Implementation Report
TRC2003
Data Driven Methods for Assess Transportation System Resilience in Arkansas

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16. Abstract

This Implementation Report describes the data needs, processing, and files associated with the project TRC2003 titled Data Driven Methods to Assess Transportation System Resilience in Arkansas. The Implementation Report is structured as follows. Chapter 1 provides an overview of the project objectives. Chapter 2 summarizes the data needs and sources. Chapter 3 describes the transportation network model update procedures. Chapter 4 summarizes the cost-benefit calculations. Chapter 5 summarizes the files described in the report and where to locate them. This report is meant to provide an overview of the procedures used in the study in a way that the reader would be able to carry out the main tasks of the project. Full details on the methodology and findings can be found in the Final Report associated with this project.

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METRIC CONVERSIONS

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)		
°F	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	°C
		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)		
°C	Celsius	1.8C+32	Fahrenheit	°F
		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

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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 Judgements
AIP	Aggregating Individual Priorities
ARC	Asset Replacement Cost
ARDOT	Arkansas Department of Transportation
ARNOLD	All Roads Network of Linear referenced Data
ARSTDM	Arkansas Statewide Travel Demand Model
B/C	Benefit Cost Ratio
CBC	Concrete Box Culvert
CDOT	Colorado Department of Transportation
CTDOT	Connecticut Department of Transportation
DEM	Digital Elevation Map
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	Geographical Information System
LoR	Loss of Resiliency
LRS	Linear Reference 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
R&R	Risk and Resilience
RIK	Replace-In-Kind
SIR	System Information and Research
SoVI	Social Vulnerability Index
TAMP	Transportation Asset Management Plan
TnDOT	Tennessee Department of Transportation
TPP	Transportation Planning and Policy
USDOT	U.S. Department of Transportation
USGS	US Geological Survey

EXECUTIVE SUMMARY

TRC2003 titled Data Driven Methods for Assess Transportation System Resilience in Arkansas provides a resilience score for each link in the state-maintained roadway network. This data gives ARDOT a means to rank and prioritize resiliency mitigation projects across the state. The methods developed can be updated with new data to maintain the relevancy of the assessment method.

This Implementation Report describes the data needs, processing, and files associated with the project TRC2003 titled Data Driven Methods to Assess Transportation System Resilience in Arkansas. The Implementation Report is structured as follows. Chapter 1 provides an overview of the project objectives. Chapter 2 summarizes the data needs and sources. Chapter 3 describes the transportation network model update procedures. Chapter 4 summarizes the cost-benefit calculations. Chapter 5 concludes with a list of files and where to locate them. This report is meant to provide an overview of the procedures used in the study in a way that the reader would be able to carry out the main tasks of the project. Full details on the methodology and findings can be found in the Final Report associated with this project.

CHAPTER 1: PROJECT OVERVIEW

1.1 STRUCTURE OF THE REPORT

This Implementation Report is organized as follows:

- Chapter 2 reviews the data needed to perform the criticality and vulnerability assessment,
- Chapter 3 presents the process to update the road transportation network,
- Chapter 4 presents the benefit-cost analysis template, and
- Chapter 5 concludes with the list of files and their location.

1.2 BACKGROUND

The processes described in this Implementation Report provide a foundational and repeatable resiliency assessment methodology to identify top critical and vulnerable assets. Implementing resiliency in the transportation infrastructure system creates a need for developing metrics that measure the resiliency of the system. Metrics provide insight about the current resiliency of the system; they provide stakeholders the opportunity to determine the amount of resiliency that is incorporated in the system and to identify its most critical segments. The metrics can also be used as an indication of improvements of 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 overall network resiliency as a combination of the probability of disruptions in one or more of the network links (threats) and importance of the link to mobility (criticality). This project provides ARDOT with a resilience assessment that can be incorporated into existing planning, design, construction, operations, and maintenance activities

1.3 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. The research had four supporting objectives as follows:

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 current state of practices within ARDOT. The method developed by the Colorado Department of Transportation (CDOT) was adopted. Six criteria are used to estimate system criticality: traffic volume (Annual Average Daily Traffic or AADT), roadway classification, freight output, tourism output, Social Vulnerability Index (SoVI), and redundancy. Three threat types are used to estimate system vulnerability: floods, landslides, and earthquakes. Criticality and vulnerability values are converted to intensity scores then combined so that the highest scoring links are considered the most critical and most vulnerable.

