle Operating Costs	VOC_PC	$0	$0
	Lost Wages	LW_PC	$0	$0
		Total User Consequences	**$42,975,461**	**$42,976,000**

Vulnerability Assessment	*Event*	*Variable*	*Vulnerability*	
Based on condition, capacity,	100 yr flood	V_{100}	0.12	*Lookup from Vulne*
and flood event	500 yr flood	V_{500}	0.99	*Lookup from Vulne*

Risk Assessment	*Event Occurance*	*Total Risk*	*Annual Risk*	*Rounded*
Risk = Consequence x	100 yr flood	$1,261,000.00	$1,513	$2,000
Vulnerability x Threat Likelihood	500 yr flood		$2,497	$3,000
		Annual Owner Risk	**$4,010**	**$5,000**
	100 yr flood	$42,976,000.00	$51,571	$52,000
	500 yr flood		$85,092	$86,000
		Annual User Risk	**$136,664**	**$137,000**
		Total Annual Risk (User + Owner)	**$140,674**	**$142,000**

Mitigation of Asset Risk Assessment

Owner Consequences	*Asset Cost*	*Cleanup Cost*	*Owner Consequence*	*Rounded*
C_{owner}	$ 500,000.00		**$500,000**	**$500,000**

User Consequences	*Cost*	*Variable*	*Estimate*	*Rounded*
Full Closure	Vehicle Operating Costs	VOC_FC	$20,130,662	$20,131,000
	Lost Wages	LW_FC	$22,844,799	$22,845,000
Partial Closure	Vehicle Operating Costs	VOC_PC	$0	$0
	Lost Wages	LW_PC	$0	$0
		Total User Consequences	**$42,975,461**	**$42,976,000**

Vulnerability Assessment	*Event*	*Variable*	*Vulnerability*	
Based on condition, capacity,	100 yr flood	V_{100}	0.005	*Lookup from Vulne*
and flood event	500 yr flood	V_{500}	0.1	*Lookup from Vulne*

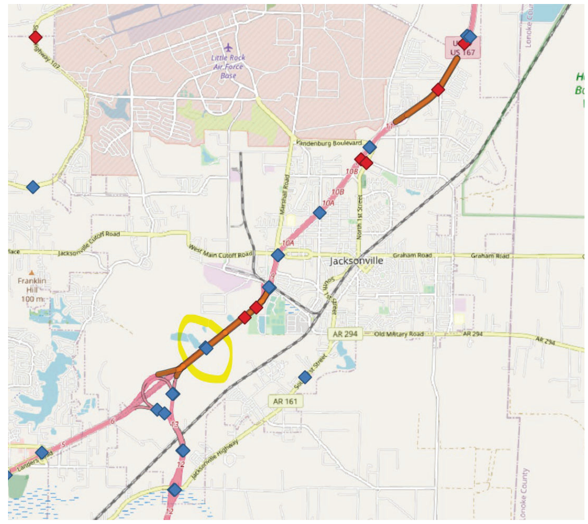
Risk Assessment	*Event Occurance*	*Total Risk*	*Annual Risk*	*Rounded*
Risk = Consequence x	100 yr flood	$500,000	$25	$30
Vulnerability x Threat Likelihood	500 yr flood		$100	$100
		Annual Owner Risk	**$125**	**$130**
	100 yr flood	$42,976,000	$2,149	$2,150
	500 yr flood		$8,595	$8,600
		Annual User Risk	**$10,744**	**$10,750**
		Total Annual Risk (User + Owner)	**$10,869**	**$11,000**

Benefit Cost Analysis	*Baseline*	*Mitigation*	*Annual Mitigation Benefit*	*Rounded*
Total Annual Risk	$142,000	$11,000	$131,000	$131,000
		Total Cost	*Annual Mitigation Cost*	*Rounded*
	Mitigation alternative	$500,000	$35,040	$36,000
		Benefit	*Cost*	*BC Ratio*
	Benefit- Cost Ratio	$131,000	$36,000	**3.639**

Figure 51. Summary Calculations for Highway 67 Culvert

SITE 1B: HIGHWAY 67 BRIDGE, PULASKI COUNTY

(A) Aerial Image



(B) Location (Open StreetMap)

