The Resilience and Disaster Recovery Tool Suite

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13. ABSTRACT (Maximum 200 words)

Volpe developed the Resilience and Disaster Recovery (RDR) Tool Suite in support of the USDOT Office of Research, Development and Technology in collaboration with the Federal Highway Administration’s Office of Natural Environment. The RDR Tool Suite enables transportation practitioners to assess the return-on-investment of resilient infrastructure across a range of potential hazard conditions to help prioritize resilience investments. This Technical Document provides users with an overview of the structure and function of the Tool Suite and its components. It is complemented by the RDR Tool Suite User Guide, Quick Start Tutorial, and Run Checklist.

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Acronyms

Acronym	Meaning
ABC	Accelerated Bridge Construction
ARTBA	American Road Transportation and Builders Association
BCA	Benefit-Cost Analysis
BCA-U/Regret	Benefit-Cost Analysis under Uncertainty/Regret Analysis
CMIP	Coupled Model Intercomparison Project
DOT	Department of Transportation
EMAT	Exploratory Modeling and Analysis Tool
FEMA	Federal Emergency Management Agency
FHWA	Federal Highway Administration
GIS	Geographic Information System
HERS	Highway Economic Requirements System
HRTPO	Hampton Roads Transportation Planning Organization
IRI	International Roughness Index
MPO	Metropolitan Planning Organization
OST	Office of the Secretary of Transportation
PHT	Person Hours Traveled
PMT	Person Miles Traveled
RDRM	Resilience and Disaster Recovery Metamodel
ROI	Return on Investment
STRAHNET	Strategic Highway Network
TAZ	Traffic Analysis Zones
TDM	Travel Demand Model(ing)
TMIP	Travel Model Improvement Program
USDOT	United States Department of Transportation
VAST	Vulnerability Assessment Scoring Tool
VDOT	Virginia Department of Transportation
VHT	Vehicle Hours Traveled
VMT	Vehicle Miles Traveled
XLRM	EXternal factors, policy Levers, Relationships, and Metrics

Executive Summary

The **Resilience and Disaster Recovery (RDR) Tool Suite** was developed to help transportation agencies explore a large scenario space and evaluate the performance of resilience investments in the context of long-range transportation planning. The tool suite utilizes established Robust Decision-Making concepts[1,2] to build on current Travel Demand Model (TDM) analyses and address deeply uncertain future scenarios. Robust Decision-Making has been used under a similar modeling context by the FHWA Travel Model Improvement Program – Exploratory Modeling and Analysis Tool (TMIP-EMAT)[3], a scenario-based decision-making tool that can be integrated with existing travel demand forecasting models. The RDR Tool Suite enables transportation agencies to assess transportation resilience return on investment (ROI) for specific transportation assets over a range of potential future conditions and hazard scenarios, which can then be used as a consideration in existing project prioritization processes.

Motivation

Transportation planning decision-makers need to make decisions today about investing in the transportation systems of the future, decisions whose consequences will last many decades. Investments may take several forms, such as adding capacity via a new highway lane or transit line, making improvements aimed at safety, or making resilience investments (e.g., designing a road or bridge to withstand an earthquake or flood).

The classic paradigm for transportation planning is to first, **forecast** what will happen in the future (e.g., trips in a region will increase 20%), and then **act** on that forecast (e.g., add transportation capacity). This paradigm breaks down when the future is highly uncertain, such as trying to predict storms, earthquakes, or other hazards. Under these conditions, the prediction of a single future is unlikely to be correct, and the resulting decisions may be grossly sub-optimal.

An alternative approach is to focus on performance across a **range** of potential futures rather than selecting specific forecasts. With robust decision-making (RDM), the objective is not to predict the future, but rather, to make decisions today that produce good outcomes under a wide range of plausible futures. This alternative approach is especially appropriate for prioritizing which projects will be included in long-range investment plans, as long-range investment planning tends to focus on which assets will be deployed or improved to provide the best return.

The objective of the RDR Tool Suite is to help state Departments of Transportation (DOTs), Metropolitan/Regional Planning Organizations (MPOs) and others make informed infrastructure investment decisions by evaluating the performance of potential resilience investments across the set of uncertain future events of interest. It supports long-range investment analyses where agencies need to decide which assets to improve using general information about the options and future conditions. The RDR Tool Suite can be used whether agencies already have proposed projects or are simply exploring what potential assets they could improve. The outputs of the RDR Tool Suite are focused on total and net benefits of the project in terms of investment cost, repair cost, and network performance.

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[1] RAND. Robust Decision Making. *RAND.* [Online] [Cited: July 20, 2022.] https://www.rand.org/pubs/tools/TL320/tool/robust-decision-making.html

[2] Lempert, R. (2019). Robust Decision Making (RDM). Decision Making under Deep Uncertainty: From Theory to Practice. V. A. W. J. Marchau, W. E. Walker, P. J. T. M. Bloemen and S. W. E. Popper, Springer**:** 329.

[3] TMIP-EMAT Development Team. TMIP-EMAT. [Online] https://tmip-emat.github.io/.

Approach

Transportation agencies prioritize investments in transportation infrastructure based on their ROI with regard to reducing congestion (vehicle miles and hours traveled) and other locally important factors. Many state DOTs and MPOs currently use Travel Demand Models (TDMs) to forecast traffic flows on the transportation system and evaluate changes in performance resulting from future conditions and transportation infrastructure projects. However, there is currently no standard tool or approach used by state DOTs and/or MPOs to analyze resilience investment ROI. Additionally, the frequency of high-cost hazard events is increasing,[4, 5] making resilience a critical element of long-range transportation planning.[6] MPOs and state DOTs need tools and resources to evaluate resilience ROI across a range of future scenarios and hazard conditions as part of their project prioritization processes.

The RDR Tool Suite provides modeling tools to estimate performance of resilience investments across a range of uncertain hazard-related disruptions, recovery patterns, and ROI analysis periods, leveraging existing TDM analysis approaches and performance metrics. U.S. DOT has developed the RDR Tool Suite to be usable in any geographic setting and enable state DOTs and MPOs to incorporate the costs and benefits of resilience into the project prioritization process. The RDR Tool Suite is intended to be location and hazard agnostic, so that any agency can utilize it for any hazard that results in geospatially-predictable impacts on network capacity.

A resilience-focused ROI analysis must take into account:

(1) the range of potential hazard events;
(2) the range of hazard impacts on transportation assets and operations, including travel disruption during hazard events, asset damage, and the travel disruption due to subsequent repairs;
(3) the costs associated with travel disruptions, measured by changes in system performance and asset damage repair and cleanup costs due to hazard events; and
(4) the investment required to mitigate the impact of the range of potential hazard events.

Measures of system performance include changes in

- Person hours traveled (PHT), monetized using value-of-time for the person traveling
- Person miles traveled (PMT)
- Vehicle hours traveled (VHT)
- Vehicle miles traveled (VMT), monetized using per-mile vehicle operating cost
- Trips (a disruption may prevent some trips from being made).

The RDR Tool Suite allows the user to determine priority assets for resilience investment by assessing the disruption and repair costs associated with different levels of hazard events. The RDR Tool Suite also

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[4] National Oceanic and Atmospheric Administration. (2020) "National Centers for Environmental Information (NCEI) U.S. Billion-Dollar Weather and Climate Disasters." DOI: 10.25921/stkw-7w73. Accessed on November 13, 2020 from https://www.ncdc.noaa.gov/billions/

[5] FHWA. (June 21, 2017). "Texas Resilience and Planning Workshop: Summary Report." FHWA-HEP-17-095. Accessed on November 13, 2020 from https://www.fhwa.dot.gov/environment/sustainability/resilience/workshops_and_peer_exchanges/texas_06_2017/index.cfm

[6] For the purposes of this project, resilience refers to the ability of an asset to tolerate or recover from a given hazard. A resilience-related investment intends to mitigate the impacts of a hazard on transportation assets by reducing damage and the resulting disruption of travel.

calculates the benefits of deploying a resilience investment (including up front/deployment investment versus performance and repair costs) against what would have occurred under the same hazard events if the resilience investment had not been deployed.

This technical document describes the structure and functions of the components of the RDR Tool Suite and their application for a Resilience ROI Analysis. The RDR Tool Suite (see Figure 0-1) includes the RDR Metamodel (RDRM), the RDR ROI Analysis Module, and an optional RDR Exposure Analysis Tool.

The RDRM takes the performance metrics results from a TDM and performs complementary disruption analyses using an open-source routing model called AequilibraE.[7] The RDRM then performs regressions and iterative scenario expansion to estimate the change in VHT and VMT associated with a range of hazard conditions and investment scenarios. The RDRM models travel behavior response to disruptions in link capacity and availability by assigning a value of trip demand elasticity,[8] which determines how many trips will be made, their mileage, and the time of those trips in an equilibrium state. The RDRM calculates the impact of a resilience investment (represented as mitigation of the hazard-related disruption at that location) as changes in system performance when the investment is deployed versus a baseline disruption scenario in which the project alternatives are not deployed, and estimates the impact of hazard duration and repair recovery times and costs.

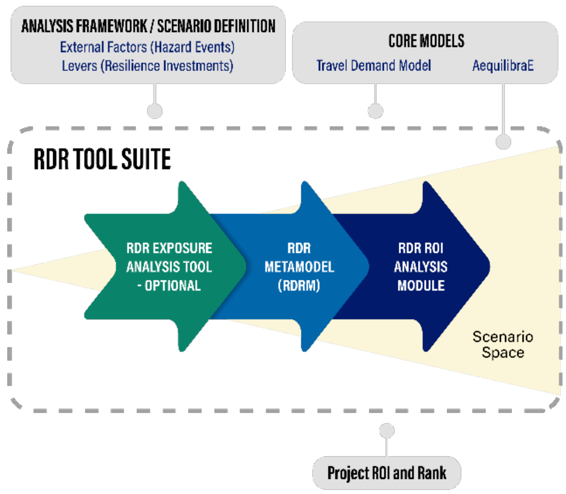

Figure 0-1: Structure of the RDR Tool Suite. The scenario space increases as more potential hazard severities, durations, recovery periods, and resilience investments are assessed.

The RDR ROI Analysis Module uses the RDRM disruption and network performance outputs to estimate economic net benefits of avoiding disruption over the economic analysis period for a range of resilience investments and recovery patterns. It then collates the performance of different resilience investments into a visualization dashboard and ranks the projects based on their performance across the full range of uncertainties analyzed.

[7] AequilibraE. [Online] [Cited: 07 26, 2022.] http://aequilibrae.com/python/latest/. RDR 2022.1 was developed using AequilibraE 0.7.2.

[8] Trip demand elasticity is an economic concept that relates the cost in travel time for a trip made on an asset to the number of trips that will be made on that asset in an equilibrium. A value of 0 implies that the trip will continue to be made if possible, even if the travel time becomes much longer. A value of –1 indicates that if the travel time between two zones doubles, the number of trips will be cut in half. Although there is little if any published literature on the elasticity of travel in response to a disruption, there is literature on steady state elasticities, assembled in VTPIs 2019 report on elasticities (vtpi.org/elasticities.pdf, starting on page 48). This report suggested short term elasticities in the range of –0.5 (more-or-less) and long-term elasticities in the range of –1.

Section 1 of this document presents an overview of the approach and the analytical framework. The following sections 3-7 provide detailed documentation of each component of the RDR Tool Suite, and the processes included in each, as follows:

- Scenario Definition: Taking in information on hazard events, travel demand, and resilience investments as defined by the analyst (Section 3).
- RDR Exposure Analysis: Overlay of hazard severity grids (e.g., inundation depth grids) and network links, to create network exposure severity scenarios (Section 4)
- RDR Disruption Module: Calculation of disruption based on exposure extent and default or user-defined relationship between exposure severity and roadway link capacity (RDR Exposure Analysis Tool for visualization, RDRM for full ROI analysis; Section 5.1).
- RDRM Parameterization: Identification of core model sample runs using Latin Hypercube Sampling, initial scenario runs in the core models, and use of a fast user equilibrium routing model, the open-source AequilibraE software package, to supplement runs from the MPO's more time-intensive TDM (Section 5.2).
- RDRM Regression: Regression on these results to generate performance measure estimates for the entire scenario space (Section 5.3). Performance measures include trips completed, miles traveled, and hours of travel.
- RDR ROI Analysis Module: Assignment of economic value, economic performance analysis (benefit, cost, and regret), project prioritization (Section 6).
- Reporting and Data Visualization: Enable results exploration and comparison of resilience investments (Section 7).

Section 8 acknowledges our pilot partner organizations, and Section 9 provides a list of known limitations and caveats for the current RDR Tool Suite.

A companion document, the RDR User Guide enables a user to install the tool suite and execute analyses. The RDR Quick Start Tutorial provides step-by-step instructions for running test analyses in the RDR Tool Suite on a toy road network. The RDR Run Checklist provides a short reference on the required input file and parameter changes needed to execute a custom analysis. The RDR Tool Suite and documentation are available on GitHub at https://volpeusdot.github.io/RDR-Public, along with test data for executing the Quick Start exercises.

Agencies vary in their level of data availability, analytical tools and resources, and knowledge of potential hazards and disruptions in their region. The RDR Tool Suite is set up to allow for different levels of analysis depending on the information the analyst can bring to the model. If an analyst does not have access to a travel demand model but can estimate trip tables for AequilibraE, all parameterization of the RDRM can be performed using the open source AequilibraE. And if an agency does not have specific project plans for investing in resilience and therefore does not have an estimate of the total cost of an investment, the RDR Tool Suite can still be used to estimate a breakeven point (total benefits). Thus, the RDR Tool Suite is intended to be used by agencies with a range of information and capabilities.

It should be noted that the RDR Tool Suite is not a "one-stop shop" for all resilience planning needs. It does not provide or incorporate engineering evaluation considerations, except to the extent that these define the capacity and availability of links in the transportation network and the costs associated with resilience investment actions. It also does not help agencies determine what kind(s) of project(s) would be appropriate for a given asset based on predicted vulnerability to exposure. The outputs are based on investment cost, repair cost, and network performance; it does not calculate economic impact analysis at the broader societal level (e.g., impact on employment, transfers between parties, etc.).

In summary, the RDR Tool Suite provides a transportation agency with a set of tools for evaluating the ROI provided by a set of resilience investments across a range of transportation assets and uncertain future hazard conditions, and for ranking those projects based on performance. The RDR ROI Analysis Module project rankings and thorough visualizations can be used as a factor in overall transportation infrastructure project prioritization for long-range transportation planning in combination with other prioritization factors such as congestion reduction, safety, engineering considerations, and budgets.

1 Introduction

1.1 Background and Overview

Transportation agencies, including state Departments of Transportation (DOTs) and Metropolitan Planning Organizations (MPOs), prioritize investments in transportation infrastructure based on their return on investment (ROI) with regard to reducing congestion and improving flow (e.g., reducing vehicle hours or miles traveled) as well as other locally important factors. Objective analytical processes such as Benefit-Cost Analysis (BCA) can assist agencies in justifying project investments both for their constituents and to obtain federal funding for their projects. Many state DOTs and MPOs currently use Travel Demand Models (TDMs), which forecast traffic flows on the transportation system, to evaluate changes in performance resulting from future conditions and transportation infrastructure projects.

TDMs can provide the necessary inputs to execute a BCA for transportation investments. However, standard TDMs do not incorporate the potential for hazard events (such as storms, earthquakes, etc.) to disrupt and damage transportation assets. Even where hazards could be modeled mechanically by turning off individual links, standard TDMs lack the temporal resolution to model hazard events that occur over multiple days, weeks, or months. Nor do TDMs have a method for evaluating the benefit of mitigating those impacts by investing in resilience to specific hazards. Thus, there is currently no standard tool or approach used by state DOTs and MPOs to analyze how investments in resilience can contribute to ROI, particularly under uncertainty in the frequency and magnitude of future hazard events. Yet external hazards such as storms and flooding can lead to massive transportation disruptions and billions of dollars in repair costs. Additionally, the frequency of high-cost hazard events is increasing,[9,10] making resilience a critical element of long-range transportation planning.[11] There is a need for tools and resources to enable MPOs and state DOTs to evaluate the ROI of resilience investments across a range of future scenarios and hazard conditions as part of their project prioritization processes.

To fill this gap, the Federal Highway Administration (FHWA) and the Office of the Secretary of Transportation (OST) of the U.S. Department of Transportation (USDOT) worked with the Volpe National Transportation Systems Center to develop the Resilience and Disaster Recovery (RDR) Tool Suite, which includes the RDR Exposure Analysis Tool, the RDR Metamodel (RDRM), and the RDR ROI Analysis Module. The RDR Tool Suite extends standard TDM analyses to address resilience investments in roadway infrastructure (roads and bridges) using established Robust Decision Making concepts[12,13] developed to address future scenarios in an environment of deep uncertainty. The RDR Exposure Analysis Tool optionally provides a method to link exposure data to a transportation network and test

[9] National Oceanic and Atmospheric Administration (NOAA). (2020) "National Centers for Environmental Information (NCEI) U.S. Billion-Dollar Weather and Climate Disasters." DOI: 10.25921/stkw-7w73. Accessed on November 13, 2020 from https://www.ncdc.noaa.gov/billions/

[10] FHWA. (June 21, 2017). "Texas Resilience and Planning Workshop: Summary Report." FHWA-HEP-17-095. Accessed on November 13, 2020 from https://www.fhwa.dot.gov/environment/sustainability/resilience/workshops_and_peer_exchanges/texas_06_2017/index.cfm

[11] For the purposes of this project, resilience refers to the ability of an asset to tolerate or recover from a given hazard. A resilience-related investment intends to mitigate the impacts of a hazard on transportation assets by reducing damage and the resulting disruption of travel.

[12] RAND. Robust Decision Making. *RAND.* [Online] [Cited: July 20, 2022.] https://www.rand.org/pubs/tools/TL320/tool/robust-decision-making.html.

[13] "RDM" is typically used as an acronym for Robust Decision Making in the literature, but this document does not use it to avoid confusion with the Resilience and Disaster Recovery (RDR) and similar acronyms.

various disruption scenarios to generate impacts for input to the RDRM. The RDRM uses an initial sampling of scenarios produced in the TDM along with other travel demand model tools and the impacts associated with a specific subset of hazards and mitigation options. It then computes travel impacts for all of the scenarios and resilience investment alternatives and compares the total outcome against the hazard event baseline (i.e., without resilience investment). The RDR ROI Analysis Module analyzes these scenario outcomes using the benefit cost analysis (BCA), benefit cost analysis under uncertainty/regret analysis (BCA-U/Regret) or breakeven approach to inform agencies' exploration of a wide range of future conditions and scenarios. This approach enables transportation agencies to assess transportation asset-specific resilience ROI over a range of potential future conditions and hazard scenarios, which can then be used as a consideration in existing project prioritization processes.

Resilience investment planning is particularly challenging because hazard events are rare and unique. The impacts of a hazard on travel inherently involve uncertainties regarding the probability, severity, timing, location, and duration of a hazard. That challenge is compounded by the fact that different resilience investments may perform differently under the wide variety of potential hazard events. In addition to uncertainty about hazard events and the suitability of resilience investments, there is also uncertainty about how land-use patterns, demographics, trip demand and traveler behavior will impact system performance.

The RDR Tool Suite allows the user to determine priority assets for resilience investment by calculating the difference between impacts of exposure of the roadway network at different levels of hazard events without and with an additional resilience investment, and aggregates this information across the range of potential hazard scenarios. This analysis approach complements existing federal and other resources.[14] The RDR Tool Suite is intended to be location and hazard agnostic, so that any state DOT or MPO can utilize the methods to assess how a range of physical hazards may impact the transportation network and how resilience projects can provide economic benefits.

This technical documentation describes the components of the RDR Tool Suite (see Figure 1-1), their purpose, structure, and functions.

- The RDR Exposure Analysis Tool (optional) helps the analyst overlay agency-supplied hazard severity information onto their transportation network.
- The RDR Metamodel rapidly estimates network performance under a range of uncertain future hazard scenarios and resilience investments using travel demand model (TDM) results to provide initial inputs and an open-source routing model called AequilibraE to produce disruption scenario results.
- The RDR ROI Module monetizes investment, repair, and change in performance under disruption with and without resilience investments that mitigate the disruption at a given location.
- The RDR ROI Module evaluates return on investment using Benefit-Cost Analysis (BCA), Benefit-Cost Analysis under Uncertainty/Regret Analysis, or Breakeven Analysis, depending on the user's data.

[14] Including the National Cooperative Highway Research Program (NCHRP) 20-101: Extreme Weather and Climate Change: Guidelines to Incorporate Costs and Benefits of Adaptation Measures, FHWA tools and resources including the Vulnerability Assessment and Adaptation Framework and U.S. DOT BUILD Discretionary Grant Program guidance.

- The outputs of the tool suite include rank ordering of project performance over all scenarios and future conditions. Results can be explored using a series of graphical dashboards.

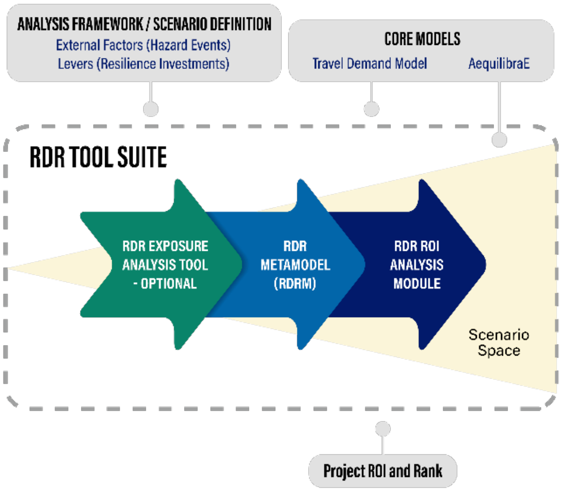

Figure 1-1: Structure of the RDR Tool Suite. The scenario space increases as more potential hazard severities, durations, recovery periods, and resilience investments are assessed.

A companion document, the RDR User Guide, provides more instruction on preparing data, executing analyses, and interpreting results as well as test data for running sample scenarios. The RDR Quick Start Tutorial provides step-by-step instructions for running test analyses in the RDR Tool Suite on a toy road network. The RDR Run Checklist provides a short reference on the inputs to check before executing an analysis. The RDR Tool Suite is available at https://volpeusdot.github.io/RDR-Public.