Objective 2: Methodology Development and Application

The research team applied the CDOT methodology to perform a resiliency assessment of the Arkansas state-maintained roadway network. This included identifying necessary data elements to estimate the six vulnerability criteria and three threat types. Both passenger and freight networks and flows were considered within the criteria. Criteria data was 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 was gathered from ARDOT GIS Office, the US Geological Survey, the Arkansas Geological Survey, and Federal Emergency Management Agency (FEMA). Methods to estimate scores for criticality and vulnerability were developed and applied to the statewide network to identify the most critical and vulnerable assets. A survey was conducted among the project sub-committee members to rank order 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 the top five most critical and vulnerable transportation assets. The five sites are: (1) Highway 67 in Pulaski County which contains one bridge and two culverts, (2) Interstate 55 in Crittenden County with contains one bridges, (3) Interstate 40 in Crittenden County which contains one bridge, (4) Interstate 430 in Pulaski County which contains one bridge, and (5) Interstate 55 in Crittenden County which contains one bridge. For each case study location, the research team conducted a benefit/cost analysis that estimates the benefits and costs of mitigative solutions to reduce the risk of damage and increase resilience of the asset.

Objective 4: Recommendations and Implementation
This project provides a resilience score for each link in the state-maintained roadway network. This data gives ARDOT a means to rank and prioritize resiliency mitigation projects across the state. The methods developed can be updated with new data to maintain the relevancy of the assessment method.

CHAPTER 2: DATA FOR CRITICALITY AND VULNERABILITY ANALYSES

This chapter summarizes the data needs and sources used to estimate criticality and vulnerability including the metadata for provided data files.

2.1 CRITICALITY METRIC DATA NEEDS AND SOURCES

The approach in this project is to calculate a numeric criticality value ('metric') for each transportation network link operated by ARDOT using the criteria shown in Table 1. Note that AADT and roadway classification can be obtained from existing data sources at the link level, redundancy is calculated via an approach developed for the project at the link level, and freight, tourism, and SoVI are only available at the zonal (county) level and must be estimated for each link.

Table 1. Criticality Criteria Data Needs and Sources

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 of 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.	U.S. Department of Transportation, Bureau of Transportation Statistics and Federal Highway Administration, Freight Analysis Framework, Version 4.5, 2019	County
Tourism	Tourism value as 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[1]	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

2.2 VULNERAILITY METRIC DATA NEEDS AND SOURCES

In this report, we consider flooding, earthquakes, and landslides as threats. We consider vulnerable links as those most likely to be exposed to the defined threats. All measures of

[1] Arkansas Department of Parks, Heritage, and Tourism: https://www.arkansas.com/industry-insider/research-and-development/research-services

threat likelihood were derived at the link-level for floods, landslides, and earthquakes (Table 2). Data sources include the Department's GIS office, the US and AR Geological Surveys, and the FEMA Hazus Model.

Table 2. 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, 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 from frequency of occurrence.
Earthquake	Federal Emergency Management Agency (FEMA) Hazus Model; AR GIS Digital Elevation Map (DEM), AR Geologic Map Data[2]	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'.

2.3 METADATA AND FILE NAMES

This section summarizes the data file names and metadata needed for the criticality and vulnerability analyses.

2.3.1 Criticality

Data for criticality metrics is provided in the file titled **"Criticality Values and Scores.xls"**. Metadata for the criticality metrics is provided in Table 3.

