The Resilience and Disaster Recovery Tool Suite

User Guide Version 2022.1

Volpe Project: OS20A121

Final Report — August 2022

VNTSC-OST-22-02

DOI: 10.21949/1527574

Prepared for:

United States Department of Transportation
Office of Research, Development, and Technology
Washington, D.C.

The Federal Highway Administration
Office of Natural Environment
Washington, D.C.

Recommended citation:

Jonathan Badgley, Daniel Flynn, Olivia Gillham, Michelle Gilmore, Kristin C. Lewis (Project Manager), Alexander Oberg, Gretchen Reese, Scott Smith, Kevin Zhang. The Resilience and Disaster Recovery Tool Suite: User Guide Version 2022.1. Volpe National Transportation Systems Center, Cambridge, MA, 2022. DOI: 10.21949/1527574

Notice

REPORT DOCUMENTATION PAGE			*Form Approved* *OMB No. 0704-0188*
Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302, and to the Office of Management and Budget, Paperwork Reduction Project (0704-0188), Washington, DC 20503.			
1. AGENCY USE ONLY (Leave blank)	2. REPORT DATE August 2022		3. REPORT TYPE AND DATES COVERED Report (6/2021-8/2022)
4. TITLE AND SUBTITLE The Resilience and Disaster Recovery Tool Suite: User Guide Version 2022.1			5a. FUNDING NUMBERS OS20A121
6. AUTHOR(S) Jonathan Badgley, Daniel Flynn, Olivia Gillham, Michelle Gilmore, Kristin C. Lewis (Project Manager), Alexander Oberg, Gretchen Reese, Scott Smith, Kevin Zhang			5b. CONTRACT NUMBER 693JK421NT800008
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) U.S. Department of Transportation John A Volpe National Transportation Systems Center 55 Broadway, Cambridge, MA 02142-1093			8. PERFORMING ORGANIZATION REPORT NUMBER VNTSC-OST-22-02
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) US Dept. of Transportation Office of Research, Development and Technology 1200 New Jersey Ave, SE, Washington, DC 20590			10. SPONSORING/MONITORING AGENCY REPORT NUMBER DOI: 10.21949/1527574
11. SUPPLEMENTARY NOTES			
12a. DISTRIBUTION/AVAILABILITY STATEMENT This document is available to the public at https://volpeusdot.github.io/RDR-Public.			12b. DISTRIBUTION CODE
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 User Guide provides users with information on how to run the RDR Tool Suite and its components. It is complemented by the RDR Tool Suite Technical Document, Quick Start Tutorial, and Run Checklist.			
14. SUBJECT TERMS			15. NUMBER OF PAGES 79
			16. PRICE CODE
17. SECURITY CLASSIFICATION OF REPORT Unclassified	18. SECURITY CLASSIFICATION OF THIS PAGE Unclassified	19. SECURITY CLASSIFICATION OF ABSTRACT Unclassified	20. LIMITATION OF ABSTRACT Unlimited

NSN 7540-01-280-5500

Standard Form 298 (Rev. 2-89)

Prescribed by ANSI Std. 239-18

298-102

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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 for transportation disruption and mitigation 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] that build on current travel demand modeling (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 Analysis and Modeling Tool (TMIP-EMAT), 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.

The user guide provides a step-by-step instruction for running the RDR Tool Suite, from installing software to interpreting the results of the analysis.

[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.

1 Introduction

The RDR Tool Suite allows agencies to estimate performance under a broad array of hazard conditions and recovery patterns. There are three main components to the tool suite structure as shown in Figure 1-1. The RDR Exposure Analysis Tool is an optional, standalone GIS-based tool for automating the process of assessing disruption to a road network based on exposure to a hazard. The RDR Metamodel (RDRM) takes the performance metrics results from a TDM, including number of trips, vehicle miles traveled (VMT), and vehicle hours traveled (VHT), and performs complementary disruption analyses (taking hazard exposure data that can be generated by the RDR Exposure Analysis Tool) using an open-source routing model called AequilibraE as an alternative core model. The RDRM then performs regressions and iterative scenario expansion to estimate the change in trips, 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 inferring how many trips will be made, their mileage, and the time of those trips in an equilibrium state from sampled core model runs. The RDRM calculates the impact of a resilience investment, measured by changes in system performance when the investment is deployed versus a baseline disruption scenario in which the project and project alternatives are not deployed.

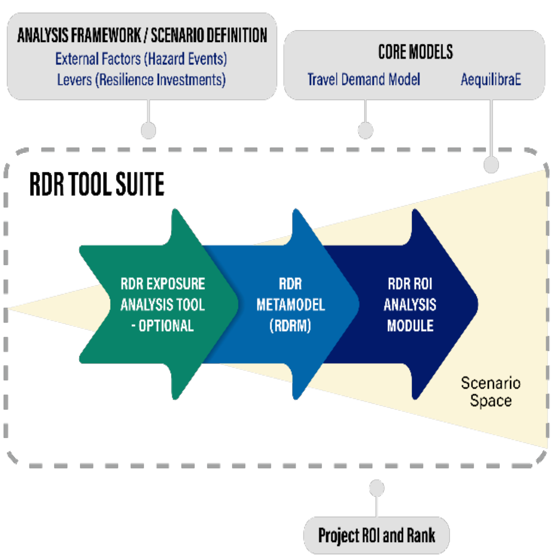


Figure 1-1: Structure of the RDR Tool Suite. The scenario space increases as more potential hazard severities, durations, recovery periods, and resilience investments are assessed.

The RDR Return on Investment (ROI) Analysis Module calculates the net benefits of resilience investments by monetizing system performance metrics to estimate the economic impacts of disruption and the resilience investment. The module uses these performance metrics to calculate annual costs associated with a range of recovery patterns. The RDR ROI Analysis Module also uses default or user-provided values for road and bridge cost of repair to estimate the cost of repair and cleanup associated with the exposure to the hazard from the RDRM. 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.

The RDR Tool Suite allows the user to explore a variety of problems using one or more of its components. A full run of the tool suite takes the user through the entire analysis, from building out the analysis framework of all possible future scenarios to calculating return on investment across a range of resilience projects. The user can also focus on more specific problems, either by running individual modules or adjusting a subset of input files. Below is a (non-comprehensive) list of potential use cases the RDR Tool Suite can help the user analyze:

- To assess which network assets are vulnerable under a given hazard condition, run the RDR Exposure Analysis Tool. Detailed documentation is provided in Appendix F: RDR Exposure Analysis Tool.
- To assess network effects of a hazard event, generate network-level performance metrics using the core model, with inputs detailed in Section 4.5.1.
- To estimate network-level performance metrics across a full range of possible futures from a set of core model runs, configure and fit the RDR regression model, as detailed in Section 4.6.1.
- To analyze a wider range of hazard recovery times but otherwise use the same scenario space, adjust the recovery module parameters in the configuration file and consider running an analysis run (Section 3.2).
- To build the RDR regression model on a larger set of core model runs, adjust the metamodel parameters in the configuration file, and consider running an additional run (Section 3.3).
- To adjust repair costs with updated numbers, create user-defined repair cost look-up tables, as detailed in Section 4.6.3.
- To switch from running a regret analysis, or a breakeven analysis, to a benefit-cost analysis, associate future hazard events with probabilities (see the model parameters file in Section 4.1.2) and provide resilience project costs (see the resilience project files in Section 4.7.2).
- To understand how to communicate resilience costs and benefits to an audience, refer to Section 5.

This User Guide for the Resilience and Disaster Recovery (RDR) Tool Suite enables a user to install the tool suite and execute analyses. A companion document, the RDR Technical Document, provides details on the structure and functions of the RDR Tool Suite. 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 and documentation are available on GitHub at https://volpeusdot.github.io/RDR-Public, along with test data for executing the Quick Start exercises.

2 RDR Setup Instructions

2.1 Software Requirements

Required software to run the RDR Tool Suite:

1. Conda dependency management system[3]
2. Python 3.7[4]
3. R 4.1.3[5]
4. Tableau Reader v. 2020.3 or later[6] or Tableau Desktop full version (any license level)
5. ArcGIS v 10.x or ArcGIS Pro (if using RDR Exposure Analysis Tool) (see Appendix F: RDR Exposure Analysis Tool).
6. The RDR Tool Suite

The RDR Tool Suite is written in Python 3.7 and R 4.1.3, and requires an installation of the dependency management system *conda*. For this installation, we recommend Anaconda or Miniconda,[7] which is a miniature version of Anaconda that only includes conda, its dependencies, and Python. Alternatively, if you already have installed other software (such as ArcGIS Pro) which uses a conda dependency management system, you are welcome to leverage that rather than install a standalone version of conda. Python will be installed with conda if using Anaconda or Miniconda and does not need to be installed separately by the user. R will be installed when setting up the RDR conda environment (Section 2.3) and does not need to be installed separately by the user.

2.2 Software Installation

The RDR Tool Suite can be downloaded from the RDR repository on GitHub (https://volpeusdot.github.io/RDR-Public). To download, follow the instructions in the "Installation and Usage" section; download the ZIP file for the latest release. If downloading directly from the GitHub repository, click the Code dropdown and select "Download ZIP". Once downloaded, it is recommended that the user unzip the file contents into the directory "`C:\GitHub\RDR`", though the tool suite will work regardless of directory location. The user should keep track of the directory file path, which is needed to edit the batch files used to execute the RDR Tool Suite.

[3] Conda. [Online]. User Guide: Installation. Accessed 26 July 2022 from https://docs.conda.io/projects/conda/en/latest/user-guide/install/.
[4] Python. [Online]. Download. Accessed 26 July 2022 from https://www.python.org/downloads/
[5] R. [Online]. The R Project for Statistical Computing. Accessed 26 July 2022 from https://www.r-project.org/
[6] Tableau Reader. [Online]. Accessed 26 July 2022 from https://www.tableau.com/products/reader
[7] Anaconda. [Online]. Documentation: Installation. Accessed 26 July 2022 from https://docs.anaconda.com/anaconda/install/

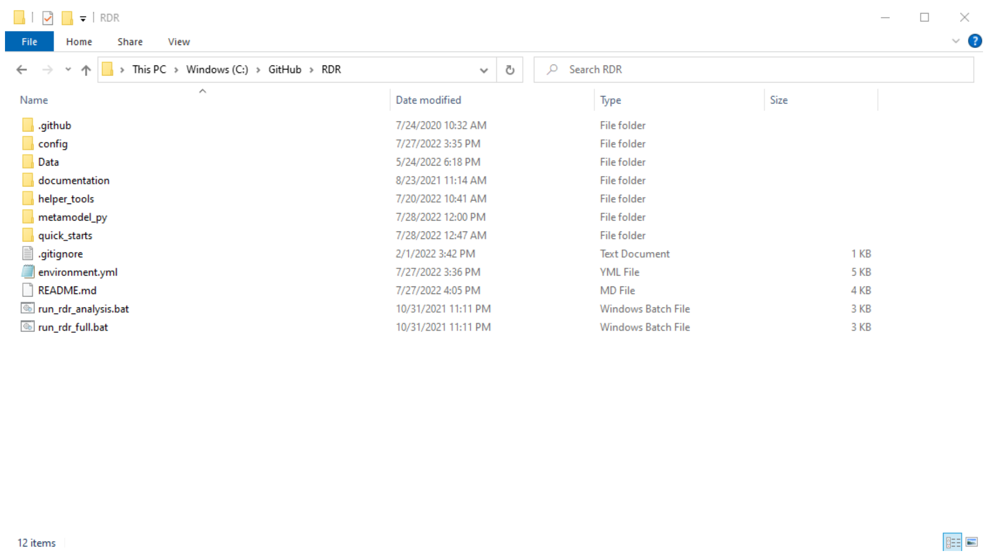


Figure 2-1: RDR Directory Structure

Figure 2-1 shows the directory structure for the RDR Tool Suite, including:

1. ‘`README.md`’: provides background on how to use the tool suite.
2. ‘`environment.yml`’: specifies the necessary code and package dependencies installed in the steps given in Section 2.3.
3. ‘`run_rdr_full.bat`’ and ‘`run_rdr_analysis.bat`’: templates of the batch files used to run the RDR Tool Suite, as described in Section 3.
4. “`config`” subfolder: contains a sample version of the configuration file (detailed in Section 4.1) used to set parameters for components of the tool suite, as well as a set of default and sample input files.
5. “`Data`” subfolder: serves as the recommended central location where the user can place input files and where the RDR Tool Suite components can generate output files.
6. “`documentation`” subfolder: contains the Technical Document, User Guide, Quick Start Tutorial, and Run Checklist for the RDR Tool Suite.
7. “`helper_tools`” subfolder: contains a set of auxiliary code files for preparing inputs for the RDR Tool Suite, including the RDR Exposure Analysis Tool and the Base Year Run Helper Tool.
8. “`metamodel_py`” subfolder: contains the Python and R code files that comprise the RDR Tool Suite.
9. “`quick_starts`” subfolder: contains all of the sample input files and network data for the Quick Start examples described in the Quick Starts Tutorial.

2.3 Software Configuration

The RDR Tool Suite is run from a custom conda environment, detailed in the ‘`environment.yml`’ file. The ‘`environment.yml`’ file lists the specific Python and R dependencies and versions used by the tool suite. See Section 6.1 for installation troubleshooting tips. In order to run the RDR Tool Suite, the user first needs to create the conda environment from the ‘`environment.yml`’ file:

1. Open an Anaconda Prompt terminal window. Searching for “Anaconda Prompt” in the Start menu should locate the application.

2. In the Anaconda Prompt terminal window, navigate to the location of the RDR directory containing the 'environment.yml' file using the "cd" command:
   - `cd C:\GitHub\RDR`

   In the above command, replace "C:\GitHub\RDR" with the full file path location of the user's RDR directory if it is not C:\GitHub\RDR.
3. Run the following commands in the terminal window:
   - `conda env create –f environment.yml`
   - `conda info --envs`

   Note that there is one hyphen in "-f" in the first command and two hyphens in "--envs" in the second command.
4. The second command in step 3 should output a list of available conda environments in the terminal window. Check that an environment named "RDRenv" shows up as an available environment.
5. (Optional) If for some reason the "RDRenv" conda environment is not functioning as expected, remove the environment using the following command, then start again at step 3. Refer to the conda documentation[8] for details.
   - `conda env remove --name RDRenv`

   Note that there are two hyphens in "--name".

Once the conda environment has been created following the steps laid out in Section 2.3, the user can use the Quick Start Tutorial to execute each of the Quick Start examples. To conduct their own custom analyses, the user will need to provide the required input files detailed in the Run Checklist for their specific application before following the steps laid out in Section 3.

[8] Conda. [Online]. User Guide: Managing environments. Accessed 26 July 2022 from https://docs.conda.io/projects/conda/en/latest/user-guide/tasks/manage-environments.html

3 Running the RDR Tool Suite

Batch files are collections of executable commands used to run the RDR Tool Suite; templates for the two types of batch files are found in the main RDR directory. To run the Quick Start examples, a batch file is provided separately for each example in the "`quick_starts`" subfolder; see the Quick Start Tutorial for next steps.

There are three types of runs executed by the batch files included in the RDR Tool Suite: (1) a full run, corresponding to the '`run_rdr_full.bat`' batch file, that executes the RDR Metamodel and the RDR ROI Analysis Module; (2) an analysis run, corresponding to the '`run_rdr_analysis.bat`' batch file, that executes just the RDR ROI Analysis Module given a previously fit metamodel (e.g., to test a subset of the scenario space); (3) an additional run, also using the '`run_rdr_full.bat`' batch file, that expands a previously-run full run and uses its existing core model runs as part of the sampling for a new scenario space (e.g., to populate an alternate regression model). Each batch file executes a series of command line statements that runs a sequence of steps corresponding to the different modules of the RDR Tool Suite.

Table 3-1 describes the different modules and whether they are executed in a full run (or additional run) and/or an analysis run.

Table 3-1: RDR Tool Suite Modules

RDR Tool Suite Module	Function	Executed in Full Run and Additional Run ('`run_rdr_full.bat`')	Executed in Analysis Run ('`run_rdr_analysis.bat`')
'lhs' (Metamodel Parameterization – Latin Hypercube Sampling)	Select core model runs to conduct with AequilibraE	Yes	No
'aeq_run' (Transportation Disruption, Core Model Runs)	Calculate core model results using AequilibraE for selected runs	Yes	No
'aeq_compile' (Core Model Runs)	Compile core model results	Yes	No
'rr' (Scenario Expansion – Metamodel Regression)	Construct regression model for full set of scenarios	Yes	No
'recov_init' (Scenario Expansion – Exposure Recovery, Damage and Repair Recovery)	Build out hazard exposure, damage, and repair recovery for	Yes	Yes

RDR Tool Suite Module	Function	Executed in Full Run and Additional Run (`'run_rdr_full.bat'`)	Executed in Analysis Run (`'run_rdr_analysis.bat'`)
	set of scenarios		
'recov_calc' (ROI Analysis, Reporting and Visualization)	Consolidate metamodel outputs and calculate metrics across period of analysis	Yes	Yes
'o' (Reporting and Visualization)	Write report for RDR Tool Suite run	Yes	Yes

To use a batch file to execute a run, the user should follow these steps:

1. Open the batch file in a text editor (e.g., Notepad, Notepad++, PyCharm, etc.).
2. Edit the environment variables and "change directory" command found in lines 13 to 20 of the batch file (see Figure 3-1):
    a. Edit the `'PATH'` variable at line 13 of the batch file to include the full path of the "`Scripts`" subfolder of the user's conda installation. (See note below for tips to find the location of the user's conda installation.) This is required for the batch file to activate the RDR environment. Make sure the command appends to the existing `'PATH'` variable, i.e., line 13 should always end with "`;%PATH%`".
    b. Set the `'PYTHON'` variable at line 14 of the batch file to the full path of the user's local Python executable for the RDR environment. The Python executable can be found in the user's conda installation, within the RDR environment created in Section 2.3. (Note: To find the location of the user's local Python executable, open an Anaconda Prompt terminal window. Run the commands:
        - `activate RDRenv`
        - `where python`

       The second command should return the full path of the user's local Python executable for the "RDRenv" conda environment, ending in `RDRenv\python.exe`).
    c. Set the `'RDR'` variable at line 15 of the batch file to the full path of the main Python script `'Run_RDR.py'` used to run the RDR Tool Suite. The Python script can be found in the "`metamodel_py`" subfolder of the user's RDR directory.
    d. Set the `'CONFIG'` variable at line 17 of the batch file to the full path of the user configuration file for the run. Make sure the file location and name entered match the configuration file for the analysis being run by the batch file.
    e. Set the directory in the "`cd`" command in line 20 of the batch file to the "`metamodel_py`" subfolder of the user's RDR directory, which contains the Python and R code files that comprise the RDR Tool Suite.
3. (Optional) There is a pause in the batch file at the end of executing a run (e.g., for debugging or confirming the run was executed as expected). To remove the pause, comment out line 60 of

the file by adding "REM " in front of the command "pause" (see Figure 3-2). Note that there is a space at the end of "REM ". The pause command at line 68 is only reached if an error occurs during the run, though the user may wish to comment that "pause" command out as well.

