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TRANSPORTATION RESEARCH BOARD

Measuring Resiliency – Tools for Analyzing Resilient Transportation Systems

March 18, 2021

2:00-4:00 PM Eastern

@NASEMTRB
#TRBwebinar

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Learning Objectives

1. Identify state-of-the-practice in measuring resiliency

2. Identify federal, state, and local resources to help with infrastructure investment decisions

3. Discuss policies and standards that advance transportation resilience

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Transportation Research Board Webinar
The National Academies of Sciences
Measuring Resiliency – Tools for Analyzing Resilient Transportation Systems

Steven Olmsted – Arizona Department of Transportation – March 2021

Agency Resilience

Critical Transportation Infrastructure Protection

State

- Arizona State Emergency Response and Recovery Plan (SERRP)
- Planning Branch – AZ Department of Emergency and Military Affairs

ADOT

- Emergency Preparedness Management

https://azdot.gov/business/highway-maintenance/emergency-preparedness-management

- Business Continuity - pandemic - Director's Office revamp
- Roadway - Incident Response Unit
- Physical, chemical, biological – dedicated Emergency Manager
- Road Weather AZ 511 app / ADOT Alerts app
- Cyber - IT Security Risk Management & Compliance team
- Transportation Infrastructure - Weather & Natural Hazard

Transportation Infrastructure Resilience

FHWA 5520 - anticipate, prepare for, and adapt to changing conditions and withstand, respond to, and recover rapidly from disruptions

Program Definition - The management of assets (bridges, culverts, pavement, and roadside vegetation/stabilization) in relation to the extreme weather-climate risks of; intense precipitation, system flooding, wildfires, wildfire-induced floods, drought-related dust storms, rockfall incidents, slope failures, and measurable climate trends (especially as it relates to precipitation and direct effects of increased surface temperatures); by regions or specific segments, emphasized as critical to contribute to the safety of the traveling public, improve weather and natural hazard risk management, and improve the long term life cycle planning of transportation infrastructure.

Internal Working Group

ADOT Pilot Project Team

TSMO System Risk	Brent Cain, Transportation Systems Management and Operations Division, Director
Geotechnical Design	Brent Connor, Geotechnical Design Section Leader and Planning Engineer
Bridge Asset Class Risk	David Benton, Bridge Group Manager
Traffic Management	Derek Arnson, ADOT Traffic Management Group Manager
Emergency Management	Don Angell, ADOT Emergency Manager
Statewide Operations - District Risk	Jesse Gutierrez, Deputy State Engineer for Statewide Operations
Geotechnical/Geomorphology Risk	J.J. Liu, Geotechnical Group Manager
Materials and Pavement Risk	Kevin Robertson, Surface Treatment Engineer & Pavement Condition & Evaluation Manager
Materials and Pavement Risk	Nye McCarty, Flagstaff Regional Materials Engineer
Roadside Vegetation Risk	Kristin Gade, Roadside Resources Specialist – 2015 EW & Climate Vulnerability Co-Team Lead
Bridge Hydraulics	Nicholas Fiala, Transportation Engineering Specialist
Architecture/Landscaping	LeRoy Brady, Chief Landscape Architect
Materials	Paul Burch, Assistant State Materials Engineer
Construction Program Delivery Risk	Steve Boschen, Infrastructure Delivery and Operations, Director

Eligible Risks Inventory

- Intense Precipitation
- System Flooding
- Wildfires
- Wildfire-Induced Floods
- Drought-Related Dust Storms
- Rockfall Incidents
- Slope Failures
- Increased Surface Temperatures

Impacts Narrative

There is currently a multitude of natural hazard and weather related stressors present in Arizona, but they can largely be separated into two categories: extreme heat and extreme precipitation.

The negative impacts of extreme heat include: pavement deformation, shorter pavement construction windows, heat-related worker safety issues, and public safety during lengthy delays. Extreme heat can also lead to an increase in dust storms, due to a decrease in vegetation coverage on soil, as well as contributing to an increased number of wildfires. Areas affected by wildfires may see increases of runoff to levels that the current drainage system cannot handle. On the other hand, extreme heat has the benefit of reducing the amount of freeze-thaw impacts to pavements and a reduced amount of snow removal.

Impacts Narrative - continued

Precipitation levels are expected to remain consistent for the near future. However, if precipitation levels rise, the existing drainage and pump stations in the state may become overwhelmed. Another impact of oversaturated soils includes the increased likelihood of rock falls, subsidence, and landslides. Lower number of precipitation events but a higher intensity is a concern. This scenario can heavily impact rural and urban areas alike for safety and economic development.

Resilience Financial Decision Making Steps (1)

A critical part of ADOT's TAMP financial plan is the agency's investment strategy. A major contributor to that investment strategy is the identification of ways to maintain the asset categories by using risk-based lifecycle planning strategies. One of the fundamental ways in which an Agency can begin to sort and prioritize risk is through the use of the TAMP required risk register. Inherently, there are regulations, constraints, and existing commitments on available funding sources. Once ADOT considers all the asset needs against available resources, making room for extreme weather and measurable long-term climate (EX W & C) trend mitigation strategies is difficult.

Resilience Financial Decision Making Steps (2)

Even in light of those difficulties, ADOT prioritized conducting EX W & Climate vulnerability assessments, developing a Resilience Program, conducting extreme weather event modeling and engineering analysis, working with climate models, and begin resilience building.

In concert with using lifecycle planning to support asset management decision making and incorporating risk management into TAMP reporting, an Agency needs a formal financial process to consider extreme weather and climate in financial decision making.

Resilience Financial Decision Making Steps (3)

- Assessment of - Agency/SEO /5-yr Construction Program/Divisions/Districts
- Screen through - Resilience Program
- Looking for - All historical actions and known locations to catalogue (GIS)
- Identified by - Design/Construction/Operations/Maintenance
- Financially justified with - Resilience Investment Economic Analysis (RinVEA)
- Programmed using - Financial tool box
- Support garnered - Decision maker consensus

Resilience Financial Decision Making Steps (4)

- Funding confirmed - Project Resource Board, Project Management, Project Finance
- Resilience Scope of Work developed blending Risk/Science/Technology/Engineering
- Funded projects commences
- System resilience advances
- Lessons learned gained
- Feedback loop to TAM Program Manager and Resilience Program Manager
- Feedback loop to methodology - Risk/Science/Technology/Engineering

Resilience Investment Economic Analysis (RinVEA)

A need for a process to assess cost viability and develop a tool to integrate extreme weather and climate justification into asset management and financial decision making. It amounts to a:

- CBA (total systems / sustainability centric)
- Project Justification
- Resilience Investment

Agency Chinle, AZ project photos

Investment Decision Tools

Resilience Investment Economic Analysis (RinVEA)

The main objectives of the RinVEA is to conduct basic economic analysis (CBA Analysis) that included the following basic parameters:

- Protect the new $5.2M roadway investment
- Address severe erosional and drainage issues that has led to a 25%-100% degradation at sixty-one (61) of the eighty-six (86) CMP drainage structures
- Address drainage excavation, barrow and slope stabilization issues at those structures and severely compromised stormwater management capabilities along this segment of SR 191
- Comply with and proactively address expected regulatory actions on stormwater management, FHWA Order 5520, Presidential Executive Order on Federal Flood Risk Management, and MAP21 asset preservation performance requirements
- Upgrade ADOT's application of risk-based assessment modeling at the asset class, project development, and localized hydrological event level
- Further ensure use of SR 191 in the remote far northwest of Arizona and a main Apache County connector between SR 264 and US 160 in the advent of an extreme weather event

Resilience Building Tracking

Project Number	Rt.	System Location	Resilience Work Completed	Project Cost	Resilience & Financial Decision-Making Outcome
Resilience Building Project #1	SR 191	Chinle, AZ	31 Drainage Structures Rehab	$6m	Roadway and embankment now protected to the 50-year storm event
Resilience Building Project #2	SR 160	Laguna Creek Bridge	Gabion basket bank protection	$1m	Bridge now protected to the 500-yr storm event - Tribal Partner - key corridor
Resilience Building Project #3	SR 95	Fortuna Wash Bridge	Bridge replace	$9.3m	Bridge now protected against Fortuna Wash floodwaters flowing over the road, secured the $500m in area economic impact, reduced/eliminated considerable detour
Resilience Building Project #4	I-8	Foothills Blvd to Dome Valley	Roadway deterioration and clogged and corroded drainage structures due to storm events and aging repaired	$14m	Vulnerable NHS asset improved - Access for City of Yuma, Yuma Port of Entry, State of California, Yuma International Airport, USMC Air Station Yuma, Barry M. Goldwater Air Force Base, Port of San Luis SR 95, MP .01 Mexico Border
Resilience Building Project #5	I-17	New River Bridges Structures - N and S	Concrete floor approximately 3 feet below the channel bed underneath the bridges. Cutoff walls at both upstream (approximately 4 feet deep) and downstream (approximately 6 feet deep)	$2m	Vulnerable NHS asset improved Maricopa County and its 4.2m residents
Resilience Building Project #6,7,8 underway					
Resilience #9,10 identified entering design					
Resilience Operating Project #1 (TSMO)	Phx		Pump Station Optimization Tool for operators and capital investment	$200K	Developing predictive model of probability of pumping station failure. Variable examples: season, condition, manufacturing date, date of last repair, size, sufficiency of capacity, precipitation magnitude, and manufacturer type.

Asset Management

Asset Management Tools

Asset Management Risk Register - 25
Weather/Natural Hazard Risks – 6 (links to 6 other)
Agency – Extreme Weather Trends
Asset – Flooding, Scour, Pump Stations
Asset – Landslide/Slope Failure
Asset – Rockfall
Asset – Culvert Failure
Activity – Redundant Routes

Table 6-1 Risk Type

Risk Type	Affect
Agency Risk	Risk to the agency that affects the implementation of the strategic goals of the asset management plan. Examples include changes in leadership, legislative actions, unfunded mandates and the ability to convey the importance of asset management to decision-makers and the public.
Financial Risk	Affect the availability of adequate funding or accurate prediction of future funding needed to implement the TAMP. Examples include inflation, unexpected funding shortfalls, solvency of the Highway Trust Fund, financial markets, interest rate increases and inaccurate predictions in financial plans.
Program Risk	Affect the ability to deliver a program of projects in a timely manner and meet performance targets. Risks may include the inability to effectively manage data, the loss of institutional knowledge via attrition, competing spending priorities, inaccurate cost-estimates and construction/materials price volatility.
Asset Risk	Affect individual assets, such as structural deterioration, extreme weather and obsolescence. Assets risks include flooding, landslides, hazardous materials spills, collisions with bridge elements and assets that do not meet current design standards.
Project Risk	Associated with projects to restore or replace individual assets. An example of a project risk is the impacts associated with lengthy construction detours in areas where redundant, alternative routes don't exist. Project delivery risks include delays caused by environmental, utilities, right-of-way, geotechnical, procurement, scope creep and inter-governmental agreements.
Activity Risk	Associated activities like routine maintenance, including slow or inadequate response to damaged assets (e.g., pothole or guard rail repair) or extreme weather events (e.g., clearing blocked drainage structures, repairing scour weakened bridge foundations or risks to workers such as heat, fires, etc.).

Risk Rating Scale

		Consequence (C)				
Likelihood(L)		1	2	3	4	5
Level	Descriptor	Negligible	Minor	Major	Critical	Catastrophic
1	Low	1	2	3	4	5
2	Medium Low	2	4	6	8	10
3	Medium	3	6	9	12	15
4	Medium High	4	8	12	16	20
5	High	5	10	15	20	25

Agency Action Process

Agency Action	Description
Prevention	Vulnerability and risk assessments; Hardening of structures and materials; Detection and monitoring; Asset management techniques; Resiliency Plans
Response	Training; Emergency response guidelines; Practice drills; Alternative service strategies
Recovery	Alternative routing; Fast contracting and project initiation; Staff allocation plans
Investigation (Root-cause)	Engineering studies; Probabilistic analysis; Service planning reviews
Learning	After action reports; Research; Performance assessments

CEA-TA

A Climate Engineering Assessment for Transportation Assets (CEA-TA)
Incorporating Probabilistic Analysis into Extreme Weather and Climate Change Design Engineering

Steven Olmsted, Arizona Department of Transportation; Alan O'Connor, Trinity College Dublin; Constantine Samaras, Carnegie Mellon University;
Beatriz Martinez-Pastor, Trinity College Dublin; Lauren Cook, Carnegie Mellon University

Abstract

Transportation infrastructure is a complex system of assets required to deliver a myriad of services and functions. As fiscal constraint for the development and rehabilitation of such structures remains; and endless retrofitting continues to be cost prohibitive; new and novel approaches to long term planning and project development, engineering design, and life cycle assessment are paramount. The management of these infrastructure systems has now evolved from a decentralized, project-based focus, to one that now encompasses enterprise wide endeavors – administration, technology adoption, planning, design, construction, operations and maintenance. In addition, the expansion of risk analysis for extreme weather management and climate change adaptation has complicated the long term delivery of these complex transportation systems. At the 2015 Transportation Research Board (TRB) Annual Meeting, Session 197: *Mainstreaming Climate Change and Extreme Weather Resilience into Transportation*, the Arizona Department of Transportation (ADOT) introduced the challenge ahead for public entities to coordinate a host of known and unknown extreme weather and climate change issues. That challenge – Continue considering the balance between predictable asset deterioration curves, the sudden and unpredictable nature of extreme weather events and long term climate trends, new models for risk assessment and life cycle cost analysis, and appropriate adaptation strategies. This multiple part challenge necessitated a new end-to-end engineering approach to incorporate such current and future risks. At the 2016 Annual Meeting ADOT submitted a paper representing the core of that new approach – a Resilience Program and an ADOT/United States Geological Survey Partnership. That paper was graciously recognized as a best paper by the TRB Special Task Force on Climate Change and Energy. In the spirit of continuing that forward progress – this paper presents the remaining parts needed to develop a new end-to-end engineering-based asset adaption process – a structured sequence to incorporate extreme weather and climate change adaptation into the design engineering process. The paper benefits from preeminent researchers in the two integral, and practice ready, remaining parts – probabilistic modeling for engineering design and infrastructure system design life cycle outcomes for extreme weather and climate change in a transportation engineering setting.