Table 3. Metadata for Criticality Metric File

No.	Column Title	Description	Data Format	Units
1	link_id	Roadway link ID, corresponds to the hybrid network file roadway ID field	Numeric	N/A
2	County	Name of Arkansas county	String	N/A
3	Length_mi	Length of the road segment in miles	Numeric	miles
4	Shape_Leng	GIS derived length of the polyline	Numeric	map units
5	rdwyclassc	Roadway classification as functional class, 1 through 5, 99 indicates unknown	Categorical	N/A
6	AADT_altou	Annual Average Daily Traffic for free flow conditions	Numeric	vehicles per day

[2] Arkansas Geologic Map Data available from the USGS at https://mrdata.usgs.gov/geology/state/state.php?state=AR

No.	Column Title	Description	Data Format	Units
7	Freight_M	Freight value for the county in which the link resides	Numeric	millions of US dollars
8	Tourism_M	Tourism expenditures for the county in which the link resides	Numeric	millions of US dollars
9	CountySoVI	Social Vulnerability Index for the county in which the link resides	Numeric	unitless
10	DiffFreeFl	Redundancy measure reported as the difference in the free flow travel time for fully operational network and link closure scenario	Numeric	vehicle-hours
11	Disconnect	Number of disconnected trips when the link is non-operational	Numeric	vehicles
12	RdwyClassi	Criticality score, 1-5 for roadway classification	Categorical	N/A
13	AADTcritic	Criticality score, 1-5 for AADT	Categorical	N/A
14	FreightCri	Criticality score, 1-5 for freight value	Categorical	N/A
15	TourismCri	Criticality score, 1-5 for tourism value	Categorical	N/A
16	SoVICritic	Criticality score, 1-5 for SoVI	Categorical	N/A
17	Redundancy	Criticality score, 1-5 for redundancy	Categorical	N/A
18	LinkCritic	Estimated criticality score using equal weights (1/6), e.g., weighted average	Numeric	N/A

2.3.2 Vulnerability

Data for vulnerability metrics is provided in the file titled **"Vulnerability Values and Scores.xls"**. Metadata for the vulnerability metrics is provided in Table 4.

Table 4. Metadata for Vulnerability Metric File

No.	Column Title	Description	Data Format	Units
1	link_id	Roadway link ID, corresponds to the hybrid network file roadway ID field	Numeric	N/A
2	County	Name of Arkansas county	String	N/A
3	SegmentNam	Name of the segment	String	N/A
4	Length_m_1	Length of the road segment in miles	Numeric	miles
5	Shape_Length	GIS derived length of the polyline	Numeric	map units
6	LandslideCount	Number of landslides within a 1 mile radius	Numeric	count
7	FloodCount	Number of floods resulting in road closures	Numeric	count
8	nodamage	Probability of no damage due to 7.7 magnitude earthquake	Numeric	decimal (/100 percent)
9	extensivedamage	Probability of extensive damage due to 7.7 magnitude earthquake	Numeric	decimal (/100 percent)
10	completedamage	Probability of complete damage due to 7.7 magnitude earthquake	Numeric	decimal (/100 percent)
11	lsvuln	Vulnerability score, 1-3 for landslides	Categorical	N/A
12	eqvuln	Vulnerability score, 1-3 for probability of extensive damage for earthquake	Categorical	N/A
13	flvuln	Vulnerability score, 1-3 for floods	Categorical	N/A
14	vuln	Estimated vulnerability score using equal weights (1/3), e.g., weighted average	Numeric	N/A

CHAPTER 3: ROADWAY NETWORK DEVELOPMENT

The All Roads Network Of Linear referenced Data (ARNOLD) network file was used in this project. The ARNOLD network contains all public road geometry and is available as a Geographical Information System (GIS) compatible file, e.g., a .'shp' file and geodatabase. At the time of this project, the ARNOLD network was available but was not complete. ARNOLD was incomplete in that it contained duplicate and missing geometry and was not designed to be a routable network. A routable network means that 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. The research team combined the ARNOLD LRS with the network represented in the Arkansas Statewide Travel Demand Model (ARSTDM). The ARSTDM network is a routable network with abstract representation of geometric. It is not complete in that it represents all state-maintained highways but lacks the geometry for local and other non-state roads. The following section details the procedure to combine the ARNOLD and ARSTDM roadway network representations to produce a complete and routable network file for this project.

3.1 NETWORK UPDATES OVERVIEW

The ARNOLD network data was provided by the Department and consists of centerline geometry, road identification number, functional class, road design, road length, and others The ARNOLD network is geometrically representative of roadway segments and is the most updated and complete road network inventory available.