Figure 52. Highway 67 Bridge Study Site

Table 43. Site Summary for Highway 67 Bridge Site

Category	Site Characteristic	Information	Units
Site Location	**Location**	Highway 67, Pulaski County	
	Lat/Long	34.84992	-92.14432
	Asset ID (NBI, ArDOT)	7093	7093
	Lane	Six-lane freeway (three lanes in each direction)	
	Direction	"US 67 SB Log 7.55"	"7.55 MI NE I-40"
	Replacement cost	$ 9,974,486	
Site Characteristics	**Type**	Bridge	
	Name	"Bayou Meto"	
	Width	67.2	ft
	Length	842	ft
	Span length	49.87	ft
	Hydraulic capacity	50 yr	
Site Condition	**Superstructure condition**	7	
	Scour condition	5	
	Substructure condition	8	
	Channel condition	7	
	Drainage basin land cover type	Trees	
	Mean basin slope	Low	
Site Traffic	**AADT vehicle**	68,245	vehicles per day
	AADT truck	6,825	trucks per day
Detour and Work Zone	**Detour length (C7)**	25	miles
	Extra travel time on detour (Dt)	27	minutes
	Number of days of full closure (dfc)	180	days
	Number of days of partial closure (dpc)	0	days
Mitigation Alternative	**Solution**	Flow-relief Structures	(Cross culverts with 100-yr hydraulic capacity for flood response)
	Cost	$500,000	
	Life (n)	100	years

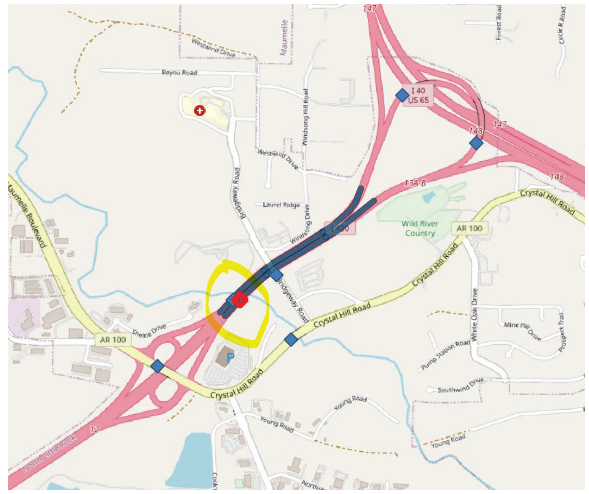
Existing Asset Risk Assessment				
Owner Consequences	*Asset Cost*	*Cleanup Cost*	*Owner Consequence*	*Rounded*
C_{owner}	$ 9,974,486	$5,000	**$9,979,486**	**$9,980,000**
User Consequences	*Cost*	*Variable*	*Estimate*	*Rounded*
Full Closure	Vehicle Operating Costs	VOC_FC	$160,614,608	$160,615,000
	Lost Wages	LW_FC	$182,269,633	$182,270,000
Partial Closure	Vehicle Operating Costs	VOC_PC	$0	$0
	Lost Wages	LW_PC	$0	$0
		Total User Consequences	**$342,884,241**	**$342,885,000**
Vulnerability Assessment	*Event*	*Variable*	*Vulnerability*	
Based on condition, capacity, and flood event	100 yr flood	V_{100}	0.007	*Lookup from Vulne*
	500 yr flood	V_{500}	0.071	*Lookup from Vulne*
Risk Assessment	*Event Occurance*	*Total Risk*	*Annual Risk*	*Rounded*
Risk = Consequence x Vulnerability x Threat Likelihood	100 yr flood	$9,980,000.00	$699	$1,000
	500 yr flood		$1,417	$2,000
		Annual Owner Risk	**$2,116**	**$3,000**
	100 yr flood	$342,885,000.00	$24,002	$25,000
	500 yr flood		$48,690	$49,000
		Annual User Risk	**$72,692**	**$73,000**
		Total Annual Risk (User + Owner)	**$74,807**	**$76,000**