Arizona DOT Resilience Program

Transportation infrastructure is a complex system of assets required to deliver a myriad of services and functions. The expansion of risk development for extreme weather management and climate change adaptation has complicated the long term delivery of these complex transportation systems.
In order to develop an innovative approach, the first step was to create a system process that allowed for a shift from a deterministic preset design parameter and/or frequency basis, statistical risk of failure, and historic project and programs budgeting focus – i.e. extreme events not considered – to a probabilistic analysis approach that inputs additional data, vulnerabilities, and considerations not previously considered. In 2015 and 2016 ADOT focused on linking scientific evidence-driven data capture with the design engineering processes through the development of a partnership with the United States Geological Society (USGS). Extensive 2-D/3-D engineered modeling underway.

(CEA-TA) – A Structured Sequence

WHY IS MOVING TO A PROBABILISTIC APPROACH EVEN NEEDED?
This question could cover pages and pages. The short answer is easy. In addition to sustainable transportation attributes, there is growing consensus that if transportation systems are going to incorporate extreme weather and climate change, consideration must be developed that account for hydrometeorology/climatology, hydrology, hydraulics, and hydrodynamics. Since all these areas continue to adopt advanced mathematical modeling approaches, it is therefore logical that transportation systems and projects develop also incorporate these progressions.

Identify EX W & CC project and program candidates - *Vulnerability Assessment*

2015 FHWA Pilot Project - The study examined baseline (historical) and potential future extreme weather conditions, focusing on temperature and precipitation variables. Two future analysis periods were selected: 2025 to 2055 (referred to subsequently as 2040, the median year), which reflects the time horizon of ongoing long-range planning efforts, and 2065 to 2095 (2080), roughly associated with the expected design lifespans of some critical infrastructure types, such as bridges. To provide a long term baseline against which to compare the projections, the team also examined temperature and precipitation observations from 1950 through 1999. The report was issued by FHWA in the Spring of 2016.

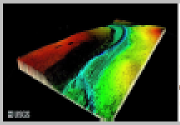
Develop economic analysis process - *Justification*

An economic analysis for the CEA-TA process would consist of using a probabilistic approach to life cycle cost analysis. The life cycle cost of an infrastructure asset such as a roadway or bridge, is the total cost to an agency throughout the asset's useful life. This includes the planning, design, construction, maintenance and decommissioning phases of infrastructure delivery. State DOTs typically initially approach this process without considering risk and uncertainty that future conditions will be different from the past, and assume a uniform distribution of annual maintenance costs and major reinvestment intervals. Long-lived infrastructure must perform under future climate conditions and climate-influenced usage that deviates from the historical data now populating infrastructure economic analysis and asset management models. Climate change impacts, such as sea-level rise, storm surges, changes in precipitation, hotter temperatures, and others are potential vectors of infrastructure failure and should be taken into consideration in infrastructure economic analysis and asset management models.

Resilience Program
Economic Analysis Pilot
US 191 MP 436 to Chinle
PROJECT NO. 191 AP 436 H8676 01 C
FEDERAL AID NO. STP-191-E(214)T
Apache County
Holbrook District

Design probabilistic modeling approach to produce an array of results - *Quality Control*

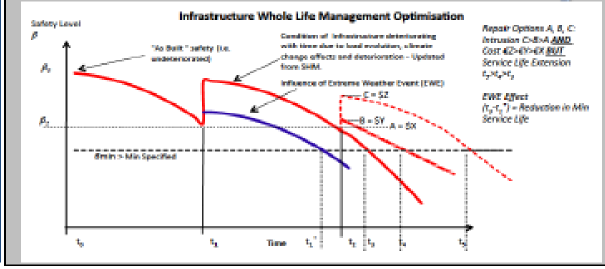
Optimize operation and maintenance of an increasingly aging stock, which is subjected to evolving loads (e.g. both live loading and climate induced loading). In response to this challenge the past decade has seen increased interest by infrastructure owners and managers in the use of probabilistic methods for the assessment/management of their assets. Employed once a deterministic assessment has rendered a repair/rehabilitate/replace now scenario



Define limits of simulation runs that incorporates latest science/engineering - *Policy*

Climate models can provide insight into future conditions, projecting air temperature, precipitation, evapotranspiration, and other factors of interest to engineers, at various temporal and spatial resolutions. However, there is a considerable disparity in the outputs provided from climate models for impacts analyses and the inputs needed by engineers for planning and design. These discrepancies include mismatches in temporal and spatial scales, complicated data extraction and preparation requirements, sizeable model, data, and scenario uncertainties, and a lack of direction for the rigorous selection of models for use in different engineering applications.
Innovative change examples:

- Every Day Counts – 4 : Collaborative Hydraulics: Advancing to the Next Generation of Engineering (CHANGE)
- NCHRP 15-61 - Applying Climate Change Information to Hydrologic and Hydraulic Design of Transportation Infrastructure
- NCAR - *The Future Intensification of Hourly Precipitation Extremes* - Andreas F. Prein et al. December 2016
- LiDAR, UAS/UAV, 2-D water modeling, 3-D visualization and animation tools
- Translational organizations to provide rigorous standards for interpretation of climate data, development of a single, simplified user interface that accesses all downscaled data sources, and tools that automatically post-process data based on defined standards



Systematically record location and resilience efforts GIS/TAMP - *Risk Management*

ADOT has been systematically capturing data sets for extreme weather and climate change use through an extensive geographic information system (GIS) effort that will subsequently support ADOT's transportation asset management planning (TAMP). ADOT's studies showed concerns with the climate and extreme weather vulnerability of bridges, culverts, pavement, and roadside vegetation / stabilization. Legislation - Focus in MAP-21 on performance based management and risk-based asset management plans; Inclusion of "resilience" in FAST Act.

Develop life cycle models to monitor investment - *BCA/ROI*

Civil infrastructure systems are among the largest local, state and Federal investments, and these infrastructure systems are critical to U.S. economic, environmental and social outcomes. Yet longstanding underinvestment in infrastructure has resulted in the poor condition of much of U.S. infrastructure, with an estimated $3.6 trillion of re-investment needed by 2020. New methods for benefit cost analysis, return on investment studies, and major rehabilitation timeline analyses are needed that incorporate probabilistic approaches, and minimize regret by DOTs under a changing climate. The results of CEA-TA provides that method.

Acknowledgments
The completion of this project would not have possible without assistance from many stakeholders both within and outside ADOT that contributed to this effort. Specifically, the International Symposium - *Transportation Resilience: Adaptation to Climate Change and Extreme Weather Events*, June 16-17, 2016 at the European Commission in Brussels, Belgium that was the catalyst for the transatlantic partnering. The ADOT author wishes to acknowledge the efforts and support of: ADOT State Engineer's Office and ADOT Environmental Planning.

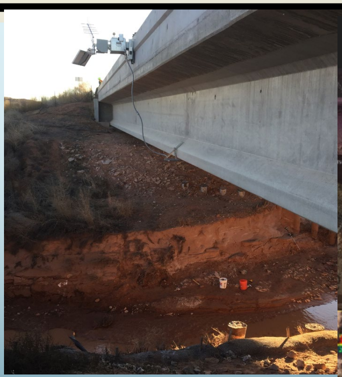
Engineering Tools

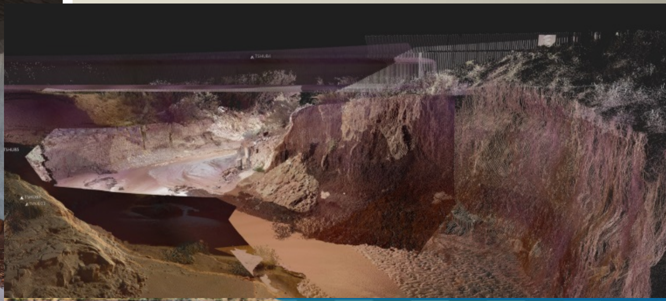
USGS Partnership - Reach Monitoring in Dynamic Channels

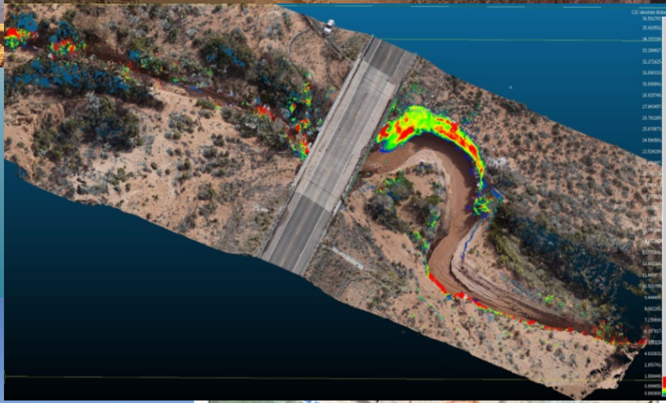
Understanding bank erosion and impacts to infrastructure

Laguna Creek Pilot Project Reach Monitoring:

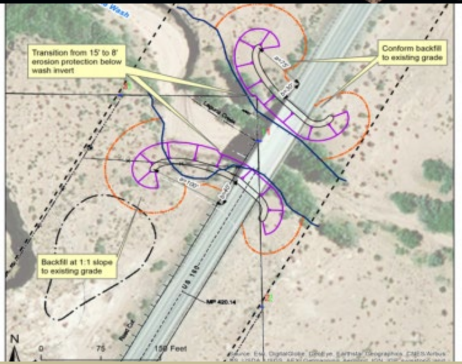
- Rapid deployment stream gage
- Surface velocity radar sensor
- Particle tracking video cameras
- Indirect discharge measurements
- Repeat LiDAR scans of bridge structure and surrounding channel
- sUAS (drone) survey







Agency Dennehotso, AZ project photos



Engineering Tools

Geohazard Management Plan

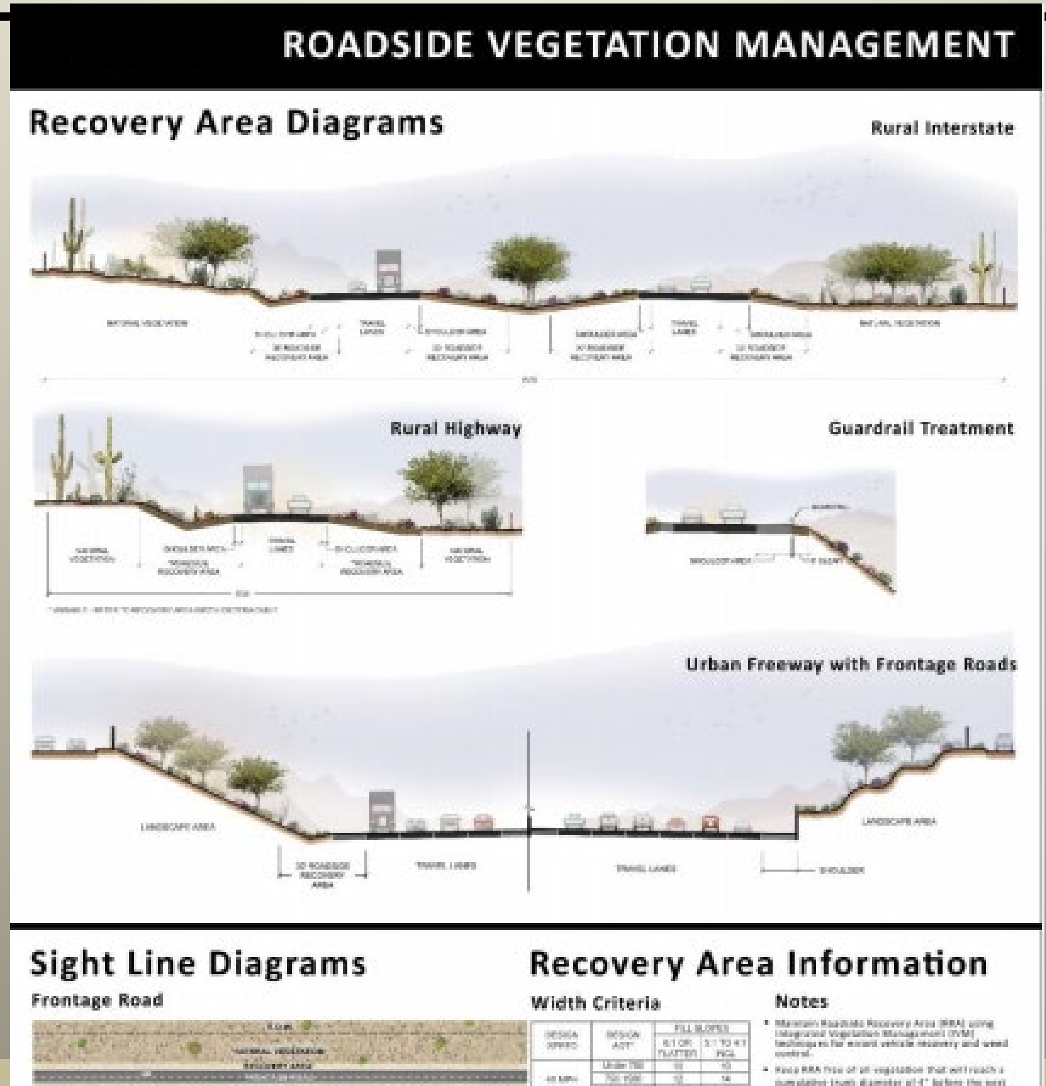
After experiencing significant impacts to mobility of the system due to geohazards in the analysis period of 2010 to 2015, ADOT has proactively managed many geohazards through preventative projects thought the Slope Management Subprogram. Geohazards such as landslides, rockfall, debris flow, sink holes, and heaving roadway subgrade have impacts to the maintenance, mobility and risk allocation in an asset management model.

Pavement Tool Box

The 2021 effort, already underway, will assess measurable climate trends against the impacts to ADOT's pavement asset class, surface treatments and materials, difficult to manage known freeze-thaw zones, and impacts to roadside vegetation/stabilization (biotic and seeding). All these have been framed to remain in the context of future asset management reporting for infrastructure health opportunities.