The ARSTDM network was collected from the Arkansas Statewide Travel Demand Model implemented in TransCAD, a proprietary travel demand modeling software. The ARSTDM network is a geometric abstraction of roadways and is outdated.

3.2 HYBRID NETWORK DEVELOPMENT

A hybrid network can be created by merging the ARNOLD and ARSTDM networks. Treating ARSTDM as the base network, first omit the overlapped links from the ARNOLD network. To do this, apply a spatial buffer of 0.25mi to the base map (ARSTDM) to indicate links in which there was no ARNOLD link within the buffer. Then compare and identify non-overlapping links, e.g., links in ARSTDM without an ARNOLD link within its buffer and vice versa. For the case where links do not overlap, manually review the hybrid network to find and remove the topology errors that appeared after the merging. Using GIS tools, identify topology errors to ensure the new links from ARNOLD snapped to the old links and created a continuous link (routable).

3.3 HYBRID NETWORK FILES

The file containing the hybrid network is provided as a Shapes File, e.g., .shp file. A Shapes File contains geospatial vector data formatted for GIS software. It is interoperable in most GIS software systems including ArcGIS and QGIS (an open source GIS software). The name of the Shapes File containing the hybrid network is **"BaseNetwork.shp"**. The .shp and associated files (.shx, .dbf, .sbn) are also provided under the same name.

CHAPTER 4: BENEFIT/COST ANALYSIS CASE STUDIES

This chapter introduces and explains how to use the template developed for this project to estimate the costs and benefits of resilience mitigation activities.

5.1 OVERVIEW OF BENEFIT-COST METHODOLOGY

Benefit-Cost analyses are used to compare cost effective asset mitigation and/or protection solutions to address system vulnerabilities for the most critical links. We follow the procedures outlined in the Risk and Resilience Analysis Procedure developed for the Colorado DOT (CDOT, 2020) (Figure 1).