Mitigation of Asset Risk Assessment				
Owner Consequences	*Asset Cost*	*Cleanup Cost*	*Owner Consequence*	*Rounded*
C_{owner}	$ 500,000.00	$0.00	**$500,000**	**$500,000**
User Consequences	*Cost*	*Variable*	*Estimate*	*Rounded*
Full Closure	Vehicle Operating Costs	VOC_FC	$160,614,608	$160,615,000
	Lost Wages	LW_FC	$182,269,633	$182,270,000
Partial Closure	Vehicle Operating Costs	VOC_PC	$0	$0
	Lost Wages	LW_PC	$0	$0
		Total User Consequences	**$342,884,241**	**$342,885,000**
Vulnerability Assessment	*Event*	*Variable*	*Vulnerability*	
Based on condition, capacity, and flood event	100 yr flood	V_{100}	0.001	*Lookup from Vulne*
	500 yr flood	V_{500}	0.019	*Lookup from Vulne*
Risk Assessment	*Event Occurance*	*Total Risk*	*Annual Risk*	*Rounded*
Risk = Consequence x Vulnerability x Threat Likelihood	100 yr flood	$500,000	$5	$5
	500 yr flood		$19	$20
		Annual Owner Risk	**$24**	**$30**
	100 yr flood	$342,885,000	$3,429	$3,430
	500 yr flood		$13,030	$13,030
		Annual User Risk	**$16,458**	**$17,000**
		Total Annual Risk (User + Owner)	**$16,482**	**$17,000**
Benefit Cost Analysis	*Baseline*	*Mitigation*	*Annual Mitigation Benefit*	*Rounded*
Total Annual Risk	$76,000.00	$17,000	$59,000	$59,000
		Total Cost	*Annual Mitigation Cost*	*Rounded*
	Mitigation alternative	$500,000	$35,040	$36,000
		Benefit	*Cost*	*BC Ratio*
	Benefit- Cost Ratio	$59,000	$36,000	**1.639**

Figure 53. Summary Calculations for Highway 67 Bridge

SITE 2: INTERSTATE 430 BRIDGE, PULASKI COUNTY

(A) Aerial Image



(B) Location (Open StreetMap)

Figure 54. Interstate 430 Bridge Study Site

Table 44. Site Summary for Interstate 430 Bridge Site

Category	Site Characteristic	Information	Units
Site Location	Location	Interstate 430, Pulaski County	
	Lat/Long	34.81365	-92.35291
	Asset ID (NBI, ArDOT)	0000000000B5322	B5322
	Lane	Six-lane freeway (three lanes in each direction)	
	Direction	"I-430 NB Log 11.92"	"1.0 MI SW I 40 (I-5)"
	Replacement cost	$ 4,470,677	
Site Characteristics	Type	Bridge	
	Name	"WHITE OAK BAYOU"	
	Width	63.2	ft
	Length	288.9	ft
	Span length	61.35	ft
	Hydraulic capacity	50 yr	
Site Condition	Superstructure condition	7	
	Scour condition	5	
	Substructure condition	7	
	Channel condition	7	
	Drainage basin land cover type	Trees	
	Mean basin slope	Low	
Site Traffic	AADT vehicle	64,182	vehicles per day
	AADT truck	6,418	trucks per day
Detour and Work Zone	Detour length (C7)	25	miles
	Extra travel time on detour (Dt)	27	minutes
	Number of days of full closure (dfc)	180	days
	Number of days of partial closure (dpc)	0	days
Mitigation Alternative	Solution	Flow-relief Structures	(Cross culverts with 100 yr hydraulic capacity for flood response)
	Cost	$500,000	
	Life (n)	100	years

Existing Asset Risk Assessment

Owner Consequences	Asset Cost	Cleanup Cost	Owner Consequence	Rounded
C_{owner}	$ 4,470,677	$5,000	**$4,475,677**	**$4,476,000**

User Consequences	Cost	Variable	Estimate	Rounded
Full Closure	Vehicle Operating Costs	VOC_FC	$151,052,337	$151,053,000
	Lost Wages	LW_FC	$182,269,633	$182,270,000
Partial Closure	Vehicle Operating Costs	VOC_PC	$0	$0
	Lost Wages	LW_PC	$0	$0
		Total User Consequences	**$333,321,970**	**$333,322,000**

Vulnerability Assessment	Event	Variable	Vulnerability	
Based on condition, capacity, and flood event	100 yr flood	V_{100}	0.005	*Lookup from Vulne*
	500 yr flood	V_{500}	0.071	

Risk Assessment	Event Occurance	Total Risk	Annual Risk	Rounded
Risk = Consequence x Vulnerability x Threat Likelihood	100 yr flood	$4,476,000.00	$224	$230
	500 yr flood		$636	$640
		Annual Owner Risk	**$859**	**$1,000**
	100 yr flood	$333,322,000.00	$16,666	$17,000
	500 yr flood		$47,332	$48,000
		Annual User Risk	**$63,998**	**$64,000**
		Total Annual Risk (User + Owner)	**$64,857**	**$65,000**

Mitigation of Asset Risk Assessment

Owner Consequences	Asset Cost	Cleanup Cost	Owner Consequence	Rounded
C_{owner}	$ 500,000.00	$0.00	**$500,000**	**$500,000**