More specific to climate adaptation efforts

Roadside Vegetation / Stabilization



Resilience GIS Database

Data

- ADOT's USGS Data
- Drought & Wildfire
- Layers from ADOT's USGS Flood map
- Dust storm data (I-10 pilot)
- 5-yr program priority project information
- Bridges (including scour program)
- Culvert
- ADOT system base layers
- Geohazard locations
- Soils
- Live Feeds

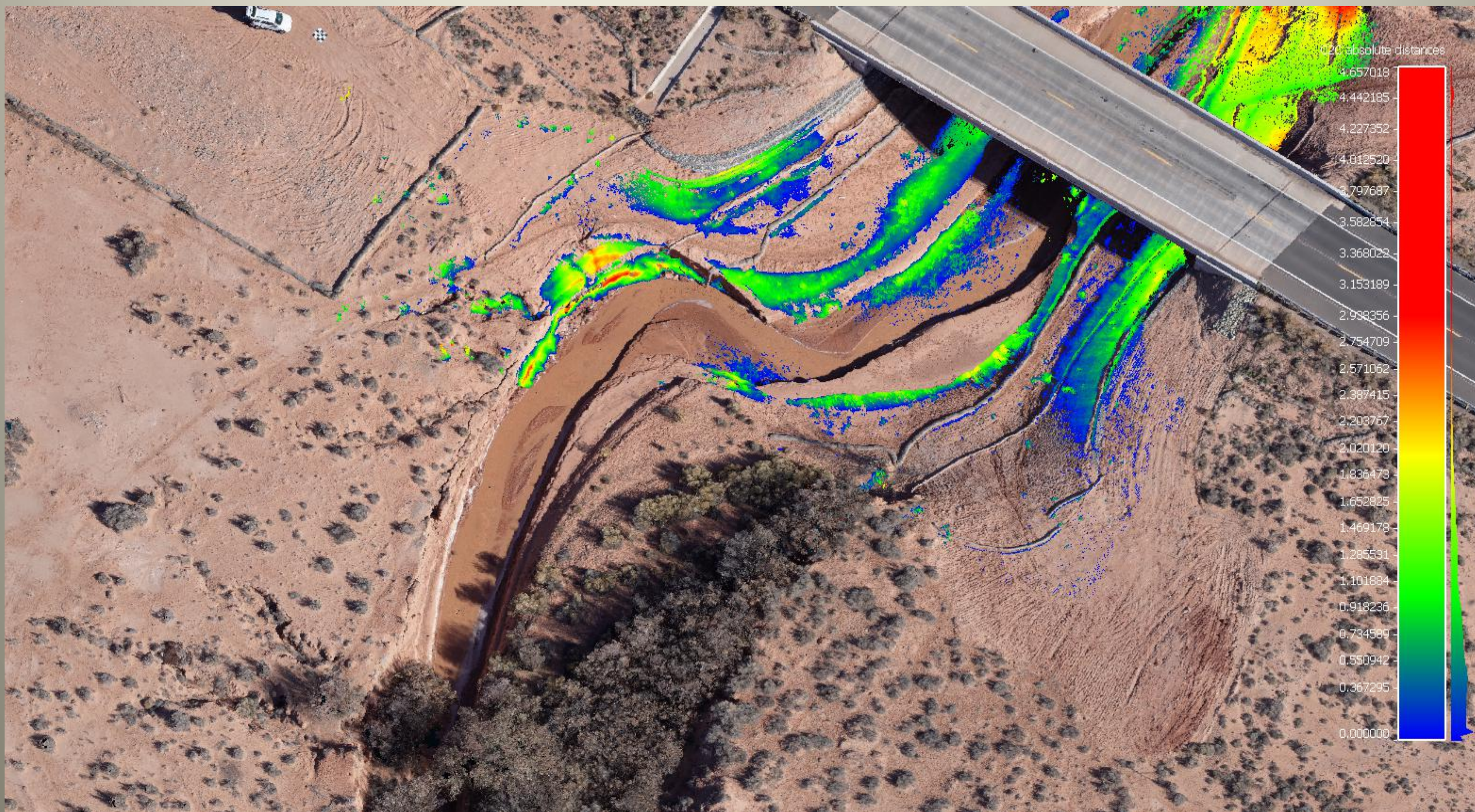
Data

- ADOT/USGS Project Work
- Resilience (Extreme Weather and Climate) Building
- Resilience Investment Economic Analysis assessment locations
- Climate Engineering Assessment for Transportation Asset (CEA-TA) locations
- Every Day Counts CHANGE 2-D modeling projects
- 2050 and 2100 climate data downscaling mapping
- Statewide drainage dashboard
- Weather event dashboards

Post Construction Monitoring Process

USGS Drone Data Capture – On-going Monitoring - Built Condition Wash Meander / Ox-bow

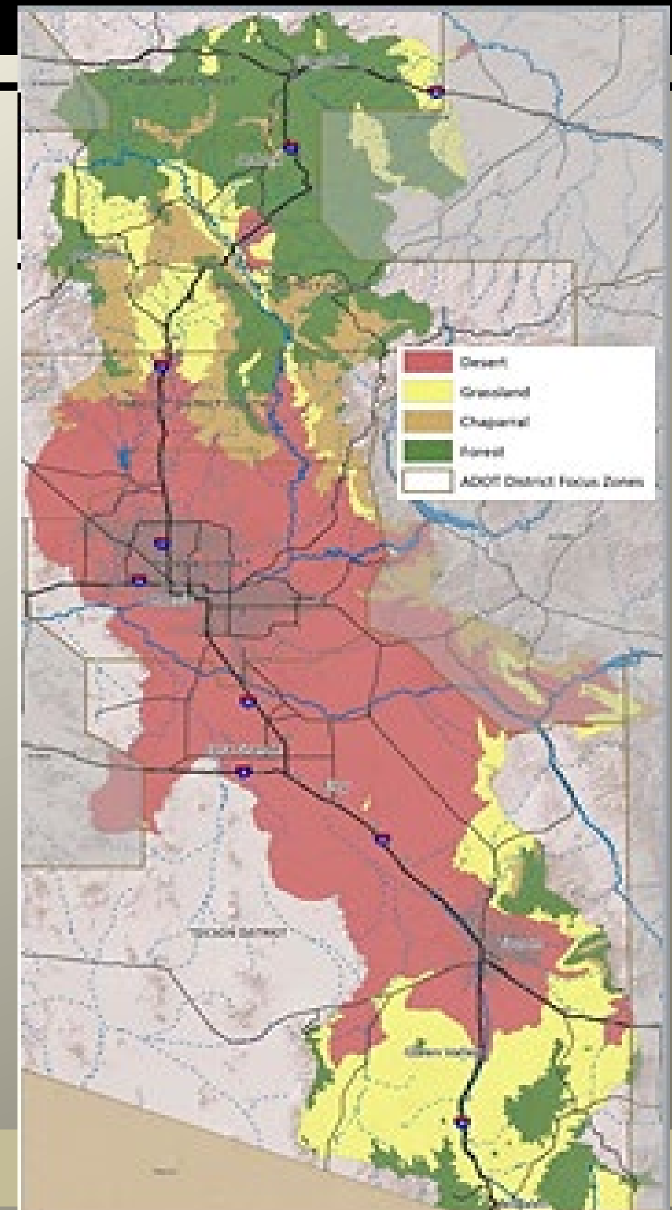
Post Construction Monitoring Process



2-D Erosion Change Detection Mapping

Develop Geographic Specific Climate Models

- Large, geographically diverse study area (over 30,000 square miles)
- High spatial resolution climate data desired
- Stressors included both average and extreme temperature and precipitation
- Helpful existing tools (e.g., FHWA CMIP Processer), but customization required
- Modest resources for collection and processing



Climate Data Selection

Parameter	Specification
Projections and Historical Data Source	Downscaled CMIP5 Bias Corrected Constructed Analogs (BCCA) daily projections with accompanying historical data
Emissions Pathway	Representative Concentration Pathway 8.5
Downscaled General Circulation Models (GCM)	NorESM1-M, HadGEM2-ES, CSIRO-MK3.6, CanESM2, MPI-ESM-LR, MPI-ESM-P, GFDL-ESM2M
Horizontal Spatial Resolution	1/8° (~7.5 mile or ~12km)
Temporal Resolution	Daily for 1950-2000 (backcastings from models in addition to historical data), 2025-2055, and 2065-2095
Model Outputs	Temperature (daily maximum and minimum) and precipitation (daily total)

Climate Output Metrics

Maximum 1-Day Precipitation Event (by time period)
100-/200-Year Maximum Precipitation Event using Generalized Extreme Value distribution
Minimum Annual Precipitation
Average Annual Precipitation
Average Number of Days Per Year in which Precipitation Exceeds Baseline Period's 99th-Percentile Precipitation Event
Average May-June-July-August Precipitation
Average Daily Maximum Temperature
Average Number of Days Per Year in which Temperature equals or exceeds 100 degrees
Average Number of Days Per Year in which Temperature equals or exceeds 110 degrees
Average Number of Days Per Year in which Temperature falls below or is equal to 32 degrees
Average Daily Minimum Temperature

Highway Stormwater Pumps – Reliability Tool

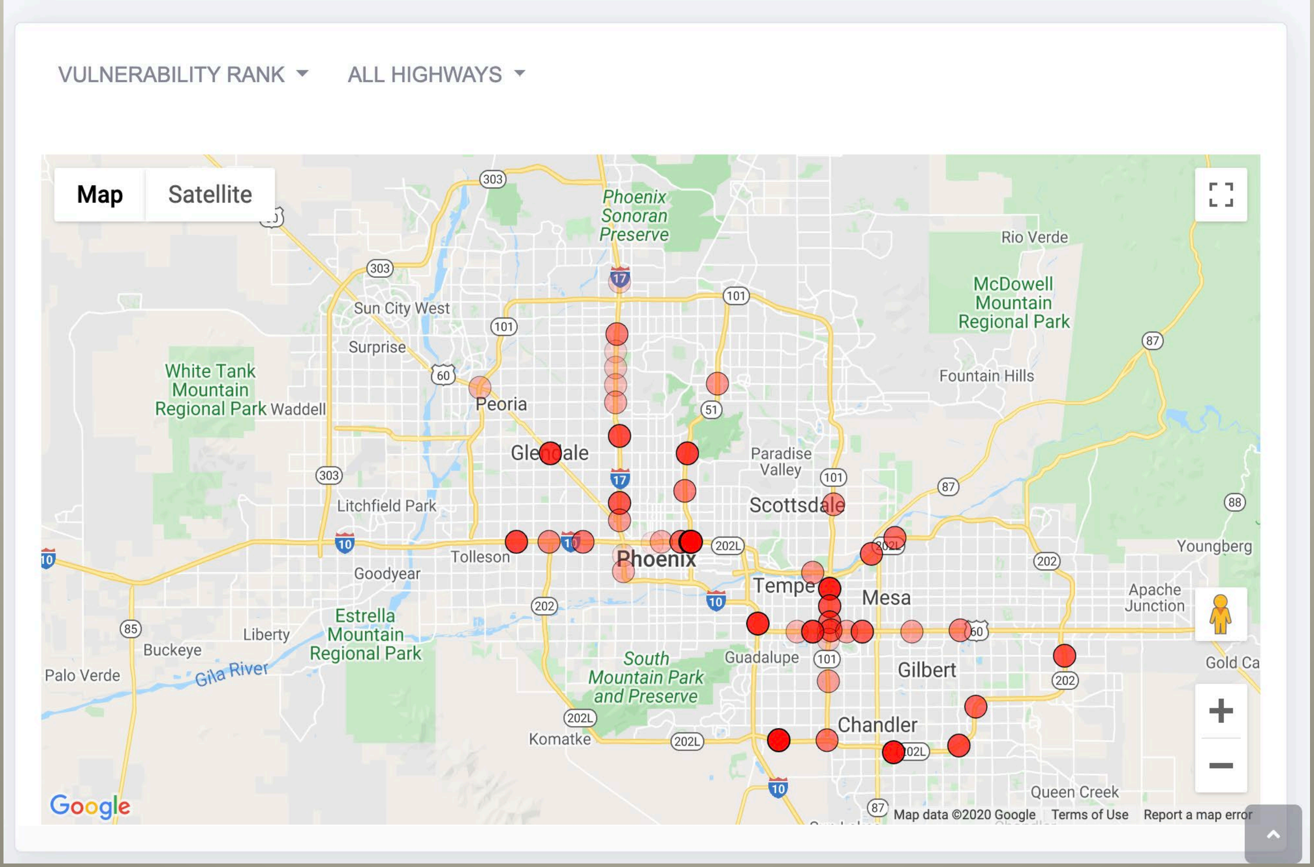
Increasing Accuracy

Pumping stations are critical hardware that must operate during the most extreme events to ensure roadway reliability. Yet little is known about the factors that contribute to pumping unit and station failure.

Developed a dynamic reliability analysis decision-support tool which considers individual pump component vulnerability, overall pump station vulnerability, and the risk of pump station failure (given vulnerability and traffic flow) to provide information to aid operators considering hardware and environmental conditions tin prioritizing maintenance and rehabilitation

Highway Stormwater Pumps – Reliability Tool

Prioritization Map Page: Ranking data is displayed visually on a geo-spatial map of pump stations in the Phoenix Metro area



Highway Stormwater Pumps – Reliability Tool

Statistical Model Description (E. Bondank)

Used description of which pump station component failed in the telemetry data, created a statistical model for each of the components to estimate their vulnerabilities.