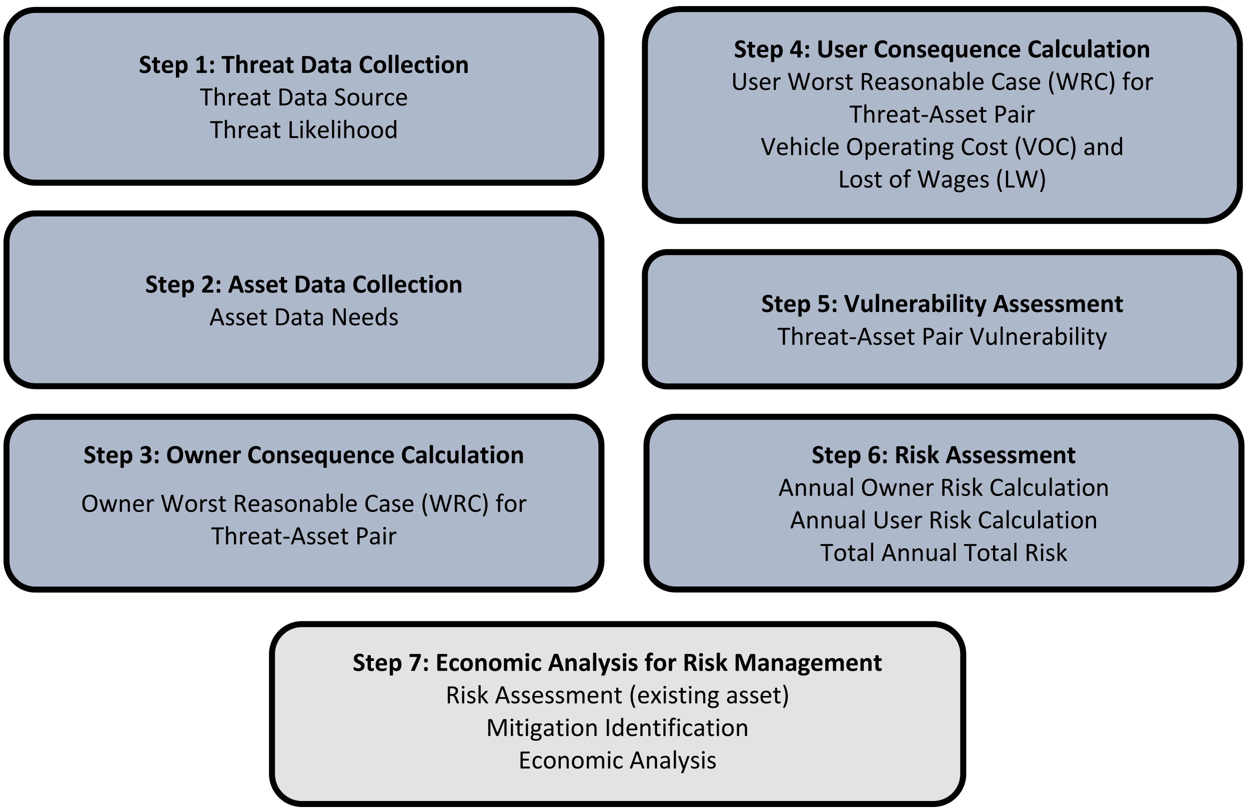

Figure 1. Overview of the Benefit-Cost Analysis procedure (adapted from CDOT, 2020)

5.2 DATA SOURCES

The Benefit-Cost analyses require the following data: asset characteristics, location, condition, replacement cost, threat likelihood, vulnerability potential, user consequence costs including closure days, value of time, vehicle operating costs, vehicle occupancy, work zone characteristics, detour lengths, and others, owner consequence costs including asset replacement and retrofit costs. Data on all of the above-mentioned items are provided in the Excel template and described in Section 5.3 of this report with the exception of asset characteristic data which is described below.

Asset location, characteristics, condition, and replacement costs were gathered from the Department in a file titled **"StateOwnedReplacementCosts.xls"**. Metadata for the file is shown in Table 5. In some cases, additional condition data and asset characteristics were needed beyond what was provided by ARDOT. The National Bridge Inventory (NBI) data was gathered from the USDOT FHWA Bridges and Structures website[3]. Metadata for the NBI records are provided by FHWA and can be found on the NBI website[4]. The NBI data extracted for Arkansas is provided in the file titled "**NBI Arkansas Data.xls**".

Table 5. Metadata for State Owned Replacement Costs

No.	Column Title	Description	Data Format	Units
1	Structurenumber	Structure identification number	String	N/A
2	BridgeorCulvert	Bridge or culvert designation	String	N/A
3	Owner	Asset owner, e.g., local, state, federal	String	N/A
4	District	ARDOT District number	String	N/A
5	CountyName	Name of Arkansas county	String	N/A
6	ArnoldRoadID	Roadway ID from ARNOLD map	Numeric	N/A
7	ArnoldLM	Log mile from ARNOLD map	Numeric	N/A
8	YearBuilt	Year asset was built	Numeric	year
9	LatitudeCalculated	Longitude coordinate (approximate)	Numeric	N/A
10	LongitudeCalculated	Latitude coordinate (approximate)	Numeric	N/A
11	Width	Width of the asset	Numeric	feet
12	Length	Length of the asset	Numeric	feet
13	Condition	Condition rating	Categorical	N/A
14	OpenPostedClosed	Noted closure or load posting	String	N/A
15	ReplacementCost	Estimated replacement cost	Numeric	US Dollars

5.3 TEMPLATE FOR BC ANALYSES

We developed a Microsoft Excel Workbook template called "**BC Analysis for Study Sites**" to calculate Benefit-Cost ratios for the study sites described in this project. This section describes the template.

5.3.1 Reference Values

The first three tabs of the Workbook contain the reference values for threat likelihood, vulnerability, and user consequence. These tabs are labeled 'Threat Likelihood', 'Vulnerability', and 'User Consequence'. Threat likelihood contains the tables for flood recurrence, landslide likelihood, and earthquake likelihood. Changing values in these tables will automatically update the calculations in the case study spreadsheets.