User Consequences	Cost	Variable	Estimate	Rounded
Full Closure	Vehicle Operating Costs	VOC_FC	$151,052,337	$151,053,000
	Lost Wages	LW_FC	$182,269,633	$182,270,000
Partial Closure	Vehicle Operating Costs	VOC_PC	$0	$0
	Lost Wages	LW_PC	$0	$0
		Total User Consequences	**$333,321,970**	**$333,322,000**

Vulnerability Assessment	Event	Variable	Vulnerability	
Based on condition, capacity, and flood event	100 yr flood	V_{100}	0.001	*Lookup from Vulne*
	500 yr flood	V_{500}	0.019	

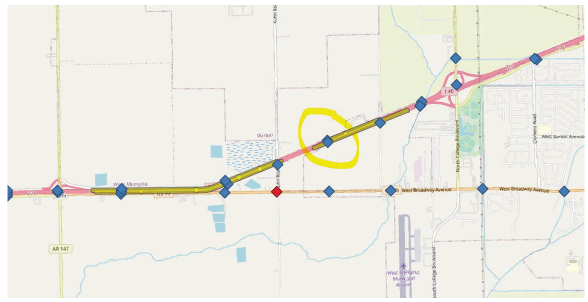
Risk Assessment	Event Occurance	Total Risk	Annual Risk	Rounded
Risk = Consequence x Vulnerability x Threat Likelihood	100 yr flood	$500,000	$5	$5
	500 yr flood		$19	$20
		Annual Owner Risk	**$24**	**$30**
	100 yr flood	$333,322,000	$3,333	$3,340
	500 yr flood		$12,666	$12,670
		Annual User Risk	**$15,999**	**$16,000**
		Total Annual Risk (User + Owner)	**$16,023**	**$17,000**

Benefit Cost Analysis	Baseline	Mitigation	Annual Mitigation Benefit	Rounded
Total Annual Risk	$65,000.00	$17,000	$48,000	$48,000
		Total Cost	*Annual Mitigation Cost*	*Rounded*
	Mitigation alternative	$500,000	$35,040	$36,000
		Benefit	*Cost*	*BC Ratio*
	Benefit- Cost Ratio	$48,000	$36,000	**1.333**

Figure 55. Summary Calculations for Interstate 430 Bridge

SITE 3: INTERSTATE 40 BRIDGE, CRITTENDEN COUNTY

(A) Aerial Image



(B) Location (Open StreetMap)

Figure 56. Interstate 40 Bridge Study Site

Table 45. Site Summary for Interstate 40 Bridge Site

Category	Site Characteristic	Information	Units
Site Location	**Location**	Interstate 40, Crittenden County	
	Lat/Long	35.153736	-90.246643
	Asset ID (NBI, ARDOT)	0000000000B6848	B6848
	Lane	Six-lane freeway (three lanes in each direction)	
	Direction	"I-40EB/Se52/273.8"	"2.2 Miles East Of Sh 147"
	Replacement cost	$ 806,658	
Site Characteristics	**Type**	Bridge	
	Name	"Ditch Number 9"	
	Width	43.1	ft
	Length	57	ft
	Span length	55.12	ft
	Hydraulic capacity	50 yr	
Site Condition	**Superstructure condition**	8	
	Scour condition	5	
	Substructure condition	8	
	Channel condition	8	
	Drainage basin land cover type	Trees	
	Mean basin slope	Low	
Site Traffic	**AADT vehicle**	31,975	vehicles per day
	AADT truck	3,198	trucks per day
Detour and Work Zone	**Detour length (C7)**	11	miles
	Extra travel time on detour (Dt)	12	minutes
	Number of days of full closure (dfc)	180	days
	Number of days of partial closure (dpc)	0	days
Mitigation Alternative	**Solution**	Seismic retrofit	superstructure only, see Table 34
	Cost	$ 2,500,640	3.1
	Life (n)	100	years

Existing Asset Risk Assessment

Owner Consequences	Asset Cost	Cleanup Cost	Owner Consequence	Rounded
C_{owner}	$ 806,658	$5,000	**$811,658**	**$812,000**

User Consequences	Cost	Variable	Estimate	Rounded
Full Closure	Vehicle Operating Costs	VOC_FC	$33,111,392	$33,112,000
	Lost Wages	LW_FC	$182,269,633	$182,270,000
Partial Closure	Vehicle Operating Costs	VOC_PC	$0	$0
	Lost Wages	LW_PC	$0	$0
		Total User Consequences	**$215,381,025**	**$215,382,000**