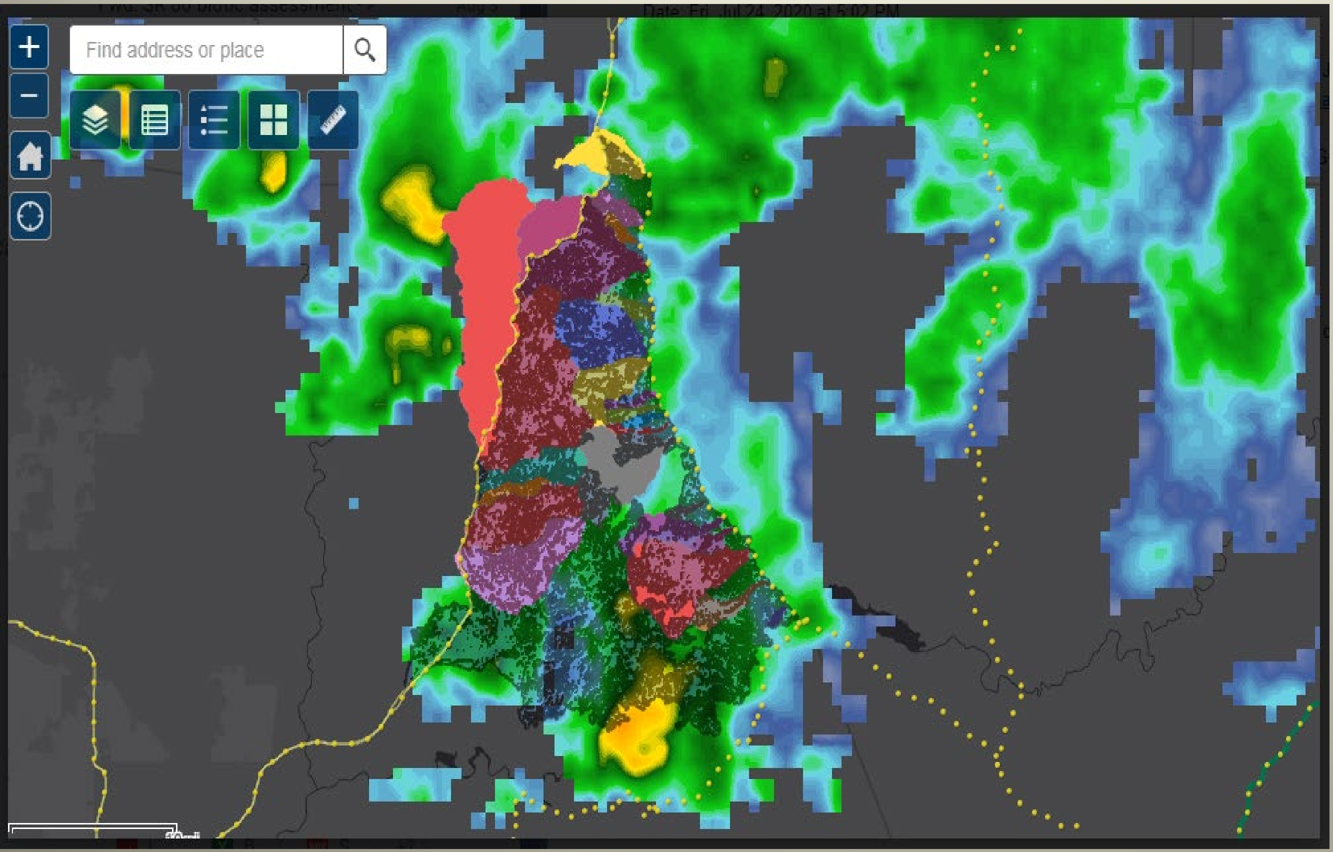
Used a form of non-linear statistical regression called a logistic model which can predict the probability of binary outcomes (such as pump failed or not failed). Transformed the data into panel data to assess for each rain event day, whether each pump station had a failed component.

The logistic regression equation is shown in the equation. The predicted values are calculated using the cumulative probability distribution function of the standard logistic.

$$\mathrm{P}(\mathrm{Failure} = 1) = \frac{1}{1 + e^{-z}}$$

2020 Arizona State University Metis Center Sustainable Infrastructure Award

Resilience GIS Database Event Dashboards



Bush Fire impacted
SR 87 & 188
195,000 Acres

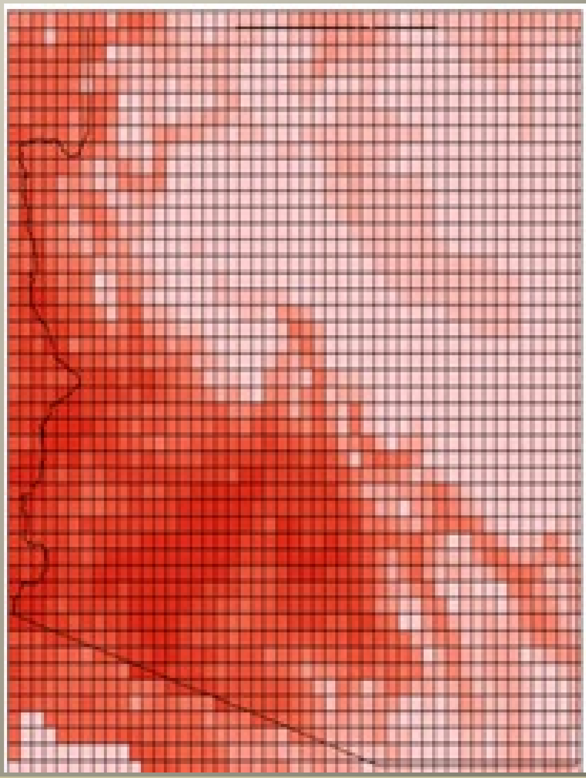
Dashboard layers:

- Debris Flow
- Bush Burn Severity
- Bush Fire Watersheds
- Rain Gages
- Pressure Transducers
- Roads with Mile Posts
- Main Highways
- Scour Critical Bridges
- NOAA Radar live feed
- Watches, Warnings, Advisories live feed
- NDFD Precipitation live feed
- Active Hurricanes live feed

Climate Adaptation

- Arizona was laid out in 12 km x 12 km grid (total of 2680 grid elements)
- Grids are consistent with format of downscaled climate data from

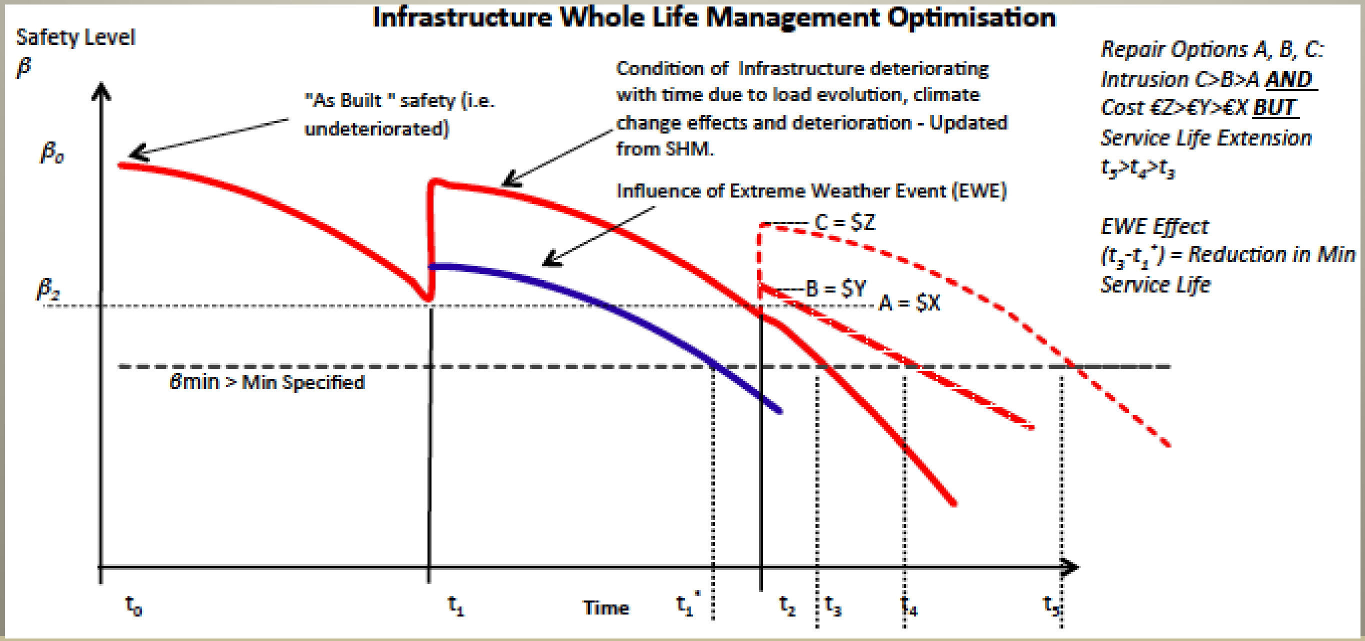
https://gdo-dcp.ucllnl.org/downscaled_cmip_projections/dcpInterface.html



- 19 climate models
- Considered two time periods
  - 2025-2055
  - 2065-2095
- 2021 Pavement binder and freeze thaw project
- Transportation will need 2125 climate data

Design Engineering Tool

Developing bridge asset class probabilistic engineering approach that assesses the stressors inherent to the built structure itself – live loading, extreme weather loading, climate induced loading using watershed, runoff data, topo, hydraulics, bridge design, and computation of the probability of failure at the considered limit state(s)



A. O'Connor

Tools Projects through 2021

Four Partnerships – Trinity College Dublin, Carnegie Mellon University, North Carolina State, and Texas Transportation Institute CAARTEH consortium:

- Finalize Resilience Performance Measures, Indicators, Metrics
- Further Economic Analysis Processes
- Further Life Cycle models to monitor resilience investment
- Account for the differences in the deterioration model with new climate-informed asset management models
- Customized intensity-duration-frequency (IDF) curves

Future Analysis Tools Needs

While different methods to quantify the economic impact of weather & natural hazard for infrastructure exist, advancing resilience tools for:

- Cost benefit analysis
- Return on investment
- Risk thresholds identification (fortify – rebuild – or absorb event risk)
- Identifying specific durability limit states
- Major rehabilitation timeline analyses
- Resilience bond adoption - Improved public agency awareness

are needed that incorporate probabilistic approaches, and minimize regret by DOTs under changing extremes and climates.

NCHRP Report 938:

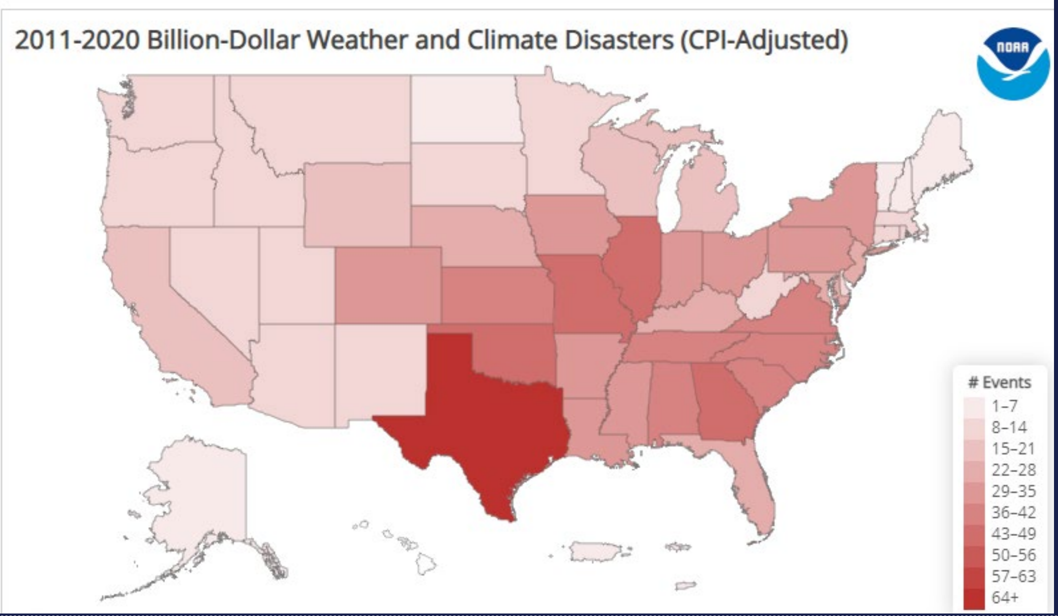
Evaluating the Costs and Benefits of Adaptation

Building Climate Resilience into Roads and Transport Infrastructure

LAUREL McGINLEY, PE, PMP

The Issue

2011-2020 Billion-Dollar Weather and Climate Disasters (CPI-Adjusted) by state:



Problem Statement:

"Extreme weather events and a changing climate can result in significant costs to transportation agencies…Research is needed to assist in an **understanding of the cost/benefit payoff of adaptation measures to allow for better decision making.**"