1.2 Approach

A resilience-focused ROI analysis must take into account:

- the range of potential hazard events;
- the range of impacts of those hazard events on transportation assets and operations including travel disruption during hazard events, the asset damage from those events, and the travel disruption due to the subsequent necessary repairs;
- the costs associated with travel disruptions measured by changes in system performance (PHT, VMT, and trips) and asset damage repair and cleanup costs due to hazard events; and
- the investment required to mitigate the impact of the range of potential hazard events.

The RDR Tool Suite is designed to overcome these challenges of calculating the impact of resilience investments under a wide range of possible futures. It accomplishes this using the established Robust Decision Making framework,[15,16] which has been used under a similar modeling context by the Travel

[15] RAND. Robust Decision Making. *RAND.* [Online] [Cited: July 20, 2022.] https://www.rand.org/pubs/tools/TL320/tool/robust-decision-making.html.

[16] Lempert, R. (2019). Robust Decision Making (RDM). Decision Making under Deep Uncertainty: From Theory to Practice. V. A. W. J. Marchau, W. E. Walker, P. J. T. M. Bloemen and S. W. E. Popper, Springer: 329.

Model Improvement Program – Exploratory Analysis and Modeling Tool (TMIP-EMAT),[17] a scenario-based decision-making tool that can be integrated with existing travel demand forecasting models of all types.

The Robust Decision Making approach provides a method for comparing alternatives under deep uncertainty by comparing alternative policy approaches under a wide range of scenarios. It includes the following steps:

1. **Define the analysis framework:** Apply an “XLRM” framework to guide stakeholder engagement, data assembly, and model development.[18] The X refers to external factors, or uncertainties (e.g., hazard scenarios); the L refers to possible policy levers (i.e., resilience investments); the R refers to relationships between the other elements that are reflected in the TDMs and RDR Tool Suite to estimate performance; and the M refers to performance metrics. The scenario space is the set of all possible scenarios that the analysis will consider and is defined by the unique combinations of external factors and policy levers.
2. **Run a core model**: The underlying travel demand model is called the “core model,” and reflects the relationships of the XLRM framework, i.e., how the causal factors are related. In the transportation context, the core model represents the transportation network and its system performance, which is typically computed using a TDM. The RDR Tool Suite uses two core models to populate the metamodel:
    a. **A regional travel demand model (TDM)** which is commonly used by State DOTs and MPOs. It typically provides
        i. Tables describing baseline movements;
        ii. Mode choice;
        iii. Network routing of the trips.
    b. **The RDR core model leveraging the open-source AequilibraE**,[19] which provides a fast simplified representation of network routing for a representative day. The RDR core model is run many times, using the trip tables from the regional travel demand model, to compute the outcomes for many scenarios in the full scenario space. The RDR Tool Suite uses AequilibraE to enhance initial TDM core model sampling to populate the metamodel.
3. **Use a metamodel to analyze full scenario space**: If the core model has a longer run time (e.g., several hours to days for an MPO TDM), then in most cases the scenario space will be too large to use the core model to calculate all results. The metamodel works by running regressions on a limited set of runs from the core model that are then used to fill in the gap where the core model has not been used to produce scenario results. A metamodel typically involves the use of regression models that are parameterized using a subset of results produced by the core model.

[17] TMIP-EMAT Development Team. TMIP-EMAT. [Online] https://tmip-emat.github.io/.
[18] Lempert, R. J., D. G. Groves, S. W. Popper and S. C. Bankes (2006). "A General, Analytic Method for Generating Robust Strategies and Narrative Scenarios." Management Science 52(4): 514-528.
[19] AequilibraE. [Online] [Cited: 07 26, 2022.] http://aequilibrae.com/python/latest/. RDR 2022.1 was developed using AequilibraE 0.7.2.

4. **Simulate and analyze:** Experiments are run using the metamodel to build a range of outcomes across multiple axes of variation. Analysis is then performed to determine the best course of action based on the range of potential futures.

The RDR Tool Suite calculates results for different time units at different steps in the overall analysis. At the initial stage, the scenario space is defined at the single day level in the configuration file. Successive steps within the RDR Tool Suite build the scenarios up from single-day "steady state" outcomes of network performance up to complete hazard events with defined hazard duration and recovery processes that occur as a series or stream of annual evaluations of hazard events occurring with some probability over the economic analysis period as follows:

- The core models produce single-day estimates of network performance based on the variables of hazard severity, economic scenarios, and trip demand elasticity for a subset of the scenario space. The analyst must provide core model results for the base year for each hazard event severity (see Sections 5.2.2.3 through 5.2.2.6).
- The RDRM regression computes single-day estimates of network performance for the remaining scenarios in the scenario space that were not estimated in the core models (see Section 5.3.2.1).
- The Recovery step of the RDRM analysis incorporates the hazard duration and hazard recovery process into the scenario space, by extending the single-day event estimations into multi-day events over which the hazard event recedes (see Sections 5.3.2.2 through 5.3.2.3).
- The RDR ROI Analysis Module extends the scenarios from single-event outcomes to a stream of future events over the economic analysis period of interest using hazard event probabilities and economic parameters. The start and end years of the period of analysis can be different from the base and future years of the scenario (see Sections 5.3.2.4 and 6.2.2).

Figure 1-2 shows how the RDR Tool Suite develops the results for the full scenario space in successive steps of the tool suite where each circle represents a scenario within the scenario space.

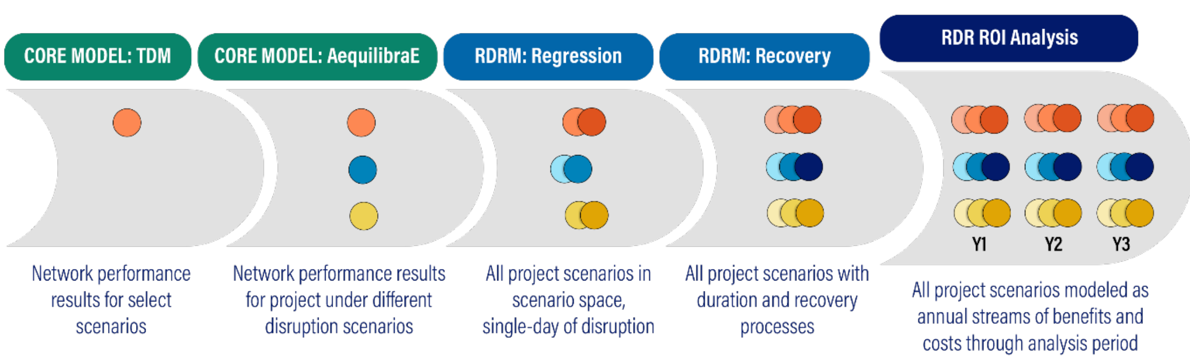

Figure 1-2: Diagram of how the RDR Tool Suite develops the scenario space results through the successive steps of the RDR Tool Suite analysis process. Different color groups represent different hazard severities, different color intensities within color groups represent different durations and recovery processes.

1.3 Return on Investment Analysis

Hazard events affect travel (transportation network performance) through the loss of network links or reduction in level of service (capacity). This disruption persists at least until the hazard ends and may also necessitate repair for travel to return to normal levels. Lost network performance can be quantified in terms of costs of repair/replacement and/or cleanup of the asset (e.g., debris removal) as well as the cost assigned to the increase in vehicle hours traveled (VHT), vehicle miles traveled (VMT), and lost trips resulting from the disruption.

To maintain and enhance the reliability of the transportation network, state DOTs and MPOs seek to make specific infrastructure investments that will increase the resilience of transportation assets (i.e., reduce impacts and/or speed recovery time). In practice, there may be some resilience investments that would provide network performance or cost saving benefits in the absence of hazards, but the focus of the RDR Tool Suite is on investments that mitigate the impact of a hazard (reduce disruption and associated costs), but do not necessarily provide improvements in network performance under non-hazard scenarios.

Figure 1-3 shows a hypothetical comparison of the loss of network performance and period of recovery for a hazard event without resilience investment (peach-lined area) and with resilience investment (blue-shaded area). The impact on system performance is lessened both during the event and during the repair period, as the asset was less damaged due to the resilience investment.

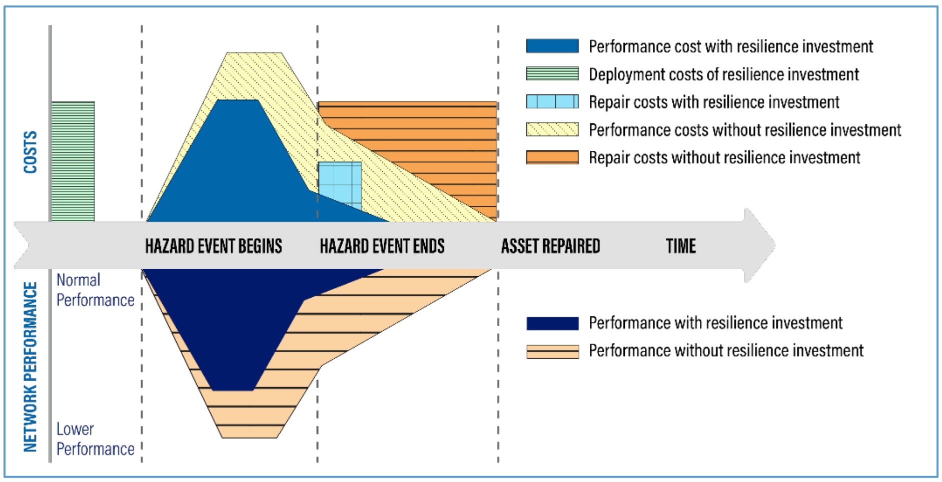

Figure 1-3: Resilience investment analysis concept: network performance during exposure and repair with and without a resilience investment (lower half) and components of the associated benefit-cost analysis (upper half). In the area below the timeline axis, the peach-lined area shows a hypothetical disruption to network performance during a hazard event and the disruption after the hazard event due to damage of a transportation asset. The disruption to the network ends when the asset is repaired to working order as it was before the hazard event. The blue-shaded area shows the disruption that occurs in the case of the same hazard event when a resilience investment is deployed. The area above the timeline axis shows components of the benefit-cost analysis of a single hazard event, including monetized loss of network performance and repair costs in the absence of resilience investments (yellow and orange areas) and the cost of resilience investments and associated reduced network performance and repair costs (green and blue areas).

This hypothetical resilience investment example can be extended to an ROI analysis appropriate for long-range decision making like benefit cost analysis, as shown in Figure 1-3. In Figure 1-3, network performance has been monetized as costs, and the costs of damage repair and the cost of the resilience investments have been included. The benefit of resilience investment is the difference between the costs when the investment is deployed (green and blue regions) versus when it is not deployed (yellow and orange regions).

Hazard events can vary in their severity, frequency, and duration in significant ways that would have a differential impact on transportation. Standard methods of infrastructure investment analysis are not designed to accommodate significant uncertainty, and therefore new methods and tools are needed to support the ROI analysis of resilience investments, such as the RDR Tool Suite Robust Decision-Making approach.

1.3.1 Benefit Cost Analysis

The Return on Investment (ROI) metrics can be used to support a Benefit-Cost Analysis (BCA). In standard BCA, analysts use a "predict then act" (or "agree-on-assumptions") approach that relies on a singular best prediction of future conditions under which the proposed policy alternatives are tested.[20] In such analyses, a best estimate of the conditions of the future world is predicted (or assumptions about the future are agreed upon) using the expected utility approach.in which agencies assign their best estimate of the probabilities of the mutually exclusive possible future conditions of the world, and then the probability of each future state of the world is applied to the value of the outcomes of those futures. The sum product of all outcomes by its probability represents the best estimate of the expected outcome of the future. Analysts are then able to compare the impact of each of the investment alternatives against one another using a baseline scenario as the basis of comparison.

> The NCHRP 20-101 report provides guidance for how to compute a BCA for transportation investments in resilience. It is a great resource for agencies who are still developing an understanding of the fundamentals of BCA. The NCHRP 20-101 guidebook chapters 7 and 8 describe a pen and paper method for building out a BCA analysis for a single flood resilience project that considers a range of future flood levels. This technical document expands on the NCHRP guidebook in that it broadens the analysis to include more assets and more uncertainties.

The RDR Tool Suite BCA approach uses all of the standard assumptions of BCA including an exhaustive list of the benefits and costs of the project; ignores transfers between parties; avoids double counting; and the application of discounting of future costs and benefits to reflect the time value of money.

1.3.2 BCA-U/Regret

The Return on Investment metrics also allows an alternative ranking approach called BCA under uncertainty (BCA-U) or Regret analysis which uses an "agree on decisions" approach in which the investment alternatives are determined first, and then those alternatives are tested under all of the potential future conditions.[21] The project prioritization approach within the BCA-U/Regret analysis approach addresses the need to appropriately balance the project costs and benefits across the wide range of potential hazard exposures with uncertain probabilities. The BCA-U/Regret approach is a way of adapting the expected utility functions for situations of in which there is low confidence in the estimated probabilities of future events.[22] These methods are designed to produce better decisions under inherent

[20] Lempert, R.J., Steven W. Popper, and Steven C. Bankes. (2003). "Shaping the Next One Hundred Years: New Methods for Quantitative Long-Term Policy Analysis." Rand Pardee Center. Accessed on 12/19/2019 from https://www.rand.org/content/dam/rand/pubs/monograph_reports/2007/MR1626.pdf

[21] Lempert, R.J., Steven W. Popper, and Steven C. Bankes. (2003). "Shaping the Next One Hundred Years: New Methods for Quantittavie Long-Term Policy Analysis." Rand Pardee Center. Accessed on 12/19/2019 from https://www.rand.org/content/dam/rand/pubs/monograph_reports/2007/MR1626.pdf

[22] Society of Decision Making under Deep Uncertainty: http://www.deepuncertainty.org/. Accessed on 15 July 2019.

and unresolvable uncertainty through exploratory analysis, rather than to improve predictions of future conditions.

In BCA-U/Regret, the expected net benefits criterion for prioritizing projects cannot be used because there are no probabilities associated with the future scenarios and therefore the results of the scenarios cannot be risk-weighted. Instead of expected net benefits, an alternative concept is used called regret, which is defined as "the difference between the performance of the option in a specific state of the world and the performance of the best possible option in that state of the world."[23] In this context, regret is measured by comparing the outcome of each alternative project scenario with the outcome of the scenario that would have been the ideal course of action under an assumed future state of the world, and this process is repeated under each possible future state. The project scenario outcome is compared against what the agency would have elected to do instead if it had known what would actually occur. The difference from the best choice is then aggregated for a given project across the range of scenarios to estimate a cumulative regret metric.

The RDR Tool Suite calculates the BCA-U/Regret in cases where the user does not have probabilities for each uncertainty which allows the user to prioritize projects by their cumulative regret value summed over all possible future scenarios or a subset of future scenarios that are most relevant for the user.

1.3.3 Breakeven

Finally, the RDR Tool Suite can also be used to calculate a breakeven analysis in which the maximum possible cost of the project is estimated by calculating the sum of the expect social benefits (the benefits as in a BCA).[24] The breakeven value can be used to determine whether an investment is potentially viable based on the benefits it could produce, and it can also be used to rank projects based on their benefits. The breakeven calculation is flexible and can be used whether the user has associated probabilities for each uncertainty (as in the expected utility approach to BCA) or when they do not (as in the BCA-U/Regret approach).

Breakeven analysis is useful for agencies that have not yet identified candidate investments and want to explore how hypothetical investments would impact their roadway network in order to help them select candidate projects. It is also useful for agencies that already have candidate investments but do not yet have cost estimates and to better understand what their constraints are in terms of their projects' deployment costs.

1.4 RDR Tool Suite Use Cases

The RDR Tool Suite is designed to help transportation agencies address questions regarding their potential resilience investments, including:

[23] Kwakkel J.H., Haasnoot M. (2019) Supporting DMDU: A Taxonomy of Approaches and Tools. In: Marchau V., Walker W., Bloemen P., Popper S. (eds) Decision Making under Deep Uncertainty. Springer, Cham. Accessed on 12/19/2019 from https://link.springer.com/chapter/10.1007/978-3-030-05252-2_15

[24] Breakeven analysis is a special case of BCA in which the net benefits are $0, by construction. Breakeven analysis is a partial BCA approach that calculates the benefits of notional resilience projects and interprets the potential benefits as defining the upper bound of costs that such a project could have and still produce a positive economic outcome. This approach works under the assumption that agencies would be indifferent between project alternatives that produce zero net positive benefits compared to the baseline but can also be applied "in reverse" to define the range of net benefits that a project would need to provide under a given scenario in order to justify its initial investment and recurring costs.

1) Which of my road and bridge assets are vulnerable under a given hazard condition or range of conditions?
2) What will link-level capacity loss be under a given hazard condition?
3) Which resilience projects will give the most benefit across the range of hazards of concern?
4) Under which hazard conditions does a project perform well? How is the performance of a given project distributed across the range of hazards?

Agencies vary in their level of data availability, analytical tools and resources, and knowledge of potential hazards and disruptions in their region. The RDR Tool Suite is set up to allow for different levels of analysis depending on the information the analyst can bring to the model. If an analyst does not have access to a travel demand model but can estimate trip tables for AequilibraE, all parameterization of the RDRM can be performed using the open source AequilibraE. And if an agency does not have specific project plans for investing in resilience and therefore does not have an estimate of the total cost of an investment, the RDR Tool Suite can still be used to estimate a breakeven point (total benefits). Thus, the RDR Tool Suite is intended to be used by agencies with a range of information and capabilities.

It should be noted that the RDR Tool Suite is not a “one-stop shop” for all resilience planning needs. It does not provide incorporate engineering evaluation considerations, except to the extent that these define the capacity and availability of links in the transportation network and the costs associated with resilience investment actions. It also does not help agencies determine what kind(s) of project(s) would be appropriate for a given asset based on predicted vulnerability to exposure. The outputs are based on investment cost, repair cost, and network performance; it does not calculate economic impact analysis at the broader societal level (e.g., impact on employment, transfers between parties, etc.).

In summary, the RDR Tool Suite provides a transportation agency with a set of tools for evaluating the ROI provided by a set of resilience investments across a range of transportation assets and uncertain future hazard conditions, and for ranking those projects based on performance. The RDR ROI Analysis Module project rankings and thorough visualizations can be used as a factor in overall transportation infrastructure project prioritization for long-range transportation planning in combination with other prioritization factors such as congestion reduction, safety, engineering considerations, and budgets.

2 Software Components

The RDR Tool Suite is written in Python and R. Both programs are required software and will be downloaded and installed during the RDR Tool Suite setup process. The required Python packages for installation, specifically the Python package AequilibraE, are managed using the conda dependency management system. Current installation instructions are available in the RDR User Guide.

The following programs are used by the RDR Tool Suite to run an analysis:

1. Conda dependency management system[25] is used for software package management. Installation through Anaconda or Miniconda[26] is recommended for conda functionalities.
2. Python[27] is the primary coding language of the RDR Tool Suite.
3. AequilibraE[28] is an open-source Python-based routing model use as the core model to compute network flows and summary statistics for quantifying the impact of disruption on the transportation network.
4. R[29] is used to run the Latin hypercube sampling and regression modules. R will be installed when setting up the conda environment and does not need to be installed separately by the user.
5. SQLite is used to store core model inputs and results. If the user would like to fully explore SQLite-generated outputs, they are encouraged to install a SQLite database browser, such as DB Browser for SQLite.
6. Tableau Reader[30] or Tableau Desktop is used for visualizing RDR ROI Analysis Module outputs.
7. ESRI ArcGIS Desktop or ArcGIS Pro is only required if using the RDR Exposure Analysis Tool. It performs the geospatial analysis elements of applying exposure grid data for hazard events to a geospatially-explicit transportation network.
8. The RDR Tool Suite Version 2022.1 is the tool itself and can be downloaded from the public GitHub repository at https://volpeusdot.github.io/RDR-Public.

See the RDR User Guide for more information on installation of RDR Tool Suite required software.

[25] Conda. [Online]. User Guide: Installation. Accessed 26 July 2022 from https://docs.conda.io/projects/conda/en/latest/user-guide/install/.

[26] https://docs.anaconda.com/anaconda/install/

[27] Python. [Online]. Download. Accessed 26 July 2022 from https://www.python.org/downloads/

[28] AequilibraE. [Online] [Cited: 07 26, 2022.] http://aequilibrae.com/python/latest/. RDR 2022.1 was developed using AequilibraE 0.7.2.

[29] R. [Online]. The R Project for Statistical Computing. Accessed 26 July 2022 from https://www.r-project.org/

[30] Tableau Reader. [Online]. Accessed 26 July 2022 from https://www.tableau.com/products/reader

3 RDR Scenario Definition Inputs

3.1 Purpose: Defining Scenario Space

The first step in the analytical process is to define the analysis framework, which includes the hazard scenarios, resilience investments, and other uncertainties. The hazard scenario(s) will determine which assets are affected and where a resilience investment could be implemented to reduce impacts.[31] For the RDR Tool Suite, hazard characteristics such as magnitude and duration will influence the extent of impacts on travel behavior, while the probability of the hazard scenario occurring influences the anticipated costs and benefits associated with investing in an asset to improve resilience.

In the XLRM framework used in Robust Decision Making (as described in the Introduction), the scenarios comprise the external factors ("X") that have a causal role in the overall outcome of a given scenario. In the RDRM context, these uncertainties can be grouped into the hazard event uncertainties and the travel demand uncertainties, listed below:

- Hazard uncertainties:
  - Hazard severity
  - Hazard duration
  - Hazard event annual probability (probability of occurring each year)
  - Future hazard event frequency, i.e., the change in a hazard probability over time
- Travel demand uncertainties
  - Future demographics
  - Future land use decisions
  - Future economic activity
  - Trip demand elasticity with respect to travel time (the hazard event may lead to longer travel times for some trips)

The policy levers of the XLRM framework in this context are the resilience investments, or "project alternatives," that will mitigate the impact of a hazard event either through reducing travel disruption, damage, or both (e.g., project alternatives could include raising a roadway, or scour prevention for a bridge).

The total scenario space is defined by the unique combinations of each possible value for each uncertainty. Each project alternative is tested in each scenario in the scenario space. Figure 3-1 shows a notional example of this: each arrow represents a different value of the given uncertainty. Each path following the arrows from top to bottom represents one scenario in the scenario space and is a unique combination of values of the uncertainties that represents one possible future. The diagram highlights one possible path with red enlarged arrows. The RDR Tool Suite approach tests the impact of each project alternative in each of these different possible futures.[32]

[31] In this document, a "hazard" will refer to the hazard type such as flooding or earthquake, and a "hazard scenario" will refer to a particular hazard type event where characteristics of the hazard scenario are fully defined (e.g., 500-year flood, 6.1 magnitude earthquake).