Vulnerability Assessment	Event	Variable	Vulnerability	*Lookup from Vulne*
Based on HAZUS Predctions for damage	No Damage	V_no damage	0.7531	
	Extensive Damage	V_extensive	0.1974	
	Complete Damage	V_complete	0.0493	

Risk Assessment	Event Occurance	Total Risk	Annual Risk	Rounded
Risk = Consequence x Vulnerability x Threat Likelihood	No Damage	$812,000.00	$245	$1,000
	Extensive Damage		$64	$1,000
	Complete Damage		$16	$1,000
		Annual Owner Risk	**$325**	**$1,000**
	No Damage	$215,382,000.00	$64,882	$65,000
	Extensive Damage		$17,007	$18,000
	Complete Damage		$4,247	$5,000
		Annual User Risk	**$86,136**	**$87,000**
		Total Annual Risk (User + Owner)	**$86,460**	**$88,000**

Mitigation of Asset Risk Assessment

Owner Consequences	Asset Cost	Cleanup Cost	Owner Consequence	Rounded
C_{owner}	$ 2,500,640	$0.00	**$2,500,640**	**$2,501,000**

User Consequences	Cost	Variable	Estimate	Rounded
Full Closure	Vehicle Operating Costs	VOC_FC	$33,111,392	$33,112,000
	Lost Wages	LW_FC	$182,269,633	$182,270,000
Partial Closure	Vehicle Operating Costs	VOC_PC	$0	$0
	Lost Wages	LW_PC	$0	$0
		Total User Consequences	**$215,381,025**	**$215,382,000**

Vulnerability Assessment	Event	Variable	Vulnerability	*Lookup from Vulne*
Based on condition, capacity, and flood event	No Damage	V_no damage	0.7531	*Only consider no da*
	Extensive Damage	V_extensive	0.0000	
	Complete Damage	V_complete	0.0000	

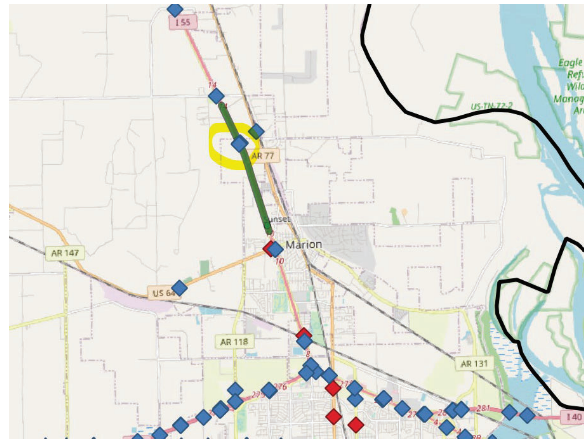
Risk Assessment	Event Occurance	Total Risk	Annual Risk	Rounded
Risk = Consequence x Vulnerability x Threat Likelihood	No Damage	$2,501,000	$753	$1,000
	Extensive Damage		$0	$0
	Complete Damage		$0	$0
		Annual Owner Risk	**$753**	**$1,000**
	No Damage	$215,382,000	$64,882	$65,000
	Extensive Damage		$0	$0
	Complete Damage		$0	$0
		Annual User Risk	**$64,882**	**$65,000**
		Total Annual Risk (User + Owner)	**$65,635**	**$66,000**

Benefit Cost Analysis	Baseline	Mitigation	Annual Mitigation Benefit	Rounded
Total Annual Risk	$88,000.00	$66,000	$22,000	$22,000
		Total Cost	*Annual Mitigation Cost*	*Rounded*
	Mitigation alternative	$2,501,000	$175,272	$176,000
		Benefit	*Cost*	*BC Ratio*
	Benefit- Cost Ratio	$22,000	$176,000	**0.125**

Figure 57. Summary Calculations for Interstate 40 Bridge

SITE 4: INTERSTATE 55 (HWY 63) BRIDGE, CRITTENDEN COUNTY

(A) Aerial Image



(B) Location (Open StreetMap)