4. Save and close the batch file.
5. Execute the batch file using one of the following two methods (Note: The user's initial run of the tool suite may take longer than usual as it installs necessary software packages):
   a. Double-click on the batch file. A terminal window should open automatically.
   b. Manually execute the batch file:
      - Open any terminal window (e.g., Command Prompt, Terminal, Anaconda Prompt).
      - In the terminal window, navigate to the location of the batch file using the "cd" command, for example:
        - `cd C:\GitHub\RDR`

        In the above command, replace "`C:\GitHub\RDR`" with the full file path location of the directory containing the batch file.
      - Run the following command in the terminal window to execute the batch file:
        - `run_rdr_full.bat`

        In the above command, replace "`run_rdr_full.bat`" with the name of the batch file.

For either method, a set of informational logging statements will be output in the terminal window, indicating progress of the run as well as any error messages. Detailed logging is also provided in the "`logs`" subfolder of the output data folder specified in the configuration file.

```
run_rdr_full.bat

@ECHO OFF
cls
set PYTHONDONTWRITEBYTECODE=1
REM   default is #ECHO OFF, cls (clear screen), and disable .pyc files
REM   for debugging REM @ECHO OFF line above to see commands
REM -------------------------------------------------


REM ==============================================
REM ======== ENVIRONMENT VARIABLES ===============
REM ==============================================
set PATH=C:\Users\%USERNAME%\Anaconda3\Scripts;%PATH%
set PYTHON="C:\Users\%USERNAME%\Anaconda3\envs\RDRenv\python.exe"
set RDR="C:\GitHub\RDR\metamodel_py\Run_RDR.py"

set CONFIG="C:\GitHub\RDR\config\sample_RDR.config"

call activate RDRenv
cd C:\GitHub\RDR\metamodel_py

```

Figure 3-1: Environment Variables in Batch File run_rdr_full.bat

```
REM recov_calc: consolidate metamodel and recovery results for economic analysis
%PYTHON% %RDR% %CONFIG% recov_calc
if %ERRORLEVEL% neq 0 goto ProcessError

REM o: summarize and write output
%PYTHON% %RDR% %CONFIG% o
if %ERRORLEVEL% neq 0 goto ProcessError

REM test: use to test methods under development
REM %PYTHON% %RDR% %CONFIG% test
REM if %ERRORLEVEL% neq 0 goto ProcessError

call conda.bat deactivate
pause
exit /b 0

:ProcessError
REM error handling: print message and clean up
echo ERROR: RDR run encountered an error. See above messages (and log files) to diagnose.

call conda.bat deactivate
pause
exit /b 1
```

Figure 3-2: End of Batch File

3.1 Executing a Full Run

The first time a user executes an RDR analysis on a new location, set of hazards, and/or set of resilience projects (i.e., a new scenario space definition), the user should execute a full run in RDR to set a baseline analysis for the new scenario space. A full run of the RDR Tool Suite executes each module sequentially, starting from building out the scenario space and sampling core model runs to calculating ROI and other output metrics. A full run is executed using the `'run_rdr_full.bat'` batch file.

3.2 Executing an Analysis Run

The user can conduct an analysis run, comprised of just the recovery module and the ROI analysis module, if they are only making adjustments that do not affect the scenario space definition or regression model. Changes to the scenario space (e.g., addition of a new hazard event, analysis of a new resilience project) or regression model (e.g., a change in link availability calculation method) require a new regression model to be fit, so a full run is needed. To execute a full run that uses existing core model runs, see Section 3.3.

Because the RDR ROI Analysis Module relies on the RDR Metamodel, **a full run must be executed before any analysis runs**, though multiple analysis runs may be executed consecutively if the metamodel does not need to be updated. For example, if the user just wants to run an ROI analysis for a subset of resilience investments but the scenario space has not changed, they can modify the relevant input files and execute an analysis run. An analysis run is executed using the `'run_rdr_analysis.bat'` batch file.

3.3 Executing an Additional Run

To use existing core model runs along with new AequilibraE core model runs in an RDR analysis, either due to a change in the scenario space or to provide more sampled points to the regression model, re-run a full run of the tool suite (e.g., using the `'run_rdr_full.bat'` batch file) with the same 'run_id' parameter in the configuration file. The user should indicate that this is an additional run within the configuration file using the parameters ‘do_additional_runs’ and ‘lhs_sample_additional_target’ in the [metamodel] section. See Section 4.1.1 for more details. The ‘lhs’ module will select more scenarios to run with the core model, and the ‘aeq_run’ module will create more AequilibraE outputs in the same output directory labeled by the ‘run_id’ parameter. The ‘aeq_compile’ module references this shared output directory to compile core model runs used to fit the regression model. New output files will overwrite any files of the same name that were generated by previously-run analyses. If the user wishes to save the output files from a previously-run analysis, they should make renamed copies or move them out of the output folder.

The user can also create their own batch file to run just the RDR Tool Suite modules they need, e.g., if they already have core model runs and want to fit a regression model.

4 RDR Data Inputs

The RDR Tool Suite relies on several required inputs, in addition to a few optional inputs the user can provide for a more case-specific analysis. This section provides an in-depth description of these inputs. Several samples of data inputs are provided in the Quick Start scenarios detailed in the Quick Start Tutorial. The user is welcome to start with a copy of a Quick Start scenario as a template for their own scenario; the user will need to replace each Quick Start input file with their own data to execute a run that reflects their transportation scenario and hazards of interest.

All input files should be placed in the data input folder specified in the user configuration file. The user needs to manually create the following subfolders within the input data folder:

1. "`AEMaster`" – Used as a template for the directory structure created for each AequilibraE core model run. Contains demand files and the SQLite database used by AequilibraE.
    a. Within the "`AEMaster`" folder, the user should manually create the "`matrices`" subfolder.
2. "`Hazards`" – Contains exposure analysis files.
3. "`LookupTables`" – Contains resilience project files, in addition to being the recommended location for all user-created look-up tables used by the RDR Tool Suite.
4. "`Networks`" – Contains network attribute files.

An example of the structure of the input data folder is shown in Figure 4-1.

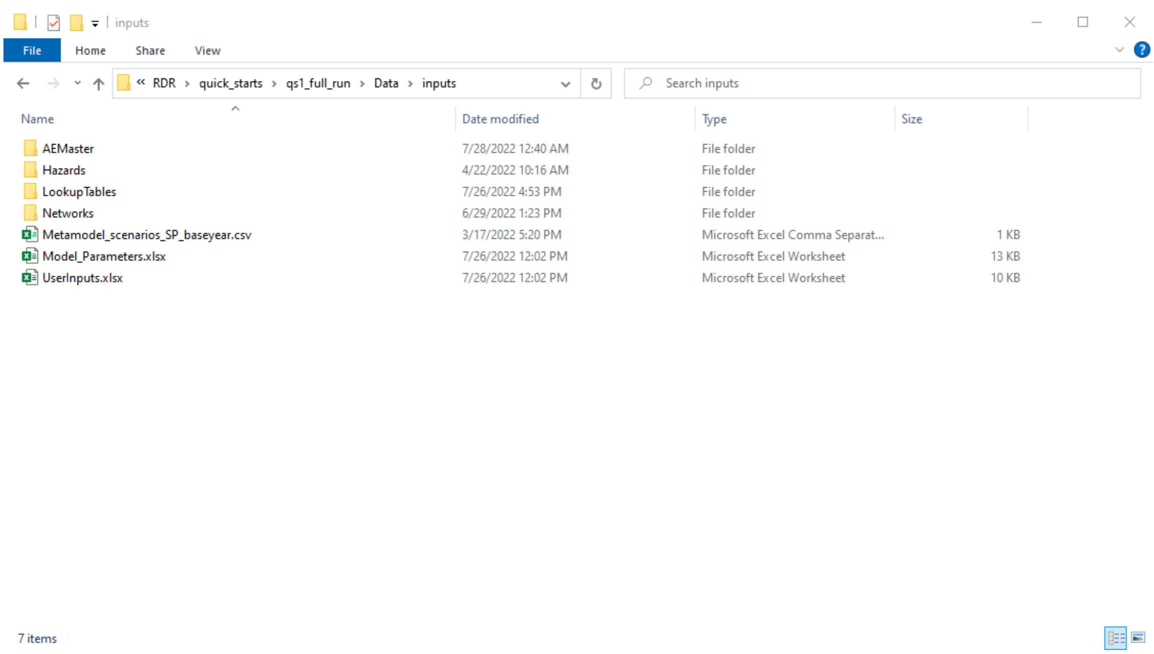


Figure 4-1: Input Data Folder Structure

Figure 4-2 shows the substructure of the "`AEMaster`" subfolder.

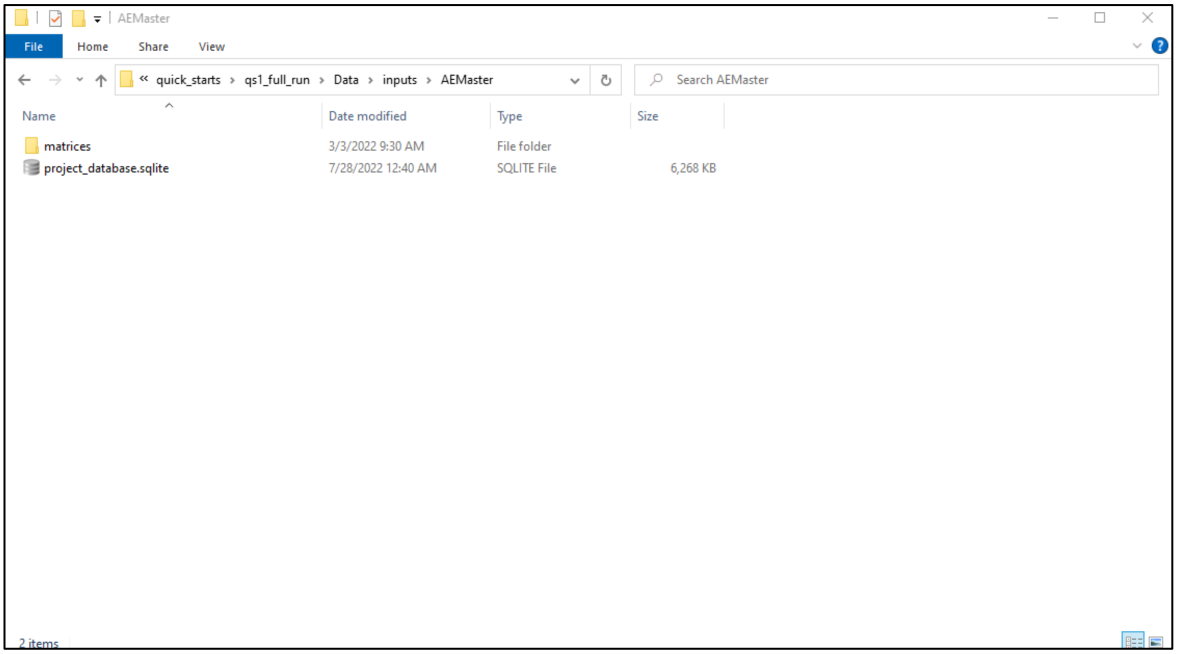


Figure 4-2: AEMaster Subfolder Structure

Appendix A: RDR Tool Suite Input Files provides a comprehensive list of all of the types of input files, where they should be located, what they should be named, required fields, and which RDR Tool Suite modules use them. Depending on the set of modules the user wishes to run in their analysis, they will need to provide the corresponding input files.

4.1 Configuring Scenario Definition Inputs

The input parameters defining the uncertainties modeled in an RDR analysis are specified by the user using three distinct input files, each detailed in one of the following subsections.

The specific dimensions used by the RDR Tool Suite to build out the scenario space are:

- Hazard events
- Hazard recovery stages
- Hazard event frequency factors
- Economic scenarios
- Trip loss elasticities
- Project groups
- Resilience projects

The model parameters file (Section 4.1.2) defines these dimensions for the RDR Metamodel module; the user inputs file (Section 4.1.3) defines these dimensions for the RDR ROI Analysis module. The configuration file (Section 4.1.1) further parameterizes the scenario space by building out the list of possible hazard recovery periods.

The look-up table given in the ProjectGroups tab of the model parameters file defines the mapping between the project group categories, which represent sets of potential resilience projects that have been grouped together, and the individual resilience projects. The project group categories are also used to specify and group future network attributes that encompass any new roads and assets built for planned infrastructure projects. If the user does not have pre-defined groups of resilience projects, they can create a single project group using an arbitrary project group value that encompasses all potential resilience projects.

The table defined in the Hazards tab of the model parameters file provides specifications for each hazard event. The RDR Tool Suite automatically builds out hazard recovery stages during the hazard period based on user parameters provided in the configuration file and the number of recovery stages specified in the model parameters file; the recovery module selects potential recovery stages for each hazard event based on these parameters. The “Event Probability in Start Year” field is used in the benefit-cost analysis (BCA) to evaluate the performance of resilience projects across different hazard events.

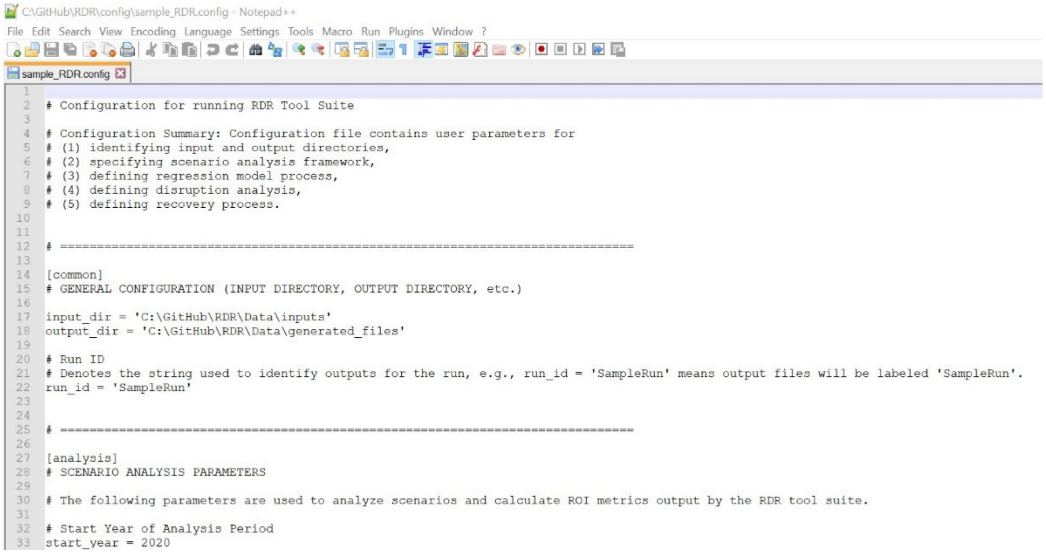
4.1.1 Configuration File

The configuration file is the primary input file for running the RDR Tool Suite, specifying the parameters that define a run of the tool suite. The user should modify the parameters for their specific analysis.

A sample version of the configuration file named `‘sample_RDR.config’` (seen in Figure 4-3 and located at https://github.com/VolpeUSDOT/RDR-Public/blob/master/config/sample_RDR.config) is provided in the `“config”` subfolder of the main RDR directory. The sample configuration file provides definitions of the parameters, values each parameter can take, and specifications of where in the RDR Tool Suite each parameter is used. Default values for most parameters are provided, which the user can replace if they have case-specific information for their analysis. In addition, several parameters are only required for specific settings (e.g., the ‘link_availability_csv’ parameter is only required if the ‘link_availability_approach’ parameter is set to ‘Manual’); these are identified within the sample configuration file. The user can create a copy of the sample file for their own run and modify the contents as needed.