[32] The RDR Tool Suite uses different approaches for estimating the outcomes of these scenarios. Some of the scenarios are estimated in the core model using the TDM and AequilibraE, while the remaining are estimated in the RDR Metamodel. The process for estimating each of these scenarios is describe in section 5.

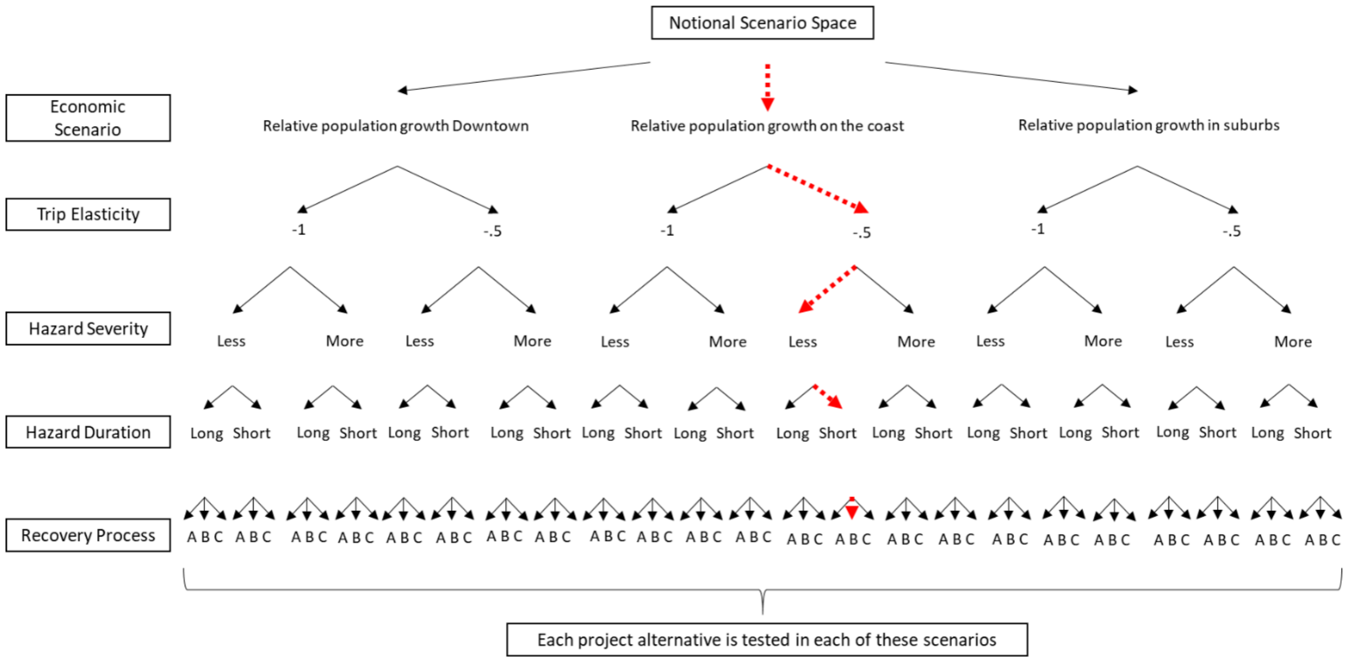

Figure 3-1: Tree diagram of notional scenario space in which each resilience project alternative is tested. Red arrows highlight one scenario in the scenario space, which is a unique combination of uncertainty values, leading to one possible future.

It is important that the hazard scenarios are defined to accurately capture, to the best available knowledge, the future potential hazards, and how those hazards may impact the transportation network. Understanding the full range of potential hazards ensures the resilience investments being deployed will appropriately mitigate future hazard impacts. The agency will need to identify the potential hazards that they face, as well as develop reasonable ranges of values for the variables of hazard event severity, hazard event probability, and future hazard event frequency.

Two other constraints may limit the ability to define hazards in the most robust way: data quality and study area definition. For example, in the case of flooding, the data available may only specify whether a roadway section is inundated, but not the depth of inundation. Similarly, the data available may only be capable of specifying the conditions of certain flooding events, such as a storm surge/sea level rise, but not for others such as extreme precipitation events.

The RDR Tool Suite is agnostic about both the hazards and the resilience investments to mitigate those hazards. However, the RDR User Guide provides background information on developing hazard scenarios for input into the RDRM and provides a few potential data sources that can help an agency estimate hazard extent and severity conditions. Hazard event duration and hazard event recovery variables can be informed by agency knowledge of the probability of certain kinds of events or can be estimated as assumptions for analysis purposes.

Note that the RDR Tool Suite is a region-specific analysis and will not capture the interaction with regions that are not included in the analysis, even though they may affect travel into and out of the area.

3.2 Structure, Functions, and Parameters

3.2.1 Hazards Event Uncertainties

The hazard event uncertainty parameters include:

- Hazard severity: The hazard event severity in terms of how much exposure it causes is operationalized in the RDR Exposure Analysis module, but the hazard event parameter here supplies the label that the RDR Tool Suite will use associated with different hazard exposure impacts. The hazard severity and hazard frequency are typically linked.
- Hazard duration: This parameter defines how long the hazard event lasts in days.[33] The impact of a hazard event is aggregated to an annual impact for project prioritization regardless of hazard event probability.
- Hazard event recovery: This parameter defines how hazard events will subside over time.
- Hazard event annual probability: This parameter defines the hazard event's annual probability of occurrence, which the user should be able to justify based on existing data. Hazard severity and hazard frequency are typically linked. In the case of flooding, annual flood risk is defined by its "return period" which essentially is the annual probability of occurrence of a flooding event of a given level of flooding (in feet). This parameter can be set to more than 1 for events that are expected to occur more than once per year.
- Hazard event frequency factor: This parameter defines how the risk of hazard events will change over time. This parameter is a fixed annual increase in probability which is applied as a multiplier to the costs and benefits incurred in each year. The parameter applies to all hazard events uniformly. The relationship between severity and probability also impacts the future event probability value. For example, in the context of flooding, changes in climate may increase the frequency and severity of storms and thus the depth and duration of flooding events.[34] With a changing climate, the likelihood of what is currently considered a 100-year storm may be greater than the estimated one percent probability per year, and the storms with a 100-year return period in the future may be stronger than the current 100-year storms.[35]

The user is responsible for ensuring the scope of hazards and their parameters are appropriate for the decision-making task at hand and should use best practices and expert knowledge to determine hazard parameters. It is possible for users to bias their results by selecting unrepresentative or unrealistic set of hazard events. Agencies should avoid selecting hazard scenarios to obtain a predetermined, desired result, or that do not encompass the range of likely scenarios. For example, if the analysis considers only the most severe hazard events, the analysis is more likely to identify a significant need for investment, while other investments may actually perform better under more likely hazard severities.

3.2.2 Travel Demand Uncertainties

In addition to the hazard event uncertainties, more standard uncertainties associated with human travel behavior could impact the outcome of a hazard event and/or the potential of a resilience investment to mitigate a hazard. The two primary behavioral choices in the RDR Tool Suite are captured in the following mechanisms:

[33] The RDR Core Models estimates travel at the daily level so that hourly level assessments cannot be made.
[34] https://www.fhwa.dot.gov/engineering/hydraulics/pubs/hif16018.pdf
[35] Holmes, R.R., Jr., Dinicola, K., 2010, 100-Year flood–it's all about chance: U.S. Geological Survey General Information Product 106, 1 p. Accessed on 1/2/2020 from https://pubs.usgs.gov/gip/106/

- Elasticity of Travel Demand: Travel demand elasticity is the change in travel (driver decision to make their trip) in response to a change in generalized cost. For example, if the elasticity is -0.5, a 10% increase in generalized cost will result in a 5% decrease in travel. There is empirical uncertainty about the specific value of this parameter, and it has substantial impact on the travel behavior as modeled by the core models. The RDR Tool Suite allows the user to use multiple elasticity of demand values to capture this uncertainty.
- Economic Scenario: The economic scenario reflects uncertainty about long-term changes in land-use, demographics, and trip demand patterns in the region over the period of analysis. This is operationalized in the trip demand tables that come from the core model, which reflect the pattern of trips demand to and from each travel analysis zone (TAZ). Users must create a future year trip table to represent the expected pattern of trip demand for the region, which itself reflects land-use and demographics of the future year. Users can use a single future economic scenario to represent their best guess as to how their region will grow over leading up to the future year. Or, if there is uncertainty about how the region will grow over the period of analysis, the user can generate multiple economic scenarios to reflect the different potential future patterns of trip demand.

The variables of economic scenario and trip demand elasticity are already part of agency scenario planning, and most agencies will already have a range of possible values that they want to consider. Agencies should be careful not to be too narrow in their assumptions about future conditions.

4 RDR Exposure Analysis Module

4.1 Purpose: Applying Hazards to Networks

An asset hazard exposure analysis is used to determine how a transportation asset is impacted by a hazard. The RDR Exposure Analysis Tool is an optional tool that provides a method to link exposure data to a transportation network. Agencies that have already assessed exposure using other techniques (e.g., have overlaid flooding depth grids on their transportation network or linked earthquake vulnerability estimates for transportation assets) can proceed directly to using the RDRM.

Hazards do not impact all transportation assets uniformly, as hazard severity varies across geography, e.g., flood levels depend on land elevation and soil composition. Hazard exposure also depends on the on the asset location and characteristics such as elevation, construction materials, condition, and context (e.g., surrounding topography, etc.).

To conduct an exposure analysis, a user must obtain geospatial data on the transportation assets (roadway network), identify a specific hazard type to be analyzed (e.g., flooding), and identify the intersection of a particular hazard type and event with transportation assets in the region. The RDR Exposure Analysis Tool combines individual asset information with hazard severity to evaluate the potential asset exposure (e.g., flood inundation depth on individual network links). The output of the RDR Exposure Analysis is used in the Disruption Analysis Submodule to assess the impact of exposure on travel.

A resilience investment in the context of this analysis is considered to be an additional or unique project that is intended to reduce the impact of a hazard on the transportation system. Resilience projects can reduce hazard exposure by moving or redesigning a transportation asset (e.g., moving a roadway out of a floodplain or raising it to reduce flooding exposure). Resilience projects could also involve adding infrastructure away from the transportation asset (e.g., adding a sea wall or berm to reduce exposure of the asset to flooding). The effect of these projects on exposure can be represented in an additional resilience-investment exposure output table that reflects reduced exposure on the modified links where the resilience investment is planned.

4.2 Structure, Functions, and Parameters

The RDR Exposure Analysis Tool uses the following inputs:

- Routable transportation network: a routable transportation network can be acquired from a TDM (see the User Guide for more detail). For the RDRM process, using a TDM roadway network is the simplest approach since results are directly linked to the TDM assets. Most TDMs can export their network in a GIS format to combine with other geospatial data, such as existing geospatial hazard severity datasets. However, if the TDM network is highly schematized (i.e., not representing links in real-world geography), it may be better to use a true shapes file that is more geospatially-explicit and then match up the links to a TDM network after calculating exposure.
- Exposure Data: These data are generated for each hazard scenario. More information on defining exposure data, identifying relevant individual asset data, and surveying potential data sources can be found in the User Guide. Users may have already conducted vulnerability assessments that may be appropriate as input data for this analysis. To incorporate data from

such analyses, the data must link hazards to assets of interest (links in the transportation network), including the magnitude of exposure.
- Resilience investment-related exposure data: mitigation of exposure associated with a given resilience investment.

The RDR Exposure Analysis Tool outputs are a file containing a list of the roadway links and the exposure of those links under different hazard scenarios and resilience investment scenarios.

5 RDR Metamodel (RDRM)

5.1 RDR Disruption Analysis Submodule

5.1.1 Purpose: Translating Exposure Severity to Network Capacity

To evaluate how a hazard impacts travel as well as how the resilience investment mitigates that impact, the hazard exposure for assets in the roadway network is translated into reduction in capacity (disruption). The RDRM approach handles hazards as changes in network link capacity. While potentially limiting, this allows the RDRM tool to be completely hazard-agnostic – exposure from any hazard can be modeled. The RDR Disruption Analysis Submodule provides several options to define how exposure translates to capacity loss. Agencies that have estimates of asset disruption for each hazard event can proceed directly to the core model runs that inform the metamodeling.

5.1.2 Structure, Functions and Parameters

5.1.2.1 Disruption Calculations

Either the RDR Exposure Analysis Tool or the main RDR Metamodel (RDRM) can be used to calculate disruption of the network based on exposure using the same methodology options and parameters that are defined by the user. The RDR Exposure Analysis Tool requires an ArcGIS or ArcGIS Pro license and outputs spatial data that can be mapped using GIS software. The RDRM disruption analysis (which does not require a license to ArcGIS or ArcGIS Pro) converts exposure data into disruption levels to be used downstream in the RDR Tool Suite.

If disruption information is available from a source other than the RDR Exposure Analysis Tool, the asset capacity can be modified manually in the TDM network file.

The same four options for the disruption analysis are built into both the RDR Exposure Analysis Tool and the RDRM:

- Default (flood-specific): The default flood exposure function utilizes depth-disruption function adapted from an existing function from the literature (Pregnolato et al. 2017), where the availability of a roadway decreases from 100% to 0% at a linear rate between 0 and 300 millimeters of flood depth.[36] This function is only applicable to flooding depth grids, not other exposure grids. This method can be used when a simple linear function converting flood depth to disruption is desired, without the complexity of a manual approach or custom exposure-disruption function.
- Binary: If the binary approach is selected, any road segment with an exposure above 0 is assigned a link availability of 0. Any road segment without any hazard exposure is assigned a link availability of 1 (fully available). This option is useful when data limitations in the underlying exposure analysis do not allow fine-grained assessment.
- Manual: The manual method allows users to define their own bins (ranges of severity) for converting exposure values to disruption (e.g., severity of level x to y corresponds to reduction in capacity of z). This method is used when the user does not have a specific exposure-disruption function but can still estimate categories of disruption based on exposure.

[36] Pregnolato, M., Ford, A., Wilkinson, S., & Dawson, R. (2017). "The impact of flooding on road transport: A depth-disruption function." *Transportation Research Part D: Transport and Environment*, Vol. 55, pp.67-81. https://www.sciencedirect.com/science/article/pii/S1361920916308367

- Beta Distribution: This option allows the user to define a custom curve representing the relationship between hazard severity and transportation capacity change.[37] This gives the user flexibility in determining how link availability could change in a non-linear fashion due to varying levels of exposure.

5.1.2.2 Resilience Investment Disruption Mitigation

Different types of resilience investments can mitigate the impact of a hazard at a given location (see Table 5-1).

Table 5-1 Resilience Investments in the RDR Tool Suite

Resilience investment	How this is implemented in the RDR Tool Suite
New alternate route	New links in the network
Modify existing route to make its disruption less likely (e.g., a road subject to flooding is raised)	Greater link availability in the resilience project networks at those links
Ability to recover faster	Reflected in the recovery times and damage recovery path, model will reflect a less disrupted network earlier in the recovery process
Lower cost of repair	Reflected in the cost analysis

5.1.2.3 Calculating Emergency Response, Evacuation Disruption, and Other Analyses

In addition to supporting project prioritization, the RDR Tool Suite disruption module can be used to estimate which roads would still remain accessible to emergency vehicles or other high clearance vehicles. Exposure and disruption data can also be used to determine the disruptions to emergency response and evacuation routes.

Emergency response vehicles usually have higher clearance than passenger vehicles; therefore, emergency vehicle access limitations during a hazard may differ from those for passenger vehicles when clearance affects passage (e.g., flooding). The emergency response disruption analysis allows users to identify impacted routes based on ground clearance. For example, in a flood-based scenario, a user could specify that inundation levels between one and two feet are only passable by emergency vehicles and inundation levels above two feet are impassable to everyone. However, it should also be noted that the resulting damage and therefore disruption will also impact the ability of emergency response vehicles to respond and the corresponding increases in travel time should be accounted for.

The emergency response disruption analysis feature of the RDR Exposure Analysis Tool can be further used assess viability of evacuation routes under various hazard conditions. An analyst can use the map feature in GIS to find critical failure points in an evacuation route and identify alternative routes for affected segments. The analyst can also evaluate the changes to travel times on the degraded evacuation or alternative route using either the TDM or the AequilibraE core models tools.

[37] There are examples of predictive relationships such as depth velocity functions defined by Pregnolato et. al (see Appendix G in the User Guide) that can be used for a more nuanced analysis estimating level of change in capacity or speed based on level of exposure.

The results of the disruption analysis can also be exported for use outside of the RDR Tool Suite such as to inform regional analyses of access disruption to other transportation modes (e.g., ports, airports) as well as key regional assets, such as military bases, hospitals, and utilities.

5.2 RDR Metamodel Parameterization Submodule

5.2.1 Purpose: Calculating Network Performance Under Select Hazard Conditions

RDRM performs a regression to estimate performance across the range of scenario conditions at the daily level. To do this, the RDRM needs a starting set of analyses to parameterize the regressions. The RDRM leverages a sample of core model runs (Travel Demand Model, if user has one, and open-source AequilibraE) to calculate daily network performance under the baseline and select hazard and scenario conditions.

5.2.2 Structure, Functions and Parameters

The metamodel parameterization submodule has two components:

- Latin Hypercube Sampling: The Latin Hypercube Sampling selects the array of scenarios from across the scenario space that that will provide sufficient data to parameterize the regression model.
- Core Models: The core model component runs the scenarios selected by the Latin Hypercube Sampling module so that the outputs can be used in the regression module to estimate network statistics for all scenarios in the scenario space. The core model used to model network effects of scenario uncertainties is AequilibraE.

The following subsections detail the functions and parameters for each of these components.

5.2.2.1 Latin Hypercube Sampling

The Latin hypercube sampling (LHS) module is used to select the set of core model runs that populate the regression model in the RDRM. The module chooses scenarios randomly and runs a series of coverage tests to make sure the selected set provides adequate data to fully fit a regression model for the entire scenario space. The module outputs a set of Core Model runs to pass to the RDRM based on the scenario space and the regression model to be used.

The full universe of parameter combinations depends on the agency's decisions about which uncertainties to include, which subsequently define the scenario space. For example, a set of inputs to the RDRM defined on the given uncertainties might include:

- Socio economic – 1 level
- Project group – 3 levels
- Resilience investment – 2 levels
- Elasticity – 3 levels
- Hazard – 3 levels
- Recovery – 6 levels

1 x 3 x 2 x 3 x 3 x 6 = 324 combinations of 'scenario factors'

The LHS module enumerates the full scenario space specified by the analyst and randomly selects a number of combinations of 'scenario factors' (a parameter chosen by the analyst) such that all levels of each uncertainty are represented by a core model run. Based on the regression model selected, additional coverage checks are run to ensure the regression can be expanded to cover the full scenario space (e.g., full coverage of hazard-recovery interactions if the regression model with interactions is chosen). While the LHS module will confirm the RDRM can construct a full regression model based on selected set of core model runs, the performance and model fit of the RDRM improves as the analyst opts to select more core model runs. Practically, the number of core model runs is limited by the computationally intensive nature of those model runs. In the above example, an analyst may only be able to conduct 75 core model runs in a reasonable amount of time using AequilibraE. The RDRM regression can then use those as 'training data' and provide interpolated outputs for the remaining 249 combinations of scenario factors.

The LHS module provides additional functionality to the analyst for supplementing an existing set of selected core model runs with additional samples for use in the modified scenario space. This allows for reuse of previously-run core model runs, as long as core model inputs have not been changed from what was used in the previous run (e.g., routable network, trip tables). To supplement an existing set of core model runs, the LHS module follows these steps:

1. The modified scenario space is constructed.
2. Existing core model runs are filtered to only those that still fall within the modified scenario space.
3. A new random set of core model runs is chosen as indicated by the number of additional combinations the analyst wishes to select. A buffer of additional runs is included in this initial selection of new core model runs to account for overlap with the existing set.
4. The existing and new sets are combined, with duplicate selections removed. The final set is down selected to only the number of combinations indicated by the analyst.
5. The full selection is checked for coverage of the scenario space based on the regression model to be used.

5.2.2.2 Travel Demand Model (TDM) Core Model

Many transportation planning organizations use travel demand models (TDM) to analyze flows within the planning region. The RDR Tool Suite can take in information from standard TDM analyses as the primary core model that forms the basis for the metamodeling.

A classic "four-step" TDM uses the following four steps: trip generation, trip distribution, mode choice, and vehicle routing.

Normally, a TDM is calibrated and validated for current conditions by comparing TDM outputs with observed conditions. The TDM is then applied to future year scenarios. These scenarios may include changes in:

- Population, employment and the resulting changes in trip generation and distribution.
- Infrastructure changes (e.g., planned highway or transit expansions).

These are steady-state futures, as distinguished from hazard scenarios, which disrupt the network for a specific time period as described in Section 5.2.2.5.

Trip generation primarily depends on land use data at the TAZ level. Land use data includes population, employment, and other socio-economic data, including household car ownership (which acts as a proxy for vehicle access) and income. Trips are categorized by various purposes (home-based work, home-based shop, home-based social/recreation, home-based other, nonhome-based work, and nonhome-based other). Trips are then produced (origin) or attracted (destination) depending on established trip production and attraction rates. Home-based work attractions can be adjusted based on an accessibility factor for each zone.[38] That is, if a zone is highly accessible (high employment combined with low travel times to other zones), then the attractions are adjusted upwards. There are separate procedures for dealing with external trips and with truck trips. Outputs of the trip generation step include trip-ends for both peak and off-peak periods**.**

Trip distribution estimates the number of trips that will travel between each TAZ pair. A gravity model uses a generalized cost (i.e., travel time plus toll/value-of-time) between zone pairs to estimate the distribution of trips. These costs are estimated based on congested highway travel times from a previous model run. The output of trip distribution is a set of person trip tables, typically organized as productions (e.g., home) and attractions (e.g., work, shopping). They may be further organized by peak and off-peak periods, divided by trip purpose and auto availability.

To be used by the RDR Tool Suite, these trips tables must, first, be converted from production-attraction to origin-destination, and second, be aggregated to daily person trips. Table 5-2 lists the trip tables for the peak period set for an example based on an existing sample TDM.