Figure 58. Interstate 55 (Hwy 63) Bridge Study Site

Table 46. Site Summary for Interstate 55 (Hwy 63) Bridge Site

Category	Site Characteristic	Information	Units
Site Location	**Location**	Interstate 55 (HWY 63), Crittenden County	
	Lat/Long	35.247032	-90.219742
	Asset ID (NBI, ArDOT)	0000000000A2808	A2808
	Lane	Six-lane freeway (three lanes in each direction)	
	Direction	"I-55SO/Sec11/12.68"	"2.5 Mi N Of Marion Ark"
	Replacement Cost	$ 1,147,037	
Site Characteristics	**Type**	Bridge	
	Name	"15 Mile Bayou"	
	Width	42.6	ft
	Length	81	ft
	Span length	28.87	ft
	Hydraulic capacity	50 yr	
Site Condition	**Superstructure condition**	7	
	Scour condition	5	
	Substructure condition	7	
	Channel condition	8	
	Drainage basin land cover type	Trees	
	Mean basin slope	Low	
Site Traffic	**AADT vehicle**	20,405	vehicles per day
	AADT truck	2,041	trucks per day
Detour and Work Zone	**Detour length (C7)**	18	miles
	Extra travel time on detour (Dt)	20	minutes
	Number of days of full closure (dfc)	180	days
	Number of days of partial closure (dpc)	0	days
Mitigation Alternative	**Solution**	Seismic retrofit	superstructure only, see Table 34
	Cost	$ 3,555,815	3.1
	Life (n)	100	years

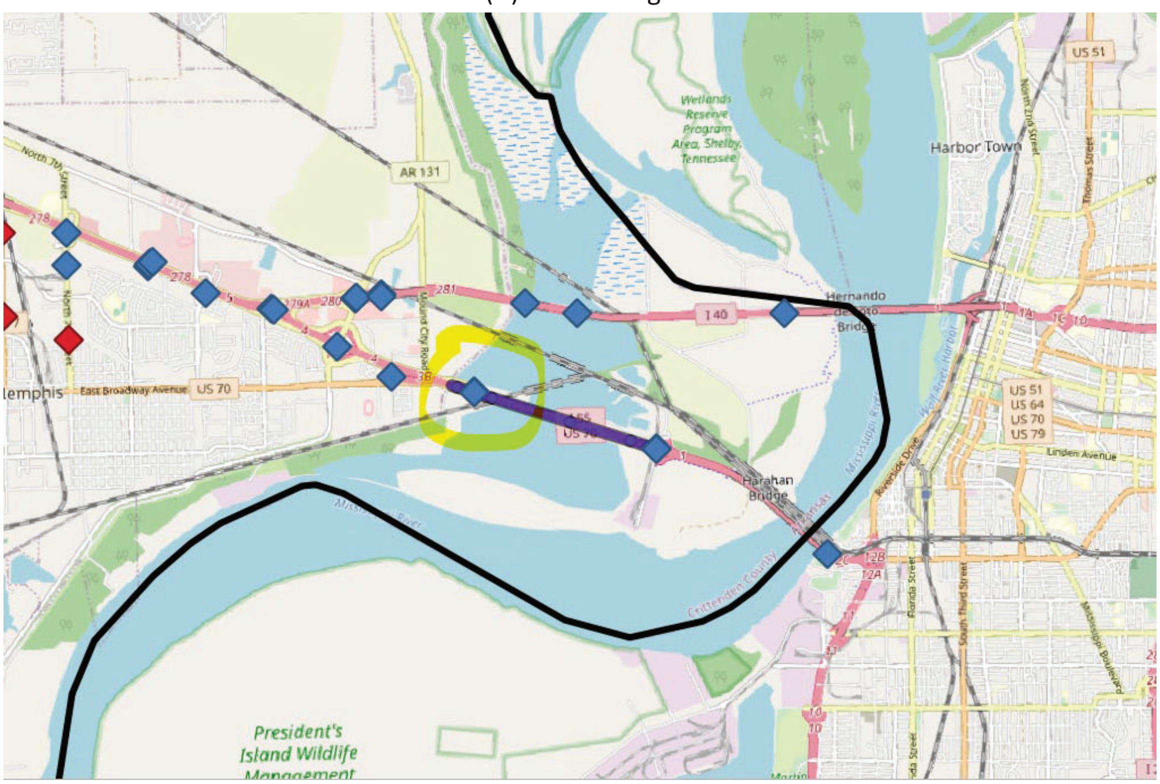
Existing Asset Risk Assessment				
Owner Consequences	*Asset Cost*	*Cleanup Cost*	*Owner Consequence*	*Rounded*
C_{owner}	$ 1,147,037	$5,000	**$1,152,037**	**$1,153,000**
User Consequences	*Cost*	*Variable*	*Estimate*	*Rounded*
Full Closure	Vehicle Operating Costs	VOC_FC	$34,576,681	$34,577,000
	Lost Wages	LW_FC	$182,269,633	$182,270,000
Partial Closure	Vehicle Operating Costs	VOC_PC	$0	$0
	Lost Wages	LW_PC	$0	$0
		Total User Consequences	**$216,846,314**	**$216,847,000**
Vulnerability Assessment	*Event*	*Variable*	*Vulnerability*	*Lookup from Vulne*
Based on condition, capacity, and flood event	No Damage	V_no damage	0.7522	
	Extensive Damage	V_extensive	0.1981	
	Complete Damage	V_complete	0.0496	
Risk Assessment	*Event Occurance*	*Total Risk*	*Annual Risk*	*Rounded*
Risk = Consequence x Vulnerability x Threat Likelihood	No Damage	$1,153,000.00	$347	$1,000
	Extensive Damage		$91	$1,000
	Complete Damage		$23	$1,000
		Annual Owner Risk	**$461**	**$1,000**
	No Damage	$216,847,000.00	$65,245	$66,000
	Extensive Damage		$17,183	$18,000
	Complete Damage		$4,302	$5,000
		Annual User Risk	**$86,730**	**$87,000**
		Total Annual Risk (User + Owner)	**$87,191**	**$88,000**