5.3.2. Summary

The tab labeled 'Summary' contains a table and graphs that summarize the calculated risk and benefit values for the baseline and mitigation alternatives for each of the study sites. The summary table automatically populates any calculated field. The table includes the following values for the existing asset (baseline) and mitigation alternative (improvement): annual owner risk, annual user risk, and total risk. The table also contains the annual mitigation benefit,

[3] National Bridge Inventory, Download NBI ASCII files, https://www.fhwa.dot.gov/bridge/nbi/ascii.cfm
[4] National Bridge Inventory, NBI ASCII files, NBI Record Format, https://www.fhwa.dot.gov/bridge/nbi/format.cfm

annual cost of mitigation, and the calculated B/C ratio. Following the table, the spreadsheet contains bar charts to compare the existing and mitigation alternative user and owner costs as well as the B/C ratio.

5.3.3 Threat-Asset Pairs

The template is set up to calculate the risks and benefits for the five study sites described in the Final Report. However, the template can be easily adapted to model the B/C values for any future study site by using each case study spreadsheet as a template for a particular threat-asset pair. In this section, we describe the templates for the following threat-asset pairs: flood-culvert, flood-bridge, and earthquake-bridge. In general, each spreadsheet contains a table of asset characteristics (example in Table 6). This table varies slightly depending on the asset and threat data that is needed. Data should be gathered from "**NBI Arkansas Data.xls**" or **"StateOwnedReplacementCosts.xls"** and manually entered into the cells highlighted in yellow.

Table 6. Asset Characteristics Data for Flood-Culvert pair

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 freeway (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 chnl protection condition	8	
	Drainage basin landcover type	Trees	
	Slope	Low	%
Site Traffic	AADTVehicle	25,887	vehicles per day per direction
	AADTTruck	2,589	trucks per day per direction
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

Following the asset characteristics table, the spreadsheet contains a section for 'Threat Assessment'. This is followed by sections for 'Existing Asset Risk Assessment', 'Mitigation of Asset Risk Assessment', and 'Benefit Cost Analysis'. Each is described in the next section.

5.3.3.1 Flood-Culvert

The analysis of user and owner risks for culvert mitigation due to the threat of floods requires the data elements shown Table 6. Threat data (Table 7) should be gathered from the reference tab, 'Threat Likelihood', for the threat events of interest, and entered into the cells highlighted in yellow.

Table 7. Threat Assessment for Flood Event

Threat Assessment	*Event*	*Variable*	*Threat Likelihood*
Based on flood interval	100 yr flood	T_{100}	0.01
	500 yr flood	T_{500}	0.002

To calculate the existing asset risk assessment, the user should input the vulnerability of the asset into the cells highlighted in yellow in Figure 2. These can be pulled from the 'Vulnerability' tab of the Workbook. Note that vulnerability is an asset specific value. The user can use the generic values provided in the Workbook but should ideally estimate the vulnerability of the asset specific to the asset's characteristics and area. All other cells shown in Figure 2 will automatically calculate. The darker orange cells indicate the estimated total annual risk (user and owner) for the baseline.

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	$10,154,176	$10,155,000
	Lost Wages	LW_FC	$11,523,223	$11,524,000
Partial Closure	Vehicle Operating Costs	VOC_PC	$0	$0
	Lost Wages	LW_PC	$0	$0
		Total User Consequences	**$21,677,398**	**$21,678,000**
Vulnerability Assessment	*Event*	*Variable*	*Vulnerability*	
Based on condition, capacity, and flood event	100 yr flood	V_{100}	0.12	*Lookup from Vulner*
	500 yr flood	V_{500}	0.99	*Lookup from Vulner*
Risk Assessment	*Event Occurance*	*Total Risk*	*Annual Risk*	*Rounded*
Risk = Consequence x Vulnerability x Threat Likelihood	100 yr flood	$1,261,000.00	$1,513	$2,000
	500 yr flood		$2,497	$3,000
		Annual Owner Risk	**$4,010**	**$5,000**
	100 yr flood	$21,678,000.00	$26,014	$27,000
	500 yr flood		$42,922	$43,000
		Annual User Risk	**$68,936**	**$69,000**
		Total Annual Risk (User + Owner)	**$72,946**	**$74,000**

Figure 2. Existing Asset Risk Assessment Template for Flood-Culvert Pair

The mitigation alternative risk assessment includes calculations for total annual risk based on the reduced vulnerability of the asset stemming from structural or other improvements to the asset under analysis. To calculate the mitigation alternative risk assessment, the user should input the (reduced) vulnerability of the asset into the cells highlighted in yellow in Figure 3. These can be pulled from the 'Vulnerability' tab of the Workbook. All other cells shown in

Figure 3 will automatically calculate. The green cell indicates the estimated total annual risk (user and owner) of mitigation.