The configuration file is split into five sections:

1. [common] – Identifies ‘input_dir’, the directory where all input files except the configuration file are located, ‘output_dir’, the directory where output files of the tool suite are created, and ‘run_id’, a text string identifier for the RDR run.
2. [analysis] – Specifies parameter values for model analysis, reporting, and benefit-cost analysis. Primarily used by the RDR ROI Analysis Module; see Section 4.8 for more details.
3. [metamodel] – Specifies parameter values for how the AequilibraE core model is run and how AequilibraE outputs are sampled and used to fit the regression model in the RDR Metamodel; see Section 4.4 for more details.
4. [disruption] – Specifies parameter values for disruption analysis related to hazard events and resilience investments. Primarily used by the RDR Exposure Analysis Tool and the RDR Metamodel; see Sections 4.4 and 4.6.1 for more details.
5. [recovery] – Specifies parameter values for the hazard recovery and damage repair processes. Primarily used by the RDR Metamodel and the RDR ROI Analysis Module; see Sections 4.6.2 and 4.6.3 for more details.



```
C:\GitHub\RDR\config\sample_RDR.config - Notepad++
File Edit Search View Encoding Language Settings Tools Macro Run Plugins Window ?
sample_RDR.config

# Configuration for running RDR Tool Suite

# Configuration Summary: Configuration file contains user parameters for
# (1) identifying input and output directories,
# (2) specifying scenario analysis framework,
# (3) defining regression model process,
# (4) defining disruption analysis,
# (5) defining recovery process.


# ==============================================================================

[common]
# GENERAL CONFIGURATION (INPUT DIRECTORY, OUTPUT DIRECTORY, etc.)

input_dir = 'C:\GitHub\RDR\Data\inputs'
output_dir = 'C:\GitHub\RDR\Data\generated_files'

# Run ID
# Denotes the string used to identify outputs for the run, e.g., run_id = 'SampleRun' means output files will be labeled 'SampleRun'.
run_id = 'SampleRun'


# ==============================================================================

[analysis]
# SCENARIO ANALYSIS PARAMETERS

# The following parameters are used to analyze scenarios and calculate ROI metrics output by the RDR tool suite.

# Start Year of Analysis Period
start_year = 2020
```

Figure 4-3: Sample Configuration File

4.1.2 Model Parameters File

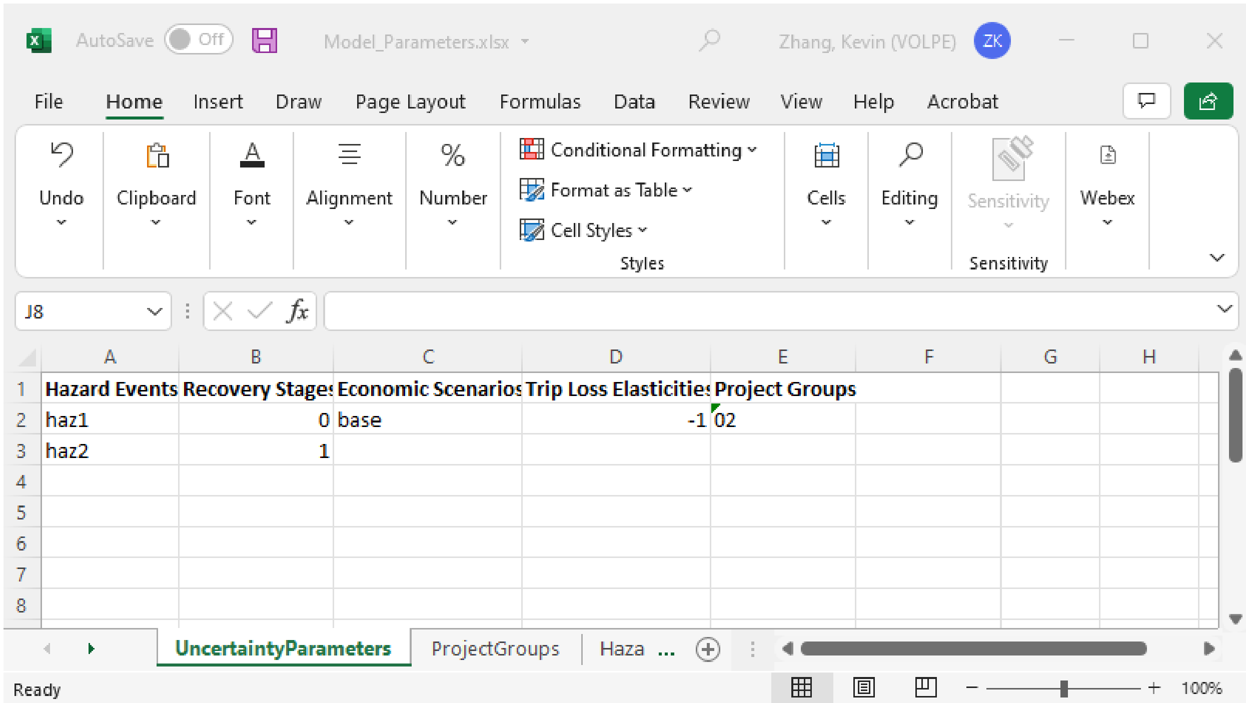
The model parameters file is the key user input file for defining the analysis framework. It specifies the complete scenario space for the RDR Metamodel and defines the list of hazard events and recovery stages. The model parameters file is named `'Model_Parameters.xlsx'` and is located in the input data folder specified by 'input_dir' in the configuration file.

The model parameters file contains three sheets, which jointly define the analysis framework. The "UncertaintyParameters" tab (Figure 4-4) lists all possible values for scenarios dimensions; the "ProjectGroups" tab (Figure 4-5) supplies a mapping of project groups to resilience projects; the "Hazards" tab (Figure 4-6) defines all hazard events.

The "UncertaintyParameters" tab has five required columns:

1. 'Hazard Events' are text strings describing the possible hazard events and match the "Hazards" tab;
2. 'Recovery Stages' are non-negative integers starting from 0 (indicating initial hazard event severity) that enumerate the potential hazard recovery stages. The stages represent levels of receding exposure a hazard event may pass through during the hazard exposure period from initial hazard severity to end of the hazard event (e.g., larger integers represent further recession);
3. 'Economic Scenarios' are text strings naming the possible future economic scenarios and correspond to the filenames for demand files and network attribute files;
4. 'Trip Loss Elasticities' are numeric values (less than or equal to zero) quantifying the change in trip demand due to increased travel time used by the core model;
5. 'Project Groups' are text strings naming all groupings of resilience projects and match the "ProjectGroups" tab and correspond to the filenames for network attribute files.

Note that data in this tab are entered column by column; depending on how many values each uncertainty parameter can take, the number of entries per column may vary. For example, in Figure 4-4, there are two recovery stages but only one economic scenario, so the number of rows in each of those columns differs. The uncertainty scenarios are built exclusively from the uncertainty parameter dimensions listed here, and the tool will not recognize additional parameters. A user may enter any number of parameter values for each uncertainty parameter; users can also choose to ignore an uncertainty by entering exactly one value. For example, a user may only have one economic scenario, reflecting a single best guess at future trip demand tables.



Hazard Events	Recovery Stages	Economic Scenarios	Trip Loss Elasticities	Project Groups
haz1	0	base	-1	02
haz2	1			

Figure 4-4: UncertaintyParameters tab of model parameters file for Quick Start 1

The “ProjectGroups” tab has two required fields:

1. ‘Project Groups’ are text strings naming all groupings of resilience projects and match the “UncertaintyParameters” tab and correspond to the filenames for network attribute files;
2. ‘Resiliency Projects’ are text strings identifying resilience projects and match the ‘`project_table.csv`’ and ‘`project_info.csv`’ input files.

In mapping the relationship between project groups and resilience projects in the “ProjectGroups” tab, the user does not need to include the baseline scenario of no resilience investment for each project group; the RDR Tool Suite creates that baseline automatically for the ROI analysis of each resilience investment.

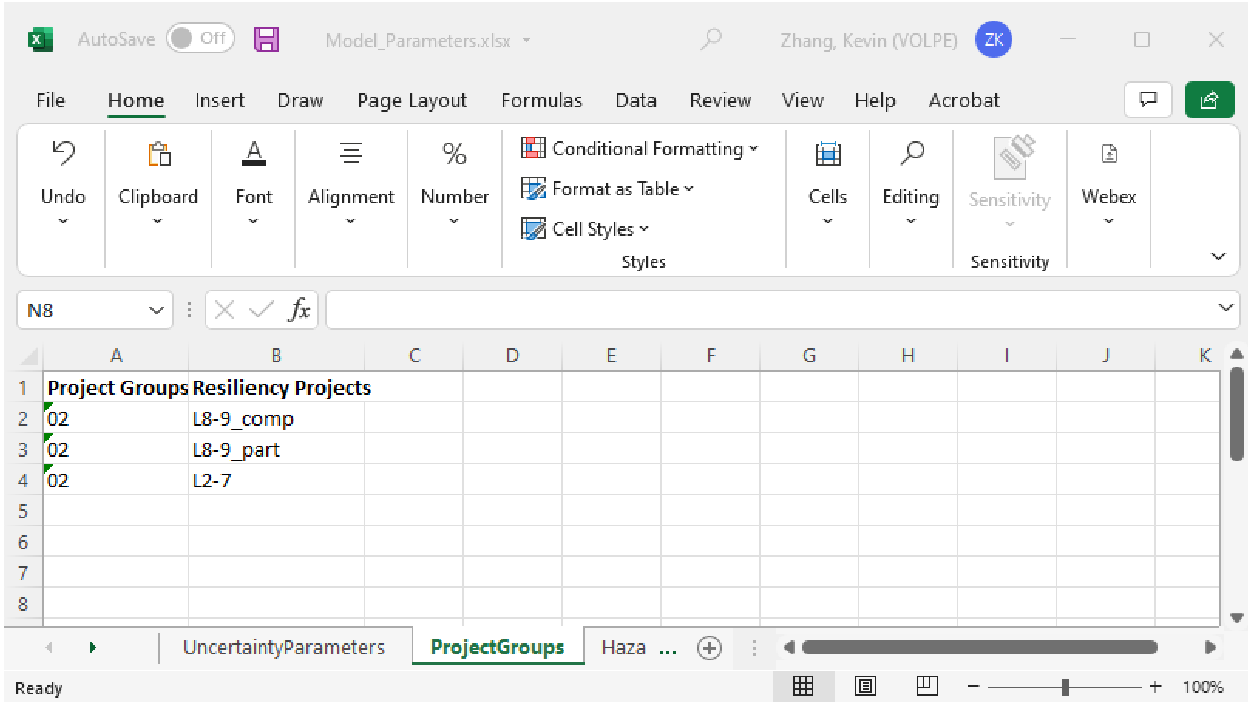
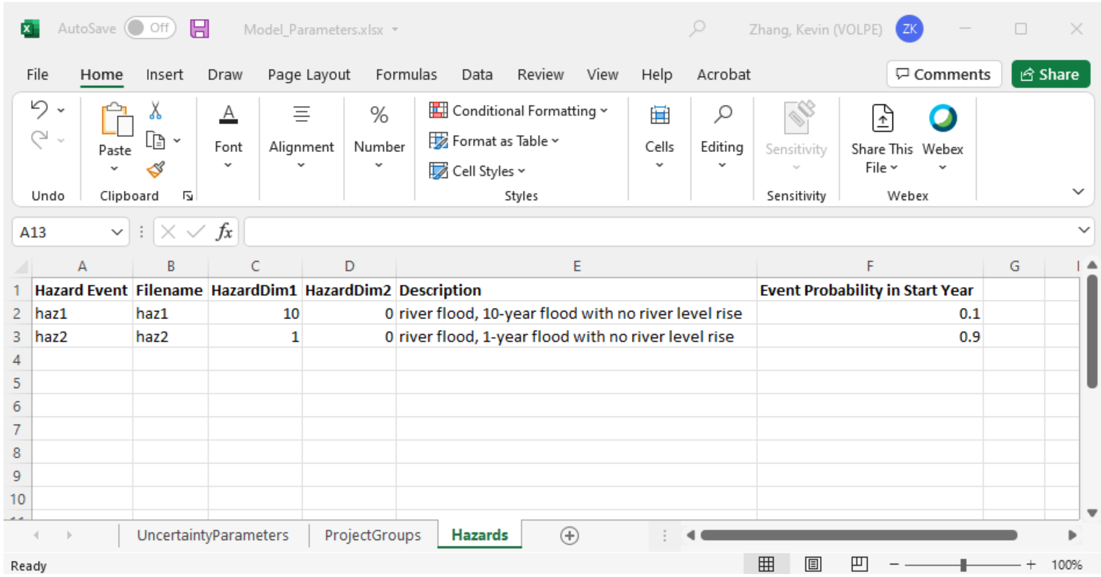


Figure 4-5: ProjectGroups tab of model parameters file for Quick Start 1

The “Hazards” tab has five required fields:

1. ‘Hazard Event’ are text strings describing possible hazard events and match the “UncertaintyParameters” tab;
2. ‘Filename’ are text strings connecting hazard events to exposure analysis files and correspond to the filenames of exposure analysis files (without the “.csv” file type extension);
3. ‘HazardDim1’ are text strings describing the short-term dimension of the hazard event (e.g., ‘100’ for 100-year storm surge for flooding event);
4. ‘HazardDim2’ are text strings describing the long-term dimension of the hazard event (e.g., ‘3’ for 3-foot sea-level rise for flooding event);
5. ‘Event Probability in Start Year’ are numeric annual probabilities of the hazard event occurring. Note that the hazard event probabilities are specified for the start year of the analysis period, not the base year.

The ‘Hazard Event’ and ‘Filename’ fields are used in the ‘recov_init’ module, while the ‘recov_calc’ module uses the ‘Hazard Event’, ‘HazardDim1’, ‘HazardDim2’, and ‘Event Probability in Start Year’ fields.



Hazard Event	Filename	HazardDim1	HazardDim2	Description	Event Probability in Start Year
haz1	haz1	10	0	river flood, 10-year flood with no river level rise	0.1
haz2	haz2	1	0	river flood, 1-year flood with no river level rise	0.9

Figure 4-6: Hazards tab of model parameters file for Quick Start 1

4.1.3 User Inputs File

The `UserInputs.xlsx` Excel workbook is used to generate the benefit-cost analysis and corresponding visualizations in the Tableau dashboard and is located in the input data folder specified by 'input_dir' in the configuration file. This user inputs file is the primary input for the RDR ROI Analysis Module. It specifies the set of scenarios for which the ROI analysis is run. The user inputs file should specify a subset of the scenario space defined in the model parameters file for the RDRM, and values within each column of the user inputs file must be drawn from the values contained in the model parameters file. The structure of the input file is similar to the "UncertaintyParameters" tab of the `Model_Parameters.xlsx` input file (shown in Figure 4-4), but there is an additional field for the Event Frequency Factor (Figure 4-7 below). As with the "UncertaintyParameters" tab of the model parameters file, note that data in this input file are entered column by column; depending on how many values each uncertainty parameter can take, the number of entries per column may vary. While the `Model_Parameters.xlsx` input file only needs to be specified at the beginning of using the RDRM to construct the metamodel, the `UserInputs.xlsx` input file may be updated for each use of the ROI Analysis Module to generate different analyses that compare a subset of the uncertainty scenarios.

The "UserInputs" tab (Figure 4-7) has five required fields:

1. 'Hazard Events' are text strings and should be a subset of the list in the model parameters file;
2. 'Economic Scenarios' are text strings and should be a subset of the list in the model parameters file;
3. 'Trip Loss Elasticities' are numeric and should be a subset of the list in the model parameters file;
4. 'Resiliency Projects' are text strings and should be a subset of the list in the model parameters file;
5. 'Event Frequency Factors' are numeric and define how the probability of each hazard event will increase or decrease year-on-year during the analysis period. A value of 1 means no change across years in hazard event probability values; a value above 1 means an increase in frequency; a value below 1 means a decrease in frequency.

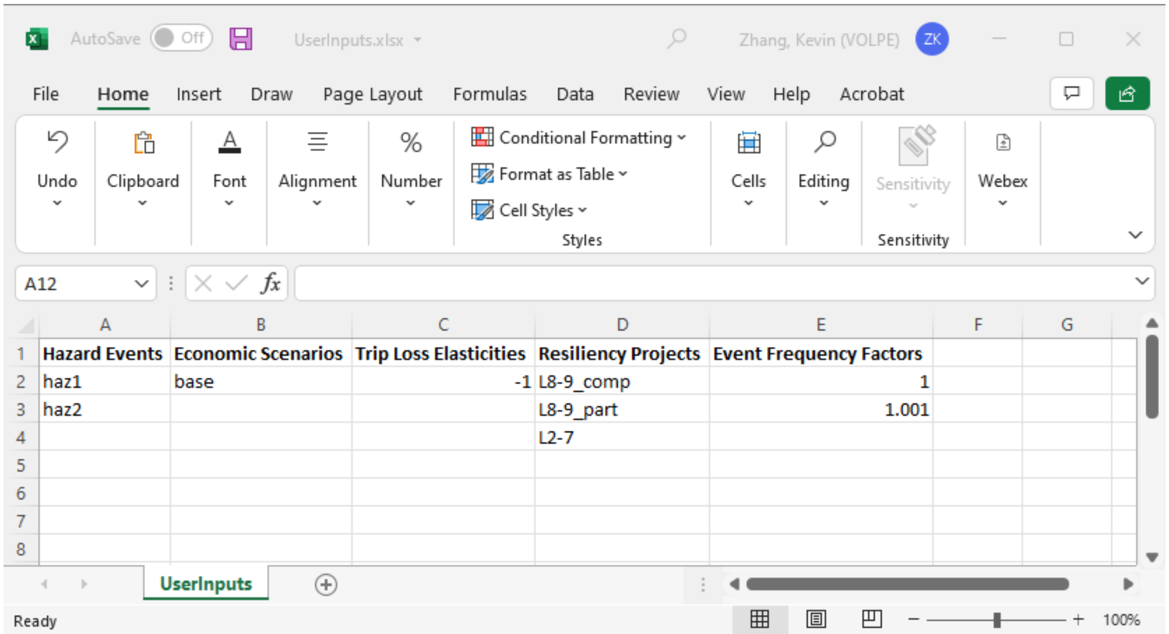


Figure 4-7: User inputs file for Quick Start 1

4.2 Configuring Exposure Scenarios

4.2.1 Configuring the Exposure Analysis Network Map

An exposure analysis applies geospatial information regarding hazard severity onto the transportation network to assess hazard exposure severity on the network links specifically; therefore, an exposure analysis should be performed on a geospatially accurate network dataset. If using the TDM network to conduct an exposure analysis, it is important to assess the source of the network and its geographic accuracy. Some TDM roadway networks, sometimes called stick-networks, do not accurately reflect the geographic location of the roadways. Figure 4-8 below shows a screenshot of a section of the TDM network (red lines) overlaid on top of a road map in ArcGIS in the Virginia Beach area of Virginia. While some of the segments match the ArcGIS road map fairly well, there are some components of the TDM network that are much coarser than the real-world network (Figure 4-9 below is zoomed in on one such area). If this network were used in a GIS-based hazard exposure analysis (e.g., flooding), it would be inaccurate.