Mitigation of Asset Risk Assessment				
Owner Consequences	*Asset Cost*	*Cleanup Cost*	*Owner Consequence*	*Rounded*
C_{owner}	$ 3,555,815	$0.00	**$3,555,815**	**$3,556,000**
User Consequences	*Cost*	*Variable*	*Estimate*	*Rounded*
Full Closure	Vehicle Operating Costs	VOC_FC	$34,576,681	$34,577,000
	Lost Wages	LW_FC	$182,269,633	$182,270,000
Partial Closure	Vehicle Operating Costs	VOC_PC	$0	$0
	Lost Wages	LW_PC	$0	$0
		Total User Consequences	**$216,846,314**	**$216,847,000**
Vulnerability Assessment	*Event*	*Variable*	*Vulnerability*	*Lookup from Vulne*
Based on HAZUS Predctions for damage	No Damage	V_no damage	0.7522	*Only consider no da*
	Extensive Damage	V_extensive	0.0000	
	Complete Damage	V_complete	0.0000	
Risk Assessment	*Event Occurance*	*Total Risk*	*Annual Risk*	*Rounded*
Risk = Consequence x Vulnerability x Threat Likelihood	No Damage	$3,556,000	$1,070	$2,000
	Extensive Damage		$0	$0
	Complete Damage		$0	$0
		Annual Owner Risk	**$1,070**	**$2,000**
	No Damage	$216,847,000	$65,245	$66,000
	Extensive Damage		$0	$0
	Complete Damage		$0	$0
		Annual User Risk	**$65,245**	**$66,000**
		Total Annual Risk (User + Owner)	**$66,315**	**$67,000**
Benefit Cost Analysis	*Baseline*	*Mitigation*	*Annual Mitigation Benefit*	*Rounded*
Total Annual Risk	$88,000.00	$67,000	$21,000	$21,000
		Total Cost	*Annual Mitigation Cost*	*Rounded*
	Mitigation alternative	$3,556,000	$249,207	$250,000
		Benefit	*Cost*	*BC Ratio*
	Benefit- Cost Ratio	$21,000	$250,000	**0.084**

Figure 59. Summary Calculations for Interstate 55 (Hwy 63) Bridge

SITE 5: INTERSTATE 55 (HWY 64) BRIDGE, CRITTENDEN COUNTY

(A) Aerial Image



(B) Location (Open StreetMap)

Figure 60. Interstate 55 (Hwy 64) Bridge Study Site

Table 47. Site Summary for Interstate 55 (Hwy 64) Bridge Site

Category	Site Characteristic	Information	Units
Site Location	Location	Interstate 55 (HWY 64), Crittenden County	
	Lat/Long	35.14508	-90.12085
	Asset ID (NBI, ARDOT)	0000000000B5528	B5528
	Lane	Six-lane freeway (three lanes in each direction)	
	Direction	"I-55 SB LNS"	"1.8 E JCT I-40"
	Replacement cost	$38,960,256	
Site Characteristics	Type	Bridge	
	Name	"CRI&P & MISS RIV REL"	
	Width	42.8	ft
	Length	3476.1	ft
	Span length	106.96	ft
	Hydraulic capacity	50 yr	
Site Condition	Superstructure condition	6	
	Scour condition	5	
	Substructure condition	7	
	Channel condition	8	
	Drainage basin land cover type	Trees	
	Mean basin slope	Low	
Site Traffic	AADT vehicle	34,298	vehicles per day
	AADT truck	6,860	trucks per day
Detour and Work Zone	Detour length (C7)	8	miles
	Extra travel time on detour (Dt)	9	minutes
	Number of days of full closure (dfc)	180	days
	Number of days of partial closure (dpc)	0	days
Mitigation Alternative	Solution	Seismic retrofit	superstructure only, see Table 34
	Cost	$50,648,333	1.3
	Life (n)	100	years