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	$10,154,176	$10,155,000
	Lost Wages	LW_FC	$11,523,223	$11,524,000
Partial Closure	Vehicle Operating Costs	VOC_PC	$0	$0
	Lost Wages	LW_PC	$0	$0
		Total User Consequences	**$21,677,398**	**$21,678,000**
Vulnerability Assessment	*Event*	*Variable*	*Vulnerability*	
Based on condition, capacity, and flood event	100 yr flood	V_{100}	0.005	*Lookup from Vulner*
	500 yr flood	V_{500}	0.1	*Lookup from Vulner*
Risk Assessment	*Event Occurance*	*Total Risk*	*Annual Risk*	*Rounded*
Risk = Consequence x Vulnerability x Threat Likelihood	100 yr flood	$500,000	$25	$30
	500 yr flood		$100	$100
		Annual Owner Risk	**$125**	**$130**
	100 yr flood	$21,678,000	$1,084	$1,090
	500 yr flood		$4,336	$4,340
		Annual User Risk	**$5,420**	**$5,420**
		Total Annual Risk (User + Owner)	**$5,545**	**$6,000**

Figure 3. Mitigation Alternative Asset Risk Assessment Template for Flood-Culvert Pair

The final section of the spreadsheet template contains the calculations for the benefit-cost ratio calculations (Figure 4). The user does not need to input any values into this section as all cells are automatically calculated based on prior inputs. The cell in bright blue shows the resulting B/C ratio.

Benefit Cost Analysis	*Baseline*	*Mitigation*	*Annual Mitigation Benefit*	*Rounded*
Total Annual Risk	$74,000	$6,000	$68,000	$68,000
		Total Cost	*Annual Mitigation Cost*	*Rounded*
	Mitigation alternative	$500,000	$35,040	$36,000
		Benefit	*Cost*	*BC Ratio*
	Benefit- Cost Ratio	$68,000	$36,000	**1.889**

Figure 4. Benefit Cost Ratio Calculation Template for Flood-Culvert Pair

5.3.3.2 Flood-Bridge

The asset characteristics needed for the estimation of the BC ratio for the flood-bridge asset pair are shown in Table 8. Flood-bridge threat-asset pair BC estimation requires the span length and superstructure, substructure, scour, and channel conditions. Inputs for the threat assessment, existing asset risk assessment, mitigation of asset risk assessment, and benefit cost analysis are the same as for flood-culvert and shown in Figure 2, Figure 3, and Figure 4, respectively.

Table 8. Asset Characteristics Data for Flood-Bridge pair

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	
Site Traffic	Drainage basin landcover type	Trees	
	Mean basin slope	Low	
Detour and Work Zone	AADT Vehicle	33,434	vehicles per day per direction
	AADT Truck	3,343	trucks per day per direction
	Detour length (C7)	25	miles
	Extra travel time on detour (Dt)	27	minutes
Mitigation Alternative	Number of days of full closure (dfc)	180	days
	Number of days of partial closure (dpc)	0	days
	Solution	Flow Relief Structures	(Cross culverts 100 yr hydraulic capacity for flood response)
	Cost	$ 500,000	
	Life (n)	100	years

5.3.3.3 Earthquake-Bridge

The asset characteristics needed for the estimation of the BC ratio for the earthquake-bridge asset pair are the same as for the flood-bridge pair and are shown in Table 8. Inputs for the threat assessment, existing asset risk assessment, and mitigation of asset risk assessment are shown in Table 9, Figure 5, and Figure 6, respectively.