Table 5-2 Trip distribution outputs

Table name	Trip purpose	Auto Availability
hbo_0pk	Home based other (includes social/recreation)	0
hbo_1pk	Home based other (includes social/recreation)	1 or more
hbs_0pk	Home based shopping	0
hbs_1pk	Home based shopping	1 or more
hbw_0pk	Home based work	0
hbw_1pk	Home based work	1 or more
nhb_pk	Non home based	any

Mode choice allocates trips between auto and transit modes. It allocates the trips to time periods. Four periods each day (AM, PM, midday, and night) are often used.

Finally, **vehicle routing** puts the passenger vehicle and freight truck trips onto the road network taking speed and capacity into account, and finding a user equilibrium routing where no user can improve their travel time by changing routes. The TDM outputs include PHT and PMT, VHT and VMT, and the number of trips for the scenario and future analyzed. Inputs and outputs to the core model module of the RDR Metamodel are summarized in Table 5-3, below.

The vehicle routing component of a core model requires a routable network (nodes and links) as an input. The RDR Tool Suite is designed to work with the nodes and links in a General Modeling Network

[38] One example of a TAZ accessibility factor calculation is on page 41 of the Hampton Roads Model Methodology Report Version 1.0. $Accessibility(zone\ i) = \sum_j \frac{Employment(zone\ j)}{travel\ time_{ij}^2}$

Specification (GMNS) network.[39] GMNS is a new open-source network specification, designed to facilitate sharing of networks.

Table 5-3 RDR Metamodel Core Model Inputs and Outputs

Network	Origin-Destination Trips	Origin-Destination Impedances
Baseline network (TDM or AequilibraE)	Trip tables listing number of daily trips between each origin and destination (O-D) (or between each production and attraction (P-A))	Tables (skims) listing impedances (e.g., travel time, generalized travel cost) for each O-D or P-A pair
Network with some level of disruption and (optionally) resilience investment (AequilibraE)	Trip tables listing daily trips (with a reduction in trips for those O-D pairs that are affected by the disruption)	Tables (skims) listing impedances (with an increase in impedances for those O-D pairs that are affected by the disruption), which are generated in the disruption analysis

The baseline network and trips should come from the TDM. Since the AequilibraE core model described in the following sections is used as a proxy for the TDM in generating disruption scenario origin-destination impedances, it is recommended that the analyst validate the AequilibraE core model against the TDM for the baseline network. The next few sections describe how TDM files are used as input for AequilibraE, and also the mechanics of how AequilibraE approximates the TDM.

5.2.2.3 AequilibraE Core Model

The RDR Tool Suite includes a link to AequilibraE (version 0.7.2), an externally provided open-source shortest path and routing model that may be used to compute network flows and summary statistics for baseline and disrupted networks. In the RDRM, AequilibraE is used to quickly determine daily link flows and skims (times and distances between each origin and destination) for both base and disrupted networks. AequilibraE can be used within an RDR Analysis to supplement or replace the TDM as a core model.[40]

AequilibraE requires the following inputs:

- An origin-destination trip table, stored in open matrix (.omx) format
- A routable network consisting of node and link tables, which are input as csv text files, and then stored in an SQLite database

Up to three sets of core model runs are performed, to provide the needed summary outputs.

First, a baseline run is completed on a non-disrupted network. This model run may be based on either a shortest path or user equilibrium routing calculation. Summary outputs for a day include:

    - Total trips
    - Total PMT

[39] https://github.com/zephyr-data-specs/GMNS

[40] See Appendix B for additional validation of AequilibraE as a core model and Appendix C for use of a generalized modeling network specification (GMNS) network in AequilibraE.

- Total PHT

Second, disrupted runs are completed, on a disrupted network. This run includes adjustments of the number of trips with the same summary outputs.

Finally, disrupted runs with resilience investments may be completed, on a modified disrupted network.

5.2.2.4 Base Runs

Baseline network outputs (with no disruption) are drawn from either TDM core model outputs, or from an AequilibraE base run. Figure 5-1 illustrates the data flows. The four step TDM is shown on the left, while AequilibraE is shown on the right. Both produced links flows and times, and O-D flows and times.

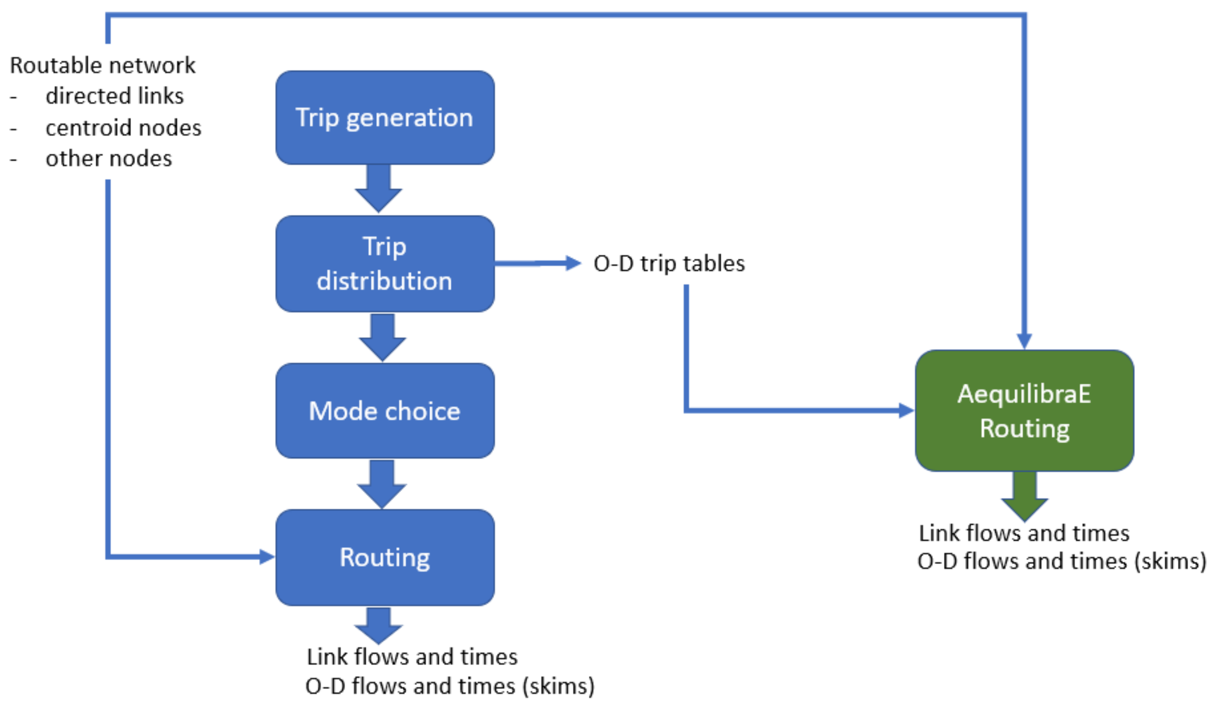

Figure 5-1 Base run data flows

5.2.2.5 Disruption Scenarios using AequilibraE

Once the trip tables and network have been assembled, the hazard disruptions can be applied to produce model outputs for a range of hazard event disruptions and resilience investments. These modifications lead to capacity and trip routing changes in the baseline hazard scenario that alter the generalized cost of travel for particular roadways in the network. These changes in the generalized cost of travel then impact travel behavior, as modeled in the core model (i.e., TDM), and changes the VHT, VMT, and trips. The core model (i.e., TDM) models how trip-makers will respond to the change in generalized cost of travel by adjusting whether or not they make trips, and by changing how those trips are routed which could mean increases in travel time or travel mileage depending on the circuity of the route under hazard exposure or roadway damage. The impact of the resilience investment is quantified as the difference between the VHT, VMT, and trip levels in the baseline hazard scenario compared to the VHT, VMT, and trip levels in the same hazard scenario when the resilience investment is deployed. The difference in VHT and VMT are monetized using standard DOT values for value of time and vehicle operating costs or using values supplied by the agency (see Section 6.2.2). The trip values are monetized using the difference in trip time multiplied by the generalized cost of those trips in the baseline.

A permanent hazard condition, such as sea-level rise, may make certain links in the network and certain TAZs permanently unusable. With these links and TAZs being removed, the transportation system will reach a new equilibrium. Therefore, for these scenarios, it is appropriate to run the entire TDM analysis, considering the broader effects of the permanent hazard on trip-making. Steps are as follows (Table 5-4):

Table 5-4: Modeling the Effects of a Permanent Hazard

What happens:	
1	Identify the scenarios of interest, for example: - Long-term hazard severity (e.g., sea-level rise) - Level and type of infrastructure investment.
2	Translate the exposure level at various times in the recovery process to the amount of disruption on previously identified TAZs and links (see Sections 4 and 5)
3	Review and approve the proposed list of TAZ and highway changes from step 2 for the model run.
4	Determine how (or whether) to adjust productions/attractions for the other TAZs. If a permanent disruption makes a TAZ much less accessible, it may be worthwhile to reassess the number of generated trips to or from that TAZ.
5	Run the TDM under the new conditions. Outputs from the TDM include - origin-destination trips and impedances (travel times) - total number of trips - Passenger and Vehicle Miles traveled (PMT and VMT) - Passenger and Vehicle Hours traveled (PHT and VHT).
6	Use the results of the core model runs in the RDRM and RDR ROI Analysis Module.

A temporary event, such as intermittent flooding due to storm surge or precipitation, temporarily removes links and TAZs from the network, but does not lead to a permanent change in trip making. Note that in many cases, the effects of temporary events (e.g., a 100 year flood), will be exacerbated by changes in permanent hazard conditions (e.g., a 3 feet sea level rise).

Recall that a disrupted network state under a hazard condition is characterized by:

- Some set of links disabled (i.e., due to a hazard)
- Some set of origin and destination zones disabled, or have reduced trip-making
- Some set of links with reduced capacity

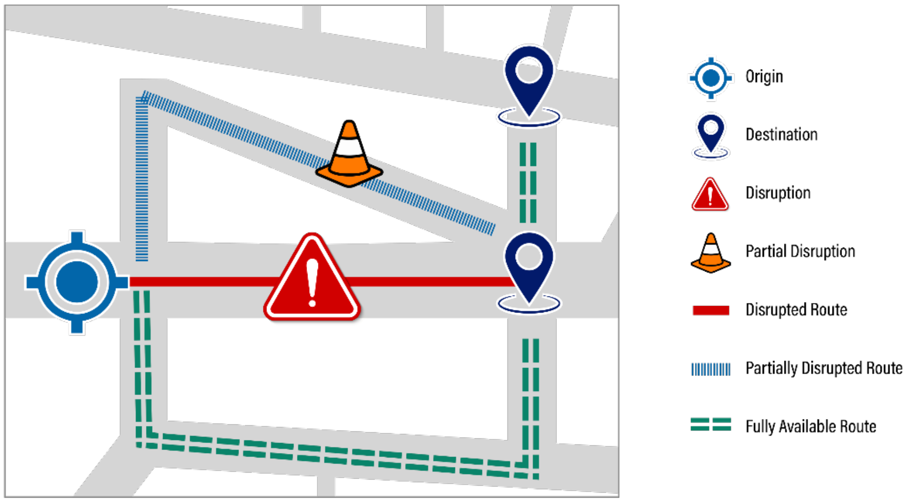

Figure 5-2 A hazard disrupts certain links in the network, leading the core model to identify alternate route(s) around a disruption and calculate the change in trip-making and performance.

The base core model run (TDM or AequilibraE) returns origin-to-destination impedances, while the disrupted run returns impedances that consider out-of-route travel.

Table 5-5: Modeling the Effects of a Temporary Hazard

What happens:	
1	Identify the scenarios of interest, for example: - Hazard event (see Section 3.2.1) – e.g., storm damage, including recovery steps (e.g., the flooding receding) - Resilience investment options (i.e., Infrastructure modifications) - Elasticity of trip demand
2	Translate the exposure level at various times in the recovery process to amount of disruption on previously identified TAZs and links (see Sections 4 and 5)
3	Adjust trip tables in accordance with the removed / disrupted TAZs as input to the TDM
4	Recalculate generalized travel costs for the remaining origin-destination pairs. Two approaches: (1) Rerun the user equilibrium routing portion of the TDM (2) AequilibraE module (See Section 5.2.2.3)
5	Adjust trip tables in accordance with more circuitous travel - This makes use of the elasticity of trip demand[41] - Alternatively, use a simple cutoff
6	Rerun traffic assignment to calculate the trips that are lost, as well as the generalized cost of the remaining trips. Again, there are two approaches (1) Run the assignment portion of the TDM to produce congested travel time and VMT Outputs are reported for each time period (typically AM, PM, midday, night), and will include: - Trips - PMT and VMT

[41] new_demand = old_demand x (new_travel_time / old_travel_time)^{elasticity} where elasticity ≤ 0.

What happens:	
	- PHT and VHT (2) Run the AequilibraE routing module on daily person trips. Outputs are reported for the entire day, and include trips, PMT and PHT
7	Using the congested travel times from the results of step 6, adjust the trip tables again. To lessen the likelihood of an unstable result (that reduces trips too much), the value of elasticity is set to one-half of the original value.
8	Rerun traffic assignment again.
9	Using the results of the core model runs, perform the meta-analysis

5.2.2.6 AequilibraE outputs: Origin-Destination impedances

Key outputs from AequilibraE include origin-destination impedances, or skims. They are determined either via a routing algorithm (which considers link capacity and congestion) or via shortest path (which only considers link impedance).

After the trips have been routed on the network, the origin-destination impedances are then multiplied by the origin-to-destination flows for each baseline and disruption scenario to calculate overall performance measures, including number of trips, person miles traveled (PMT), and person hours traveled (PHT).

Finally, the trips, PMT (which are eventually converted to VMT using occupancy computed within the TDM or using federal or state vehicle occupancy values), and PHT are scaled up from a generic hour to overall daily values in the scenario state.

5.3 RDR Scenario Expansion Submodule

5.3.1 Purpose: Estimating Network Performance Across Hazard Conditions and Resilience Investments

The RDRM uses core model runs to estimate network performance under disruption and estimate performance during hazard recession and repair recovery stages. It then concatenates outputs in terms of daily values into annualized performance based on hazard recovery and repair recovery. The annualized values are then passed to the RDR ROI Analysis Module. The RDR Metamodel has four modules:

- Regression: The RDRM regression module is used to produce outcomes for each scenario in the scenario space. The regression model circumvents needing to run the core model, which is time intensive, for every scenario. Outputs of the regression module are single-day estimates of network performance under each uncertainty scenario.
- Exposure recovery modeling: The RDRM Recovery process transforms the single-day estimates of the impact of hazard exposure calculated in the core models and RDRM regression module into realistic multi-day hazard events.
- Repair recovery modeling: The RDRM Recovery process also extends the estimates of the impact of hazard exposure to include impacts on network performance during the repair period incurred by damage on the asset after the end of a hazard event. Benefits of less severe and shorter repair recovery due to a resilience investment mitigation compared to a no-action baseline are quantified to incorporate in the ROI analysis.

- Annualization: The annualization submodule translates the scenario performance outcomes from single hazard events to annual values.

5.3.2 Structure, Functions, and Parameters

5.3.2.1 Regression

The RDRM regression model takes the parameters used in the core model runs and uses the output from those models to estimate the target network performance variables (i.e., number of trips, PHT, PMT) for combinations of parameters not run through the core model. The regression uses the core model scenario performance measures and the scenario space parameters to statistically estimate network performance measures for the full range of the scenario space across hazard severities, recovery stages, economic futures, elasticities, resilience investments, and resilience project groups. Only scenario space parameters (e.g., hazard events, economic futures, elasticities, etc.) with more than one distinct value provided by the analyst are used in the regression model.

The default model is a simple linear regression model using each scenario space parameter independently as a decision variable; this is labeled the 'base' model. Four additional models can be selected using the "metamodel_type" parameter in the configuration file. These additional models enable the use of interaction terms, project groupings, multitarget Gaussian regression, and mixed-effects modeling. Each of these has different advantages depending on needs and the input data properties:

- 'interact' – This regression model incorporates interaction terms between (a) hazard severities and recovery stages, (b) project groups and resilience investments. The model improves on the 'base' model in cases where the relationship between hazard severities and how each recedes across the network is not uniform, and in cases with several project groups with uneven impacts on network performance. Use of this model requires significantly more core model runs to be sampled by the LHS module than the default linear regresssion, as every interaction term must be represented in the sample.
- 'projgroupLM' – This regression model fits a separate (independent) linear regression model for each project group subset of the scenario space. This model also incorporates interaction terms between hazard severities and recovery stages. As a result, use of this model requires significantly more core model runs to be sampled by the LHS module.
- 'multitarget' – This regression model jointly infers all dependent variables (trips, PMT, PHT) using the same Gaussian process model.[42] The regression model outputs the inferred mean function value for each scenario in the scenario space. While the model has no explicit functional form (compared to the linear regression models) and relies entirely on fit to sampled data, it has the benefit of inferring all network performance measures together. Testing has shown this approach to outperform the 'base' model when given the same number of LHS samples.
- 'mixedeffects' – This model combines fixed effects (project group designation) and random effects (all other scenario space parameters). This model works best in cases where variation between distinct project groups is large compared to variation of resilience projects with a project group.

[42] Section 2.2 of http://gaussianprocess.org/gpml/chapters/RW2.pdf.

5.3.2.2 Metamodel Exposure Recovery

In order to assess the full cost of a temporary hazard, and the benefit of resilience investments to mitigate it, it is necessary to model the recovery process. The RDRM Recovery process transforms the single-day estimates of the impact of hazard exposure calculated in the core models and RDRM regression modules into realistic multi-day hazard events. The post-hazard event recovery process is comprised of two stages: exposure recovery and repair recovery. For each scenario identified, the recovery module models the progression of exposure stages from initial hazard exposure to no exposure as well as the progression of asset repair from maximum damage to fully repaired, keeping track of damage repair costs and times throughout. The RDRM uses a set of user-provided input parameters in the configuration file to define the recovery processes that can occur under each scenario:

- Each scenario defines a network state for a single day given by the initial exposure of the hazard event.
- Recovery modeling constructs exposure recovery paths that describe how network states progress from initial exposure to the end of the hazard event, the period described as exposure recovery. The set of exposure recovery paths is generated from six parameters in the [recovery] section of the configuration file.
- The exposure recovery path is defined by the initial hazard exposure, the duration of the entire hazard event, and the severity and duration of each network state in the series of hazard recession stages. The recovery module generates a range of exposure recovery paths to allow the evaluation of the impact of possible recoveries on potential resilience investments.
- Repair recovery modeling constructs a repair recovery path to describe how assets progress from a state of maximum damage immediately after the end of a hazard event to a fully-repaired state. The RDRM currently relies on a fixed model for repair recovery, where the asset is repaired such that capacity increases linearly from maximum damage at the start of the repair recovery period back to full capacity. This model approximates partial repair of asset damage across the repair recovery period; the benefits accrued for the resilience investment compared to the baseline factor in both the reduced damage incurred during the hazard and the shorter repair period.

The recovery process uses the scenario states defined through the core model runs and the first stage of the metamodel and further defines the scenarios by a recovery profile. The recovery profile defines how long each scenario state lasts and defines the progressing of states from the initial exposure state to the final no-exposure state.

The exposure recovery process works in the following steps. A scenario is chosen that defines the initial conditions of the scenario, such as initial flooding depth of X feet from a 100-year flood. The metamodel generates the network state for the initial condition under X feet of flooding, as well as a series of network states with incrementally less flooding. The exposure recovery path then defines the series of network states that occur after the initial scenario state, along with the number of days each network state lasts. The exposure recovery path represents a further uncertainty that is captured by the metamodel which is how the exposure will occur over time. An analyst can define many exposure recovery paths to represent the uncertainty about how recovery will occur.

The four-link example shown above in Figure 5-2 illustrates the framework for modeling of a recovery process. The example includes three zones: A, B, and C, and three hazard scenarios: Large, Medium, and

Small disruption, the impacts from which are listed in Table 5-6. The example provides a description of a single exposure recovery path for each of the three hazard scenarios and demonstrates how the hazard severity and exposure recovery interact. The RDRM builds out several potential exposure recovery paths for each hazard scenario in order to evaluate resilience investments across both hazard events and potential recoveries.

Table 5-6 Four-link disruption impacts

	Link 1	***Link 2***	***Link 3***	***Link 4***
Large disruption	*4 weeks*	*1 week*	*No effect*	*3 weeks*
Medium disruption	*3 weeks*	*No effect*	*No effect*	*1 week*
Small disruption	*1 week*	*No effect*	*No effect*	*No effect*

Figure 5-3 illustrates these impacts at weeks 1, 2, 3, 4, and later. Note that there are only 4 unique network states: the baseline with all links available, 1 link disrupted, 2 links disrupted, and 3 links disrupted. The red lines are disrupted links, the brown line is the primary alternate route, and the blue lines represent other links in the network. These unique network states are generated using the core model (full TDM run or shortest path) and/or the first stage of the metamodel (regression) which associates trips, PMT (which are eventually converted to VMT using occupancy computed within the TDM or using federal or state vehicle occupancy values), and PHT with these four network states. As stated above, the recovery process further defines scenarios by defining the progression of states from an initial exposure condition.