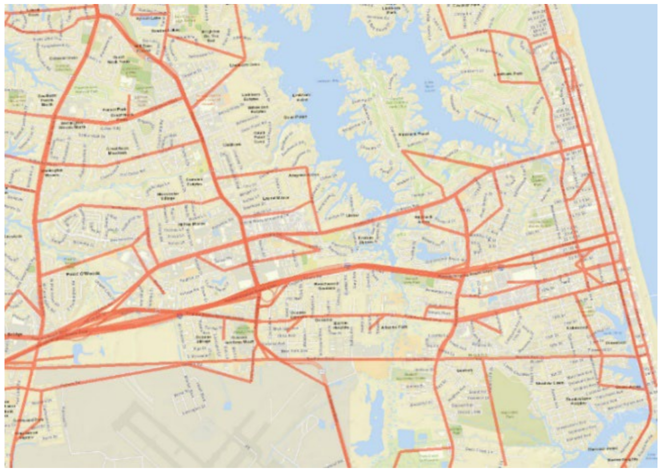


Figure 4-8: Virginia Beach TDM Network Alignment with ArcGIS Basemap

Figure 4-9: TDM Misalignment with ArcGIS Basemap

If the roadway network is schematic and geographically inaccurate, the user should first try to export a more geographically accurate network from the TDM. If this is not possible, the user will need to source a more geospatially precise network. The user will then need to translate the geographically accurate network to the TDM network, either manually or via a crosswalk linking individual GIS-based assets to TDM-based assets. The user must then manually transfer over the changes in capacity and speed to the TDM network for analysis.

A user may want to integrate other attributes from separate GIS-based transportation networks into a TDM network. Commonly used GIS software such as Esri's ArcGIS Pro (and the older ArcGIS) contain geoprocessing tools that can help facilitate this integration. For example, the **Transfer Attributes** tool can be used to spatially match a distinct roads dataset with the GIS export of the TDM. The roads dataset might contain additional attributes that are not native to the TDM network, but which could be helpful in modeling different hazard scenarios, such as road pavement, surface type, international roughness index (IRI), and soil type.

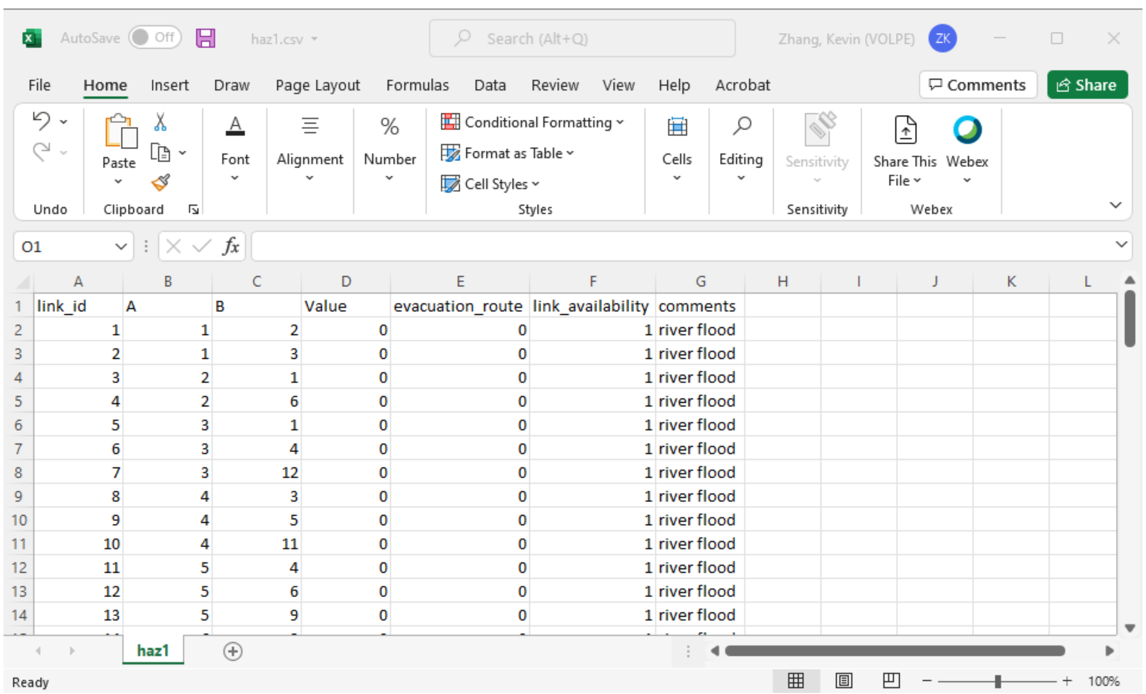
Additional information on defining exposure data and potential geospatial data sources can be found in Appendix D: Defining Exposure Data and Appendix E: Transportation Asset and Hazard Scenario Data Summary.

4.2.2 Exposure Analysis Files

The exposure analysis CSV files (name format '{Filename}.csv') provide hazard exposure data for each hazard event. The "Filename" name attribute is designated by the user in the "Hazards" tab of the model parameters file (Section 4.1.2). The exposure analysis files are located in the "Hazards" subfolder of the input data folder and are used as inputs to the AequilibraE core model and the damage and repair components of the tool suite. Each row in the file denotes a link in the true shapes network. The required fields are:

1. 'link_id' – ID of network link.
2. 'A' – ID of predecessor node of network link.
3. 'B' – ID of successor node of network link.
4. 'Value' (or corresponding text string specified by the 'exposure_field' parameter in the configuration file) – Numeric exposure level of hazard event on link. Units of the exposure level must be specified by the 'exposure_unit' parameter in the configuration file if using the default flood exposure function.

All fields are used by the 'aeq_run' and 'recov_init' modules. The exposure analysis CSV files can be created by the RDR Exposure Analysis Tool. A sample exposure analysis file from Quick Start 1 is shown in Figure 4-10.



link_id	A	B	Value	evacuation_route	link_availability	comments
1	1	2	0	0	1	river flood
2	1	3	0	0	1	river flood
3	2	1	0	0	1	river flood
4	2	6	0	0	1	river flood
5	3	1	0	0	1	river flood
6	3	4	0	0	1	river flood
7	3	12	0	0	1	river flood
8	4	3	0	0	1	river flood
9	4	5	0	0	1	river flood
10	4	11	0	0	1	river flood
11	5	4	0	0	1	river flood
12	5	6	0	0	1	river flood
13	5	9	0	0	1	river flood

Figure 4-10: Sample exposure analysis file for Quick Start 1

4.2.2.1 Creating Exposure Analysis Files from the Network Map and Exposure Data

After the hazard data and transportation network data have been identified, the final step is to bring the data together in order to determine the level of exposure associated with each asset in the network. Figure 4-11 below represents the kind of data produced in the exposure analysis in graphical form.

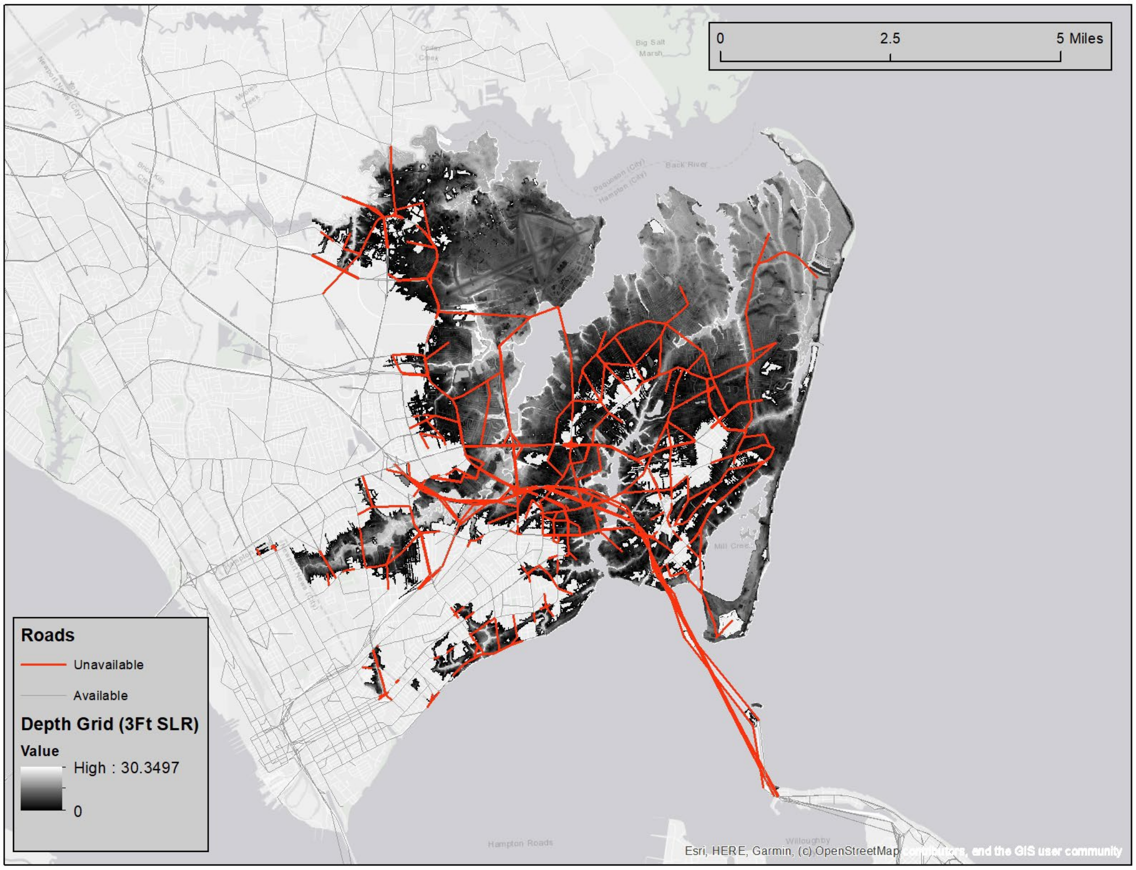


Figure 4-11: Example output from a simple GIS Exposure Analysis overlaying depth grid data onto the TDM transportation network to identify disrupted links, assuming all exposure leads to disruption.

The basic output that the RDRM needs in order to leverage exposure data is a comma-delimited table that provides the unique asset identifier and specific exposure level for each asset of interest. The asset ID must match the relevant asset ID in the TDM so that these data can be appropriately linked together.

If a user has an existing GIS network that includes exposure analysis data linking assets to hazard data, these data could be integrated into the TDM network using Esri's ArcGIS Pro.

If the user needs to create a new exposure map, there are several ways to accomplish this. First, the user could create the map manually if the number of assets exposed is small or can be assessed based on expert knowledge. The user can create a simple table which links the asset ID from the TDM to an exposure level (e.g., flood depth). Again, the asset ID must match the relevant asset ID in the TDM so that these data can be appropriately linked together.

Second, the user can use a GIS tool to overlay hazard data on top of the transportation asset data to determine where the two datasets intersect or overlap and to associate exposure levels with each asset. To aid agencies in executing a simple GIS-based exposure analysis using flooding as an example, the RDR Exposure Analysis Tool provides a simplified analysis script for use in ArcGIS or ArcGIS Pro. The documentation for this helper script and the script code can be found in Appendix F: RDR Exposure Analysis Tool. The script code is also available on GitHub at https://github.com/VolpeUSDOT/RDR/tree/master/helper_tools/exposure_grid_overlay. The script can be modified by the analyst to suit specific situations. As an added benefit, the RDR Exposure Analysis Tool allows the analyst to experiment with various methodologies for converting exposure to disruption. While the script is not required in order to run the core models or RDRM, it can be useful for creating, analyzing, and visualizing specific exposure and disruption scenarios without running the full tool.

Regardless of whether the user leveraged the RDR Exposure Analysis Tool or has existing GIS-based data capturing hazard exposure levels, the data can easily be visualized using GIS software such as QGIS or ArcGIS Pro. Since the exact structure of exposure data may vary greatly from scenario to scenario, and access to specific GIS software varies from agency to agency, this part of the process is not automated by the Exposure Analysis Tool. However, with the GIS output from the RDR Exposure Analysis Tool (or existing agency data) a user with basic GIS knowledge should be able to easily create simple maps, such as the above in Figure 4-11, that visualize a hazard scenario with the resulting disruption output.

4.2.3 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 remain accessible to emergency vehicles or other high clearance vehicles, provided the user sets up a link availability approach relevant to emergency/high clearance vehicles (e.g., using higher exposure thresholds to disrupt the network). Exposure and disruption data can also be used to determine the disruptions to emergency response and evacuation routes, provided GIS-based evacuation route information is available and defined by the user when setting up the tool. These functionalities are included in the RDR Exposure Analysis Tool. For further specifications on how to configure the RDR Exposure Analysis Tool to calculate emergency response or evacuation disruption, see Appendix F: RDR Exposure Analysis Tool.

4.3 Configuring the Core Model Network

4.3.1 Network Files

In order to run the core models and populate the RDR Metamodel, the user needs a routable network file that is associated with the various scenarios of interest (i.e., future economic scenario, resilience investment). For evaluating travel demand, a routable network of nodes and links is necessary to route trips over the transportation network to calculate VHT and VMT. Routable networks are most often taken from a TDM; these are accurate from a routing and mileage perspective but, as indicated in Section 4.2.1 above, may not be geospatially accurate. A routable network can also be built from existing GIS networks that have been created by the city, metropolitan planning organization, or state. The user might also use Open Street Map as a source, using tools such as osmnx[9] or osm2gmns,[10] to synthesize the routable network. Note that synthesizing a routable network from a GIS network often requires considerable effort to ensure that the logical connections between links (e.g., the nodes) are correct.

Some nodes in the network are labeled as centroids (origins and destinations of flow). Other nodes connect the links**. The number of nodes labeled as centroids must be the same as the number of zones in the trip table.** There are two link types:

- Travel links, representing highways (typically include freeways, arterials, and some collectors).

[9] Github: OSMNX repository: https://github.com/gboeing/osmnx

[10] Lu, Jiawei, Xuesong (Simon) Zhou. 2022. [Online]. Osm2gmns. Accessed 26 July 2022 from https://osm2gmns.readthedocs.io/en/latest/index.html

- Centroid connectors, artificial links that connect the centroids to the travel links.

Each link has a direction of flow, and other measures, such as number of lanes (in one direction), capacity, free flow speed, travel time, distance, and (optionally) toll. Centroid connectors are generally assigned a high capacity and a low speed, so that they are only used for accessing the centroids.

In the RDR Tool Suite, link files will often be different for different scenarios (e.g., additional links may be added or link capacities may change based on planned construction in response to future economic scenarios), while the same nodes file is used for all scenarios. These files are located in the "`Networks`" subfolder of the input data folder and are used as inputs to the AequilibraE core model and the RDR ROI Analysis Module.