The threat likelihood of an earthquake can be altered by the user, but the value of 0.25 is recommended as it coincides with the occurrence of a 7.7 magnitude quake at the New Madrid Seismic zone. This is the scenario that was analyzed in the FEMA Hazus model to estimate the vulnerability of each roadway segment and related asset. The vulnerability of the asset should be input by locating the asset on the roadway network using the Shape file described in Section 3.3 and the data on earthquake damage potential discussed in Section 2.3.2. Vulnerability for the baseline assessment is expressed as the likelihood of no damage (V_no damage), extensive damage (V_extensive), and complete damage (V_complete). Vulnerability for the mitigation alternative is expressed as the likelihood of no damage only. The calculated BC ratio for earthquake-bridge threat-asset pairs is the found the same as for the other threat-asset pairs (Figure 4).

Table 9. Threat Assessment for Earthquake Event

Threat Assessment	*Event*	*Variable*	*Threat Likelihood*
Based on earthquake probability	50 year	T_50	0.25

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	$17,109,192	$17,110,000
	Lost Wages	LW_FC	$89,295,962	$89,296,000
Partial Closure	Vehicle Operating Costs	VOC_PC	$0	$0
	Lost Wages	LW_PC	$0	$0
		Total User Consequences	**$106,405,154**	**$106,406,000**
Vulnerability Assessment	*Event*	*Variable*	*Vulnerability*	*Lookup from Vulner*
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	$152,879	$153,000
	Extensive Damage		$40,072	$41,000
	Complete Damage		$10,008	$11,000
		Annual Owner Risk	**$202,959**	**$203,000**
	No Damage	$106,406,000.00	$20,033,590	$20,034,000
	Extensive Damage		$5,251,136	$5,252,000
	Complete Damage		$1,311,454	$1,312,000
		Annual User Risk	**$26,596,180**	**$26,597,000**
		Total Annual Risk (User + Owner)	**$26,799,139**	**$26,800,000**

Figure 5. Existing Asset Risk Assessment Template for Earthquake-Bridge Pair

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	$17,109,192	$17,110,000
	Lost Wages	LW_FC	$89,295,962	$89,296,000
Partial Closure	Vehicle Operating Costs	VOC_PC	$0	$0
	Lost Wages	LW_PC	$0	$0
		Total User Consequences	**$106,405,154**	**$106,406,000**
Vulnerability Assessment	*Event*	*Variable*	*Vulnerability*	*Lookup from Vulner*
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	$470,876	$471,000
	Extensive Damage		$0	$0
	Complete Damage		$0	$0
		Annual Owner Risk	**$470,876**	**$471,000**
	No Damage	$106,406,000	$20,033,590	$20,034,000
	Extensive Damage		$0	$0
	Complete Damage		$0	$0
		Annual User Risk	**$20,033,590**	**$20,034,000**
		Total Annual Risk (User + Owner)	**$20,504,465**	**$20,505,000**

Figure 6. Mitigation Alternative Asset Risk Assessment Template for Earthquake-Flood Pair

CHAPTER 5. CLOSING

This Implementation Report compliments the work described in the Final Report for TRC2003, Data Driven Methods for Assess Transportation System Resilience in Arkansas. The Implementation Report summarizes data sources, methods, files, and metadata necessary to apply the methods described in the Final Report. The following set of files is described in this report and is available for download from the PI's website (https://wordpressua.uark.edu/sarahvh/research/):

1. ***BaseNetwork*** (folder)- contains the .shp files representing the Arkansas roadway network
2. ***Criticality Values and Scores*** (.xls)- contains the criticality values and scores for the six criticality metrics for each roadway segment
3. ***Vulnerability Values and Scores*** (.xls)- contains the vulnerability values and scores for the three threat types evaluated in this project for each roadway segment
4. ***NBI Arkansas Data*** (.xls)- contains the bridge and culvert characteristics and conditions data extracted from the National Bridge Inventory database
5. ***StateOwnedReplacementCosts*** (.xls)- contains the ARDOT owned and operated bridge and culvert inventory including estimated replacement costs
6. ***BC Analysis for Study Sites*** (.xls)- contains the templates for conducting a BC analysis for a study site

Questions on the methods described in this report should be directed to the project PI, Sarah Hernandez, sarahvh@uark.edu.