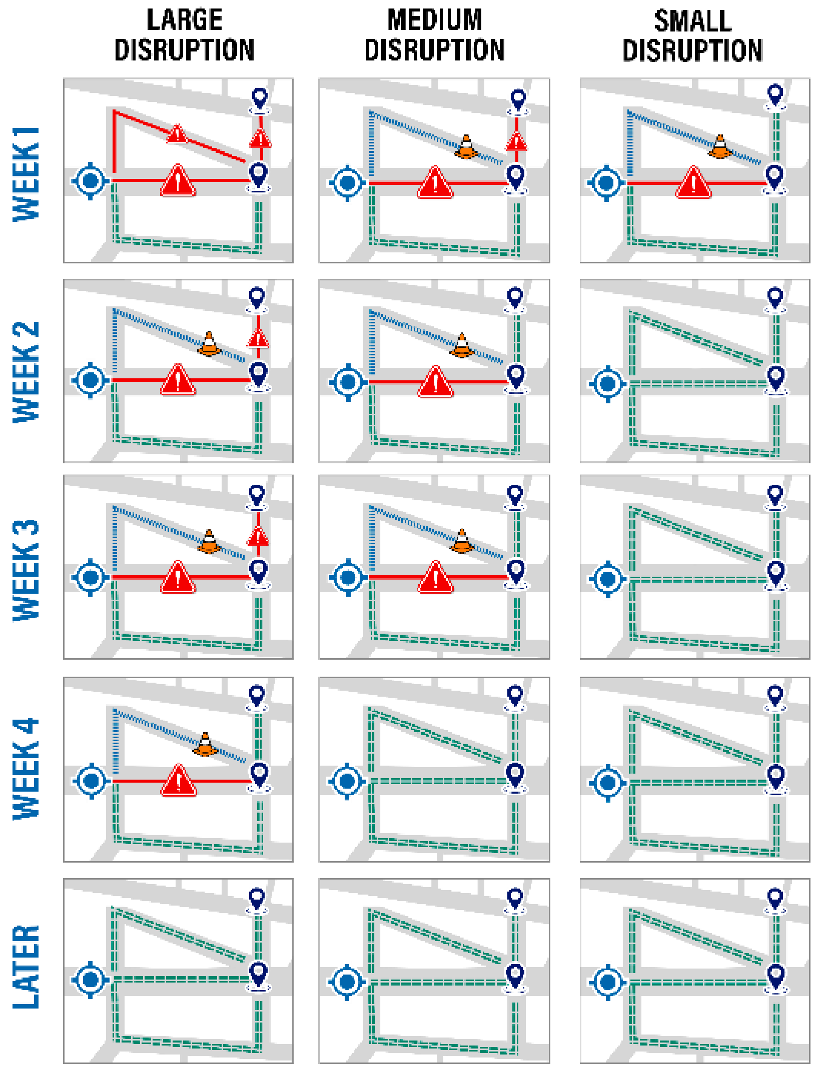

Figure 5-3 Four-link model, impacts, and network states

5.3.2.3 Metamodel Damage and Repair Recovery

If the asset damage from a hazard requires repair, a post-hazard damage estimate and repair period disruptions must be included to effectively estimate resilience ROI. The repair recovery process is modeled separately from the exposure recovery process in the metamodel, because repair is an agency decision, unlike exposure recovery which cannot be controlled by the agency. The asset damage costs include the potential disruption due to asset damage after the hazard ends and during the repair/construction period in addition to the material and labor repair/replacement costs. The RDRM Recovery module uses repair time to expand the number of days of additional disruption, as the core models and RDRM regression module only estimate a single day of travel.

Repair recovery is modeled to occur after the exposure recovery and encompasses the gradual repair of the asset from maximum asset damage to full recovery. For a specific resilience project investment, repair recovery is compared to a baseline with no resilience project investment. The impact of the resilience project investment on repair costs during the repair recovery period is quantified for the affected asset through its lessened damage and shorter repair time, while the state of the rest of the network is assumed to be the same as the baseline.

This process is similar to exposure recovery, although the repair recovery model is not configurable through configuration file parameters—a damage recovery path describes how the asset is repaired through a linear progression of network states until it is fully repaired (see Figure 5-4). Repair recovery is defined by:

- Damage to the asset
    - The level of functionality at given level of damage
    - The minimum time required to restore the asset to complete functionality (with and without resilience investment)
    - The intermediate stages of partial repair with reduced functionality
- Debris cleanup level of effort
    - Minimum time to remove debris
    - May overlap with damage repair

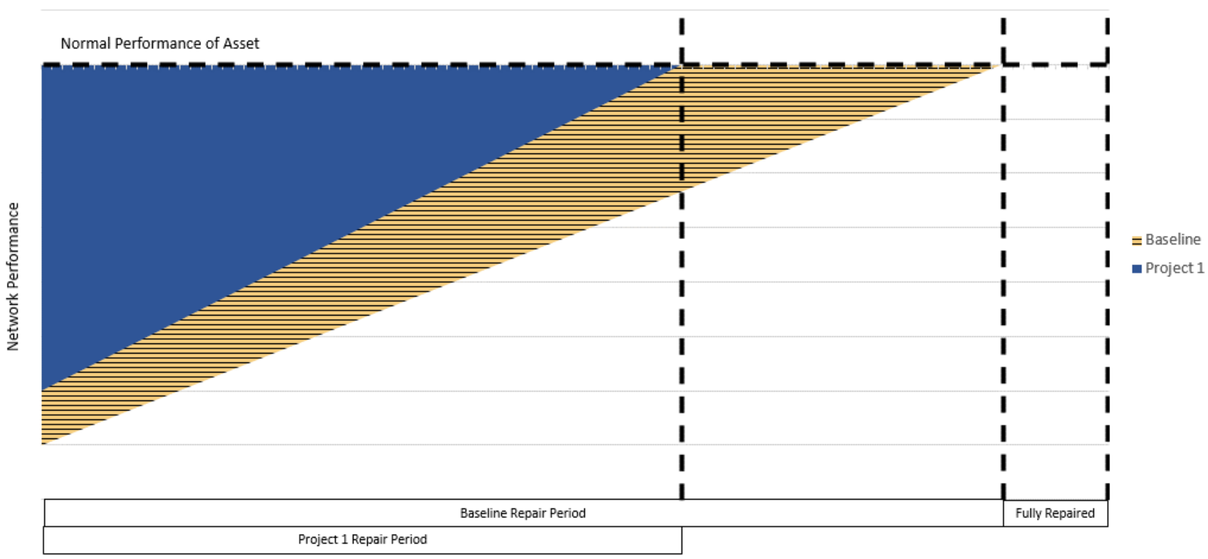

Figure 5-4: Example of Repair Recovery – One resilience project vs. no action baseline showing linear recovery for both scenarios starting at different maximum performance loss and recovering across differing repair recovery periods.

Similarly to the disruption analysis process, the RDR Tool Suite allows for multiple methods of asset damage estimation. For some hazards, standardized exposure-damage relationships exist which can inform damage estimates when faced with a hypothetical future hazard such as:

- Temperature to pavement damage[43,44]
- Earthquake road-damage scale[45]
- Flooding/inundation depth and damage[46]

The RDRM provides flexibility in calculating asset damage by allowing the analyst to provide their own exposure-damage functions or rely on a set of default options such as the binary damage option or default depth-damage function. The RDRM includes default values, and the analyst can adjust the inputs in the configuration file and look-up tables to better model the repair process of their particular use case.

Once the percent damage is estimated, it is used to set the initial baseline repair recovery network state and is monetized using standard per mile costs for regular maintenance such as resurfacing, rehabilitation, and reconstruction (see following subsections and Section 6.2.2.2).

Repair duration is related to the extent of damage and depends on multiple local factors, including the number of repairs needed in the network in response to a given event, asset priority, equipment, personnel and materials availability, and weather conditions (e.g., heavy rains can delay construction if the ground is saturated for several days after the precipitation event).[47] However, a minimum time for repair and/or rebuilding can be used as a lower bound for the exploration of recovery times in the RDRM. A table of the minimum time of repair can be entered as an optional input into the disruption analysis of the RDRM.

For a specific resilience project investment, damage recovery is compared to a baseline with no resilience project investment. The impact of the resilience project investment on repair costs during the damage recovery period is quantified for the affected asset, while the state of the rest of the network is assumed to be the same as the baseline. Damage to the asset associated with the resilience project is calculated for both the baseline case and the resilience investment case using the following steps:

1. Network links comprising the asset are identified using the project_table.csv input file.
2. Exposure to the hazard event is identified for each network link using the Exposure Analysis Tool or externally developed exposure analyses.
3. Damage to each network link is calculated according to a user-specified depth-damage approach in the configuration file: ‘Binary’, ‘Default_Damage_Table’, and ‘Manual’.
4. The resilience investment hazard disruption mitigation, either complete or link-by-link partial mitigation, is considered in the asset damage calculation step.

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[43] Lu, Wei, Kayser Sascha, and Wellner Frohmut. 2013. Impact of Surface Temperature on Fatigue Damage in Asphalt Pavement. Journal of Highway and Transportation Research and Development: 7(3). https://doi.org/10.1061/JHTRCQ.0000324

[44]Maaty, Ahmed. 2017. Temperature Change Implications for Flexible Pavement Performance and Life. International Journal of Transportation Engineering and Technology: 3(1):1. DOI:10.11648/j.ijtet.20170301.11.

[45] Panjamani, Anbazhagan, Sushma Srinivas, and Deepu Chandran. 2011. Classification of road damage due to earthquakes. Natural Hazards: 60(2). DOI:10.1007/s11069-011-0025-0

[46] Huizinga, J., De Moel, H. and Szewczyk, W., Global flood depth-damage functions: Methodology and the database with guidelines, EUR 28552 EN, Publications Office of the European Union, Luxembourg, 2017, ISBN 978-92-79-67781-6, doi:10.2760/16510, JRC105688.

[47] VDOT. 2019. Road Building: Frequently Asked Questions. Accessed on April 20, 2020 from https://www.virginiadot.org/projects/faq-road-built.asp.

5. Minimum repair duration for each network link is calculated. A default look-up table is provided, and the analyst may also provide their own minimum repair duration by setting the configuration file parameter repair_time_approach to 'User-Defined'. The default look-up table is based on input from VDOT and the values are specified in Section 6.2.2.2. Repair durations are scaled by damage percent.

Once minimum repair durations have been calculated for both the baseline and resilience project investment cases at the network link level, the damage recovery path is constructed to approximate the gradual repair of the asset. The baseline case without resilience investment will have greater maximum damage and a longer time of repair for the specified asset. The resilience investment case has lower maximum damage, thus starting the repair period at a better network performance, and also requiring a shorter repair recovery time, i.e., reaching normal performance earlier. For both cases, the asset associated with the resilience project starts at its maximum damage at the beginning of the repair recovery period and is repaired such that capacity recovers linearly to normal performance across the repair recovery time. The difference in the network performance curves between the baseline case and the resilience investment case across the total repair recovery period is attributed to benefits from the resilience investment and passed to the ROI analysis.

5.3.2.3.1 Roadway Damage Cost and Time to Repair

The parameter repair_cost_approach in the configuration file can take two values: 'Default' and 'User-Defined'. Regardless of approach taken, repair costs are scaled by the damage percent incurred on the asset based on level of hazard exposure.

Existing roadway build cost estimates provide a starting point for calculations if local/regional estimates are not readily available. The RDR Tool Suite includes a default look-up table of with roadway damage costs based a schedule of typical costs per lane mile for repair and reconstruction actions for the Highway Economic Requirements System (HERS) model, which is maintained and updated regularly by FHWA. HERS is the agency's BCA tool used in long-range funding decision making and congressionally mandated reporting.[48] The HERS model uses standard values for reconstructing and widening a lane, reconstructing an existing lane, resurfacing and widening a lane, resurfacing existing shoulder, improving shoulder, adding a lane, and new alignment for different categories of roadway including functional class, population area size for urban areas, and geographic terrain (e.g., flat, rolling, and mountainous) for rural areas.

The default roadway damage costs (Figure 5-5) are measured per lane-mile and are estimated as the cost to reconstruct an existing lane. Damage costs are broken down by functional class of the roadway. The costs in the report are given in units of 2014 dollars, which were converted to 2018 dollars for use in the RDRM using the National Highway Construction Cost Index (NHCCI).

[48] FHWA. (December 20, 2016). "Highway Investment Analysis Methodology: Appendix A."Accessed on April 20, 2020 from https://www.fhwa.dot.gov/policy/2015cpr/appendixa.cfm#_Toc464549614

Asset Type	Network Type	Facility Type	Unit	Damage Repair Cost	Total Repair Cost
Highway	Rural Flat	Interstate	Lane-mile	1339513.546	1339513.546
Highway	Rural Flat	Other Principal Arterial	Lane-mile	1072022.362	1072022.362
Highway	Rural Flat	Minor Arterial	Lane-mile	941363.2063	941363.2063
Highway	Rural Flat	Major Collector	Lane-mile	996919.0677	996919.0677
Highway	Rural Rolling	Interstate	Lane-mile	1373464.35	1373464.35
Highway	Rural Rolling	Other Principal Arterial	Lane-mile	1101857.917	1101857.917
Highway	Rural Rolling	Minor Arterial	Lane-mile	1042186.807	1042186.807
Highway	Rural Rolling	Major Collector	Lane-mile	1013380.064	1013380.064
Highway	Rural Mountainous	Interstate	Lane-mile	3008247.011	3008247.011
Highway	Rural Mountainous	Other Principal Arterial	Lane-mile	2480466.328	2480466.328
Highway	Rural Mountainous	Minor Arterial	Lane-mile	1924907.715	1924907.715
Highway	Rural Mountainous	Major Collector	Lane-mile	1585399.673	1585399.673
Highway	Small Urban	Freeway/Expressway/Interstate	Lane-mile	2390959.663	2390959.663
Highway	Small Urban	Other Principal Arterial	Lane-mile	2030875.376	2030875.376
Highway	Small Urban	Minor Arterial/Collector	Lane-mile	1533959.061	1533959.061

Figure 5-5: Default repair damage cost table (from FHWA HERS model)

The RDRM also allows the analyst to provide their own look-up table for damage costs across roadways and bridges, as there a number of resources that estimate these values nationally and regionally. The American Road Transportation and Builders Association (ARTBA)[49] estimates $2-3 million per mile to construct a new 2-lane undivided road in a rural area, which goes up to $3-5 million in urban areas, and costs go up as the number of lanes increase. ARTBA estimates milling and resurfacing a 4-lane road to cost $1.25 million per mile. Arkansas,[50] Florida,[51] and Virginia have published cost per mile estimates for road work. Both Arkansas and Florida provide the costs per mile of roadway construction for roads and bridges across a variety of functional classes (e.g., highways, non-highways, etc.) and a variety of construction or improvement types (e.g., reconstruction, new roads, etc.), whereas Virginia provides roadway construction cost for a range of functional classes. These examples can be used by an analyst as a reasonable default if they do not have locally relevant data. For agencies to provide their own damage cost look-up table, the parameter repair_cost_approach should be set to 'User-Defined' in the configuration file, and the structure of the provided table must mirror the default, breaking out the damage repair cost by roadway functional class and in units of lane-mile.

The parameter repair_time_approach can take two values: 'Default' and 'User-Defined'. Minimum repair duration for road debris removal and repair can be estimated from past experience or from existing datasets and may also be classified by roadway functional class and improvement type. The RDRM default values refer to data provided by Virginia DOT, for which repair times for a rural secondary project can take between 1 to 8 weeks, repair times for a primary 4 lane road can take up to 4 months, and repair times for an interstate can take a day or weeks. If agencies provide their own repair time look-up table, the repair durations should be broken out by roadway type. Repair times are also scaled by damage percent.

[49] https://www.artba.org/about/faq/. Cost to build a mile of road is included under "Funding, Financing & Costs".
[50] ARDOT. 2020. Estimated Costs per Mile. https://www.ardot.gov/wp-content/uploads/2021/11/2020-CPM.pdf
[51] FDOT. Costs Per Mile Models for Long Range Estimating. Accessed July 26, 2020 from https://www.fdot.gov/programmanagement/estimates/lre/costpermilemodels/cpmsummary.shtm.

5.3.2.3.2 Bridge Damage Cost and Time to Repair

As with roadway assets, the RDRM allows an analyst to use default values for bridge damage cost and time to repair or provide their own values. Bridge costs and times are stored in the same look-up tables as roadway costs and times. The configuration file is used to specify whether the 'Default' or 'User-Defined' look-up table is used by the tool. The RDRM uses the FHWA estimate for bridge replacement costs[52] in the default look-up table for bridge damage cost, adjusted with the NHCCI to 2018 dollars, and the VDOT estimates for bridge repair times.

In the FHWA-maintained annual collation of bridge replacement costs,[53] in 2018 the average national cost of bridge replacement was $223 per square foot for structurally deficient National Highway System bridges, and $252 per square foot for structurally deficient non-national highway system bridges.[54] FHWA regularly updates these values, and they can provide a basis for an initial evaluation of potential cost of repair related to hazard disruption. However, these values vary by location and also depend on what elements are included in the estimate. Based on VDOT estimates, bridge replacement averaged $850 per square foot in 2019 for new bridge deck area including all phases of the development and construction, as well as associated non-bridge construction.[55] For analysts to replace the default repair cost with their own values, the parameter repair_cost_approach should be set to 'User-Defined' in the configuration file, and the structure of the provided table must mirror the default, breaking out the damage repair cost by national highway system bridges and non-national highway system bridges and in units of per square foot.

The actual physical replacement of a bridge can take six months or more. For example, VDOT provided a rough estimate for new/replacement bridge construction on an emergency basis at:

- Bridges shorter than 20': 4 to 6 months
- Bridges greater than 20' and less than 50': 6 to 8 months
- Bridges greater than 50' and less than 100': 8 to 12 months
- Bridges greater than 100': 12 months to 18 months[56]

VDOT indicated that these would take longer on a non-emergency basis. Accelerated Bridge Construction (ABC)[57] components (prefabrication of specific bridge elements) and techniques for installing those prefabricated components have reduced the time period of bridge replacement, sometimes by up to 50 percent,[58] and in some cases compressing the actual replacement down to 24 hours to 2 weeks.[59]

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[52] FHWA. 2021. Bridge Replacement Unit Costs. https://www.fhwa.dot.gov/bridge/nbi/sd.cfm
[53] FHWA. 2021. Bridge Replacement Unit Costs. https://www.fhwa.dot.gov/bridge/nbi/sd.cfm
[54] FHWA. 2021. Bridge Replacement Unit Costs. https://www.fhwa.dot.gov/bridge/nbi/sd.cfm
[55] Eric Stringfield, VDOT, personal communication, 30 March 2020 to Dale Stith, Hampton Roads TPO.
[56] Eric Stringfield, VDOT, personal communication, 30 March 2020 to Dale Stith, Hampton Roads TPO.
[57] FHWA. 2011. Accelerated Bridge Construction. Publication no. HIF-12-013. https://www.fhwa.dot.gov/bridge/abc/docs/abcmanual.pdf
[58] Salem, Ossama, Baris Salman, Sudipta Ghorai. Accelerating construction of roadway bridges using alternative techniques and procurement methods. Transport 33(2): 567-579. https://journals.vgtu.lt/index.php/Transport/article/view/160/129
[59] FHWA. 2011. Accelerated Bridge Construction. Publication no. HIF-12-013. https://www.fhwa.dot.gov/bridge/abc/docs/abcmanual.pdf

If agencies use their own cost estimates, the bridge repair cost must be provided in units of dollars per square foot, and the bridge repair times broken out by length of the bridge.

5.3.2.4 Annualization

Once the exposure recovery and repair recovery periods are built out for each single-day scenario snapshot in the scenario space, network performance metrics have been computed for each scenario in the full scenario space. The disruption and recovery days are concatenated into a series of days modeling the full hazard impact in a hypothetical year, with the remaining days of the year assumed to be at the baseline performance. Depending on the level of data provided by the user, each scenario (e.g., hazard event) is associated with an annual probability of occurrence from which an expected impact of a resilience investment can be calculated. These annual values are used in the ROI Analysis Module to estimate performance across the full period of analysis.

6 RDR ROI Analysis Module

6.1 Purpose: Calculating Aggregated Economic Benefits Across Hazard Conditions

The RDR ROI Analysis Module applies variations of the benefit cost analysis framework to the RDRM outputs to estimate ROI across the range of hazard conditions and other uncertainties. The BCA analysis approaches included in the RDR ROI Analysis Module are BCA, BCA under Uncertainty with a regret measure (BCA-U/Regret), and break-even analysis. The different approaches allow agencies to conduct an analysis that is consistent with their own decision-making needs and available data. The RDR ROI Analysis Module uses a standard BCA when the probabilities associated with hazards are well known; BCA-U defined by a regret measure when there is uncertainty associated with the hazard probability; and a break-even analysis when the designs or costs of potential resilience projects are unknown. This is an advancement from existing approaches to resilience investment planning; the RDRM can facilitate analysis even when data are less reliable or unavailable. Additional information about the ROI approaches can be found in section 1.3.

6.2 Structure, Functions, and Parameters

This section describes how the RDR ROI Analysis Module including the tool features, inputs, outputs are generated and how to interpret the results. The analytical steps in the RDR ROI Analysis Module are:

- ROI Analysis
  - Calculate the impact of the project relative to the baseline (e.g., PHT in project scenario minus PHT in the no-project baseline scenario).
  - Apply monetization to the performance metrics.
  - Apply monetization to trips.
  - Apply discounting.
  - Incorporate estimated cost of repair of damaged infrastructure.
  - Compute net benefits (for BCA and BCA-U/Regret) and total benefits (breakeven analysis).
  - Compute regret.
  - Compute project rankings by regret.
- Export results for visualization.

6.2.1 Economic Parameters

6.2.1.1 Defining Economic Parameters

In order to conduct any of the ROI analyses (BCA, BCA-U/Regret, or breakeven analysis), the analyst will need to select the following economic parameters for inclusion in the input files.

Analysis Period: The period of analysis is the time period over which the project benefits accrue. Transportation resilience projects by their nature typically involve large capital investments whose benefits accrue over the service life of the investment.

The user will select the start year of the project; the project is assumed to be completed and begins accruing benefits in that year. The RDR Tool Suite is not a financial analysis tool and does not consider impacts of budget, deployment, or financing alternatives.

The user will also select the analysis period end year. Ideally, all of the potential resilience investments being considered would have the same service life. In practice, this will be rare. Therefore, the analyst should choose a period of analysis that is the least common multiple of the potential projects.[60] This approach is preferred because it avoids the issue of having to calculate residual value of the projects. For example, when considering three different resilience investments with service lives of 5, 25 and 50 years, the least common multiple, and therefore the period of analysis, would be 50 years. However, in practice this may be difficult given the variety of resilience investments that could be made and the challenge of predicting patterns over a long period of analysis. In those cases, the analyst should use their best judgement regarding period of analysis and should be sure to calculate the residual value of each project at the end of each. This can be accomplished by the analyst independently or can be calculated using an Excel helper tool that can be found in the RDR GitHub repository at https://github.com/VolpeUSDOT/RDR-Public/blob/master/helper_tools/resiliencyproject_cost_residual_calculator.xlsx.

Base and Future Year Inputs: The steady-state conditions for the base year and the future year are used to linearly interpolate the performance metrics for the entire period so that there are performance metrics associated with every year of the period of analysis. Given the linear interpolation/extrapolation method, the period of analysis (defined by the start year and end year) need not be between the base year and the future year; the analyst can use any period starting after the base year. There will be a base year result for each hazard event severity and recovery, as economic futures and resilience projects will not apply before the period of analysis. There will be a future year result for each scenario in the scenario space, generated by the RDRM.

Inflation Adjustments: The analyst must ensure that all monetized cost and benefit values are expressed in the same dollar year so that a meaningful comparison between benefits and costs is possible. In most cases, analysts will need to convert at least some monetary values from their current dollar year. The US DOT recommends using the Gross Domestic Product (GDP) deflator as the general method of converting nominal dollars into real dollars, based on the recommendations in the OMB Circular A-94[61] and OMB Circular A-4[62].