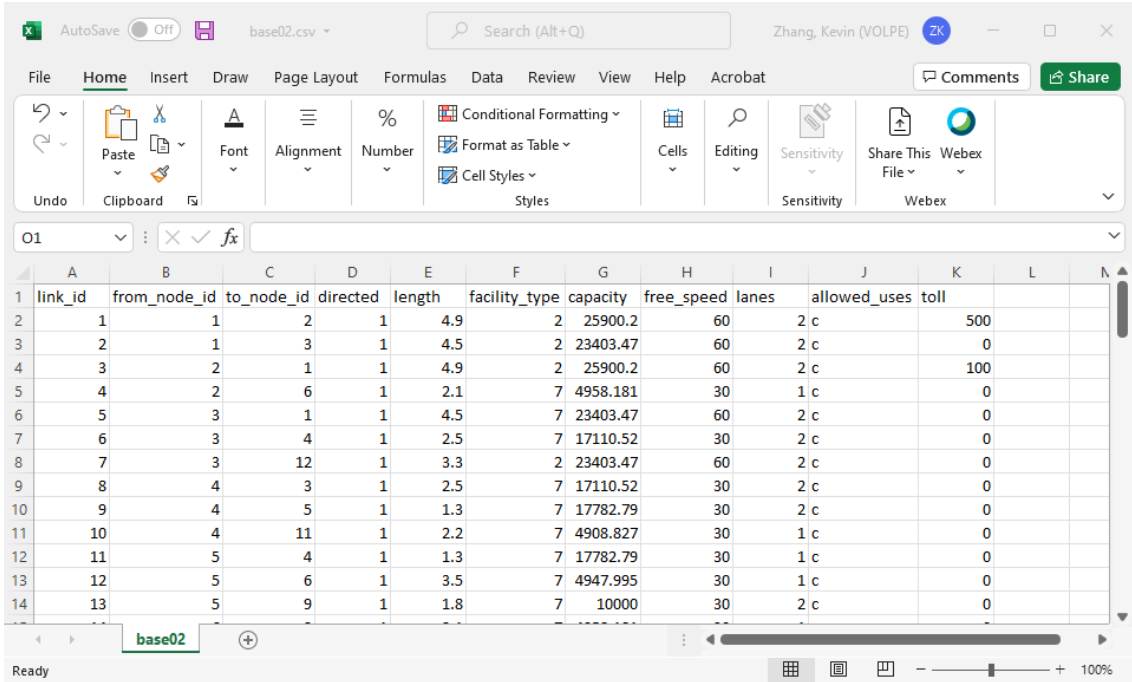
The links file (name format `'{econ}{projgroup}.csv'`) lists the full set of network links for each combination of future economic scenario and project group (each replacing the respective bracketed text in the filename) found in the model parameters file (e.g., two future economic scenario options and three project groups lead to six links files). Field names are based on those in the General Modeling Network Specification (GMNS).[11] Links are directional, meaning that a two-way road segment is represented as a pair of links, one going in each direction. The required fields are:

1. 'link_id' – ID of the network link.
2. 'from_node_id' – ID of predecessor node of network link.
3. 'to_node_id' – ID of successor node of network link.
4. 'directed' – Must be set to 1. All links are required to be directed; two-way roads should be entered as two separate directed links.
5. 'length' – Numeric length of network link in miles.
6. 'facility_type' – Text string defining the facility type of the network link. The user can provide their own custom types as long as they match the 'Facility Type' fields in the repair cost and repair time tables (and the optional link types table). To use the default repair cost and repair time tables provided with the tool suite, the facility type for road links should follow the FHWA Highway Functional Classification[12] (values 1-7)[13] and the facility type for bridge links should be either 'National' for National Highway System Bridges or 'Non-National'.
7. 'capacity' – Numeric capacity of network link in vehicles per day per lane.
8. 'free_speed' – Numeric free-flow speed of network link in miles per hour.
9. 'lanes' – Number of lanes in the direction of travel of network link.
10. 'allowed_uses' – Must be set to 'c'. The RDR Tool Suite currently supports only cars as permitted mode.
11. 'toll' – Toll (if any) in cents.

All fields are used by the 'aeq_run' module; fields 'from_node_id', 'to_node_id', 'length', 'lanes', and 'facility_type' are used by the 'recov_init' module. The 'facility_type' field is used to calculate repair cost

[11] Github: GMNS repository: https://github.com/zephyr-data-specs/GMNS/tree/master/Specification_md. Although a GMNS network can be very detailed, RDR only makes use of nodes and links.
[12] FHWA. 2013. Highway Functional Classification Concepts, Criteria, and Procedures. https://www.fhwa.dot.gov/planning/processes/statewide/related/highway_functional_classifications/fcauab.pdf
[13] 1 – interstates, 2 – other freeways and expressways, 3 – other principal arterials, 4 – minor arterials, 5 – major collectors, 6 – minor collectors, 7 – local roads

and repair time in the RDR ROI Analysis Module. A sample network attribute file from Quick Start 1 is shown in Figure 4-12.



link_id	from_node_id	to_node_id	directed	length	facility_type	capacity	free_speed	lanes	allowed_uses	toll
1	1	2	1	4.9	2	25900.2	60	2	c	500
2	1	3	1	4.5	2	23403.47	60	2	c	0
3	2	1	1	4.9	2	25900.2	60	2	c	100
4	2	6	1	2.1	7	4958.181	30	1	c	0
5	3	1	1	4.5	7	23403.47	60	2	c	0
6	3	4	1	2.5	7	17110.52	30	2	c	0
7	3	12	1	3.3	2	23403.47	60	2	c	0
8	4	3	1	2.5	7	17110.52	30	2	c	0
9	4	5	1	1.3	7	17782.79	30	2	c	0
10	4	11	1	2.2	7	4908.827	30	1	c	0
11	5	4	1	1.3	7	17782.79	30	1	c	0
12	5	6	1	3.5	7	4947.995	30	1	c	0
13	5	9	1	1.8	7	10000	30	2	c	0

Figure 4-12: Sample network file for Quick Start 1

In addition to the network link attribute CSV files, the "Networks" subfolder must also contain a CSV file named 'node.csv' with a full list of network nodes, following the General Modeling Network Specification. This file is used by the 'aeq_run' module and has required fields:

1. 'node_id' – Unique ID of network node.
2. 'x_coord' – The x coordinate of network node.
3. 'y_coord' – The y coordinate of network node.
4. 'node_type' – Text string indicating type of node (e.g., whether node is a centroid).

In RDR, centroid nodes have a node_type of 'centroid'. Non-centroid nodes can be designated by any other text string. The 'node_id' of the highest numbered centroid node must be designated by the "highest_zone_number" parameter in the configuration file.

4.3.2 Converting to Links for AequilibraE Format

The attributes of the links used by AequilibraE are slightly different from those used by GMNS.

Table 4-1 Link fields for AequilibraE compared to GMNS

GMNS field	AequilibraE field	How it is translated
link_id (unique identifier)	link_id	Simple copy
from_node_id	from_node_id	Simple copy
to_node_id	to_node_id	Simple copy
facility_type (freeway, arterial, etc.)	facility_type	Simple copy
directed (direction of flow, A->B = 1)	directed	Simple copy
length (length of the link in miles)	length	Simple copy

capacity (capacity in vehicles per day per lane)	capacity_ab (capacity in vehicles per day per link)	See Note 1, below
free_speed (in mph)	free_speed	Simple copy
lanes	lanes	Simple copy
allowed_uses (e.g., AUTO, WALK, BIKE)	allowed_uses	Simple copy
toll (toll in cents)	toll	Simple copy
geometry (geometry of the link in well-known-text, used for display in a GIS)	*not needed*	
	link_available	See Note 2, below
	alpha	See Note 3, below
	beta	See Note 3, below

Note 1: To convert from vehicles / hour / lane to vehicles / day / lane as is the required input units for the RDR Tool Suite:

- $capacity\ (\frac{veh}{day}) = peak\_hr\_to\_day\_capy\_conversion * capacity$
- Peak_hr_to_day_capy_conversion is a parameter (typically between 10 and 15) that converts a peak hour capacity to a daily capacity.

Note 2: The "link_available" field is a number, between 0 and 1, which indicates the availability of the link. A value of 0 indicates a link is not available, 1 indicates a link is fully available. Numbers between 0 and 1 represent a reduction in capacity. For each scenario that is run, RDR calculates "link_available" from the exposure field in a CSV file in the "`Hazards`" folder of the input data directory.

Note 3: The alpha and beta fields are the volume delay parameters. The volume-delay parameters describe how travel time increases as flow reaches capacity. AequilibraE supports the Bureau of Public Roads (BPR) volume/delay function, which has been around for many years,[14] and is represented as:

$$congested\_time = free\_flow\_time \times (1 + \alpha \times (flow/capacity)^{\beta})$$

Recommended parameters were initially α = 0.15 and β = 4. Today, different values are often used depending on the functional class of the road, with a larger values of β used for freeways and lower values used for other types of roads. In older versions of AequilibraE (e.g., version 0.6.x), the α parameter is labeled "b", and the β parameter is labeled "power".

Some TDMs use other options such as conical functions. The BPR functions in AequilibraE can be adjusted to more closely match those of the TDM core model as needed.

There is also an option in the RDR Tool Suite of using '`link_types_table.csv`' to fill in alpha and beta on each link. Below is an example, with notional values (Table 4-2). The default values of α = 0.15 and β = 4 are used for those links where the facility_type is blank or does not match a facility type in the link_types_table.

[14] Martin, William A., Nancy A. McGuckin. 1998. NCHRP Report 365: Travel Estimation Techniques for Urban Planning. Accessed 26 July 2022 from: https://onlinepubs.trb.org/onlinepubs/nchrp/nchrp_rpt_365.pdf. Chapter 9 of NCHRP Report 365 (1998), describes the BPR function, and provides recommended parameters.

Table 4-2 Example of link_types_table.csv (with notional values)

facility_type	alpha	beta
freeway	0.1	5
arterial	0.15	4

An Excel-based helper tool, `'GMNS_link_conversion.xlsx'`, is available to aid with the conversion. The helper tool includes the following:

- Peak_hr_to_day_capy_conversion parameter
- Lookup table for volume delay (α and β) parameters by functional class
- Lookup table for links whose availability is less than 1

The following parameters are used by the network routing model:

- Peak_hr_to_day_capy_conversion. Used to set up the network, as discussed earlier.
- vot_per_hour. Value of time in dollars / hour. This will be converted to cents / minute and is used to factor tolls into the link impedance. This parameter is specified in the configuration file.
- allow_centroid_flows. User can select 1 to allow flows to be routed through centroids/centroid connectors or 0 to block these types of paths (default). This parameter is specified in the configuration file.

The helper tool can be found here: https://github.com/VolpeUSDOT/RDR-Public/blob/master/helper_tools/GMNS_link_conversion.xlsx.

4.4 Configuring Transportation Disruption Submodule Based on Hazard Exposure

The RDRM code contains a sample configuration file (`'sample_RDR.config'`) which allows the user—among other configuration options—to set up the disruption analysis. The following parameters can be set:

- **Link Availability Approach** (link_availability_approach)—the approach used to convert exposure into a corresponding level of disruption for each individual segment in the road network. The current options are:
    - 'Default_Flood_Exposure_Function'—utilizes a depth-disruption function adapted from an existing function (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[15]. If this option is chosen, the exposure_unit must be defined so that units can be properly converted to millimeters. This function is only applicable to data for flooding depth, not other hazards. 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'—any exposure value above 0 is considered full exposure and link will not be available. Other links will remain fully available. This method is used when detailed

[15] 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

information about the relationship between the level of hazard exposure and disruption is unavailable or the user wants a "worst case" estimate of disruption.
    - 'Manual'—user-defined bins representing the conversion of exposure into link availability. If this option is chosen, the link_availability_csv path must be defined. If the manual approach is selected, the manual link availability CSV is read and processed to convert values that fall between each pair of min_inclusive and max_exclusive values into their corresponding link_availability value. For example, the user can specify that exposure values greater than or equal to 0 and less than 0.1 will be converted to a link availability value of 1 (no disruption). Subsequent ranges of values can be specified to convert to lower values of link availability until exposure values greater than or equal to 1 are converted to a link availability of 0 (fully disrupted).
    - 'Beta_Distribution_Function'—due to the complexity of this approach compared to the others, there are several additional configuration parameters that must be defined if this approach is selected. These fields include 'alpha', 'beta', 'lower_bound', 'upper-bound' and 'beta_method' (described in further detail below). The Keisan Online Calculator can be used to help the user test different alpha and beta parameters that define the shape of the customized beta distribution. The user must define the bounds of values where link availability is expected to be partially impacted by a particular hazard (values outside these bounds will default to 0% availability or 100% availability depending on the beta method chosen).
- **Exposure Field** (exposure_field)—this is the field or column name associated with the exposure level for each asset in the transportation network (e.g., Value). It may vary depending on the source of the exposure data. Examining the source exposure dataset within a program like Microsoft Excel or ArcGIS can confirm the name of the exposure grid field.

The following parameters are located in the configuration file but only need to be defined if the relevant link availability approach is selected.

- **Specific Configuration Parameters for 'Manual' Link Availability Approach**
    - **Link Availability CSV** (link_availability_csv)—must be defined if using the manual link availability approach. The user should base this off of a template CSV (`'sample_manual_link_availability_bins.csv'`) that accompanies the code in the "`config`" subfolder of the main RDR directory.
- **Specific Configuration Parameters for 'Default_Flood_Exposure' Link Availability Approach**
    - **Exposure Unit** (exposure_unit)—must be defined if using the default flood exposure link function. Compatible units are feet, yards, and meters.
- **Specific Configuration Parameters for 'Beta_Distribution_Function' Link Availability Approach**
    - **Alpha** (alpha)—a number greater than 0 that helps define the shape of the beta distribution.
    - **Beta** (beta)—a number greater than 0 that helps define the shape of the beta distribution.
    - **Lower Bound** (lower_bound)—the exposure value where link availability reaches 0% (if lower cumulative beta distribution function is utilized) or 100% (if upper cumulative beta distribution function is utilized).

    - **Upper Bound** (upper_bound)—the exposure value where link availability reaches 100% (if lower cumulative beta distribution function is utilized) or 0% (if upper cumulative beta distribution function is utilized).
    - **Beta Method** (beta_method)—user can select 'lower cumulative' or 'upper cumulative'. If 'lower cumulative', link availability reaches 0% at lower bound and 100% at upper bound. If upper cumulative, link availability reaches 100% at lower bound and 0% at upper bound. The shape of the curve defining link availability between the lower and upper bounds is determined by the alpha and beta parameters. For either method, link availability will always be 100% for links with no hazard exposure.

In addition, two other parameters in the configuration file specify how disruption is applied to centroid connector links and resilience project links, respectively:

- 'highest_zone_number' – Node ID designating the highest node ID in the network for a centroid node. Links connecting one or more centroid nodes are not impacted by hazard events.
- 'resil_mitigation'approach' – Method used to calculate mitigation for resilience projects. If 'manual' is used, then the user must provide link-level exposure mitigation data for each project link in the `'project_table.csv'` input file (see Section 4.7.2).

Links not found in the exposure analysis input files are assigned a link availability of 99.9% by default.

4.4.1 Output and Validation

The output of the exposure and disruption module is a CSV file containing the entries for each transportation network asset and its availability under each unique hazard scenario. This output file is an input for the core models. This file enables the analysis of the different hazard scenarios with resilience investments (mitigations).

The user should validate the results before proceeding to the next section regarding damage disruption analyses. For example, the user should review the outputs to check for misidentification to ensure disruption is only occurring on the appropriate roadways given the hazard severity, e.g., check to see whether bridges that cannot be inundated are disrupted.

4.5 Configuring the RDR Metamodel Parameterization Submodule

This section describes how to use the core models to generate initial data for inputs to the RDRM. TDM analysis is designed to produce a steady state that describes the travel patterns for an average weekday under a given set of specified conditions. These steady states are produced for a base year and an out year (e.g., 50 years into the future). The base year is the initial year of the analysis, and the choice of base year depends on what data are available to the user and the agency decision making goals. The out year is a future year for which the user has reasonable estimates of trip demand and is within the period of analysis.

4.5.1 RDR Metamodel Components

The analytical steps executed by the RDRM are as follows:[16]

- Latin Hypercube Sampling selects which scenarios will be run in the core models.
- Match core model outputs with their scenario factors.

[16] This process is reordered from the technical document to reflect the order of the mechanical steps rather than the conceptual steps of the process.

    - Scenario factors can include hazard attributes (e.g., sea level rise, storm surge), assumed elasticity of trip demand, resilience project, economic scenario, or other user-defined factors.
- Metamodel regression
    - Parameterize model with core model and/or supplemental model runs.
    - Response variables of the regression are total trips, PMT, and PHT aggregated across the transportation network.
    - Run regression to produce the estimated performance metrics for all combinations of scenario factors not implemented in the core model or supplemental model runs.
    - Validate regression model outputs and reconsider as needed the specification of the regression model(s) and/or number of core model runs needed.
- Scenario expansion and annualization
    - Extend daily hazard snapshots to produce logical space of scenario hazard recovery events using user-defined recovery parameters.
    - Interpolate regression model outputs to produce estimated performance metrics for all hazard events.
- Pass results to RDR ROI Analysis Module

4.5.2 Configuring the Latin Hypercube Sampling

The Latin hypercube sampling (LHS) module is used to select the set of core model runs used to fit the regression model in the RDRM. The module chooses uncertainty 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 user specifies the total number of samples selected to fit the regression using the 'lhs_sample_target' parameter in the configuration file. If the parameter value is too small and the sample is unable to provide coverage of the full scenario space, then the user will encounter an error during the run and be prompted to enter a larger number. The larger the LHS sample target, the longer the runtime, as each core model run can take several hours depending on the size of the network. As a rule of thumb, sampling at least 20% of the scenario space using the core models is recommended and can be further adjusted based on the results of the regression if needed (see Section 4.6.1 below). While there is no fixed number for scenarios sampled that should be used to parameterize the metamodel, for smaller numbers the resulting metamodel may have high uncertainty around the estimated number of trips and hours of travel and thus the ROI analysis. In addition to checking model fit in the regression module, it is recommended that the user conduct some sensitivity analysis of resulting metamodel outputs around the number of sampled scenarios.

There are a couple of additional user parameters for the LHS module when conducting an additional run (Section 3.3). In order to run an additional run, a set of core model runs must already exist; the 'do_additional_runs' and 'lhs_sample_additional_target' parameters in the configuration file are then used to indicate that new core model runs should be used to augment the existing ones. In this setting, the 'lhs_sample_target' parameter should be set to the same number as the previous run.

4.5.3 Configuring the 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 RDR, 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 requires the following inputs:

- An origin-destination trip table, stored in a square matrix in open matrix (OMX) format (see below).
- A routable network consisting of node and link tables (see Section 4.3), which are stored in an SQLite database.

Several parameters in the configuration file under the [metamodel] section are used to configure the core model. The 'aeq_run_type' parameter specifies whether a shortest path or routing methodology should be used by AequilibraE. The 'run_minieq' parameter specifies if the routing code should be run multiple times in order for vehicles to adjust route choice and settle more into an equilibrium state. A configurable parameter 'allow_centroid_flows' indicates whether routing is permitted via the centroid connectors within AequilibraE.

In addition, there are several input files required to run the AequilibraE core model. They include demand files, the (optional) true shapes file, a sample SQLite database, and a set of (optional) AequilibraE look-up tables. Technical details of how the input files are used by the core model can be found in the main technical documentation.