Existing Asset Risk Assessment				
Owner Consequences	*Asset Cost*	*Cleanup Cost*	*Owner Consequence*	*Rounded*
C_{owner}	$ 38,960,256	$5,000	**$38,965,256**	**$38,966,000**
User Consequences	*Cost*	*Variable*	*Estimate*	*Rounded*
Full Closure	Vehicle Operating Costs	VOC_FC	$30,423,698	$30,424,000
	Lost Wages	LW_FC	$182,269,633	$182,270,000
Partial Closure	Vehicle Operating Costs	VOC_PC	$0	$0
	Lost Wages	LW_PC	$0	$0
		Total User Consequences	**$212,693,331**	**$212,694,000**
Vulnerability Assessment	*Event*	*Variable*	*Vulnerability*	*Lookup from Vulne*
Based on HAZUS Predctions for damage	No Damage	V_no damage	0.7546	
	Extensive Damage	V_extensive	0.1962	
	Complete Damage	V_complete	0.049	
Risk Assessment	*Event Occurance*	*Total Risk*	*Annual Risk*	*Rounded*
Risk = Consequence x Vulnerability x Threat Likelihood	No Damage	$38,966,000.00	$11,761	$12,000
	Extensive Damage		$3,058	$4,000
	Complete Damage		$764	$1,000
		Annual Owner Risk	**$15,583**	**$16,000**
	No Damage	$212,694,000.00	$64,200	$65,000
	Extensive Damage		$16,692	$17,000
	Complete Damage		$4,169	$5,000
		Annual User Risk	**$85,061**	**$86,000**
		Total Annual Risk (User + Owner)	**$100,644**	**$102,000**

Mitigation of Asset Risk Assessment				
Owner Consequences	*Asset Cost*	*Cleanup Cost*	*Owner Consequence*	*Rounded*
C_{owner}	$ 50,648,333	$0.00	**$50,648,333**	**$50,649,000**
User Consequences	*Cost*	*Variable*	*Estimate*	*Rounded*
Full Closure	Vehicle Operating Costs	VOC_FC	$30,423,698	$30,424,000
	Lost Wages	LW_FC	$182,269,633	$182,270,000
Partial Closure	Vehicle Operating Costs	VOC_PC	$0	$0
	Lost Wages	LW_PC	$0	$0
		Total User Consequences	**$212,693,331**	**$212,694,000**
Vulnerability Assessment	*Event*	*Variable*	*Vulnerability*	*Lookup from Vulne*
Based on condition, capacity, and flood event	No Damage	V_no damage	0.7546	*Only consider no da*
	Extensive Damage	V_extensive	0.0000	
	Complete Damage	V_complete	0.0000	
Risk Assessment	*Event Occurance*	*Total Risk*	*Annual Risk*	*Rounded*
Risk = Consequence x Vulnerability x Threat Likelihood	No Damage	$50,649,000	$15,288	$16,000
	Extensive Damage		$0	$0
	Complete Damage		$0	$0
		Annual Owner Risk	**$15,288**	**$16,000**
	No Damage	$212,694,000	$64,200	$65,000
	Extensive Damage		$0	$0
	Complete Damage		$0	$0
		Annual User Risk	**$64,200**	**$65,000**
		Total Annual Risk (User + Owner)	**$79,487**	**$80,000**
Benefit Cost Analysis	*Baseline*	*Mitigation*	*Annual Mitigation Benefit*	*Rounded*
Total Annual Risk	$102,000.00	$80,000	$22,000	$22,000
		Total Cost	*Annual Mitigation Cost*	*Rounded*
	Mitigation alternative	$50,649,000	$3,549,521	$3,550,000
		Benefit	*Cost*	*BC Ratio*
	Benefit- Cost Ratio	$22,000	$3,550,000	**0.006**

Figure 61. Summary Calculations for Interstate 55 (Hwy 64) Bridge