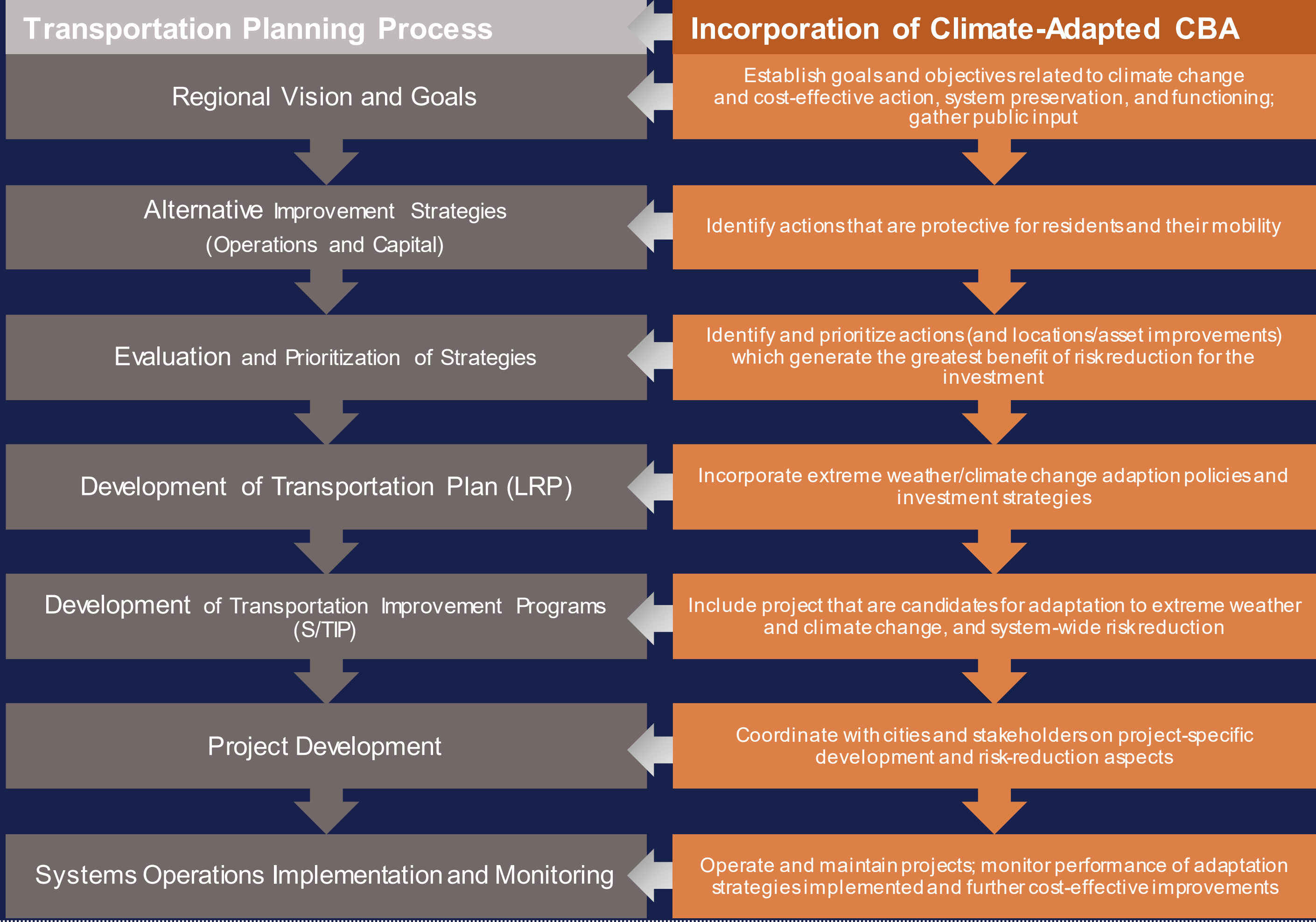
The Issue

- May require making some difficult decisions about transportation systems, funding, and resilience
- **Cost-benefit analysis can help guide decision-making**
- How to effectively minimize costs and achieve benefits is especially important to consider given fiscal constraints and the high costs of weather/climate damage
- Ultimate questions:
  - **What can we do?**
  - **What is cost-effective?**

Feedback from Interviews

- Many DOTs have completed vulnerability assessments
- DOTs increasingly are considering extreme weather and climate change in project selection and design
- DOTs **rarely complete** a CBA unless policy requires it
    - **Perceived as time-consuming and expensive**
    - **Hazard projections are difficult to assess**
    - **Information/data needed is dispersed across multiple branches/departments**
- Need tools that leverage existing processes and data to provide a basis for decision-making about adaptation measures
- **MULTI-PURPOSE PROJECTS:** MSHA moving toward integrated approach to planning, asset management, and climate change

Transportation Planning and CBA



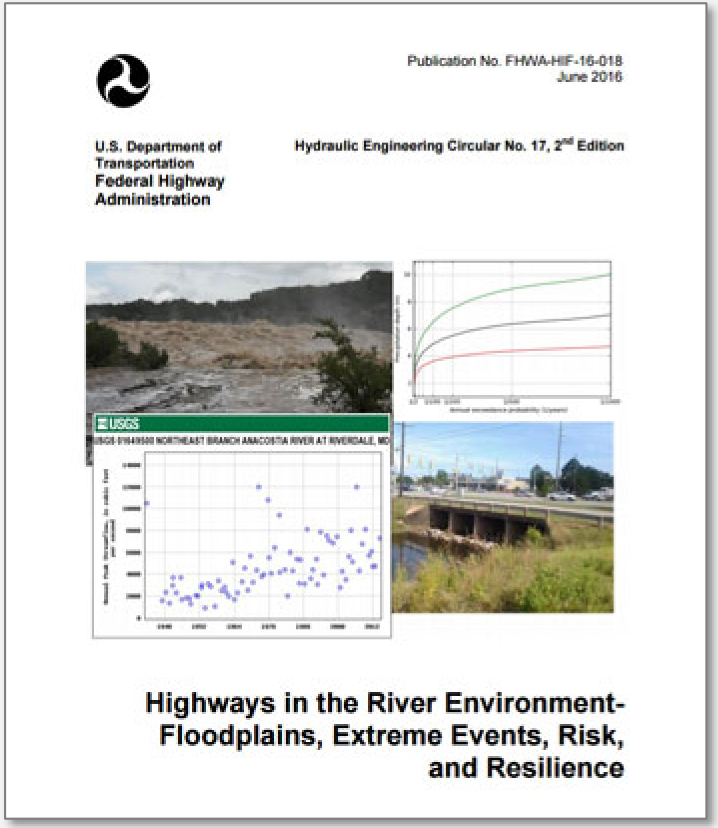
The CBA Challenge

- Available Methods
- **Data and Inputs**
- Projects and Programs
- Framework Options

DOT CBA needs vary significantly among agencies. Some are ready to collect the data necessary for engineering-level alternatives comparison and others are reluctant to perform CBAs unless required. **A major framework design challenge is accommodating this range of data inputs.**

Framework Development

- Follows FHWA HEC-17 approach
- Assumes that the level of damages associated with an event of a given magnitude will remain the same
- Assumes return period for the event will decrease (i.e., become more frequent) due to climate change impacts
- Analysis levels:
  - **Study Level 1** analysis uses 3 sets of data points and interpolates between them to estimate a threshold value for cost-effective adaptation
  - **Study Level 2** analysis adds data points to provide greater level of accuracy; adds benefit-cost ratio



Analysis Data Needs and Sources

Flood flows (or tide elevations for sea level rise analyses) associated with each return period

- H&H studies
- Flood Insurance Studies
- Past event data

Damages associated with each return period and corresponding flow

- Historic events
- Engineering estimates
- FEMA project worksheets
- Bid documents for construction

Discount rate

- OMB-recommended values of **3% and/or 7%**
- Other values will be used consistent with financing mechanisms, policies, etc.
- Present value interest factor for selected discount rate(s) and project useful life
- **OPTIONAL:** sensitivity analysis comparing discount rates

Project Useful Life

- Anticipated length of time the project will be in place and used

Study Level 1 Analysis Summary

RESULT: Provides the net present value of an incremental cost below which adaption is likely to be cost-effective.

Exisiting Conditions

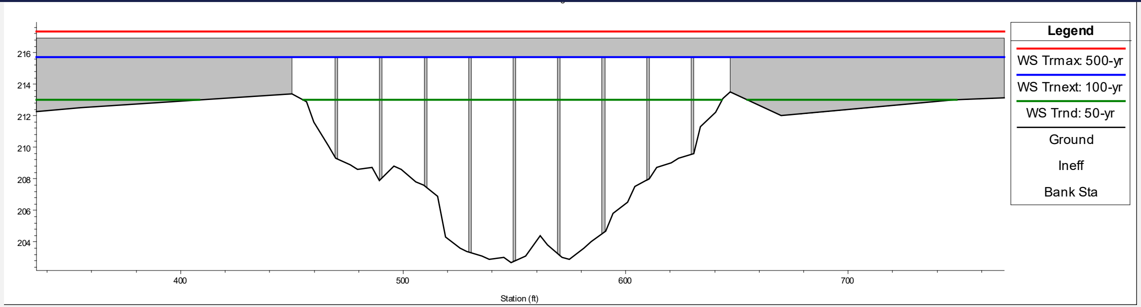
1. Identify three return periods

   T_{cnd} Largest return period with no damages under current conditions (Design Flow).

   T_{cmod} Return period with moderate structural damages, riprap displacement and scour, and/or roadway flooding and traffic interruption.

   T_{cmax} Largest return period considered; possible bridge structural failure, road embankment erosion, loss of roadway function for weeks to months.

2. Associate flood flows and corresponding damages with each return period.
3. Calculate total annualized damages and multiply by the present value interest factor for the selected discount rate and project useful life to get total damages under current climate conditions.



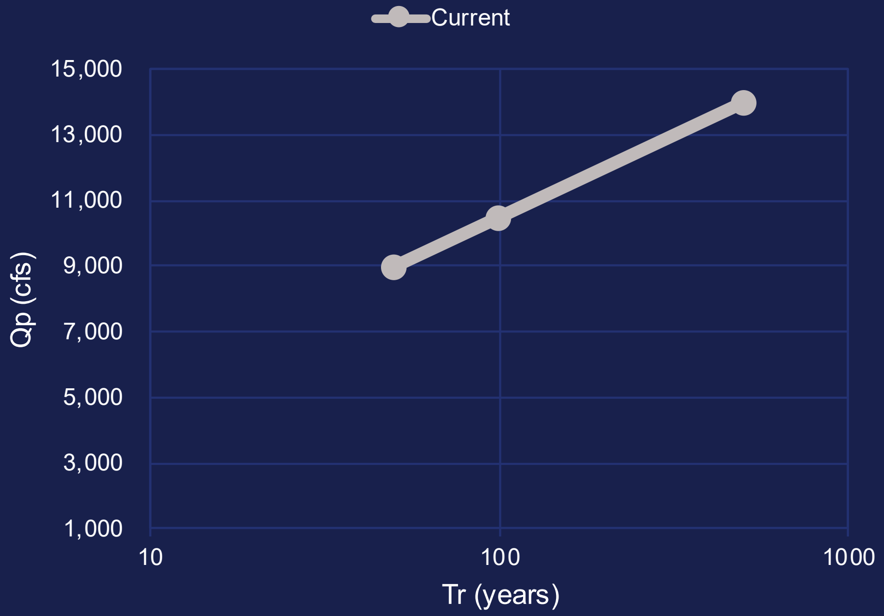
Culvert Example

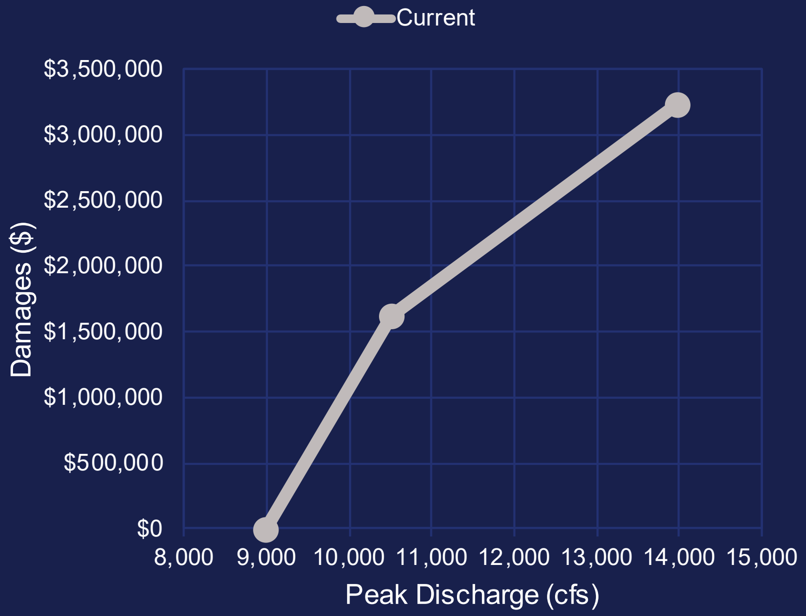
PARAMETER	VALUE USED IN SCENARIO	DATA SOURCE(S)
Facility of concern	Culvert	Project file
Geographic location of the facility/corridor under consideration	Chesterfield, VA	Site plan, maps
Hazard(s) of concern	Flood	Hazard analysis
Current design criteria – flow rate	9,000 cfs	Engineering designs and plans
Current design criteria – recurrence interval	50-year event	AASHTO design manual, DOT design manual
Discount rate(s) to be used in the analysis	7%	OMB Circular A-94
Expected useful life of current facility	Less than 2 years	Capital plan, O&M records
Expected useful life of replacement facility	50	VDOT design guides
Anticipated timeframe for implementation of adaptation strategies	Less than 2 years	Capital plan
Scenario(s) to be used for analysis	Precipitation conditions in 2049	NOAA Atlas 14, SWMM-CAT for warmer, wetter conditions 2045-2075
Design concepts of adaptation strategies	Enlarge culvert, add multiple culverts, use box or arch culvert	Engineering Department
Cost estimate for each adaptation strategy (life cycle costs, including any long-term adverse impacts from the adaptation strategy)	Cost estimates	Historical data, recent bids for similar work, cost estimating software
Identification of any non-quantifiable costs associated with the project	None	DOT analysis
Estimates of damages sustained from the hazard of concern	Loss estimates	Historical data, engineering analyses, O&M records, depth-damage curves
Estimates of additional benefits resulting from the project, separated by physical/social/environmental if using multiple discount rates	Benefits estimates	FEMA benefit-cost analysis tools for drought, ecosystem services, and post-wildfire mitigation
Identification of any non-quantifiable benefits associated with the project	None	DOT analysis

Summary of Existing Conditions

	Current Return Period, T_c	Current Damages, D_c	Current Annualized Damages, D_{ac}	Current Flow, Q_c (cfs)
T_{cnd}	50	$0	$0	9,000
T_{cmod}	100	$1,630,000	$8,150	10,505
T_{cmax}	500	$3,227,000	$19,428	13,982
Total annualized damages			$27,578	