The demand OMX files (name format '{econ}_demand_summed.omx') provide origin-destination trip table data for each future economic scenario specified in the model parameters file for AequilibraE in the 'aeq_run' module. These files are located in the "AEMaster/matrices" subfolder of the input data folder. These demand files must be provided by the user in the open matrix (OMX) data file format. The demand matrix in the OMX file should be a square matrix. The RDR Tool Suite provides a set of Python helper tools and documentation for converting trip table data into the OMX format.

The optional true shapes file is named 'TrueShape.csv' and is located in the "LookupTables" subfolder of the input data folder. It provides geospatially explicit shape information for links in the network through the well-known text (WKT) field, which can be used to visualize the impact of hazard events. The CSV file contains the required fields 'link_id' and 'WKT', all of which are used by the 'aeq_run' module.

The template SQLite database 'project_database.sqlite' is provided with the RDR Tool Suite in the "config" subfolder of the RDR directory. The database is used to input network node and link attributes to AequilibraE. The template SQLite database should be copied into the "AEMaster" subfolder of the input data folder prior to any RDR run.

To convert network and exposure data into inputs for the AequilibraE core model, a set of optional look-up tables can be used as input files. These files should be placed in the "LookupTables" subfolder of the input data folder. Currently there is only one optional look-up table used by RDR:

- 'link_types_table.csv', discussed in Section 4.3.2, specifies custom volume-delay function parameters for each link type, which are provided as input to AequilibraE. The input file has required fields 'facility_type', 'alpha', and 'beta', all used by the 'aeq_run' module. The 'facility_type' field should match the 'facility_type' field in the network attribute files.

4.5.3.1 Trip Table Preparation

The RDR implementation of AequilibraE expects a single trip table, in the shape of a square matrix in OMX format,[17] representing person trips for a generic day of travel. The documentation for the existing MPO TDM will have information on the parameters needed to synthesize such a trip table. Parameters will include:

- Appropriate conversions (if necessary) from production-attraction (home – non-home destination) trips to the actual origin and destination trips. For example, consider 100 round trips from home location H to work location W, traveling to work during the AM peak and from work during the PM peak. This would yield the following trips in origin-destination format:
    - 100 trips from H to W during the AM Peak
    - 100 trips from W to H during the PM Peak

If trip tables are not available from an existing TDM, there are several ways to synthesize them:

1. Conduct surveys of travelers, asking (at a minimum) their origins and destinations. For automobile travel, it may also be possible to survey license plates, later matching them to the locations where the vehicles are registered.
2. Estimate trips produced or attracted to various land uses, either via observations or using tools such as the ITE trip generation manual (https://itetripgen.org). It is then necessary to distribute the trips from each source to the various destinations.
3. Buy O-D data from a commercial provider (who typically prepares these data based on cellphone observations).

4.6 Configuring the RDR Scenario Expansion Submodule

4.6.1 Configuring the Regression

A number of different possible regression models can be applied by the user. The simplest is a linear regression, where each input is a predictor and each target variable has a different regression model. This leads to three linear regression models, one each to predict number of trips, hours, and miles travelled. The RDRM implements this easily interpretable linear regression model as the 'base' model. Additional models that can be run by the user using the RDRM code (specifically, in `rdr_Metamodel_Regression.Rmd`) include:

- 'interact' – inclusion of interaction terms (e.g., the statistical interaction between hazard event and recovery stage, and between project group and resilience project)
- 'projgroupLM' – separate regression models for each set of resilience projects within each project group
- 'multitarget' – a simplified implementation of TMIP-EMAT's multitarget Gaussian process regression[18]
- 'mixedeffects' – mixed-effects model with random effects for each resilience project within a project group

[17] See Open Matrix Format | TF Resource and GitHub - osPlanning/omx: Open Matrix (OMX). RDR also provides a helper tool for converting comma-separated origin-destination-trip lists to an OMX file.
[18] TMIP-EMAT. [Online]. Meta-Model Regression. Accessed 26 July 2022 from https://tmip-emat.github.io/source/emat.metamodels/regression.html.

The user can change the regression model they use in the RDRM by adjusting the 'metamodel_type' parameter in the configuration file. If the user chooses to modify the regression model used in the run after an initial analysis, additional sampling of the scenario space using AequilibraE may be required to provide adequate sample coverage for the new regression model. This can be executed using the additional run functionality detailed in Section 3.3.

As a rule of thumb, if the coefficients of determination (r^2) of the resulting regression models for trips, travel time, or travel distance are below 0.5, the user should consider sampling more scenarios with core model runs (again done using the additional run functionality). On the other hand, a very high r^2 (>0.9) may indicate overfitting of the model, particularly if the number of scenario factors used as independent variables in the regression is large.

4.6.2 Configuring Metamodel Exposure Recovery

The recovery process requires the following inputs:

- The configuration file contains parameters specifying how exposure recovery paths and repair recovery paths are built;
- "`Model_Parameters.xlsx`" and "`UserInputs.xlsx`" input files define the parameters and their values that make up the scenarios;
- Exposure analysis files for each hazard scenario to be analyzed;
- The "`project_table.csv`" look-up table mapping resilience investments to their associated network links and network files with link attributes like distance and functional class;
- (Optional) Look-up tables for exposure-damage, repair cost, and repair time that the user provides. Default look-up tables are also provided.

The configuration file contains parameters used by the RDRM to build out complete hazard recovery paths (series of network states from maximum disruption to full recovery) from the hazard scenarios described in this section. The recovery section of the RDR configuration file (Figure 4-13) is used to specify the hazard duration parameters which include: minimum duration of hazard event, maximum duration of hazard event, number of hazard duration cases to run, hazard recovery build-out type and length, and hazard recovery path model. Default values for these parameters are provided. Using these parameters, the RDRM builds out hazard scenarios with varying hazard event duration and hazard recovery paths.

sample_RDR.config

```

[recovery]
# RECOVERY MODULE PARAMETERS

# The following parameters are used to build out the recovery scenarios and calculate damage costs.

# Minimum Duration of Hazard Event [days]
# Defines the minimum number of days a hazard event may last at the initial hazard severity.
min_duration = 2
# Maximum Duration of Hazard Event [days]
# Defines the maximum number of days a hazard event may last at the initial hazard severity.
max_duration = 8
# Number of Hazard Duration Cases to Run
# Defines the number of potential hazard durations to analyze with the RDR tool suite.
num_duration_cases = 4
# Hazard Recovery Build-out Type
# User can select 'days' or 'percent'.
# If 'days', the hazard recovery period (e.g., period after initial hazard severity and before end of hazard) is specified in number of days.
# If 'percent', the hazard recovery period is specified as a percentage of the duration of the initial hazard severity.
hazard_recov_type = 'percent'
# Hazard Recovery Build-out Length
# Defines the length of the hazard recovery period in either number of days or as a percentage.
hazard_recov_length = 50%
# Hazard Recovery Path Model
# Defines the approach used to construct hazard recovery path from initial hazard severity through the end of the hazard event.
# 'Equal' (default) = Hazard recovery stages are of equal length.
# Other options may be added in the future.
hazard_recov_path_model = 'Equal'

```

Figure 4-13: Configuration file showing parameters used to define hazard event duration uncertainties

The possible exposure recovery paths for a given scenario are constructed from a set of parameters that the user can define in the configuration file or leave to the default values. The ‘min_duration’ and ‘max_duration’ parameters, specified in days, define the shortest and longest time the hazard event lasts at the initial exposure severity. The ‘num_duration_cases’ parameter specifies the number of exposure recovery paths to generate for each scenario. The ‘hazard_recov_type’, ‘hazard_recov_length’, and ‘hazard_recov_path_model’ parameters define the subsequent network states of the exposure recovery path. The recession length, which is specified by ‘hazard_recov_length’ in either days or as a percentage of the initial hazard duration (depending on the value of ‘hazard_recov_type’), defines the duration of the hazard event after the initial exposure state. The recession path model parameter specifies the relative durations of the subsequent network states. In particular, the ‘Equal’ recession path model option currently implemented specifies that the exposure recovery path network states have equal duration, after the initial exposure state until the hazard has completely receded.

As an example, consider the following default (adjustable) parameters settings in the configuration file:

- min_duration = 2,
- max_duration = 8,
- num_duration_cases = 4,
- hazard_recov_type = ‘percent’,
- hazard_recov_length = 50%,
- hazard_recov_path_model = ‘Equal’.

The RDRM Recovery process uses these parameters to construct the possible exposure recovery paths for a given scenario and hazard event. The duration of the hazard at the initial exposure severity takes 4 possible values (‘num_duration_cases’), ranging from 2 days (‘min_duration’) at the shortest to 8 days (‘max_duration’) at the longest. From this, the RDRM creates four possible exposure recovery paths in the scenario space with initial exposure severity durations of 2 days, 4 days, 6 days, and 8 days. The recovery module then defines the subsequent network states of the exposure recovery path from the initial exposure severity duration. The recession lengths are defined to be 50% of the initial hazard durations; for the 8-day initial hazard duration, this means a recession length of 4 days, etc. To assign a recovery network state to each of the 4 days of the hazard recession period, the RDRM uses the Hazards table in "Model_Parameters.xlsx" input file to determine equally spaced network states starting at the initial exposure state to the final no-exposure state (as per the 'Equal' recession path model). Within the RDRM, the progression of network states is notated using a Hazard Level field constructed by the RDRM from the Hazards table—every possible exposure recovery path is written as a text string of non-increasing Hazard Levels, with one for each day of the hazard duration. For example, the exposure recovery path '4,4,4,4,3,1' defines a hazard that lasts for six days before reaching the no-exposure state. The initial exposure severity of Hazard Level 4 lasts for four days, and the recession period is two days with the first day at Hazard Level 3 and the second day at Hazard Level 1. After the sixth day, the hazard has completely receded.

4.6.3 Configuring Metamodel Damage and Repair Recovery

There are four main input files that the user can provide to calculate damage and repair metrics. Alternate methods or default input files are also provided for these functions; sample files demonstrate how the user can create their own inputs and are located in the "config" subfolder of the RDR directory. Technical details of how the RDR Metamodel uses each of these input files can be found in the RDR Tool Suite Technical Document.

The RDRM provides the analyst with a few options for calculating asset damage. The method used is selected by the analyst in the configuration file with the parameter 'depth_damage_approach':

- The 'Binary' approach provides the coarsest damage calculation. Any level of exposure above 0 feet is considered to incur full damage to the network segment in the road network. The link is considered fully damaged and incurs the full damage cost and time to repair. Network segments with no exposure incur no damage.
- The 'Default_Damage_Table' (see Table 4-3) uses a depth-damage table adapted from London data.[19] Note that the table is specific to water hazards and provides a mapping of exposure depth to asset damage percentage. The version of the table used by the RDR Tool Suite converts exposure depth to intervals to provide full coverage of all possible exposure depth values. The adapted default table is also provided below (see Table 4-4).

Table 4-3: Default depth-damage relationship (from Simonovic et al. 2011)

Asphalt Concrete		
Depth (m)*	Damage (%)	Explanation
-0.5	0	Slight damage may occur to subgrade and substructure due to seepage
0	0.05	Presume there is no damage to the surface layer until water level is above paved elevation
1	0.2	Including modest damage due to water on asphalt surface
2	0.5	Higher degree due to floodwaters inundating paved surface
5	1	Upper boundary of road damage

[19] Simonovic, S P; Burn, D; Sandink, D; Eum, H; Sredojevic, D; Peck, A; Bowering, E. 2011. The City of London: Vulnerability of Infrastructure to Climate Change. University of Western Ontario Department of Civil and Environmental Engineering. London, England.

Table 4-4: Default depth-damage look-up table used by the RDR Tool Suite for flood-based hazards

Asset Type	min_exposure	max_exposure	Damage (%)
All	-999999	-0.82	0
All	-0.82	1.64	0.05
All	1.64	4.92	0.2
All	4.92	11.48	0.5
All	11.48	999999	1

- The ‘Manual’ approach requires the analyst to provide their own exposure-damage table. The structure of the table must match the structure of the default depth-damage table with fields named min_exposure and max_exposure providing exposure depth intervals that map to a particular asset damage percentage. The Asset Type field can be used to further differentiate the exposure-damage function for different assets (e.g., roadway, bridge). The user should base this off of a template CSV (“`sample_manual_exposure-damage_table.csv`”) that accompanies the code in the “`config`” subfolder of the main RDR directory.

The user-provided exposure-damage table CSV file calculates link damage percentage based on user-defined bins for each asset type. The required fields are:

1. 'Asset Type' – Text string categorizing the network link. These should match the ‘Category’ field in the resilience project input files.
2. 'min_exposure' – Numeric lower bound for exposure level for each bin. This is compared to the ‘Value’ field of the exposure analysis input files.
3. 'max_exposure' – Numeric upper bound for exposure level for each bin. This is compared to the ‘Value’ field of the exposure analysis input files.
4. 'Damage (%)' – Numeric damage percentage value assigned for each bin. This should be a number between 0 and 1.

All fields are used by the ‘recov_init’ module.

The user-defined repair cost table CSV file is used to calculate link repair cost based on user-defined asset and facility type categories. The user should base this off of a template CSV (“`sample_repair-cost_table.csv`”) that accompanies the code in the “`config`” subfolder of the main RDR directory. The required fields are:

1. 'Asset Type' – Text string categorizing the network link. These should match the ‘Category’ field in the resilience project input files.
2. 'Facility Type' – Text string categorizing the facility type of the network link. These should match the ‘facility_type’ field in the network attribute files.
3. 'Damage Repair Cost' – Monetary value of repair cost for a network link of a particular asset type and facility type (specified in dollar units given by ‘dollar_year’ parameter in configuration file). Repair costs must be defined per lane-mile for all asset types except ‘Bridge’, which is defined per square foot. These look-up values are scaled by damage percentage to calculate link-level repair costs in the tool.
4. 'Total Repair Cost' – Monetary value of total repair cost (includes debris clean up, etc.) for a network link of a particular asset type and facility type (specified in dollar units given by

'dollar_year' parameter in configuration file). Repair costs must be defined per lane-mile for all asset types except 'Bridge', which is defined per square foot.

The default repair cost table also contains the field 'Network Type', which must be specified in the configuration file. All fields are used by the 'recov_init' module.

The user-defined repair time table CSV file is used to calculate average repair time based on user-defined asset type categories. The user should base this off of a template CSV ("`sample_repair-time_table.csv`") that accompanies the code in the "`config`" subfolder of the main RDR directory. The required fields are:

1. 'Asset Type' – Text string categorizing the network link. These should match the 'Category' field in the resilience project input files.
2. 'category_min' – Numeric lower bound for repair category for each bin. This is compared to the 'facility_type' field of the network attribute files.
3. 'category_max' – Numeric upper bound for repair category for each bin. This is compared to the 'facility_type' field of the network attribute files.
4. 'repair_time' – Numeric repair time for a network link of a particular asset type in units of days. Repair times are average look-up values and are scaled by damage percentage to calculate link-level repair times in the tool.

All fields are used by the 'recov_init' module. The 'category_min' and 'category_max' fields create bins for determining repair time. If the default repair time is used, repair category values are created from 'facility_type' field for road links (should match FHWA Highway Functional Classification values) and summed 'length' field across links (in feet) for bridge links. If a user-defined repair time look-up table is used, the 'facility_type' field is used for all links. The default repair time values were provided by Virginia DOT and may not be applicable to all agencies; the user should use agency-specific estimates whenever possible.

4.7 Configuring Resilience Projects

4.7.1 Configuring Transportation Disruption Mitigation Based on Resilience Investment

A user can represent the mitigation of a resilience investment in three distinct ways. First, a resilience investment that adds new roadways can be modeled by adding a new roadway to the roadway network. Second, a resilience investment can be modeled as a reduction in the exposure analyses (e.g., reducing flooding depth by a given amount). The modified exposure is then carried through the disruption and damage analyses. Third, agencies can directly adjust the extent of disruption and damage associated with a resilience investment for each given hazard (e.g., to assume complete or partial mitigation on the asset). The RDR Tool Suite provides agencies with a straightforward method for the exposure modification approach for incorporating resilience alternatives.

The current RDRM disruption analysis offers two approaches for modeling mitigation of a resilience investment: complete mitigation and link-level partial mitigation. The approach followed is set by the user in the configuration file using the 'resil_mitigation_approach' parameter. The first approach models resilience investments as a complete mitigation of the impact of a hazard event on link availability and damage costs. Investment in a resilience project leads to full link availability on the associated network links and zero asset damage, which translates to no repair cost or recovery time on the associated network links, for all hazard events analyzed.