Time Value of Money/Discounting: Resources at one's disposal today are worth more than having comparable resources available in the future. To account for this, future benefits and costs are discounted to their present values so that nominal levels of costs and benefits can be compared across years and across alternatives that generate different future time patterns of costs and benefits. The concept of discounting is demonstrated in Figure 6-1. The user specifies a discount factor in the configuration file for RDRM use during the linear interpolation process.

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[60] Wolfram Mathworld. 2022. Least Common Multiple. [online]. Accessed July 26, 2022 from https://mathworld.wolfram.com/LeastCommonMultiple.html.

[61] OMB Circular A-94 "Guidelines and Discount Rates for Benefit-Cost Analysis of Federal Programs": https://obamawhitehouse.archives.gov/sites/default/files/omb/assets/a94/a094.pdf

[62] OMB Circular A-4 "Regulatory Impact Analysis: A Primer": https://www.reginfo.gov/public/jsp/Utilities/circular-a-4_regulatory-impact-analysis-a-primer.pdf

Based on OMB Circular A-94, US DOT recommends analysts use a discount rate of 7 percent per year.

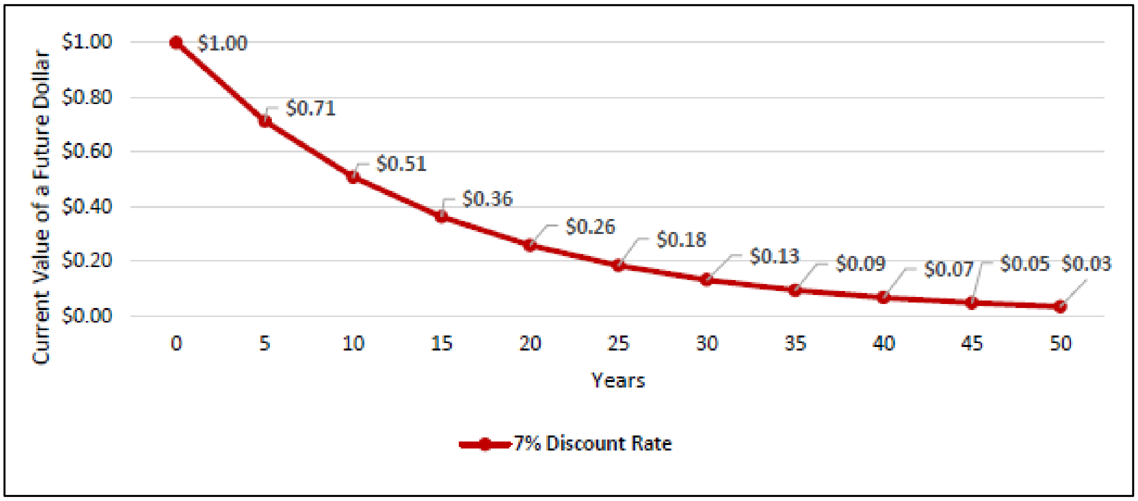

Figure 6-1: Demonstration of discounting[63]

6.2.2 Monetization

The RDR ROI Analysis Module computes the benefits of each project alternative in each scenario by monetizing the changes in transportation performance metrics.

6.2.2.1 Network Performance Benefits

In order to compute the performance metrics benefits, the user will need to assign monetary values for value of travel time, vehicle miles traveled, safety, trips, asset damage repair, and asset cleanup.

As a default in the RDR Tool Suite uses the US DOT-specified values for travel time measured as vehicle hours traveled (VHT), vehicle miles traveled (VMT), and safety measured in crashes per 100 million VMT for injury, fatal and PDO crashes. The user can adjust these to alternative monetary values if preferred (e.g., to use local values).

US DOT does not have a standard method for monetizing lost trips, trips that are foregone because the path is not traversable or if the trip time makes the trip infeasible. Instead of a fixed value, the RDR ROI Analysis Module uses the economic theory concept of consumer surplus to value lost trips. The trip values are computed using the implied value of trips based on the trip elasticity value and the network equilibrium generated in the core model. Essentially, the value of the trip is assumed to be the cost of trip in travel time and operating costs. A formal explanation of this approach is provided in Appendix D: Trip Loss Valuation.

The RDRM approach includes the following simplifying assumptions:

- treats all vehicle travel as passenger travel,
- treats all transit travel as passenger vehicle travel,
- (relatedly) does not account for potential mode shifting between vehicle and transit travel, and

[63] FHWA. (January 29, 2020). “Benefit-Cost Analysis Guidance for Discretionary Grant Programs.” Accessed on April 20, 2020 from https://www.transportation.gov/office-policy/transportation-policy/benefit-cost-analysis-guidance-discretionary-grant-programs-0

- converts tolls and similar use fees to travel time equivalents using the value of time.

These assumptions cannot be relaxed in the current version of the tool.

6.2.2.2 Damage Repair and Cleanup Cost Savings

The tool uses default repair cost and time based on the roadway type and also depends on the percent of asset damage as described in Section 5.3.2.3. Due to the limitations of the model, the user cannot make trade-offs between asset repair costs and time. In practice, post-hazard decisions about repair time and cost would be made using optimization that is inappropriate to apply within BCA.

The repair cost is only calculated for the assets on which the project is deployed. The ROI only considers the marginal impact of the project as the damage to other assets occurs in both the project scenario and the baseline and therefore cancel each other out.

Once network performance benefits (for both the exposure period and the repair period) and damage repair and cleanup cost savings have been monetized for the marginal impact of the resilience project compared to the baseline, benefits across the period of analysis are computed and compared to resilience project costs. Total benefits are the sum of network performance benefits and repair and cleanup cost savings, weighted by risk of each uncertainty scenario and discounted. Net benefits subtract out project cost. Regret metrics are computed by ranking net benefits and assigning an ordinal value within (a) the entire scenario space, (b) each uncertainty scenario, (c) all resilience investments on the same asset.

The results of the ROI analysis provide economic performance metrics for each project over the range of scenarios and conditions considered in the analysis, and over the economic analysis period. The outputs are exported from the RDR ROI Analysis Module in a comma-separated file for the user to be able to review, use for analysis and explore in the visualization module.

7 RDR Reporting and Visualization Module

7.1 Purpose: Communicating the Results

The RDR Reporting and Visualization Module provides the user with a streamlined approach for reviewing the ROI analysis within the analysis team as well as decision-makers external to the analysis team. This section describes data outputs and the visualization module that can be used to explore the analysis results. It describes how to use the analysis output and visualization to rank the performance of a given resilience investment in relation to other asset project options and/or in relation to resilience investments for other assets.

7.2 Structure, Functions, and Parameters

7.2.1 Reporting

The RDR ROI Analysis Module outputs are intended to be used in project prioritization based on the BCA, BCA-U/Regret, or Breakeven Analysis approaches. Agencies can use these outputs to rank the evaluated projects in order of their economic ROI. This ranking can contribute to overall project prioritization evaluations when combined with other prioritization factors considered by agencies.

Given that the RDR Tool Suite is used when the potential future conditions are very large in number (the scenario space is very large) reviewing and understanding the outputs of the analysis can be challenging in text form. Therefore, the RDR ROI Analysis Module final output imports into visualization dashboards that can be accessed using Tableau (full Desktop version or the free Reader version).

The RDR ROI Analysis Module output file addresses three categories of variables: scenario factors (i.e., the parameters that define the scenario including uncertainty parameters, the project alternative, and the recovery process parameters), scenario outcomes (VHT, VMT, and trips), and the monetization and analysis variables such as the monetization of VHT, VMT, and trips and the projection prioritization metrics. The variables of the RDRM output data include:

- Scenario Accounting
  - IDResiliencyScenario: unique ID for the resilience project scenario
  - IDScenario: ID for the unique combinations of uncertainty values.
  - IDScenarioNoHazard: unique ID for unique combinations of uncertainty variables not including the hazard dimensions. This variable defines the baseline scenario, namely the scenarios in which there are no project alternatives.
- Policy Levers
  - ResiliencyProject: name of the resilience project as a string.
  - Asset: asset on which a resilience project is deployed.
  - ResiliencyProjectAsset: resilience project and the asset defined jointly, as a string.
  - Project Group: an optional field that defines the project group in which a given resilience investment is tested. In some cases, analysts may have grouped potential projects in the TDM analyses.
- Uncertainties
  - Year: expresses the period of analysis as a string, e.g., “2020-2045”
  - Hazard Characteristics:
    - HazardDim1: hazard severity in numeric (e.g., flooding depth/flood event frequency, earthquake intensity).

        - HazardDim2: a second hazard dimension as a numeric. For example, in the Hampton Roads case, this is defined as the sea level rise.
        - Event Probability: annual probability of the hazard event (e.g., a 100-year flood has an annual probability of .01).
        - DurationofEntireEventdays: duration of the hazard event (including hazard event recession) in days.
        - Exposurerecoverypath: hazard event exposure recovery path describing each stage of the hazard by day before the hazard event cases. The exposure recovery paths are defined by the progression of network states (corresponding to hazard levels) for every day of the hazard event, e.g., a hazard with a duration of three days may have an exposure recovery path of '2,2,1' which denotes that the first stage at hazard level 2 lasts two days and the second stage at hazard level 1 lasts one day.
        - DamageRecoveryPath: damage recovery path which describes the level of damage at each stage of the repair duration period.
    - EconomicScenario: economic scenarios in string (e.g., future economic conditions used to estimate trip changes for TDM analyses).
    - TripElasticity: trip elasticity in numeric (reduces the number of trips based on the increase in travel time).
    - FutureEventFrequency: annual growth value of the probability of the hazard events (if probability is anticipated to change over time).
- Metrics
    - ProjectCosts_Discounted: resilience project costs discounted over the period of analysis, assuming any redeployment and subtracting the residual cost.
    - TotalNetBenefits_Discounted: risk-weighted discounted net benefits summed across each hazard event for a given unique uncertainty profile.
    - NetBenefits_Discounted: discounted net benefits for the unique IDResiliencyScenario.
    - Benefits_Discounted: discounted benefits which is the sum of the monetized performance metrics during the exposure and damage periods as well as the repair and cleanup cost savings.
    - ExpBenefits_Discounted: discounted benefits of the system performance metrics during the exposure event.
    - RepairCleanupCostSavings_Discounted: discounted repair and cleanup costs relative to those occurring in the base scenario.
    - DamBenefits_Discounted: discounted benefits of the system performance metrics for the period during which the asset is under repair after the exposure.
    - BCR_Discounted: benefit cost ratio for each scenario.
    - RegretAll: resilience project regret ranking across computed across all scenarios.
    - RegretScenario: resilience project regret ranking for individual scenarios.
    - RegretAsset: resilience project regret calculated only for projects on the same asset, by scenario.
- System Performance: There are 36 system performance variables defined by the period of performance, the system performance category, and the output category. The field names are constructed using the same convention, e.g., 'expPHTlevels' where 'exp' is the period of

performance, ‘PHT’ is the system performance category, and where ‘levels’ is the output category.

- Period of Performance: particular period over which the benefits are calculated.
  - "dam." refers to the system performance of the network when the asset is damaged and under repair and after the exposure has ended."
  - "exp." refers to the system performance of the network when the exposure event is occurring.
  - "init." refers to the system performance of the network for a single day at the highest level of exposure event.
- System performance categories: includes PHT, VMT and trips.
- Output Category
  - Levels: absolute level of the system performance category value.
  - Tripslevel_dollar: monetized value of the Levels.
  - vsBase: expresses the difference between the baseline scenario and the resilience scenario for a given system performance category.
  - vsBase_dollar: monetized value of vsBase.

- Asset Damage Performance:
  - AssetDamagelevels: damage function value for the scenario in numeric.
  - DamageDuration: number of days of repair required to return the asset to its pre-hazard condition.
  - AssetDamagevsBase: damage value in the project scenario against the damage value against the base.
  - RepairCleanupCosts: annual repair and cleanup costs for the scenario.
  - RepairCleanupCostSavings: value of the cleanup and repair costs against those costs in the base.
  - RepairCostSavings: value of repair cost only against those costs in the baseline.

7.2.2 Tableau Dashboards

The dashboard is intended to accommodate the various uncertainties and other assumptions, allowing the analyst to select ranges of uncertainty values to define their scenarios space, and/or not use a particular uncertainty category at all.

The RDR Tool Suite Tableau workbook includes four separate dashboards that provide alternative ways of representing the data and different scopes of the results.

Each dashboard except the Overview dashboard features a filter panel, shown in Figure 7-1. The filters allow the analyst to select a subset of the scenarios in the scenario space. The Asset-Project filter list allows the analyst to select which project, projects or assets are shown in the dashboard. Filtering on one variable automatically adjusts the available range of values for other filters. A reset button reverts all filters to the full range.

The dashboard graphics use color and in some cases shape to distinguish between different projects.

Each dashboard has a dictionary and a help button. The dictionary provides explanation of the different terms used throughout the dashboards. The help button provides additional information about how to use the tool and where to find particular information.

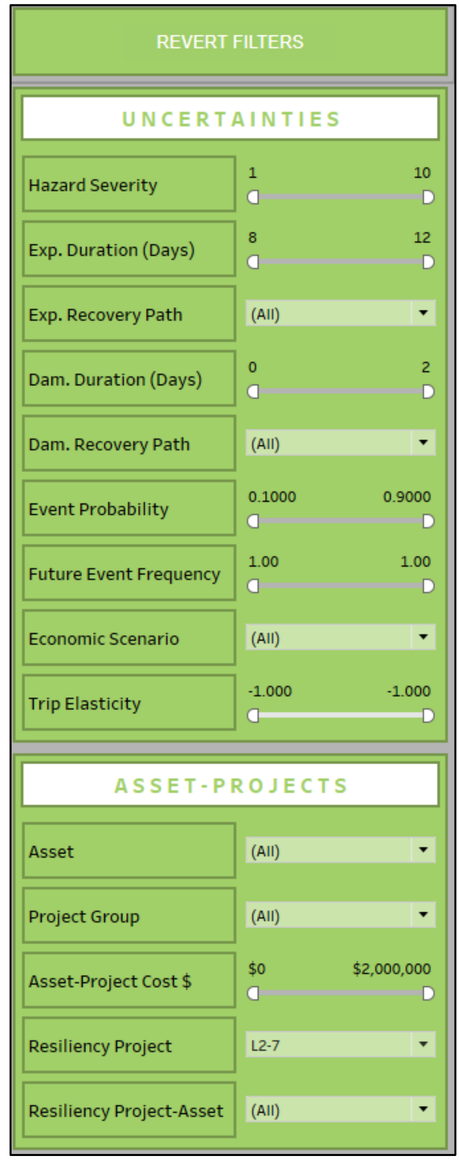

Figure 7-1: Tableau Workbook Dashboard Filter Panel.

Resilience and Disaster Recovery
Dashboard

The Overview of Scenario Regret and Net Benefits Ranking by Project.

Project	Rank Overall Regret	Average Net Benefits or Breakeven	Coef. of Variation Net Benefits or Breakeven	Average Benefit Cost Ratio	Coef. of Variation Benefit Cost Ratio
L2-7	1	$11.45M	0.99	6.72	0.84
L8-9_comp	2	$2.89M	0.28	4.85	0.23
L8-9_part	3	$628.71K	2.15	3.51	1.54
no	4	$0.00			

Figure 7-2: The Overview Dashboard in the RDR Tableau Visualization Workbook (Example from RDR Quick Start 1)

The Summary Dashboard provides the high-level BCA and BCA-U/Regret information for all of the resilience projects considered in the analysis. A single table lists each project by the Ranking of Regret over all of the scenarios as well as the mean of net benefits and BCR, coefficient of variation of net benefits and BCR, across all scenarios and ranked by the total regret score.

The example Overview dashboard shown in Figure 7-2 shows the results from RDR Quick Start 1.

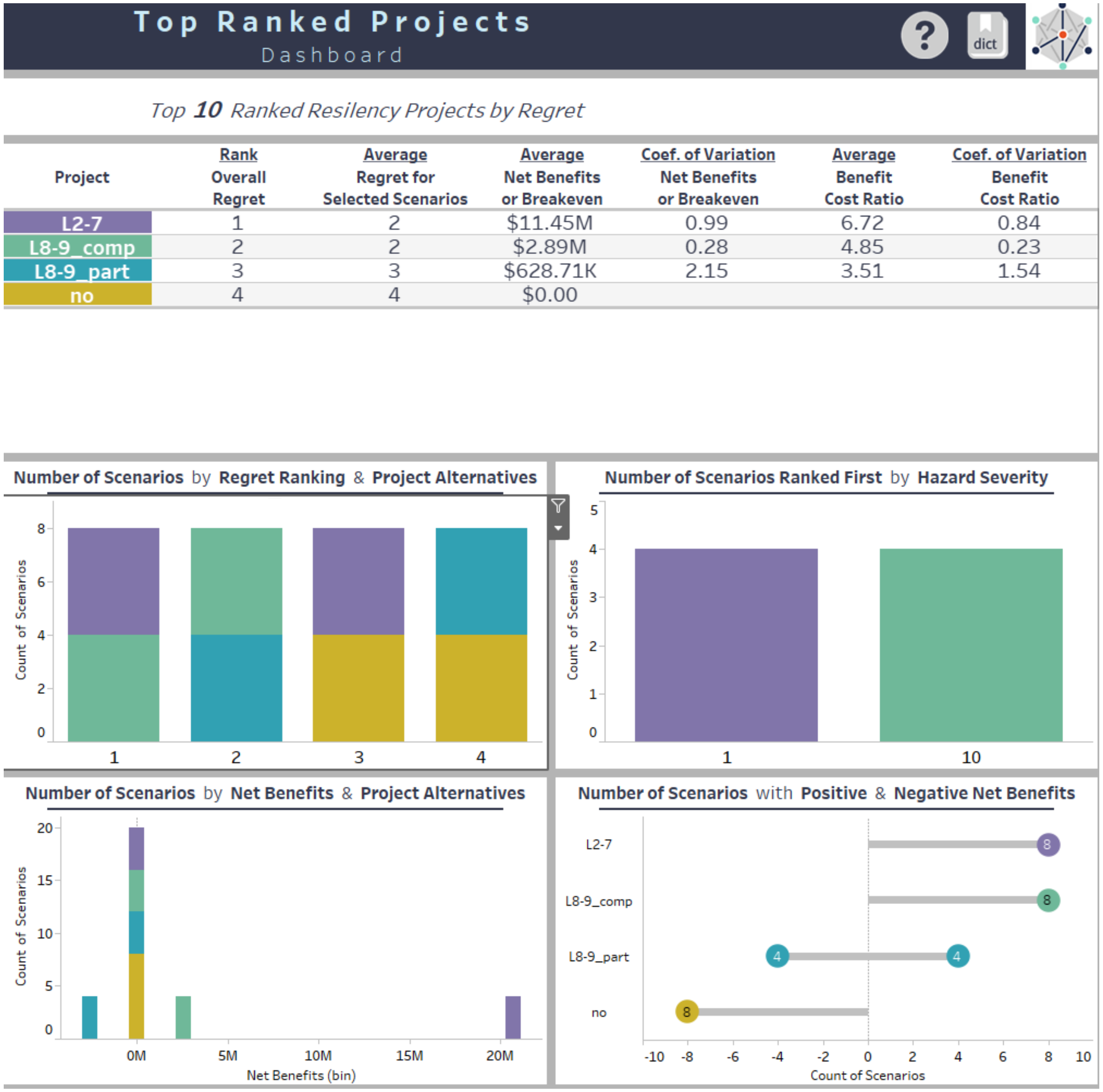

Figure 7-3: The Top Ranked Dashboard in the RDR Tableau Visualization Workbook (Example from RDR Quick Start 1)

The Top Ranked Dashboard, shown in Figure 7-3, provides summary information for the highest ranked projects in the analysis based on the BCA and BCA-U/Regret information. The analyst can select whether to see the top 5, 10, 15, or 20 projects.

The dashboard has five components:

- Summary Table: shows the regret rank, mean of net benefits and BCR, coefficient of variation of net benefits and BCR, across all scenarios and ranked by the total regret score.
- Number of Scenarios by Regret Ranking & Project Alternatives: stacked bar chart shows the number of scenarios in which the projects have a given regret ranking.
- Number of Scenarios Ranked First by Hazard Severity: stacked bar chart shows the number of scenarios in which a project is top ranked by hazard severity.
- Number of Scenarios by Net Benefits & Project Alternatives: stacked histogram shows the count of scenarios by net benefits for each project.
- Number of Scenarios with Positive & Negative Net Benefits: lollipop graph shows the number of scenarios for each project where there were positive and negative net benefits.