Return Period-Flood Flow-Damages Relationship





Study Level 1 Analysis Summary

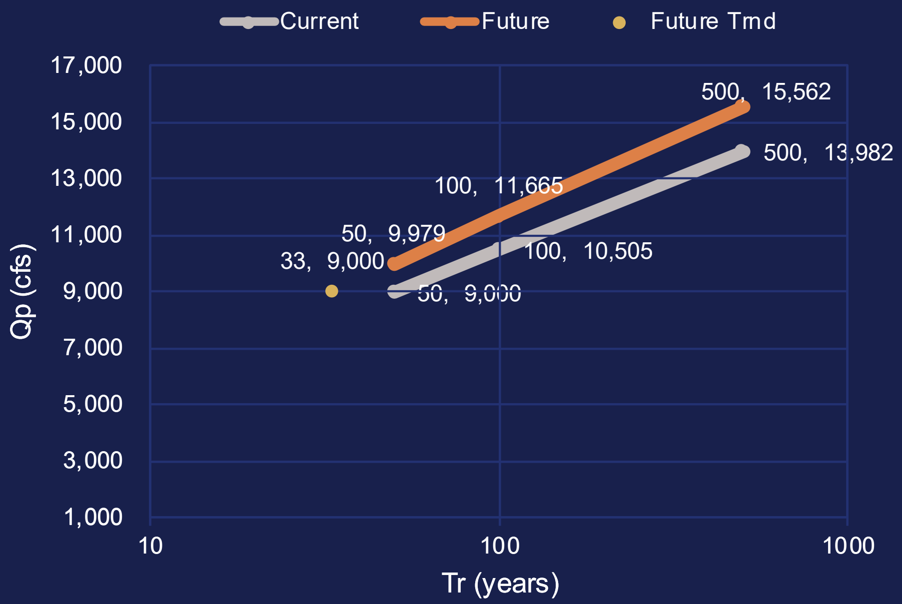
Future Conditions

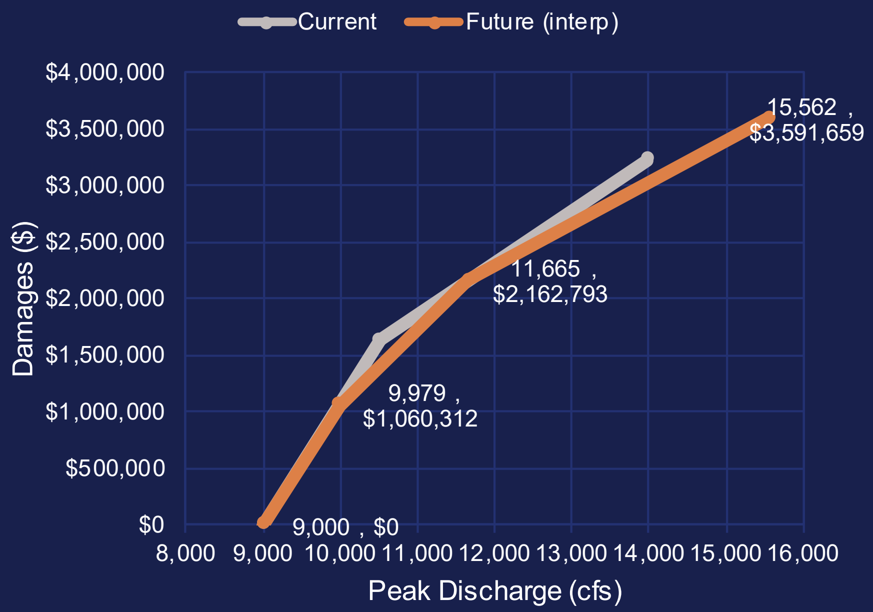
1. Estimate future flows under climate change conditions over project useful life for the three return periods (using, e.g., SWMM-CAT or SimCLIM)
2. Using known return periods and future flows, interpolate a new, climate-adjusted return period for the original (i.e., current condition) no-damage flow rate
3. Use current condition damages and flows to interpolate damages for climate-adjusted future flows
4. Calculate annualized damages for climate-adjusted future flows
5. Add annualized damages and multiply by present value interest factor to get total damages under climate change conditions
6. The total damages calculated for climate change conditions are used as the basis for evaluating cost-effectiveness of adaptation projects; adaptation project costing less than or equal to the value of the total damages are likely to be cost-effective

Summary of Future Conditions

	T	Q (cfs)	D	D_a
T_{fnd}	33	9,000	$0	$0
T'_{fnd}	50	9,979	$1,060,312	$5,270
T_{fmod}	100	11,665	$2,162,793	$16,116
T_{fmax}	500	15,562	$3,591,659	$23,018

Climate Impacts on the Return Period-Flood Flow-Damages Relationship





Study Level 2 Analysis Summary

RESULT: Calculates the Benefit-Cost Ratio (BCR) for an adaptation project under climate change conditions.

Builds on Study Level 1 analysis

- Interpolates additional frequency-damage points using climate-adapted return periods for current flow rates to render more accurate damage calculations
- Input adaptation project initial cost and annual operation & maintenance cost
- Evaluates the Benefit-Cost Ratio (BCR) for an adaptation project under climate change conditions.

Case Study Results Summary

	Analysis Results	Published Results
Culvert 5648 (MnDOT) LEVEL 1 ANALYSIS		
OPTION 1 **Replace with two-cell culvert** **$770,000**	**Cost-effective** up to **$1.0M**	**Cost-effective**
OPTION 2 **Replace with 52-foot simple span bridge** **$1,130,000**	Not cost-effective	Not cost-effective
OPTION 3 **Replace with 57-foot simple span bridge** **$1,210,000**	Not cost-effective	Not cost-effective
FHWA Gulf Coast 2: Airport Boulevard Culvert (Wetter Narrative 2070-2099) LEVEL 2 ANALYSIS	Benefits NPV/BCR (by hand): **$10.7M/7.31** Benefits NPV/BCR (in Excel): **$10.9M/7.43**	Benefits NPV: **$11.0M** BCR = **7.3**


Thank You

Evaluating Transportation Infrastructure Resilience Return on Investment:

Resilience and Disaster Recovery Tool Suite Overview

Scott Smith, Jonathan Badgley, Kristin Lewis - Volpe Center, US DOT
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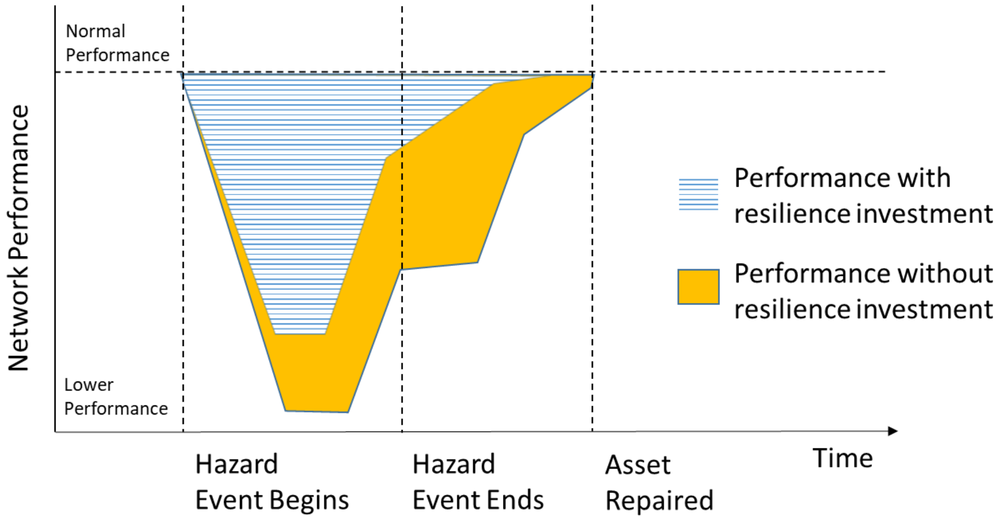
TRB Webinar, March 18, 2021

Contents

- Need and approach
  - Benefits of resilience investment
  - Analyzing travel demand disruption
  - The challenge of scaling up to include uncertainty and resilience
- Resilience and Disaster Recovery (RDR) Tool Suite Overview
- Example analysis
- Next steps

Benefits of a resilience investment

- Hazard event disrupts travel.
  - Lost asset capacity for trip making → lost trips/circuitous travel.
  - Asset may be damaged.
  - Resilient assets experience reduced disruption and damage.
- Recovery Process:
  - Hazard recedes/ends after some duration.
  - Repair time may extend disruption.
  - Assets return to full capacity upon recovery.
- Economic impacts
  - Deployment costs of resilience investment.
  - Monetized system performance.
  - Costs of damage repair.
- Net benefit = difference between areas with and without resilience investment.

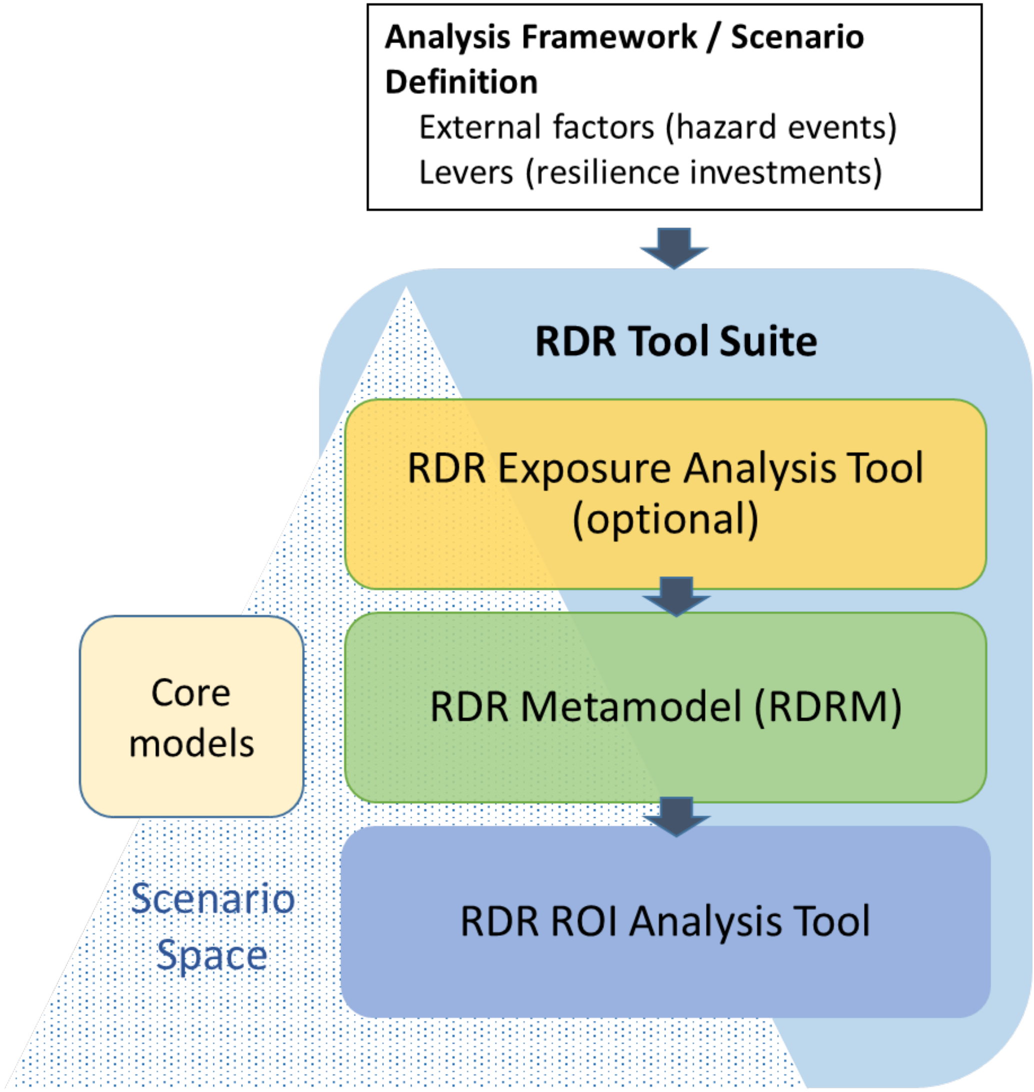


Why a resilience investment analysis tool?

Need: Current performance measures to justify transportation infrastructure project prioritization do not account for resiliency performance in the face of future hazards.

Challenge: Future hazard conditions are highly uncertain, and a range of resilience investment options can be used to address them.

Solution: A robust tool suite to help transportation practitioners evaluate resilience return on investment (ROI) for long-range planning across a range of uncertain scenarios.