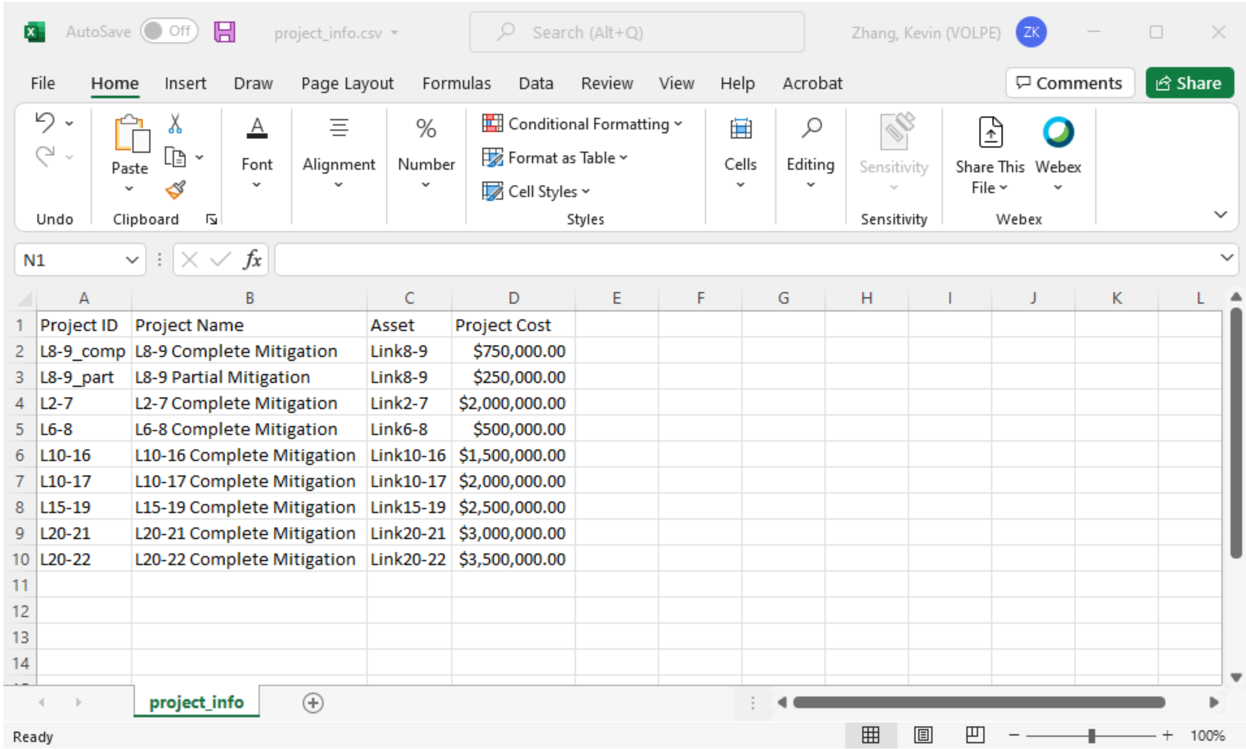
The second approach of partial mitigation allows the user to specify an exposure mitigation value for each network link of the asset associated with the resilience investment. This reduction in exposure is applied across all hazard events, the calculated impact on disruption and damage of the mitigation is attributed to the resilience investment, and associated cost savings compared to the baseline of no mitigation are aggregated for the ROI analysis. This modeling functionality is provided by the 'Exposure Reduction' field in the project table input file described in Section 4.7.2. Modeling varying mitigation effects of a resilience investment by hazard event requires manual adjustment outside the RDRM and is not within the scope of the current disruption analysis.

4.7.2 Resilience Project Files

Two input files provide data on resilience investments: the project info file and the project table file.

The project information file (Figure 4-14) lists all resilience projects ('Project ID') and their costs ('Project Cost'), and is used by the RDR ROI Analysis Module for economic analysis. Each resilience project is also given a project name ('Project Name') and associated with a specific asset of the transportation network ('Asset'). The project information file is named "`project_info.csv`" and located in the "`LookupTables`" subfolder of the input data folder. All fields are used by the 'recov_calc' module. There are four required fields in the table:

1. 'Project ID' – ID of the resilience project. These should match the resilience projects identified in the model parameters file. Resilience projects are not allowed to be given the ID 'no' as this is reserved for the no-action baseline.
2. 'Project Name' – Text string describing the asset and resilience investment associated with the resilience project.
3. 'Asset' – Text string categorizing the asset associated with the resilience project.
4. 'Project Cost' – Numeric values of the resilience investment costs for each resilience project. The costs provided in the project info file should already be standardized for the period of analysis and should reflect the dollar year units specified by the 'dollar_year' parameter in the configuration file. See Appendix H: Capital Cost and Residual Value Helper Tool for how to use the helper tool to calculate discounted capital costs over the life span of the project.



Project ID	Project Name	Asset	Project Cost
L8-9_comp	L8-9 Complete Mitigation	Link8-9	$750,000.00
L8-9_part	L8-9 Partial Mitigation	Link8-9	$250,000.00
L2-7	L2-7 Complete Mitigation	Link2-7	$2,000,000.00
L6-8	L6-8 Complete Mitigation	Link6-8	$500,000.00
L10-16	L10-16 Complete Mitigation	Link10-16	$1,500,000.00
L10-17	L10-17 Complete Mitigation	Link10-17	$2,000,000.00
L15-19	L15-19 Complete Mitigation	Link15-19	$2,500,000.00
L20-21	L20-21 Complete Mitigation	Link20-21	$3,000,000.00
L20-22	L20-22 Complete Mitigation	Link20-22	$3,500,000.00

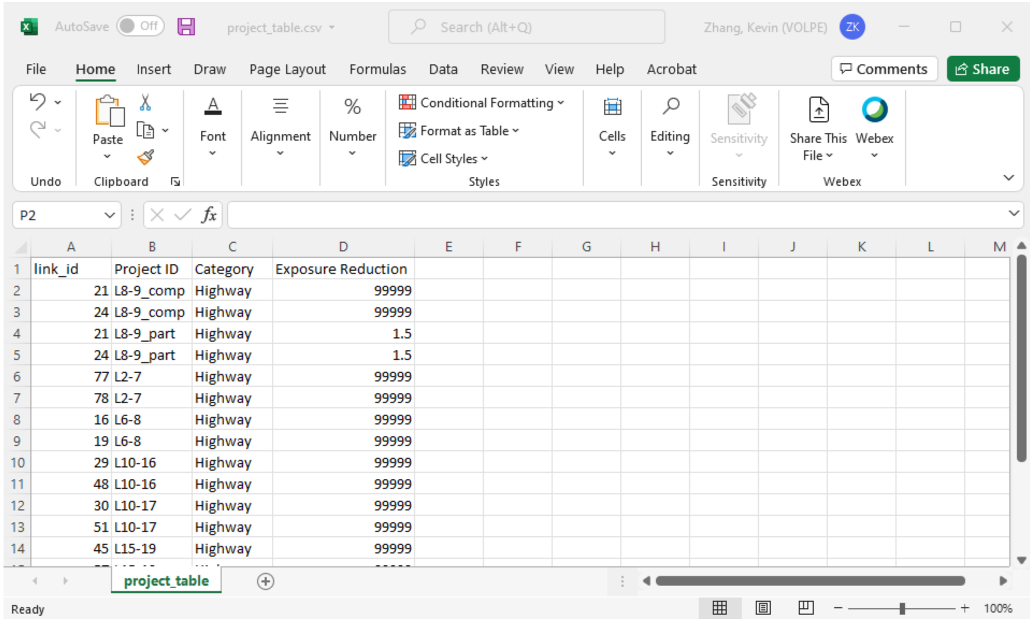
Figure 4-14: Sample project info table for Quick Start 1

The project table file (Figure 4-15) lists all resilience projects and the network links they are associated with. It is named "`project_table.csv`" and located in the "`LookupTables`" subfolder of input data folder. Each row of the CSV file represents a link associated with the specified resilience project. There are three required fields in the table:

1. 'link_id' – ID of network link.
2. 'Project ID' – ID of the resilience project associated with the link. These should match the resilience projects identified in the model parameters file.
3. 'Category' – Text string categorizing the resilience project. The 'Category' field values must correspond to the 'Asset Type' values in both the repair cost and repair time tables. To use the default repair cost and repair time tables provided with the tool suite, the 'Category' field values must be either 'Highway' or 'Bridge'. The 'Category' field should have the same value for all links associated with a resilience project.

An additional optional field for partial mitigation functionality:

4. 'Exposure Reduction' – Numeric value specifying link-level mitigation associated with the resilience project. This field is required if the 'resil_mitigation_approach' parameter in the configuration file is set to 'Manual'. Blank values in this field imply no mitigation on the project link; a value of 99999 is used to denote complete mitigation on the project link regardless of hazard event.



link_id	Project ID	Category	Exposure Reduction
21	L8-9_comp	Highway	99999
24	L8-9_comp	Highway	99999
21	L8-9_part	Highway	1.5
24	L8-9_part	Highway	1.5
77	L2-7	Highway	99999
78	L2-7	Highway	99999
16	L6-8	Highway	99999
19	L6-8	Highway	99999
29	L10-16	Highway	99999
48	L10-16	Highway	99999
30	L10-17	Highway	99999
51	L10-17	Highway	99999
45	L15-19	Highway	99999

Figure 4-15: Sample project table file for Quick Start 1

4.8 Configuring the ROI Analysis

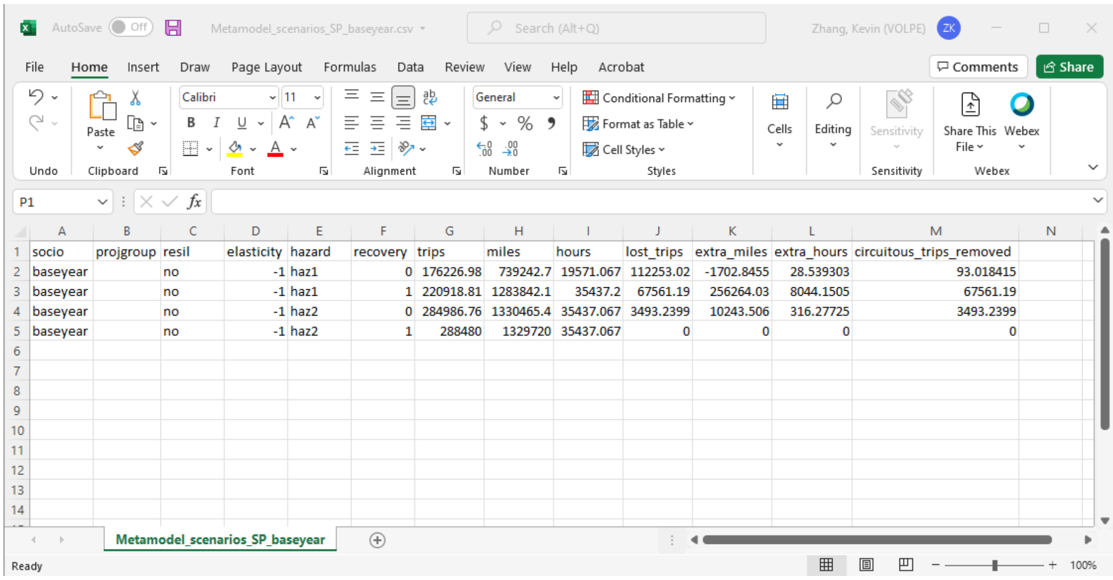
The RDR ROI Analysis Module takes the regression model built by the RDRM and monetizes the benefits and costs for each resilience project across all uncertainty scenarios for the user-specified period of analysis. Once the regression model has been constructed by the RDRM for the analysis framework specified by the user, the majority of ROI analysis inputs are contained within the configuration file (Section 4.1.1).

4.8.1 Economic Parameters

The user parameters in the configuration file pertaining to ROI analysis are contained in the [analysis] section. Most parameters have default values provided in the sample configuration file; these are referenced from USDOT BCA guidance. These include values for: year-on-year discounting factor, vehicle occupancy rate, vehicle operating cost, and value of travel time. If the user has more specific values for their region of analysis, they can set these in the configuration file.

Two parameters in the configuration file should be noted in particular. The 'base_year' and 'future_year' values correspond to the trip tables provided for the core model (see Section 4.5.3.1). Note that 'base_year' and 'future_year' cannot be the same year; the shortest period for the ROI analysis is two years. In addition, a required input file is a full set of base year core model runs.

The base year core model runs must be provided in a file named "`Metamodel_scenario_{SP/RT}_baseyear.csv`" where the bracketed text is either 'SP' or 'RT' as specified in the configuration file. The input file should be located in the input data folder, with required fields 'hazard', 'recovery', 'trips', 'miles', and 'hours', all used by the 'recov_calc' module. The base year core model runs should be run for the specified base year with the corresponding base year hazard event and recovery stage (e.g., no sea-level rise if that is only a future year condition) and with the base year demand. A sample base year core model runs file from Quick Start 1 is shown in Figure 4-16.



socio	projgroup	resil	elasticity	hazard	recovery	trips	miles	hours	lost_trips	extra_miles	extra_hours	circuitous_trips_removed
baseyear		no	-1	haz1	0	176226.98	739242.7	19571.067	112253.02	-1702.8455	28.539303	93.018415
baseyear		no	-1	haz1	1	220918.81	1283842.1	35437.2	67561.19	256264.03	8044.1505	67561.19
baseyear		no	-1	haz2	0	284986.76	1330465.4	35437.067	3493.2399	10243.506	316.27725	3493.2399
baseyear		no	-1	haz2	1	288480	1329720	35437.067	0	0	0	0

Figure 4-16: Sample file of base year core model runs for Quick Start 1

The RDR Tool Suite contains a helper tool to create the base year core model runs input file, see Appendix G: Base Year Run Helper Tool. The helper tool uses the core model input files to iteratively run the base year trip table demand through AequilibraE for each hazard event and recovery stage combination.

4.8.2 Selection of economic performance metrics

There are three methods for evaluating project performance in the RDR Tool Suite: Benefit-Cost Analysis (BCA), Benefit-Cost Analysis under uncertainty (BCA-U, also referred to as BCA-Regret analysis), and breakeven analysis. Particular user inputs are required to run each method:

- BCA – To run a BCA, the user must provide resilience project costs in the resilience project input file "`project_info.csv`" (Section 4.7.2) and hazard event probabilities in the model parameters file (Section 4.1.2).
- BCA-U – To run a BCA-U, the user must provide resilience project costs, but uncertainty scenario probabilities do not need to be specified; the user should refer to the "Regret" metrics as reported in the Tableau visualization output (see Section 5).
- Breakeven – To run a breakeven analysis, the user should set all resilience project costs to zero. Hazard event probabilities should be provided in the model parameters file.

Note that safety and emission benefits are not included in the current version of the RDR Tool Suite, but users can calculate the per-mile safety and emissions benefits manually if desired. See Appendix I: Safety and Emissions Benefits for details about how to use the output files to calculate safety and emissions benefits.

4.8.3 Selection of ROI performance period

The performance period is specified by the user in the [analysis] section of the configuration file. The two parameters, 'start_year' and 'end_year', define the beginning and ending years of the performance period for which benefits and costs are calculated by the RDR Tool Suite. Note that these two parameters are distinct from 'base_year' and 'future_year', as the ROI performance period does not necessarily need to coincide with the years for which trip tables are provided to the core model. Core model outputs for the base year and future year are adjusted during the annualization process for the ROI performance period specified by the start year and end year parameters.

5 RDR Reporting and Visualization

This section describes how to use the RDR Tool Suite's Reporting and Visualization Module in decision making. The purpose of the RDR Reporting and Visualization Module is to provide the user with a streamlined approach for reviewing the ROI analysis within the analysis team as well as with decision-makers external to the analysis team. For details on how the RDR Tool Suite Reporting and Visualization Module is structured and the data it contains, please see Section 7 in the Technical Documentation.

5.1 Opening the Tableau Workbook

The primary outputs of an RDR run are the Tableau visualizations contained in a Tableau workbook (.twbx file extension). The workbook is automatically generated after running the RDR Tool Suite (Section 3) in the "`Reports`" folder of the output directory specified by the user in the configuration file. The "`Reports`" folder contains a timestamped Tableau report folder for each run completed. The only contents of this folder are the Tableau visualizations. To open this file, Tableau must be installed. Double-click on the file to open. Note that the Tableau workbook may take some time to open initially as it loads all of the data and filters; subsequent uses of the workbook will be faster.

5.2 General guidelines for using the Tableau Visualization

The RDR Tool Suite Tableau visualizations are designed to allow users to quickly assess analysis results for high-level conclusions such as a simple rank-ordering of the projects by performance under the BCA framework as well as to explore in detail how projects perform across the range of scenarios. Each dashboard in the Tableau file is designed to help address particular questions.

- Overview Dashboard: This simple dashboard is useful for presenting results to decision makers or external stakeholders. This dashboard provides a simple listing of the projects by their regret ranking with average net benefits and average benefit cost ratio. The dashboard also shows a simple measure of the variability of the net benefits and BCR for each project called the coefficient of variation, which is a unitless measure of the variability of the project performance. Lower values mean the project performs more consistently across the scenario space while higher values mean the project performs inconsistently across the scenario space.
- Top-Ranked Dashboard: This dashboard is useful in cases where the user wants to compare the performance of the top-ranked projects (ranked by regret).
- Summary Dashboard: This dashboard provides a graphical visualization of how a project ranks across all of the different scenarios. This dashboard should be used if the user wants to see what the spread of a project's rankings are across the entire scenario space and wants to be able to quickly assess how that spread relates to other projects.
- Asset-Project Dashboard: This dashboard should be used if the user would like to get a more detailed picture of the performance of the project across the various scenarios.
- Asset Dashboard: This dashboard should be used when considering more than one project for a given asset, e.g., one project raises the bridge, while another adds scour protection. The dashboard allows the user to compare the projects for the same asset directly with three scatterplots, a scenario count by ranking bar graph, and a box-and-whisker plot graph of the main benefit categories for each project.
- Exploratory Dashboard: This dashboard is useful to explore the outcomes at the most fine-grained level. This dashboard is most useful for looking at the outcome data to see what the relationships are between the scenario parameters and the outcomes.

5.3 General guidelines for using results in decision-making

The RDR Tool Suite results can be incorporated directly into many cost-effectiveness decision-making processes. The analytical approach relies fundamentally on BCA. Users should be careful to note that the tool only estimates the resilience benefits of a project. If a project is expected to provide more benefits than those that accrue from mitigating the impact of a hazard, such as expanding capacity of an asset under normal operating conditions by adding an additional lane, the RDR Tool Suite tool does not estimate the benefits of those non-resilience aspects of the projects. The user will need to compute those non-resilience benefits using some other means. The RDR Tool Suite can be used to estimate the benefits of investments in asset resilience. Users should be very careful not to double count the capital costs and maintenance costs of the resilience project. If another BCA has been performed for an investment, and the user is using the RDR Tool Suite to calculate only those resilience benefits of the project (those produced by mitigating a hazard rather than those that accrue under normal operation), then the Breakeven analysis approach should be used as it provides only the estimate of benefits rather than net benefits.