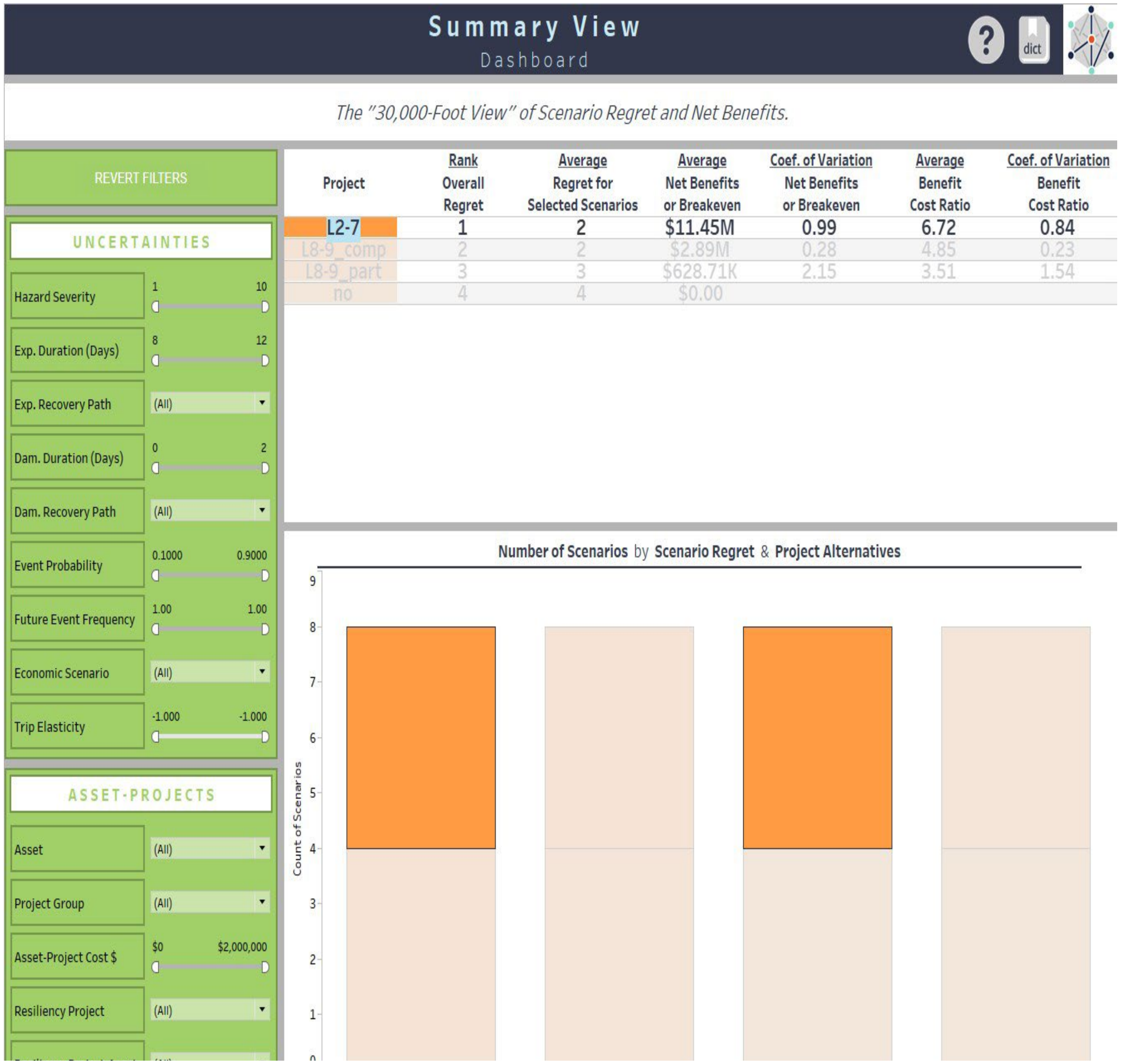

Figure 7-4: The Summary Dashboard in the RDR Tableau Visualization Workbook (Example from RDR Quick Start 1)

The Summary Dashboard, shown in Figure 7-4, shows detailed ranking information for each project. The major components of this dashboard are:

- Summary Table: shows the regret rank, mean of net benefits and BCR, coefficient of variation of net benefits and BCR, across all scenarios and ranked by the total regret score
- Number of Scenarios by Regret Ranking & Project Alternatives: stacked bar chart shows the number of scenarios in which the projects have a given regret ranking. Clicking on each project in the summary table on this dashboard shows the count of scenarios in which the project was ranked for each ranking. This graphic is very helpful for understanding the distribution of rankings by scenario for each project.

Figure 7-5: The Asset-Project Dashboard in the RDR Tableau Visualization Workbook (Example from RDR Quick Start 1)

The Asset-Project Dashboard, shows detailed information about the performance of a single project across the analysis scenarios. The major components of this dashboard are:

- Summary Boxes: show the high-level BCA and BCA-U/Regret results for the given asset.
- Scatterplot: shows the results of each scenario where each dot is a single scenario result. The analyst can select the axis variables using the X-, Y- and Z-axis dropdowns. The Z-axis is represented by the color shade where higher values are darker.
- Repair Cost Savings by Hazard Severity: box and whisker plot shows the variation in total repair cost savings across scenarios by the severity and duration of the hazard.
- Total Exp. Benefits by Hazard Severity: box and whisker plot shows the variation in the in the total exposure period benefits across scenarios by the severity and duration of the hazard.
- Total Dam. Benefits by Hazard Severity: box and whisker plot shows the variation in the total damage period benefits across scenarios by the severity and duration of the hazard.
- Severity-Duration Matrix: matrix bar chart shows the sum of net benefits across scenarios by the severity and duration of the hazard.

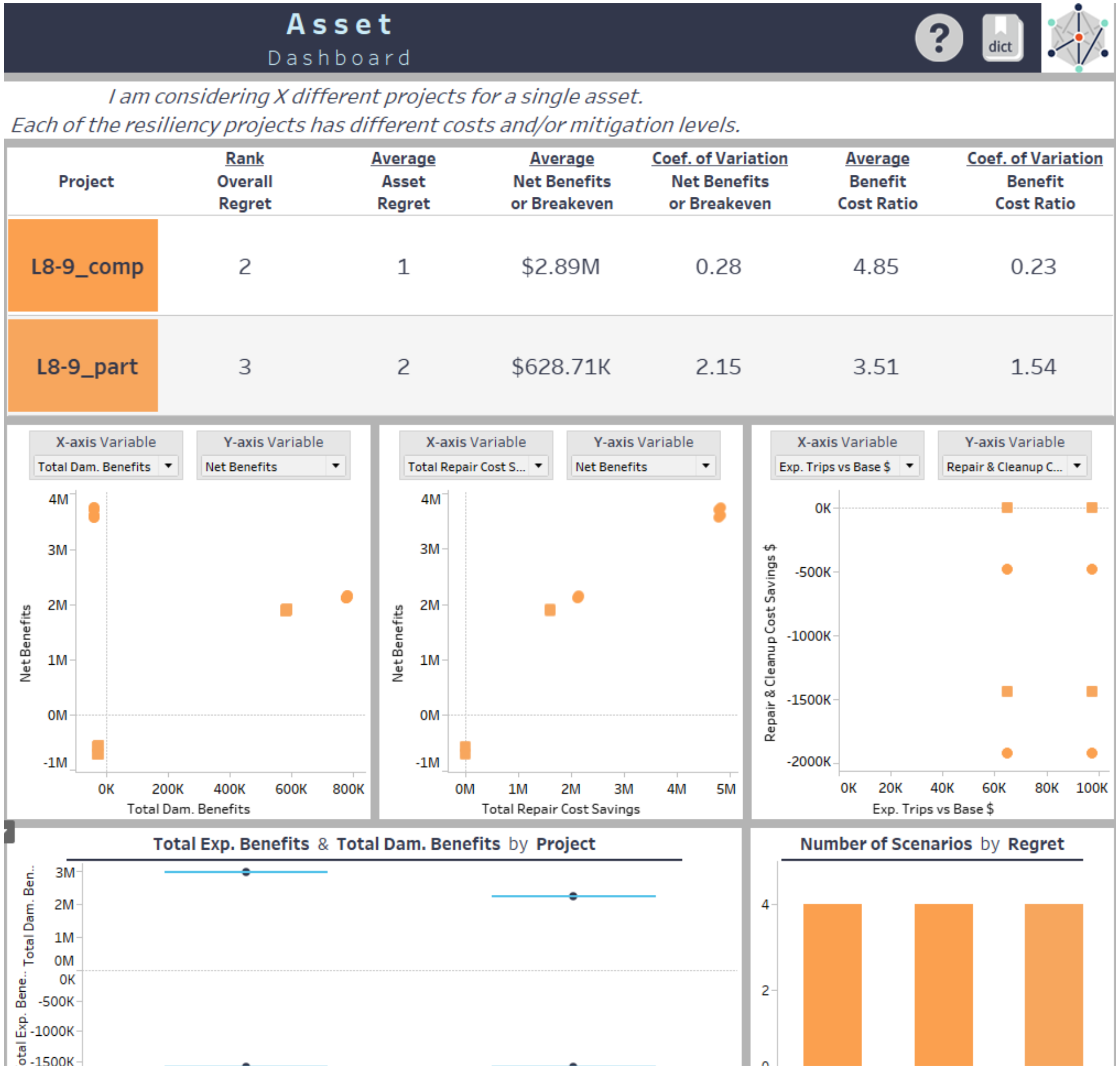

Figure 7-6: The Asset Dashboard in the RDR Tableau Visualization Workbook (Example from RDR Quick Start 1)

The Asset Dashboard focuses on comparing the alternative resilience projects for a given roadway asset. The components of the dashboard include:

- Summary table: shows the high-level BCA and BCA-U/Regret results for all projects that have been tested for a given asset, including bar charts for the mean total benefits discounted for the exposure period, the damage period, and the repair cost savings.
- Scatterplots: There are three scatterplots for which X- and Y-axes variables can the independently selected using the dropdowns. The projects are identified by unique color and shape values, each instance of which represents a different scenario. The multiple scatterplots allow exploration of the relationships between variables across the scenarios. For example, to explore how VHT, VMT, and Trips are correlated across hazard severity, by setting the X-axis for three plots to hazard severity and the Y-axes of those plots to VHT, VMT, and Trips.
- Result Table: shows the scenario factors for the selected scenarios.
-

Figure 7-7: The Exploratory Dashboard in the RDR Tableau Visualization Workbook (Example from RDR Quick Start 1)

The Exploratory dashboard allows the analyst to explore all of the projects and scenarios. There are two main components of this dashboard.

- Scatterplots: There are four scatterplots for which X- and Y-axes variables can be independently selected using the dropdowns. The projects are identified by unique color and shape values, each instance of which represents a different scenario. The multiple scatterplots allow exploration of the relationships between variables across the scenarios. For example, to explore how VHT, VMT, and Trips are correlated across hazard severity, by setting the X-axis for three plots to hazard severity and the Y-axes of those plots to VHT, VMT, and Trips.
- Ranking Column: This feature shows the ranking of projects across all of the scenarios selected. Select alternative ranking metric using the dropdown. The ranking measures include Regret All Scenarios, Mean Regret Scenarios, Net Benefits, and BCR.

8 RDR Tool Suite Pilot Testing

As part of the development for public release, the RDR Tool Suite was pilot tested with agency partners from:

1) The Hampton Roads Transportation Planning Organization (HRTPO), Hampton Roads Planning District Commission (HRPDC)
2) The Hillsborough Transportation Planning Organization
3) Houston-Galveston Area Commission (H-GAC)

The Hampton Roads partnership occurred in two phases: first, execution of preliminary analyses by the RDR Tool Suite developers to test functionality and validate the performance of the AequilibraE core model; and second, technology transfer/deployment to the HRTPO and HRPDC teams for in-house testing. The Hampton Roads partners tested the Exposure Analysis Tool as well as the main RDR Tool Suite.

The Hillsborough and H-GAC pilots focused on technology transfer and deployment of an initial version of the RDR Tool Suite for agency in-house testing and focused on the main RDR Tool Suite.

The pilot partners provided input on documentation, technology transfer, and tool usability. In addition, the RDR Tool Suite development team worked closely with the pilot partners to troubleshoot analyses. The input gained from the pilot partners during the testing led to a greatly improved initial public version of the RDR Tool Suite.

9 Limitations and Caveats

The following are known limitations and caveats to the current version of the RDR Tool Suite described in this documentation. These limitations also inform the following section on future enhancements.

1) Scenario Definition
    a. The RDR Tool Suite was developed to be hazard agnostic. However, only flooding inundation has been tested in detail in the tool suite. Therefore, the analyst is advised to exercise care in applying the tool to other hazards.
    b. The RDR Tool Suite is focused on temporary hazard events, with the assumption that network performance returns completely to the baseline after the exposure recovery and repair recovery periods. Although the decision could be made to not rebuild a damaged facility, analyzing the permanent impacts of such a decision is out of scope for the tool suite.
    c. Because only one resilience investment can be specified in a scenario, the effects of resilience investments are considered additively. Interactions between multiple resilience investments and their combined effect on the network are not considered. To model these interactions with the tool suite, the user can create a new resilience project combining the multiple resilience investments.
2) Exposure
    a. The automated RDR exposure tool provides a simple screening level method for assessing the intersection of a hazard with transportation assets. However, the assessment of potentially exposed assets should be reviewed carefully to determine if asset data (e.g., elevation for flooding) are accurately represented in the network dataset. For flood exposure, particularly care should be exercised to review bridge and tunnel elevation data.
    b. Projects that will add links to the transportation network will not be represented in the exposure analysis unless manually added, with appropriate attributes, to the network.
    c. See the User Guide for additional limitations to the RDR Exposure Analysis Tool.
3) Disruption
    a. The current RDR Tool Suite allows multiple functions to be used to define disruption based on exposure extent. The default relationship in RDRM is specific to flooding and should not be used for other hazards.
4) Damage Repair Cost and Time
    a. The current RDR Tool Suite allows for repair costs and repair times to be provided by the analyst, or for the analyst to rely on the default look-up tables. Repair costs and times are based on asset type (e.g., roadway, bridge, etc.) and further subcategories (e.g., functional class for roadways, length for bridges, etc.). Default values in the RDR Tool Suite for the potential time of repair were provided by VDOT and may not be applicable to all agencies. The analyst should use agency-specific estimates whenever possible.
    b. The damage module for the RDR Tool Suite considers repair costs and repair times independently. Agency choice of the trade-off between repair cost and repair time can be adjusted through use of analyst-provided look-up tables, but evaluation of the trade-off between repair cost and repair time is not within the scope of the tool.
    c. The RDR Tool Suite currently does not have a mechanism for addressing asset hardening that does not change disruption but does change the need for repair afterwards.
5) Metamodel

   a. The metamodel attempts to predict the effect of resilience investments on performance metrics (e.g., trips, PMT, PHT) for the entire transportation network being modeled. In cases where the resilience investment spans only a few links in a large regional network, the magnitude of the effect can be very small, which can affect the accuracy of the metamodel. In particular, when compared to the effects of other variables (e.g., hazard severity, economic scenario), the effect of a resilience investment may be statistically insignificant and lead to unreliable predictions being propagated through the ROI analysis.
   b. Relatedly, the extrapolation of metamodel outputs in the ROI analysis to calculate economic benefits across the full analysis period can lead to large levels of uncertainty in the data reported. This is particularly true at the extremes (high performing and low performing projects) for the linear regression models, as they are unbounded. Model evaluation of the RDRM regression model should be done in conjunction with analysis using the Tableau dashboards.
   c. The metamodel coefficients and outputs are highly sensitive to both the number of samples used to fit the model and the model structure of the regression. Sensitivity analysis around these metamodel parameters should be conducted.

6) Recovery modeling
   a. The model for building out exposure recovery paths is currently limited to recession stages of equal length, given by the parameter setting “stage_length_method” = ‘Equal’ in the configuration file.
   b. The RDR Tool Suite uses a fixed approach to approximate network impacts of partial asset repair during the repair recovery period, which cannot be set by the analyst.
   c. Hazard recovery and damage recovery models are independent. There may be a relationship between these sections that could be important to model (e.g., longer storms require longer repair).
7) Risk in Underestimating Damage
   a. When conducting this type of analysis there is a risk of underestimating damage because it is not possible to capture all of the complexities of synergistic interactions, such as between sea level rise, storm surge, and increased precipitation or high heat and wildfire. The combined impact of scenarios that create multiple hazard factors would potentially be far greater than any one factor alone. However, the variability and uncertainty of those interactions make it very challenging to analyze those interactions. Therefore, most agencies focus on tractable exposure analyses that are accurate, but they should recognize the potential to underestimate damage.
   b. The tool currently allows a user to prioritize projects based on the potential impact of a single hazard type. However, resilience investments are typically designed to mitigating the risk of a single hazard type, rather than providing some general kind of hazard mitigation. The tool does not yet allow a user to compare the benefits of mitigating different kinds of hazards.
8) Economic valuation
   a. There are benefits that have not been included in the tool that are proper for the ROI approaches, including noise and travel time reliability. Future development of the tool may be able to address these shortcomings.

   b. The current version of the tool does not consider the pre-hazard condition of the asset and the repair does not impact the underlying lifespan of the asset. Future development of the tool may be able to address these shortcomings.

9) Equity Considerations
   a. The tool does not allow an analyst to determine which communities or groups will be impacted or by what degree they will be impacted by the deployment of a resilience investment relative to the baseline condition. The tool also does not provide a baseline equity assessment of which communities or groups would be most impacted negatively by a hazard event.

10 Conclusion

The existing approach for transportation investment analysis using standard TDMs does not integrate the potential for hazard events to disrupt and damage transportation assets. Nor does the current method evaluate the benefit of mitigating those impacts by investing in hazard resilient projects. This technical document describes both the conceptual background of robust decision making as a way to make decisions under highly uncertain conditions (e.g., future projections) and describes the technical details of the RDR Tool Suite and methodology that applies this approach to evaluating infrastructure resilience investment ROI.

The RDR Tool Suite described in this document enables MPOs and state DOTs to evaluate resilience ROI across a range of future scenarios and hazard conditions as part of their project prioritization process, an approach that builds on previously available resources and methodology.

The RDR Tool Suite complements existing federal and other resources[64] in providing additional background, considerations, and guidance in preparation for changes in the condition of transportation assets due to external factors. The approach is intended to be location and hazard agnostic, such that any state DOT or MPO can utilize it.

The RDR Tool Suite can be accessed at: https://volpeusdot.github.io/RDR-Public.

[64] Including the NCHRP 20-101: Extreme Weather and Climate Change: Guidelines to Incorporate Costs and Benefits of Adaptation Measures, Federal Highway Administration (FHWA) tools and resources including the Vulnerability Assessment and Adaptation Framework and U.S. Department of Transportation (USDOT) BUILD Grant guidance.

Appendix A: Flow Diagram

A SIPOC (**S**uppliers, **I**nputs, **P**rocesses, **O**utputs, **C**ustomers) diagram[65] is a table that describes the functions of a model or tool, focusing on source ("supplier"), inputs, processes, outputs, and end destinations ("customers") of each function in the tool. It is a useful construct for mapping out the relationship among modules of the RDR Tool Suite. The adapted SIPOC diagram below maps out the RDR Tool Suite component functions, inputs, outputs, and destinations for each function.

RDR Tool Suite component	Process or step name	Who supplies the process inputs?	What inputs are required?	What are the major steps in the process?	What are the process outputs?	Who receives the outputs?
Scenario Analysis Framework	Tool setup	User	Configuration file. Model parameters input file. TDM futures (socioeconomic). TDM network. Future infrastructure projects. Future resilience projects.	Define matrix of hazard scenarios, TDM futures, resilience projects, recovery stages to be modeled.	Full list of scenarios output by uncertainty scenario builder (full_combos.csv).	Latin Hypercube Scenario Sampling, Metamodel Regression.
Disruption	'calc_link_availability' method in 'aeq_run' module	Exposure Analysis Tool	Exposure severity on true shapes network.	Exposure Analysis Tool and RDRM: Modify TDM network capacity based on exposure (asset level).	Modified TDM network with updated link availability (disruption) (asset/segment level).	GIS mapping, Core Models, RDRM.
Disruption	'calc_link_availability' method in 'aeq_run' module	Disruption analysis submodule	Modified TDM network. Resilience project locations and mitigation extent.	Exposure Analysis Tool and RDRM: Modify TDM network capacity based on resilience investment mitigation (asset-project level).	Modified TDM network with updated link availability (resilience) (asset/segment level).	GIS mapping, Core Models, RDRM.

65 https://www.isixsigma.com/tools-templates/sipoc-copis/sipoc-diagram/

RDR Tool Suite component	Process or step name	Who supplies the process inputs?	What inputs are required?	What are the major steps in the process?	What are the process outputs?	Who receives the outputs?
Damage	'recov_init' module	Exposure Analysis Tool and User (optional tables for damage, repair cost, and repair time)	Exposure severity on true shapes network. TDM network. Future resilience projects.	Damage and Repair analysis: Translate true shapes network exposure to repair cost and repair time (asset-project level).	Cost of repair and minimum time to repair (asset/segment level).	Metamodel Recovery, ROI Analysis Module.
Damage	'recov_init' module	Exposure Analysis Tool and User (optional tables for damage, repair cost, and repair time)	Exposure severity on true shapes network. TDM network. Future resilience projects.	Damage and Repair analysis: Recalculate repair cost and repair time based on resilience investment mitigation (asset-project level).	Cost of repair and minimum time to repair (asset/segment level).	Metamodel Recovery, ROI Analysis Module.
Core Model	'lhs' module	Scenario Analysis Framework	Matrix of scenarios/futures to be analyzed.	Latin hypercube sampling to identify Core Model runs to be performed.	List of scenarios to be analyzed in Core Models by TDM or AequilibraE.	Core Models.
Core Model	'create_network_link_csv' method in 'aeq_run' module	Scenario Analysis Framework, Exposure Analysis Tool, and User	Modified TDM network (disruption, resilience) (asset/segment level). SQLite database of network.	Network Prep for AequilibraE: Convert baseline, disruption, and resilience mitigation scenarios to AequilibraE input files.	Modified SQLite database of network, directory for AequilibraE run.	Core Models.
Core Model	'aeq_run' module	Latin hypercube sampling, and User (selection of TDM vs. AequlibraE runs), Scenario Analysis Framework	Modified SQLite database of network. Demand OMX files.	AequilibraE: Perform runs for disruption and resilience scenarios (project level).	PHT, PMT, trips for AequilibraE scenarios.	Metamodel Regression.

RDR Tool Suite component	Process or step name	Who supplies the process inputs?	What inputs are required?	What are the major steps in the process?	What are the process outputs?	Who receives the outputs?
Metamodel Regression	'rr' module	TDM, AequilibraE, Scenario Analysis Framework	TDM Trips, Hours, Miles. AequilibraE Trips, Hours, Miles. Full list of scenarios.	Fit and evaluate regression model for all scenarios.	PHT, PMT, trips for full matrix of scenarios.	ROI Analysis Module.
Metamodel Recovery	'recov_init' module	User, and Damage and Repair analysis	Configuration file. User inputs file. Model parameters input file. Time to repair (asset/segment level).	RDRM: Build out recovery modeling for uncertainty scenarios based on hazard event and repair time.	Full list of scenarios under different recovery paths (extended_scenarios.csv).	ROI Analysis Module.
ROI Analysis Module	'recov_calc' module	Scenario Analysis Framework, Metamodel Regression, Metamodel Recovery, Damage and Repair analysis	Regression PHT, PMT, Trips (full matrix of scenarios). Cost of repair and minimum time to repair (asset/segment level). Recovery paths (extended_scenarios.csv).	RDRM: Combine metamodel outputs with recovery module outputs to generate results for scenarios on VMT, PHT, trips. Interpolate across entire period of analysis.	Tableau report xlsx file of economic performance metrics (BCA, BCA-U/Regret) for scenarios under different recovery regimes.	Data Visualization.
Data Visualization		RDR ROI Analysis Module	Tableau report xlsx file.	Tableau Dashboard: Rank and filter results. Project prioritization.	Dashboard outputs.	User.