Sponsors / Collaborators:

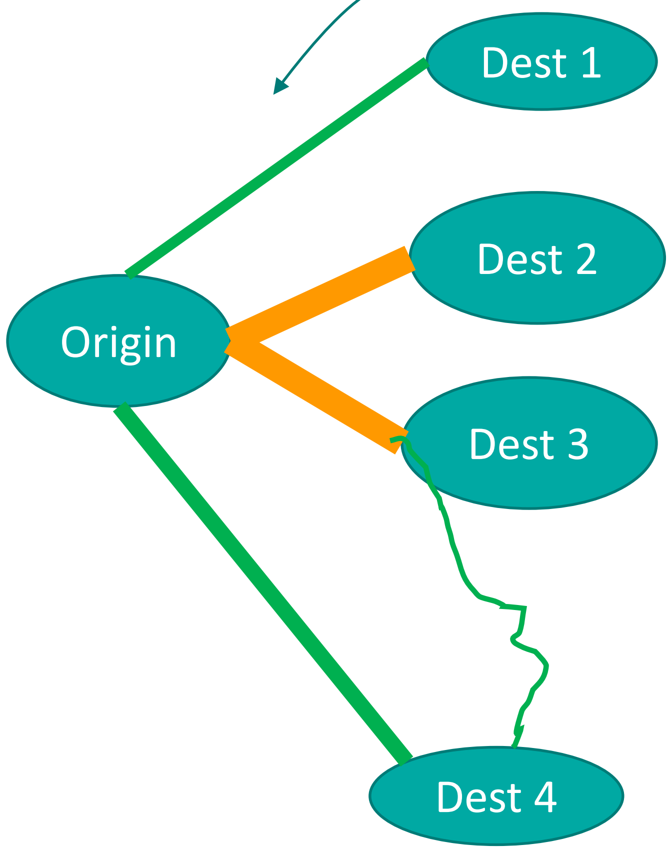
Federal Highway Administration (FHWA)
Office of the Secretary of US DOT (OST)
Office of Intelligence, Security, and Emergency Response (S-60)

Executed by: Volpe National Transportation Systems Center, USDOT

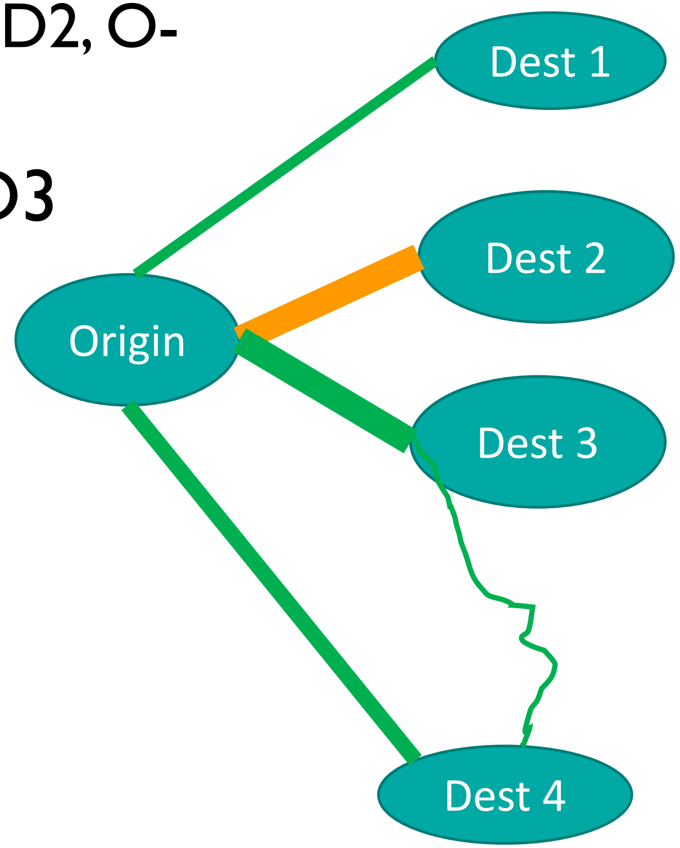
Who should perform a resilience ROI analysis with the RDR Tool Suite?

- State DOTs and MPOs that:
  - Are considering investing in resilience of roadway transportation assets.
  - Want screening-level analysis of value of investment (prior to engineering details).
  - Want to consider a range of future conditions / hazards.
  - Need measurable performance metrics for infrastructure investments across a that range of potential future conditions.
  - Want those metrics to be compatible with existing performance metrics for justifying transportation infrastructure project prioritization.

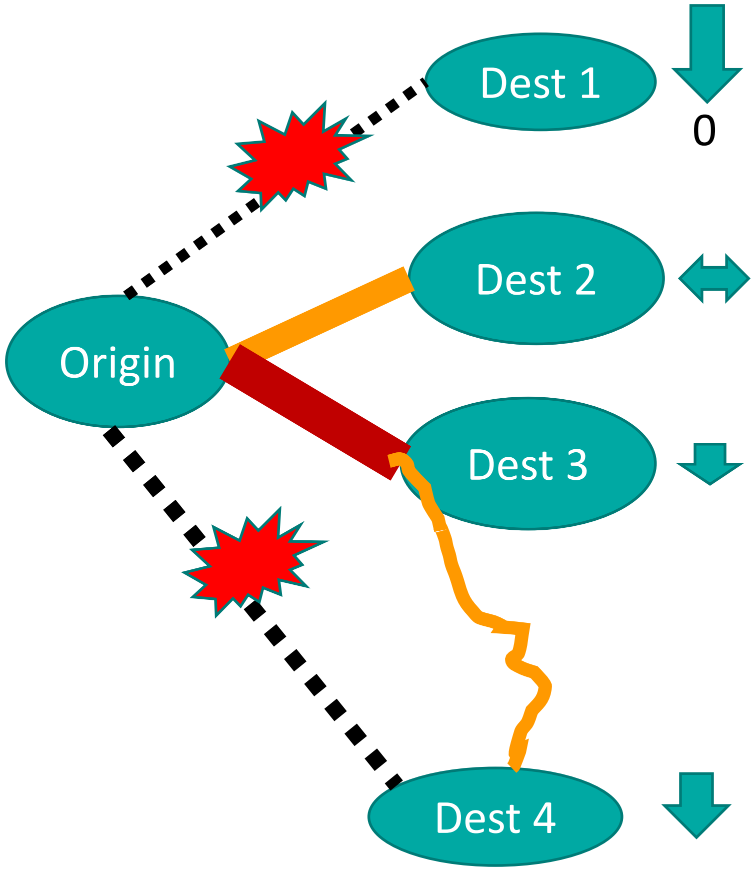
Travel Disruption Analysis – Baseline



- Baseline, non-disrupted network
- Origin to four destinations
  - Green lines → no congestion (O-D1, O-D4)
  - Orange lines → some congestion (O-D2, O-D3)
- Capacity expansion project for O-D3
- Measures
  - Trips
  - Person miles
  - Person hours



Travel Disruption Analysis – Disruption and Resilience



- Start with baseline network
- Hazard-related network disruption changes travel routes and times.
- If location no longer reachable (D1), trips are lost.
- Travel time increases when:
  - Route becomes more congested due to diverted traffic (D3).
  - Trip becomes more circuitous (D4).
- Higher travel times lead to reduced demand:
  - If *new_travel_time* > *old_travel_time*, then
  - *new_demand* = *old_demand x* (*new_travel_time* / *old_travel_time*)^{elasticity}
- Resilience project prevents disruption of link.

The problem with scaling up

- Multiple hazard severities, durations that are uncertain (a single or a couple of futures don't represent well).
- Multiple to many potential assets to invest in.
- Leads to hundreds of thousands of links, a million OD pairs, and thousands of scenarios to test.
- Existing travel demand models don't run fast enough to calculate network performance based on all these combinations.

Robust Decision-making Framework: XLRM

eXternal factors (uncertainties)
- Socio-economic conditions
- Land use
- Frequency / severity of hazard events
- New technology
- Changes in user attitudes: travel and mode choice
- Fuel prices

policy Levers
- Resilience investments
- Transportation investments
- Financial incentives
- Land use policies

Relationships
- Travel demand
- Network
- Baseline trips, miles, travel times
- Network response to hazard events
- Hazard recovery times and effects on the network
- Impact of economic conditions, trip elasticity, etc. on travel behavior
- Comparison of many scenarios

Metrics
- Trips
- Person Hours Traveled (PHT)
- Vehicle Miles Traveled (VMT)
- Asset damage repair costs
- BCA
- BCA-U/Regret
- Breakeven benefit
- Impacts on specific groups (e.g., equity).

(Lempert et al., 2003)

The RDR approach is based in part on the Travel Model Improvement Program, Exploratory Modeling and Analysis Tool (TMIP-EMAT) (see 2018 Innovations in Travel Modeling conference presentation).

Key components of the RDR ROI Analysis Tool

Analysis Framework:

- Hazard characteristics
- Resilience investments as mitigation of network impacts (change in capacity).

RDR Exposure Analysis Tool: Enables asset exposure analysis based on geospatial hazard severity information and transportation network data (optional).

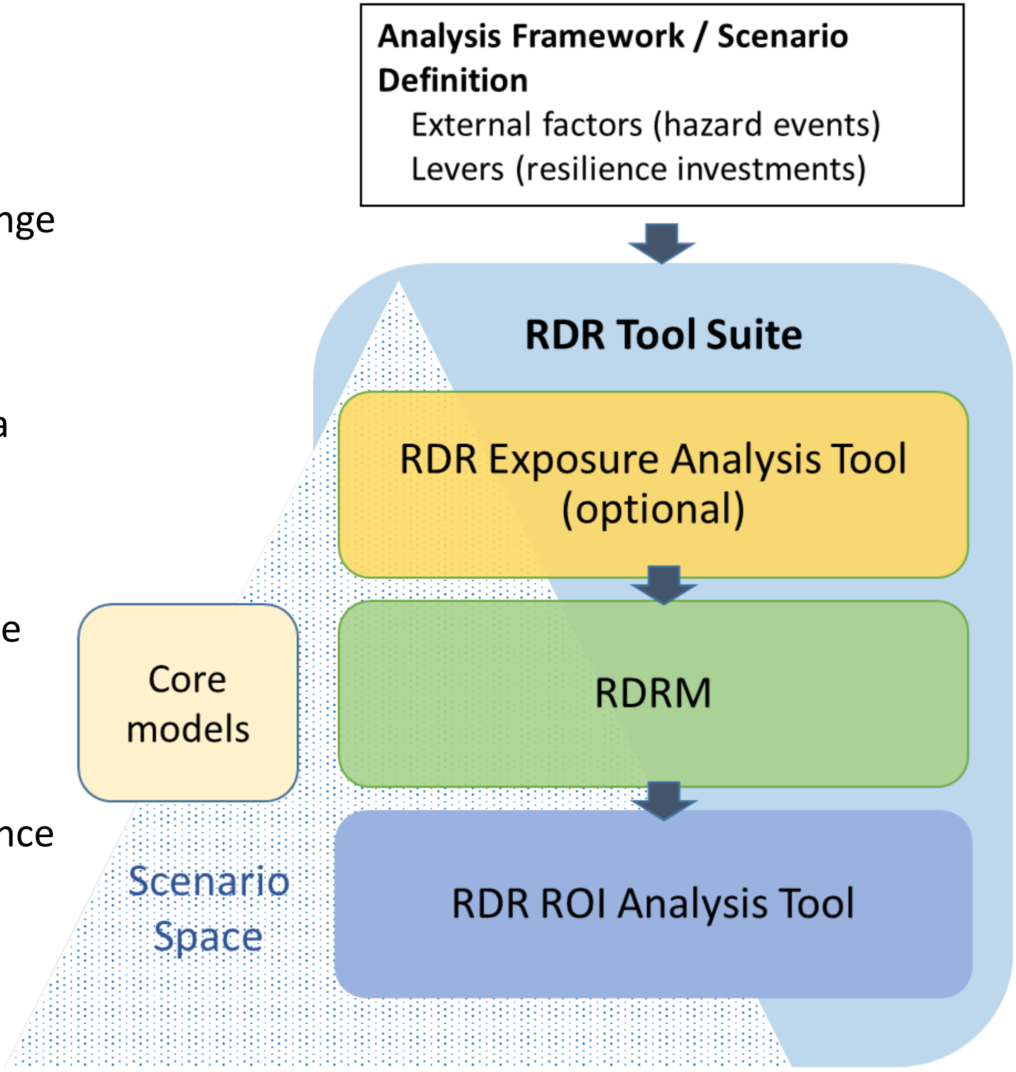
Core Models (Travel Demand Model, AequilibraE): Perform initial sampling of runs to enable the metamodel to expand the scenario space to encompass the range of uncertainties.

RDR Metamodel (RDRM):

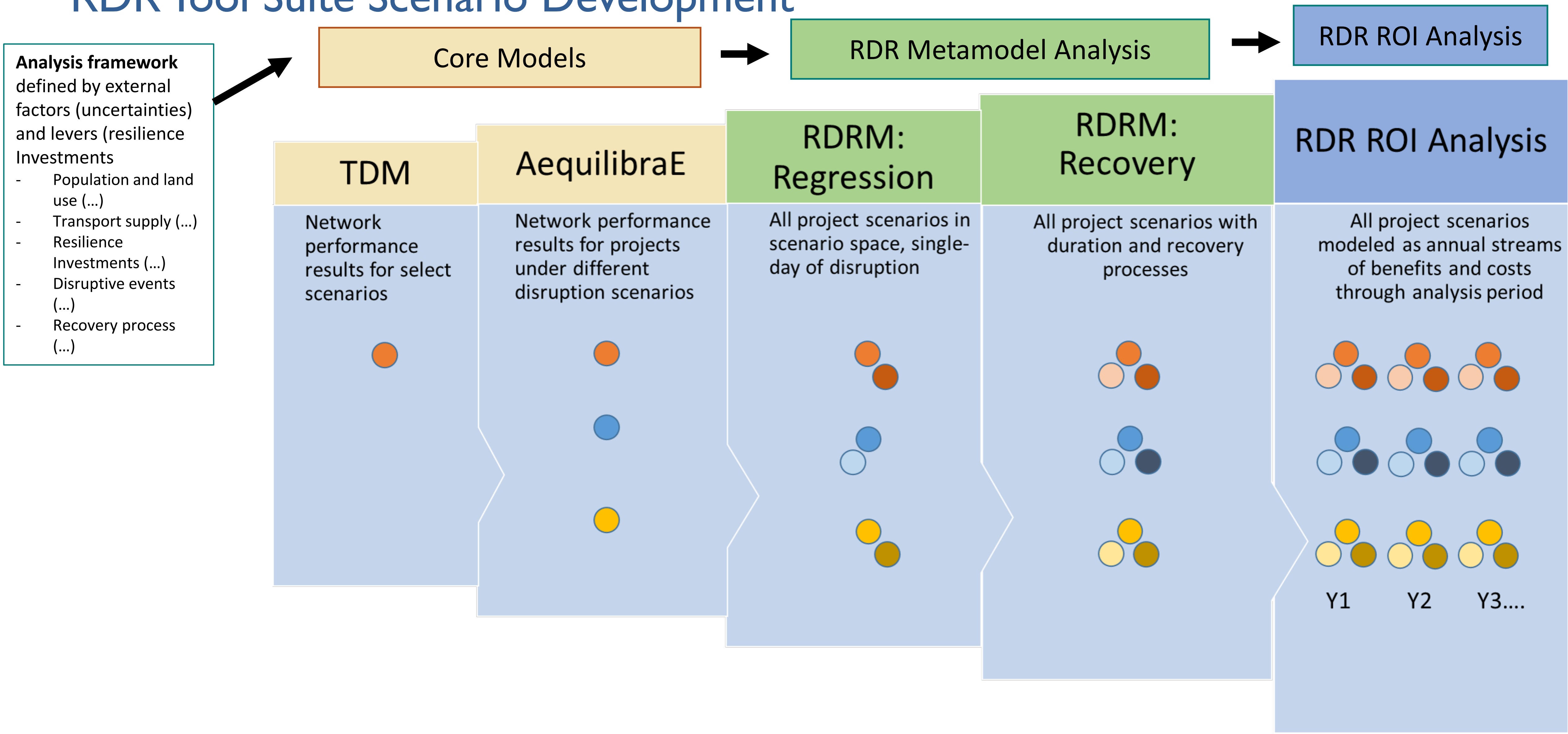
- Expands scenario space: assesses resilience project performance across range of hazard conditions, recovery times, and years.

RDR ROI Analysis Tool:

- Monetizes performance and damage/repair.
- Ranks proposed resilience investments based on ROI.



RDR Tool Suite Scenario Development



Project Prioritization: Economic Analysis Approaches

- **Benefit Cost Analysis (BCA)**:
  - Calculates total net benefits of a project over a selected analysis period (e.g., 50 years) based on probability of hazards and total cost of the resilience investment.
- **Benefit Cost Analysis under Uncertainty (BCA-U)/Regret Analysis (BCA-U/Regret):**
  - Calculates the total net benefits of a project over analysis period relative to the best investment option for each scenario, without need for hazard probability estimate. Projects are ranked by this measure, "regret," which expresses "what you would rather have done" in a given scenario.
- **Breakeven Analysis**:
  - Calculates total benefits of a project over analysis period without taking into account cost of the investment. Result tells you what you can "afford" to spend to break even on a resilience investment.

Visualizations

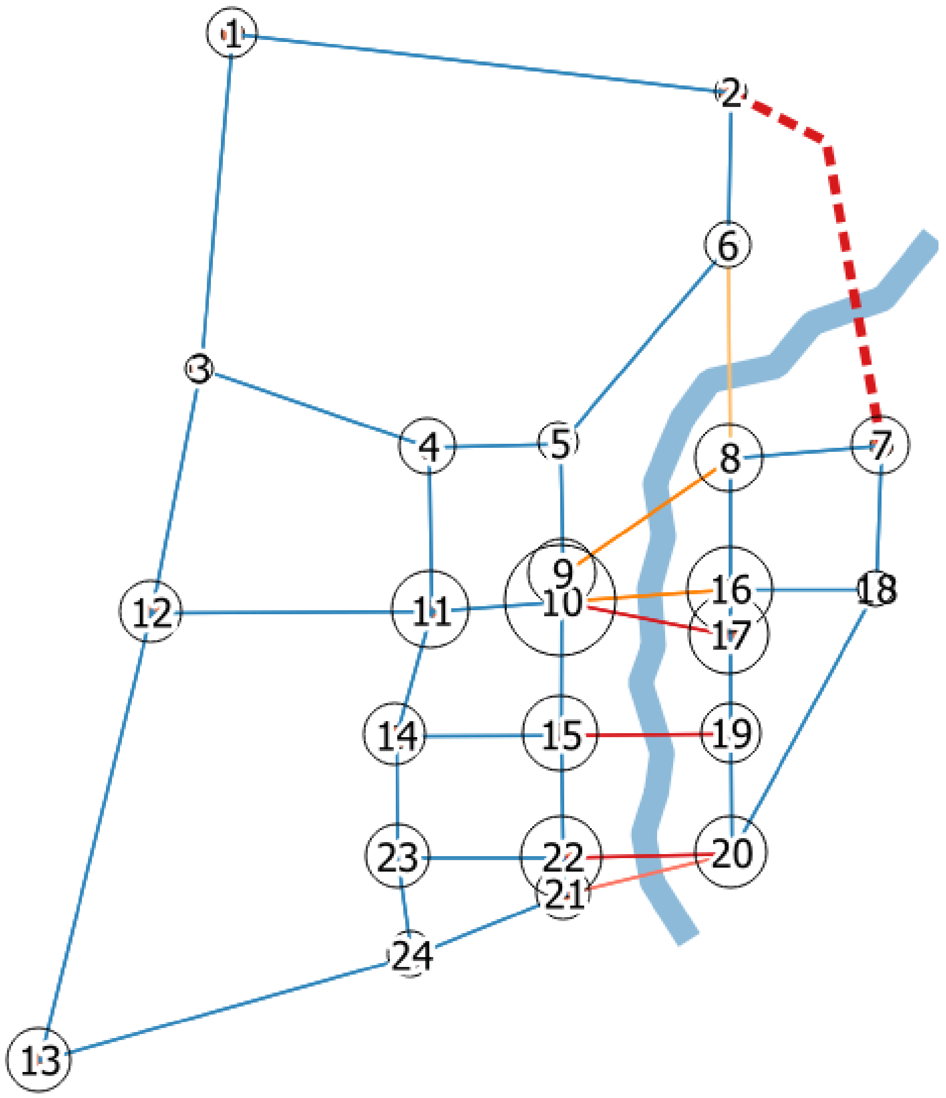
Decision - Makers
Dashboard

The "30,000-Foot View" of Scenario Regret and Net Benefits.

Project	Rank Regret All Scenarios	Rank Regret Scenario	Average Net Benefits	Std. Dev. Net Benefits	Average Benefit Cost Ratio	Std. Dev. Benefit Cost Ratio
Project 2	1	3	$2.27B	$8.61B	1.46	1.73
no	2	1	$0.00	$0.00		
Project 1	3	2	-$1.05B	$699.84M	0.37	0.42
Project 3	4	4	-$4.25B	$206.00M	0.04	0.05

Visualizations

Travel Disruption Analysis – Considering Resilience

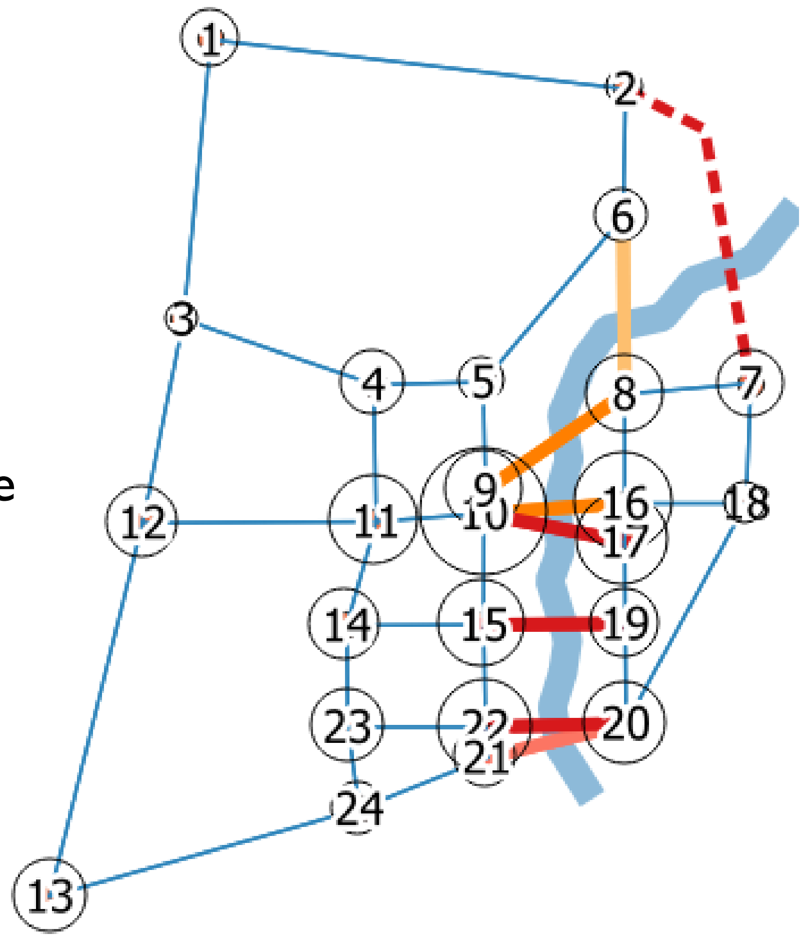


- Measures
  - Trips
  - Person miles traveled (PMT)
  - Person hours traveled (PHT)
- River is subject to flooding
  - Bridges have varying degrees of vulnerability
  - Two flooding severities
- Resilience investments
  - Engineering/cost details not required; cost data allows for full BCA.
  - Can compare multiple project options at a single location.
  - If project affects network performance without hazard, modify network characteristics (e.g., the new link between nodes 2 and 7).
  - Resilience investment fully mitigates disruption.

Sample Analysis

- Core Model Runs:
  - Base year case (2017): Current network performance, no disruption.
  - Out year case (2045): Anticipated performance, no disruption, with and without planned infrastructure (2-7).

- Metamodeling Expansion:
  - Out year exposure/disruption cases (2045): Anticipated performance based on network disruption corresponding to hazard severity.
    - Flooding reduces capacity on orange/red links (darker = more disruption).
    - Trips rerouted or eliminated based on disruption, time of travel elasticity.
  - Projects that provide resilience benefit
    - New link between nodes 2 and 7 (L2-7).
    - Resilience project between nodes 8 and 9 (L8-9).



Sample Analysis Results

- 3 core model scenarios analyzed.
- 24 scenarios analyzed in metamodel:
  - 2 flooding severities.
  - 2 recovery stages.
  - Hazard duration of 4-8 days.
  - Elasticity -1.
  - 2020-2045 analysis period.
- Project L2-7 performed best across all uncertainties.

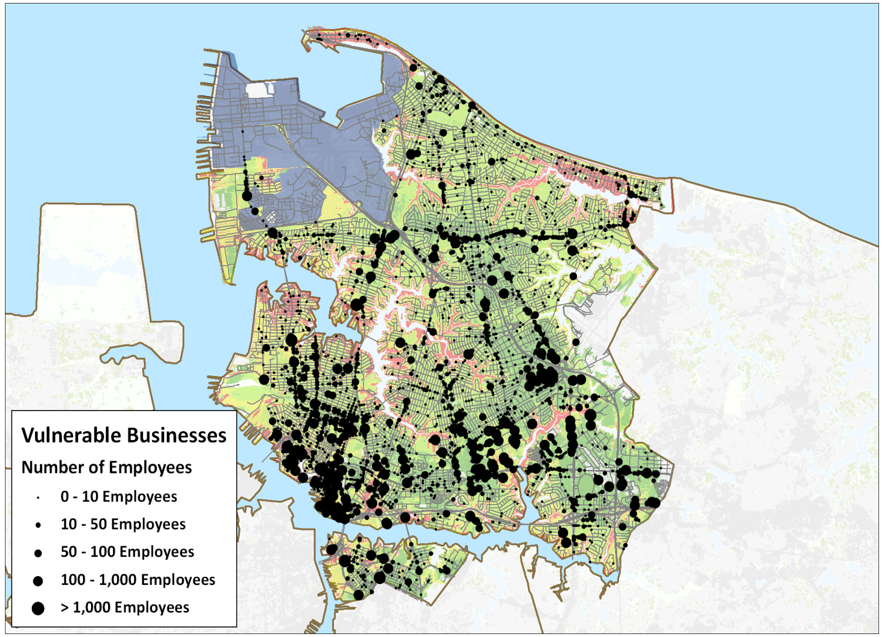
Decision - Makers
Dashboard

The "30,000-Foot View" of Scenario Regret and Net Benefits.

Project	Rank Regret All Scenarios	Rank Regret Scenario	Average Net Benefits	Std. Dev. Net Benefits	Average Benefit Cost Ratio	Std. Dev. Benefit Cost Ratio
L2-7	1	2	$377.00M	$664.54M	1.94	1.66
no	2	2	$0.00	$0.00		
L8-9	3	2	-$8.72M	$74.91M	0.96	0.37

Pilot with Hampton Roads MPOs and Virginia DOT

- The RDR Tool Suite is being piloted with:
  - Hampton Roads Transportation Planning Organization
  - Hampton Roads Planning District Commission
  - Virginia DOT
- Current analysis covers:
  - Fiscally-constrained project list (approx. 80 projects).
  - 3 feet sea level rise + up to 100 yr storm surge.
  - Region-specific cost and time of repair estimates.
- Anticipated to be completed in March 2021.
- RDR Tool Suite outputs will inform project prioritization.



Storm Surge Analysis – Norfolk, Virginia

Potential Uses of RDR Tool Suite Outputs

- Factors for Project Prioritization
  - Vulnerability/exposure across scenarios.
  - Disruption severity / change in network performance.
  - Refinement of cost effectiveness measures.
- Candidate Project Identification
  - Identification of high disruption assets for project consideration.
  - Project design/cost refinement incorporating resilience.

Feedback Group

- Convened a small feedback group to review progress and provide input during development.
- Feedback group invitees included:
  - FHWA FL regional office
  - State DOTs/MPOs:
    - California DOT
    - Iowa DOT
    - Hampton Roads Transportation Planning Organization (VA)
    - Capital Region Planning Commission (LA)
    - Hillsborough Planning Commission (FL)
    - Mid-America Regional Council (MO/KS)
    - Houston-Galveston Area Council (TX)
  - AASHTO
- Provided input on tool approach, utility, and visualizations.

RDR Project Outcomes

- Tool Suite:
  - Evaluates resilient infrastructure return-on-investment
  - Ranks resilience investments by performance.
  - ROI and/or ranking can be used by analysts as a factor or weighting to inform project prioritization.
  - Is location agnostic and geospatially explicit.
  - Leverages existing tools available to DOTs and MPOs.
  - Addresses a variety of hazard conditions and is intended to be hazard agnostic.

Next Steps

- **Current phase**
  - Finalize beta prototype and documentation
  - HR pilot
- **Future development (TBD)**
  - Continued piloting and refinement of the tool
  - Public release
- **Potential future expansions**
  - Additional modes
  - Equity analysis
  - Disaster recovery planning considerations

RDR Team

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Getting involved is free!

Be a Friend of a Committee bit.ly/TRBcommittees

– Networking opportunities

– May provide a path to Standing Committee membership

Join a Standing Committee bit.ly/TRBstandingcommittee

Work with CRP https://bit.ly/TRB-crp

Update your information www.mytrb.org

Other TRB events for you

- *April 6-8:* **Measuring and Managing Freight System Resilience Workshop**

https://www.nationalacademies.org/trb/events