Appendix B: Verification and Validation of the RDR Tool Suite

Alternative Core Model: AequilibraE model validation

This appendix briefly describes the validation performed during the Phase 1 pilot with Hampton Roads. Before the RDR Tool Suite analysis was conducted, the AequilibraE model was validated for the Hampton Roads, Virginia network. Using 2017 trip tables and network, the results of the AequilibraE routing run, and the all day network, flows for the core model were compared to average daily traffic counts on approximately 4000 one-way (2000 two-way) links in the region. The results matched the counts nearly as well as those from the Hampton Roads TDM. One would not expect the results to be the same, due to the following simplifications employed in the fast AequilibraE model:

1. The AequilibraE model uses person trips for a generic peak hour. To compare these to vehicle trips, two adjustments needed to be made:
    - Generic peak hour to daily trips, using a factor of 13.4 (from the HRTPO model documentation).[66] With this adjustment, the total number of trips match the total number of daily trips from the person trip tables.
    - Daily person trips to daily vehicle trips, dividing by a vehicle occupancy factor. The factor is chosen so that the sum of the daily vehicle volumes outbound from the centroids (on centroid connectors) is equal in the HTRPO output and the AequilibraE output. The occupancy factor thus calculated ranges from 1.13 (2017) to 1.3 (2045).

2. The trip tables also do not include truck trips and external trips. The breakdown of trip types from the HRTPO model, on outbound links from internal and external centroids, is as follows:

Table B-0-1 Trip Table from HRTPO model

Trip Type	Daily Trips	Comment
TRUCK24	83195	Truck trips, not in the AequilibraE model
HBW24	1361038	Trips that are in the AequilbraE model
HBO24	2620950	
NHB24	1537838	
VISITOR24	0	No visitor trips were included in model
EIIE24	228760	External trips, not in the AequilibraE model
EE24	10108	

3. For this pilot, AequilibraE is not using a mode choice model, and is thus not explicitly considering transit trips. Transit trips are a small proportion of overall trips in the region (58612 daily transit trips as reported in table 2.19 of the HRTPO version 2 methodology report).
4. The routing uses a generic peak hour for the entire day, rather than the 4 time periods used in the HRTPO model.

[66] The factor 13.4 is the ratio of peak hour trips to all day trips in the HRTPO model.

5. Finally, AequilibraE uses BPR volume/delay functions, while the HRTPO model uses a conical function. For the pilot, the BPR parameters used in AequilibraE were adjusted to produce volume/delay results close to those from the conical function as seen in Table B-2).

Table B-0-2 Volume Delay Function Parameters Used in Hampton Roads Pilot

Functional Class	Conical Alpha	Conical Beta	BPR Alpha	BPR Beta
Freeway	9	1.06	0.83	5.5
Minor freeway/principal arterial	7	1.08	1	4
Major/Minor Arterials, Major Collectors	4.5	1.14	1	3
Minor Collectors/Locals	2	1.5	1	2

To check the reasonableness of model results the following comparisons of daily link flows were performed (Table B-3).

Table B-0-3 Checks for Reasonableness of Model Results

AequilibraE model	HRTPO core model	Traffic counts
Group 8 – 2045, person trips	Group 8 – 2045, allday, vehicle trips	N/A
NoBuild Network 2017, person trips	NoBuild Network – 2017, allday, vehicle trips	Recent counts from several thousand links, as reported in the Loaded network tables

The evaluation assessed differences between the RDRM model results and the expected outcomes. The validation identified tolling as one factor that had not been addressed sufficiently and was driving differences between the AequilibraE runs and the HRTPO data. The tolling function was added to the AequilibraE analysis and resulted in improved matching between this alternative core model and the real-world results.

The validation of the model with the Hampton Roads pilot demonstrated that the analyst should investigate the effects of the resilience projects at the network level in the model evaluation. The network-wide aggregate effect of each project is small. Consider, for example, the number of trips made with or without resilience investment 2045-122. Figure B-0-1 shows the numbers of trips at each of 7 stages of recovery (numbered 0 through 6) for three hazards:

- The pair of lines for the 100-year flood show a difference for the earlier recovery stages: more trips are possible with the resilience investment.
- The other two pairs of lines, for the 10-year and 0-year floods, overlay each other: they show little system-wide difference in the number of trips possible.

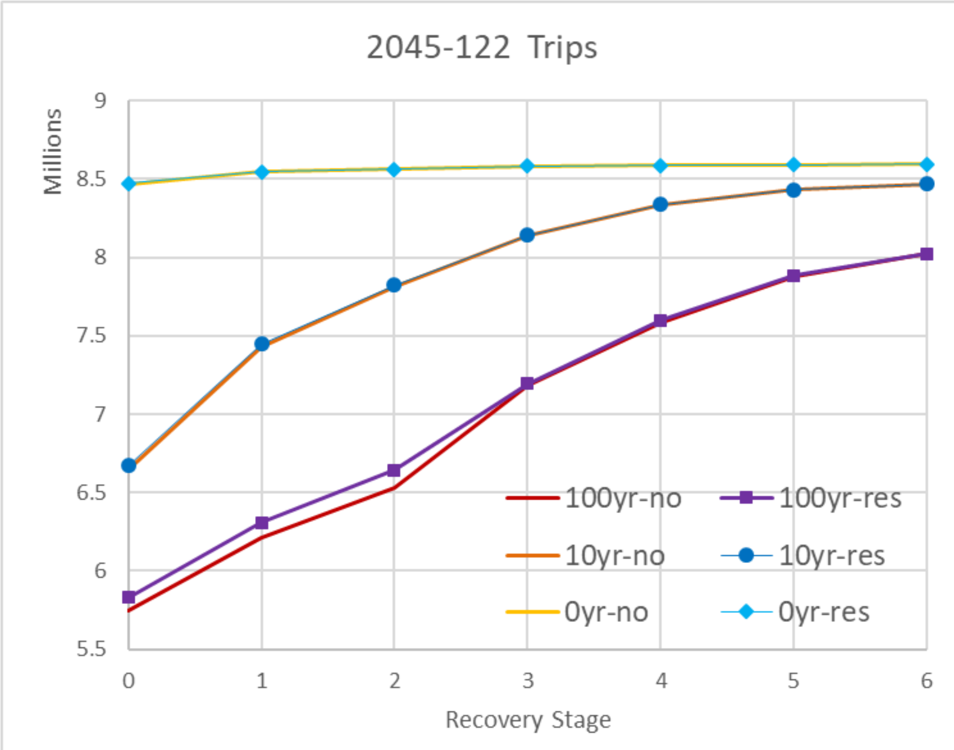

Figure B-0-1 Trips with or without resilience project 2045-122

In the future, to address the issue of small effects, it may be best to focus on origin-destination (O-D) skims, to show that while many O-D pairs will not be affected by the investment, some O-D pairs will see a significant difference in trips, PMT, and PHT. Breaking the analysis out by O-D pair will also aid with equity analysis, as each travel zone has known demographic characteristics.

A linear regression model will have difficulty fitting statistically significant coefficients for the resilience projects if their individual effects on trips, PMT, and PHT are of the same order of magnitude as the variation observed in the AequilibraE modeling.

The analyst should consider conducting sensitivity analysis around the number of samples used to fit the regression model. The RDR team observed significant shifts in the regret rankings and total benefits as the regression model was fit on more AequilibraE core model runs. This variability in model outputs led to the decision to run all possible combinations with AequilibraE for the final Hampton Roads pilot analysis.

Furthermore, the analyst should consider the structure of their scenario space in determining if a regression model will be adequate in predicting trips, PMT, and PHT. For the Hampton Roads analysis, the large number of project groups and small number of resilience projects in each project group led to many no action baselines. The corresponding regression models were then overparameterized which led to overfitting on the small number of samples used for each regression model. In these cases of overfitting, the analyst should also consider implementing alternative specifications of the regression model but may need to consult economists or others with expertise in econometrics to determine the appropriate specification for their analysis.

These factors should be weighed in the analyst's decision for whether to rely on the regression model or to rely entirely on core model runs. The RDR team plans to further improve the regression model in the next phase of development to improve performance in a range of conditions. The tool suite still provides a useful ROI function if the analyst chooses to forgo the time savings of the regression model and instead runs a core model run for every scenario in the space.

Validating Results

This section describes the verification and validation of the RDR Tool Suite that has been undertaken thus far to ensure that the tool works as intended and provides appropriate results.

Verification tests whether a model executes the functions intended and whether it works correctly as written. Verification tests check that calculations are done correctly, that outputs match inputs appropriately, and that as tool functions are added these calculations are maintained and are consistent across multiple sample analyses.

Validation tests whether the model matches expected results overall. In the case of the RDR Tool Suite, validation includes assessing whether the results of the scenarios evaluated by the RDR Tool Suite are similar enough to TDM runs to be useful and can provide results for a multitude of scenarios more quickly than could be accomplished with TDM runs alone.

Verification Testing

The following table shows a set of unit and branch test logs that ensured the proper calculation of results by various components of the RDR Tool Suite.

Table B-0-4. Log of verification tests performed during development of RDR Tool Suite.

Date completed	Module(s) tested	Code version used	Requirement Tested	Outcome
10/26/2020	lhs (rdr_LHS.py)	2020_10_20_rdr_full_metamodel_run branch	Latin Hypercube Step correctly generates a full list of scenarios for multiple resilience projects	PASS
10/27/2020	lhs (rdr_LHS.R)	2020_10_20_rdr_full_metamodel_run branch	Latin Hypercube Step correctly selects a sample of 10 to 100 runs as specified by the user.	PASS
10/27/2020	aeq_run	2020_10_20_rdr_full_metamodel_run branch	AEquilibraE module correctly generates user equilibrium routing results for base network and disrupted network (with mini-equilibrium) for sample of 10 LHS runs. Execute multiple (3+) times with different samples to ensure consistent results.	PASS
10/29/2020	Aeq manual	2020_10_20_rdr_full_metamodel_run branch	Automated aeq_run module correctly produces the same results as manually running the Aeq module for each run specified in the LHS sample.	PASS
10/29-30/2020	regression_setup	2020_10_20_rdr_full_metamodel_run branch	Regression setup step correctly prepares outputs from aeq_run as needed to parameterize the regression model.	PASS
10/30/2020	recov_init	2020_08_11_recovery_modeling branch	Creates a set of scenarios for analysis for the projects identified among HR's megaprojects.	PASS
10/30/2020	recov_calc	2020_08_11_recovery_modeling branch	Pulls together results generated by prior modules and produces Tableau dashboard input file for the projects identified among HR's megaprojects.	PASS
11/4/2020	all modules	2020_08_11_recovery_modeling branch	RDR tool can be initiated by running a batch file and executes as expected from start to finish.	PASS
11/4/2020	analysis modules (recov_init and recov_calc)	2020_08_11_recovery_modeling branch	Confirm that entire analysis section of RDR Tool Suite can be run from start to finish using batch file while keeping regression fit fixed and produces the same outputs as the initial analysis run.	PASS
11/4/2020	lhs	2020_08_11_recovery_modeling branch	Unit test for basic functionality of Latin Hypercube R code on a second machine in RDR environment.	PASS

Date completed	Module(s) tested	Code version used	Requirement Tested	Outcome
11/4/2020	analysis modules (recov_init and recov_calc)	2020_08_11_recovery_modeling branch	Analysis section of RDR Tool Suite runs correctly using batch file with a subset of uncertainty parameters used for regression fit selected in UserInputs file.	PASS
11/4/2020	analysis modules (recov_init and recov_calc)	2020_08_11_recovery_modeling branch	Analysis section of RDR Tool Suite runs correctly using batch file with uncertainty parameters in UserInputs file not used to fit the regression.	PASS
11/5/2020	analysis modules (aeq_run)	design_test_aeq	Multiple scenario runs executed to confirm that results can be used to provide pairwise comparisons of resilience investments, recovery steps, and hazards.	PASS
1/14/2021	all modules	2021_01_08_quick_starts branch	Entire RDR Tool Suite runs from start to finish using batch file for Quick Start 1 on a scenario comprised of 2 resilience projects.	PASS
1/14/2021	analysis modules (recov_init and recov_calc)	2021_01_08_quick_starts branch	Entire analysis section of RDR Tool Suite runs using batch file for: a subset of uncertainty parameters (Quick Start 2 Example A), a different set of recovery parameters (Quick Start 2 Example B), and a different method for disruption-damage calculation (Quick Start 2 Example C). Same scenario as Quick Start 1 of 2 resilience projects.	PASS
1/14/2021	all modules	2021_01_08_quick_starts branch	Entire RDR Tool Suite runs from start to finish using batch file for Quick Start 3 on a scenario comprised of 3 resilience projects across 2 project groups.	PASS

Validation Testing

Two types of validation testing were performed. First, AequilibraE-modeled link flows were compared to link flows from the HRTPO core model. Where traffic counts were available, the 2017 modelled link flows were also compared to the traffic counts. The validation identified tolling as one factor that had not been addressed sufficiently and was driving differences between the AequlibraE runs and the HRTPO data. The tolling function was added to the AequlibraE analysis and resulted in good matching between this alternative core model and the real-world results. Note that due to the differences between the AequilibraE model and the HRTPO core model, discussed in section 5.2.2.3, one would not expect the results to be exactly the same.

Second, the regression module was validated by assessing the sign and magnitude of the resulting regression models against the expected values for hazards, recovery steps, and other inputs.

For example, Figure B-0-2 shows validation tests for the trips, miles, and hours extrapolated from the regression fit using HRTPO example data. For the example scenario shown, which was not used in the fitting of the regression model, the estimated trips, miles, and hours all increase with increasing recovery steps, in ways which are expected and reasonable. Additional validation tests included similar reasonableness test for resilience investments and hazard levels.

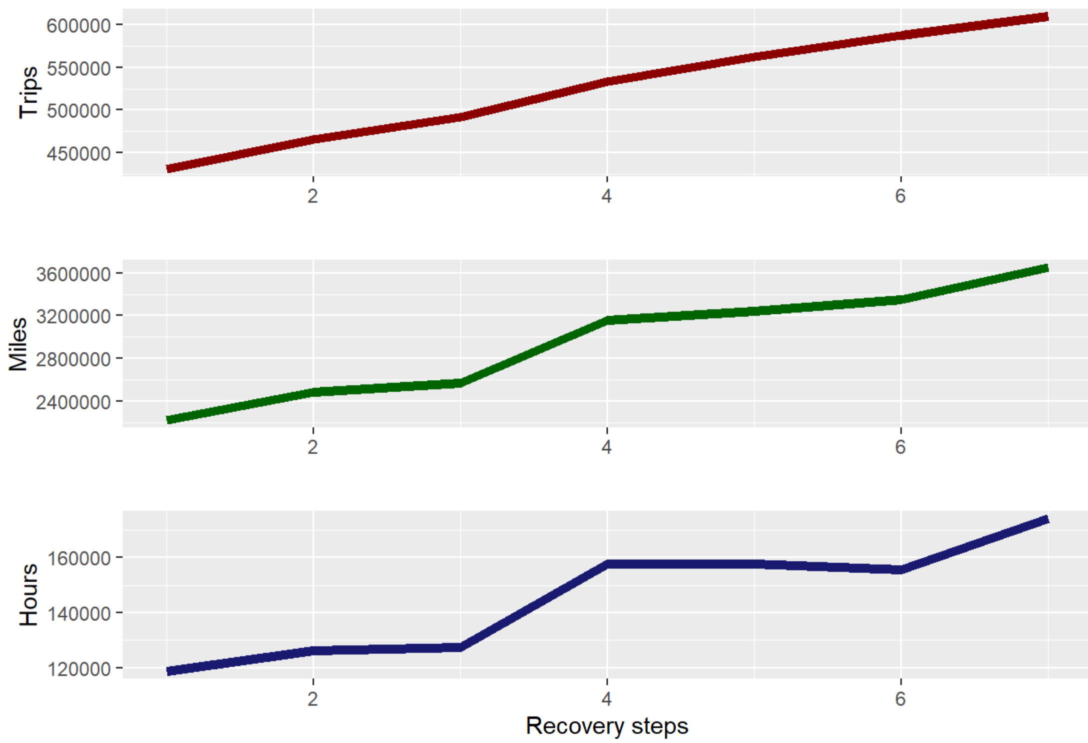

Figure B-0-2. Validation test for reasonable coefficients from the regression metamodel using HRTPO example data, for extrapolated trips, miles, and hours under a scenario not used in the fitting of the regression model across recovery.

Appendix C: Generalized Modeling Network Specification (GMNS) Network to AequilibraE Network Conversion

This appendix describes the node and link network attributes used by AequilibraE. RDR takes a CSV text file network (in GMNS format) and converts it to the SQLite tables used by AequilibraE. This material should not be needed by the end user but is documented to aid future RDR development.

Table C-0-1 Node specifications for GMNS and AequilibraE networks

GMNS Network	How to convert from GMNS to AequilibraE	AequilibraE network
node_id	Copied directly	ogc_fid and node_id
x_coord	Used only to show network in a GIS	
y_coord	Used only to show network in a GIS	
node_type	If node_type == "centroid", then is_centroid = 1, else is_centroid = 0	is_centroid

Table C-0-2 Link specifications for GMNS and AequilibraE networks

GMNS Network	How to convert from GMNS to AequilibraE	AequilibraE network
link_id	Copied directly	ogc_fid and link_id
from_node_id	Copied directly	a_node
to_node_id	Copied directly	b_node
directed	Copied directly	direction = 1
geometry	Used only to show network in a GIS	
length (miles)	Copied directly	distance (miles)
facility_type	Copied directly	link_type[67]
capacity (veh / day / lane)	Converted to a daily link capacity	capacity_ab (veh / day)
free_speed (mph)	Used to calculate free_flow_time	speed_ab (mph)
	$\frac{60\left(\frac{min}{hr}\right) * length(miles)}{free\_speed\ (mph)}$	free_flow_time (minutes)
lanes	Used to calculate capacity	
allowed_uses	For now, always set to AUTO	modes = 'c'
toll (cents)	Copied directly	toll (cents)
alpha	See RDR User Guide	alpha
beta	See RDR User Guide	beta

[67] Two link types are reserved in AequilibraE: centroid_connector and default.

Appendix D: Trip Loss Valuation

US DOT does not have a standard method for monetizing lost trips, e.g., trips that are foregone because the path is not traversable or if the trip time makes the trip infeasible. Instead of a fixed value for lost trips, the tool uses the economic theory concept of consumer surplus to value lost trips. The trip values are computed using the implied value of trips based on the trip elasticity value and the network equilibrium generated in the core model. Loss of consumer surplus represents an economic cost over and above the economic value of additional travel time and vehicle operating costs that occurs when trip that continue to be made become more circuitous or time-consuming.

This concept is demonstrated in Figure D-0-1 below. The supply curves are upward sloping and exhibit steep slopes, demonstrating the non-linear impact of congestion on trip price. The initial supply curve is that of the baseline scenario in which a hazard event occurs, but no resilience alternative has been deployed, S_0, while the supply curve S_1 exists when the resilience alternative has been deployed. The demand curve, D_0, is downward sloping and does not change between a baseline scenario and its associated alternative scenarios. The change in supply from S_0 to S_1 measures the impact of the resilience alternative relative to the baseline scenario, which enables an increase in the number of trips that can be taken in the event of a disruption from Q_0 to Q_1, while also reducing the cost (including the economic value of the time they require) of trips that would continue to have been taken during the disruption from P_0 to P_1. The economic value of the additional trips enabled by the investment in improved resilience is measured by the shaded area under the demand curve D_0 and above the supply curve S_1 between Q_0 and Q_1, which is a gain in consumer surplus.

Functionally, the trip valuation in the model is defined by the following equation:

$$Trip\ Valuation \coloneqq \frac{(P_0 - P_1) * (Q_1 - Q_0)}{2}$$

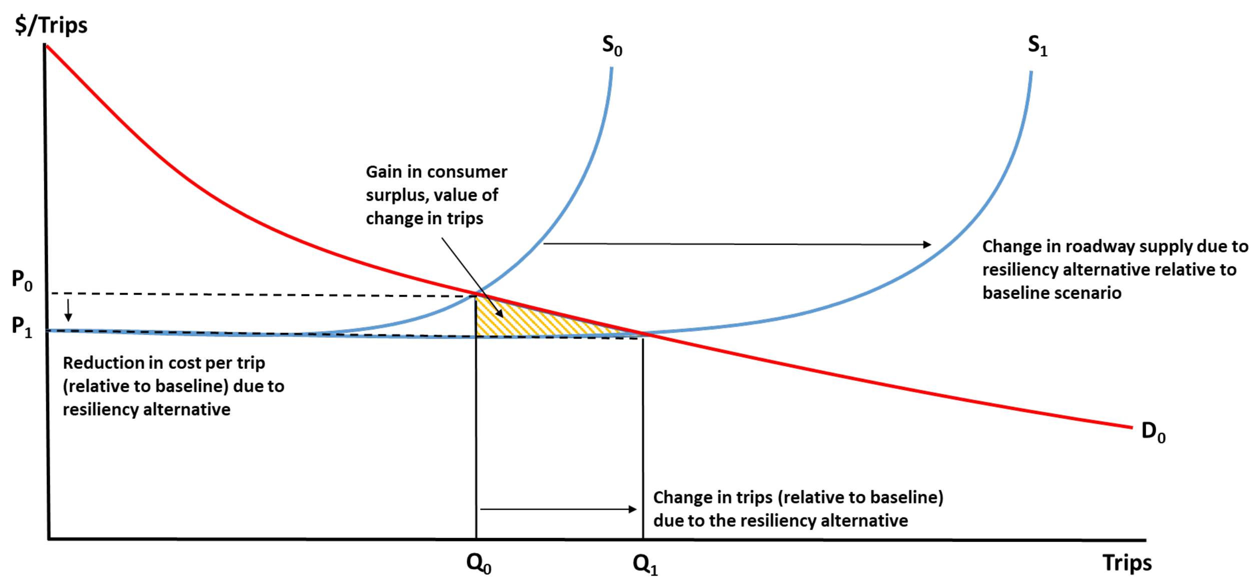

Figure D-0-1: Trip Valuation based on change in Consumer Surplus due to a given Resilience Investment

The consumer surplus valuation of lost trips is applied to both trips lost due to drivers choosing to not make the trip due to the increased travel time and trips lost on routes made impossible by the loss of links in the network. For impossible routes, the value of the trip is P_1 as P_0 is equal to 0 in the baseline representing that the consumer would be unwilling to pay any price for a trip that could not be made. Essentially, this approach values trips at their travel time under the conservative assumption that all trips are at least as valuable to make as the time it takes to make them.