5.4 General guidelines for comparing RDR to other analyses, e.g., REMI

The RDR Tool Suite provides BCA, BCA under Uncertainty, or breakeven analysis results that can be incorporated into decision-making processes that involves cost effectiveness. Some users may wish to incorporate the RDR Tool Suite results into other decision-making processes and frameworks. The RDR Tool Suite may or may not be appropriate for these approaches, and users should carefully consider whether the RDR Tool Suite results are compatible with other frameworks or analyses. In particular, users may wish to incorporate the RDR Tool Suite results into an Economic Impact Assessment (EIA) or compare the RDR Tool Suite results with those of an EIA. Users should avoid comparing the RDR Tool Suite results, which are based on the BCA framework, with those of EIA because the two frameworks are different. An EIA considers how the composition of the economy is changing as a result of a decision focusing on macro-economic factors such as sectoral output, wages, and tax revenue, etc. BCA does not consider these compositional changes but rather focuses on the direct real loss or gain of resources (e.g., gasoline used, time traveled, and crash costs, etc.) due to the project. BCA compares the project performance against a baseline which EIA does not do. BCA considers costs and benefits to all of society, rather than just a single region as is typical with an EIA. BCA also ignores transfers between parties that do result in a real resource whereas transfers between parties is an essential component of an EIA (e.g., EIA considers changes in tax revenue which BCA does not consider because it is a transfer). These crucial differences between EIA and BCA make it necessary for users to avoid comparing the results of the RDR Tool Suite with those of an EIA.

Some EIA tools estimate impacts that are appropriate for BCA in addition to those appropriate for the EIA. These tools calculate direct non-transfer costs and benefits such as the impact of the project on travel such as travel time savings, vehicle operating cost savings, and safety benefits from reduced crashes, etc.[20] The estimates of the BCA benefit categories using these models in principle can be compared to those calculated by RDR Tool Suite. However, users should also be careful to determine whether the EIA tools are estimating benefits under the same hazard scenarios that are modeled under the RDR Tool Suite. The typical EIA model does not estimate the impact of hazardous events on network performance in the way that RDR does.

[20] REMI's Transight is one such model. https://www.remi.com/model/trans-sight/

6 Troubleshooting

6.1 Installation

1) Some users may encounter a message about the Python package CFFI when building the conda environment. This package (C Foreign Function Interface) is what rpy2 uses to run R code from within Python. If you receive a message about 'ABI mode', you need to run the following in the Windows command line:

   - `set RPY2_CFFI_MODE=ABI`

   Then you should be able to proceed as outlined in Section 2.3.

2) Users should confirm that the Anaconda installation and AequilibraE package installation on their machine are located in areas where they have read/write access.

3) Users having difficulty creating the RDRenv Anaconda environment may need to run the following in Anaconda Prompt before trying again:

   - `conda config --set channel_priority false`

   The conda command `conda clean --all` may also be useful for freeing up space and removing old versions of packages.

4) Running an RDR batch file downloaded from the public GitHub repository may be blocked by the user's security settings by default. To get around this issue, right-click on the batch file, go to "Properties", go to the Security tab, and allow "Read & execute" permissions for the user.

5) If the user has trouble with R package installation during their first RDR run, they can work around this issue by running the "`rdr_Rutil.R`" file (in the "`metamodel_py`" subfolder of the main RDR directory) in the R installation of their RDRenv conda environment before executing a RDR run.

6) The RDR Tool Suite creates a custom R installation within the RDRenv conda environment during the setup process in order to ensure the correct versions of R packages are used. Depending on the user's previous R installations, the tool suite may access the wrong R package libraries, leading to dependency errors. The R variable `.libPaths()` can be used to assess which R installation is being referenced by the code. The user may find it necessary to (1) delete older versions of R from their local machine, (2) re-create the RDRenv Anaconda environment.

6.2 Input Validation and Troubleshooting

1) It is important the user confirm that all dollar inputs are converted to the same year ('dollar_year' parameter specified in the configuration file). Dollar inputs to the RDR Tool Suite include (1) 'miles_cost', 'hours_cost' parameters in the configuration file, (2) 'Project Cost' field in the project info file, (3) repair costs ('Damage Repair Cost' and 'Total Repair Cost' fields) in the repair cost look-up table, (4) link toll values ('toll' field) in the network attribute input files. Note that link-level tolls should be provided in cents, not dollars. These units should be consistent to provide accurate results in the economic analysis and project prioritization.

2) Trip table matrices as stored in OMX input files should be in a square matrix format, not a tall table indexed by origin-destination pair.

3) Large numeric values for the network node and link IDs can cause errors with AequilibraE due to a memory issue. If this occurs, renumber the IDs starting from 1 across all input files.

4) A common reason for unexpected results or zero reported benefits is a mismatch in formatting between input files. The RDR Tool Suite relies on several data table joins to pull together data across input files to calculate ROI—if two columns are supposed to be matched to each other but one is provided as a text string and the other is numeric, the data table join will fail. For example, the ‘Category’ column in the project table input file is matched to the ‘Asset Type’ column in the repair cost table. If highway functional class labels are used, but ‘Category’ is numeric (e.g., 1) and ‘Asset Type’ is text (“1.0”), then the RDR Tool Suite will fail to associate resilience project network links with their repair costs, resulting in zero benefits from mitigating incurred repair costs.

6.3 RDR Tool Suite Run and Analysis

1) The first place to diagnose an error or unexpected output from the RDR Tool Suite is the command window where the batch file was executed. If a fatal error occurs during a run, an error message will be written to the screen specifying the location in the code where an error was reached. Exception messages provide more detailed feedback on steps to take to resolve the error.

2) The text report generated by the ‘o’ module contains a compilation of errors and warnings encountered during a run. This can be used to diagnose unexpected results.

3) More detailed information on the run can be found in the log files. Log files are automatically generated during a run of the RDR Tool Suite in the “`logs`” folder of the output directory and are labeled according to the RDR Tool Suite module they correspond to. These output files provide detailed reporting on the tool run and can be used to troubleshoot any errors encountered by the user. Messages labeled “DEBUG” or “WARNING” provide step-by-step information.

4) Intermediate output files are generated by each module of the RDR Tool Suite. Descriptions are provided in Appendix B: RDR Tool Suite Module Outputs.

5) Some users using certain installations of conda may see the following messages when running an RDR bat file. However, the program still runs to completion with no additional errors.
    a. ‘activate’ is not recognized as an internal or external command, operable program or batch file.
    b. 'conda.bat' is not recognized as an internal or external command, operable program or batch file.

7 Conclusion

The RDR Tool Suite 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 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.

Appendix A: RDR Tool Suite Input Files

Table A-1: RDR Tool Suite Input Files

Input File	Location	Filename	Required Fields	Modules	Notes
Configuration file	User-defined; location of configuration file should match path specified in batch file	User-defined; filename should match batch file	See documentation within sample configuration file	'lhs' 'aeq_run' 'rr' 'recov_init' 'recov_calc'	Specifies input and output folders
Model parameters file	Input directory 'input_dir' in configuration file (e.g., `Data\inputs`)	`Model_Parameters.xlsx` ("UncertaintyParameters", "ProjectGroups", and "Hazards" tabs)	See Section 4.1.2	'lhs' 'recov_init' 'recov_calc'	Specifies all possible values for each dimension of scenario space, list of hazard event stages
User inputs file	Input directory 'input_dir' in configuration file (e.g., `Data\inputs`)	`UserInputs.xlsx` ("UserInputs" tab)	'Hazard Events', 'Economic Scenarios', 'Trip Loss Elasticities', 'Resiliency Projects', 'Event Frequency Factors'	'recov_init'	Specifies subset of scenario space to evaluate in RDR ROI Analysis Module
Resilience project files	Subfolder "`LookupTables`" in input directory (e.g., `Data\inputs\LookupTables`)	`project_table.csv`	'Project ID', 'link_id', 'Category'	'aeq_run' 'recov_init'	Maps resilience project to network links
Resilience project files	Subfolder "`LookupTables`" in input directory (e.g., `Data\inputs\LookupTables`)	`project_info.csv`	'Project Cost', 'Project ID', 'Project Name', 'Asset'	'recov_calc'	Defines project types and costs

Input File	Location	Filename	Required Fields	Modules	Notes
Network attribute files	Subfolder "Networks" in input directory (e.g., Data\inputs\Networks)	node.csv	'node_id', 'x_coord', 'y_coord', 'node_type'	'aeq_run'	Provides node attributes for each node in the network
Network attribute files	Subfolder "Networks" in input directory (e.g., Data\inputs\Networks)	{econ}{projgroup}.csv (one needed for each project group + economic scenario combination specified in model parameters file)	'link_id', 'from_node_id', 'to_node_id', 'directed', 'length', 'lanes', 'facility_type', 'capacity', 'free_speed', 'allowed_uses', 'toll'	'aeq_run' 'recov_init'	Provides link attributes for each link in the network
Exposure analysis files	Subfolder "Hazards" in input directory (e.g., Data\inputs\Hazards)	{hazard_filename}.csv (one needed for each hazard event specified in model parameters file)	'link_id', 'A', 'B', exposure_field name specified in configuration file	'aeq_run' 'recov_init'	Provides hazard exposure data at the link level
Demand files	Subfolder "AEMaster\matrices" in input directory (e.g., Data\inputs\AEMaster\matrices)	{econ}_demand_summed.omx (one needed for each economic scenario specified in model parameters file)	N/A	'aeq_run'	Provides origin-destination trip table data for AequilibraE
Base year core model runs file	Input directory 'input_dir' in configuration file (e.g., Data\inputs)	Metamodel_scenarios_{SP/RT}_baseyear.csv	'hazard', 'recovery', 'trips', 'miles', 'hours'	'recov_calc'	Provides core model outputs for base year
True shapes file (optional)	Subfolder "LookupTables" in input directory (e.g., Data\inputs\LookupTables)	TrueShape.csv	'link_id', 'WKT'	'aeq_run'	Provides link attributes for true shape network

Input File	Location	Filename	Required Fields	Modules	Notes
SQLite database	Subfolder "AEMaster" in input directory (e.g., Data\inputs\AEMaster)	project_database.sqlite	N/A	'aeq_run'	Stores network data for AequilibraE
AequilibraE look-up table files (optional)	Subfolder "LookupTables" in input directory (e.g., Data\inputs\LookupTables)	link_types_table.csv	'facility_type', 'alpha', 'beta'	'aeq_run'	Customizes volume-delay function parameters for AequilibraE
Exposure-disruption table file (optional)	User-provided path in configuration file	User-defined	'min_inclusive', 'max_exclusive', 'link_availability'	'aeq_run'	Converts hazard exposure to link-level disruption
Exposure-damage table file (optional)	Subfolder "config" in main RDR directory (e.g., RDR\config), or user-provided path in configuration file	default_exposure-damage_table.csv; or user-defined	'Asset Type', 'min_exposure', 'max_exposure', 'Damage (%)'	'recov_init'	Converts hazard exposure to link-level damage
Repair cost table file (optional)	Subfolder "config" in main RDR directory (e.g., RDR\config), or user-provided path in configuration file	default_repair-cost_table.csv; or user-defined	'Asset Type', 'Facility Type', 'Damage Repair Cost', 'Total Repair Cost'	'recov_init'	Converts link damage to repair cost
Repair time table file (optional)	Subfolder "config" in main RDR directory (e.g., RDR\config), or user-provided path in configuration file	default_repair-time_table.csv; or user-defined	'Asset Type', 'category_min', 'category_max', 'repair_time'	'recov_init'	Converts link damage to repair time

Appendix B: RDR Tool Suite Module Outputs

Several output files are generated by the RDR Tool Suite, including intermediate outputs passed between modules and final outputs for user analysis. This section provides a more in-depth description of these outputs, separated by module.

Outputs of ‘lhs’ Module

The ‘lhs’ module has two main output files. The `‘full_combos.csv’` file provides a full list of the scenario space defined by the model parameters input file. Each row represents an uncertainty scenario as defined by: (1) a hazard event, (2) a recovery stage, (3) an economic scenario, (4) a trip loss elasticity value, (5) a project group, and (6) a resilience project (or baseline of no resilience investment). The `‘full_combos.csv’` file is used by the ‘rr’ module to fill in model results for the entire scenario space.

The other output file of the ‘lhs’ module is the `‘AequilibraE_LHS_Design_{lhs_sample_target}.csv’` file, where the bracketed text is a stand-in for the value of the ‘lhs_sample_target’ parameter in the configuration file. The file provides a list of the uncertainty scenarios chosen by the Latin hypercube sampling algorithm to be run with AequilibraE. The file structure is similar to the `‘full_combos.csv’` file, with an additional column indicating the scenarios chosen. The file is used by the ‘aeq_run’ module to look up which uncertainty scenarios to execute an AequilibraE core model run for.

Outputs of ‘aeq_run’ Module

The ‘aeq_run’ module generates several outputs for each core model run, organized within the `“aeq_runs”` subfolder of the output data folder. The module executes a series of base network and disrupted network runs to generate the core model results used to build the regression model. Within the `“aeq_runs”` subfolder, there are separate subfolders for the base network runs (`“base”`) and the disrupted network runs (`“disrupt”`). Within each of these subfolders, there is a separate folder for each uncertainty scenario run by the core model, indexed by the ‘run_id’ parameter in the configuration file.

For a single uncertainty scenario, several intermediate output files are created during the AequilibraE core model run. A copy of the SQLite database is created and updated using data from a base network CSV file and a disrupted network CSV file. Additionally, a disrupted network link availability CSV file is generated. The AequilibraE software outputs several files, including a shortest-path skims OMX file (`‘sp_{basescenname}.omx’`) and a routing skims OMX file (`‘rt_{basescenname}.omx’`) for the base network run, a demand file named `‘new_demand_summed.omx’`, a shortest-path skims OMX file (`‘sp_disrupt_{scenname}.omx’`) and a routing skims OMX file (`‘rt_disrupt_{scenname}.omx’`) for the disrupted network run, a link flow CSV file (`‘link_flow_adjdem_{scenname}.csv’`), and an adjusted demand skims AEM file (`‘skim_adjdem_{scenname}.aem’`).

The primary output file for a single AequilibraE run is the `‘NetSkim.csv’` file for the disrupted network run. The `‘NetSkim.csv’` file provides the core model results in total trips, total miles traveled, and total hours traveled for the uncertainty scenario. All of these output files, for the uncertainty scenarios selected for core model runs, are used by the ‘aeq_compile’ module to create a single output file of core model results to build the regression model.

Outputs of ‘aeq_compile’ Module

The ‘aeq_compile’ module has one main output file, named ‘AequilibraE_Runs_Compiled_{run_id}.xlsx’ where the bracketed text is replaced by the ‘run_id’ parameter in the configuration file. The output file is a compilation of all of the ‘NetSkim.csv’ output files from AequilibraE across the uncertainty scenarios run by the core model. The file is used by the ‘rr’ module to build the regression model that is the main result of the RDR Metamodel.

Outputs of ‘rr’ Module

The ‘rr’ module has one main output file, named ‘Metamodel_scenarios_{SP/RT}_futureyear.csv’ where the bracketed text is either ‘SP’ or ‘RT’ depending on the value provided for the ‘aeq_run_type’ parameter in the configuration file. The output file joins the ‘full_combos.csv’ output file from the ‘lhs’ module with regression model outputs for total trips, total miles traveled, and total hours traveled, and provides model results for all uncertainty scenarios in the scenario space. The file is used by the RDR ROI Analysis Module, and particularly the ‘recov_calc’ module as an input to the economic analysis and project prioritization. The ‘rr’ module also produces another output file, named ‘rdr_Metamodel_Regression.html’, an RMarkdown report that summarizes the inputs and outputs of the regression models, as well as model fit metrics.

Outputs of ‘recov_init’ Module

There are four main output files of the ‘recov_init’ module. The recovery module creates the ‘uncertainty_scenarios.csv’ file of all combinations built out from the ‘UserInputs.xlsx’ input file, including hazard recovery paths and resilience projects with baselines. It also creates the ‘extended_scenarios.csv’ file, which separates the uncertainty scenarios into the distinct stages of their exposure recovery and repair recovery paths. The damage and repair models within the ‘recov_init’ module create the ‘repair_calculator.csv’ file reporting damage, repair cost, and repair time at the link level, and the ‘scenario_repair_output.csv’ file reporting damage, repair cost, and repair time at the uncertainty scenario level. These files all feed into the ROI analysis and project prioritization done by the ‘recov_calc’ module.

Outputs of ‘recov_calc’ Module

The ‘recov_calc’ module has three main output files. The main output file is named ‘tableau_input_file.xlsx’ and combines the outputs of all previous modules for economic analysis and project prioritization. Benefit-cost analysis metrics are included in this output file. This file is used as the input to create another one of the output files, the Tableau dashboards packaged together in the ‘tableau_dashboard.twbx’ workbook file (located in the “Reports” subfolder of the output data folder). The data visualizations and project prioritization analysis found in the Tableau dashboards are described in Section 7 of the technical documentation. The ‘recov_calc’ module also produces a third output file, named ‘bca_metrics.csv’, which is similar to ‘tableau_input_file.xlsx’ but includes all “no resilience investment” baseline scenarios (which are combined in the latter to produce a single average baseline scenario).

Other Output Files

Additional output files include logs for each module (located in the “logs” subfolder of the output data folder) and a report of the RDR Tool Suite run (located in the “Reports” subfolder of the output data folder) that summarizes where results are located, how long the modules took to run, what configuration parameters were used for the run, and any warnings or errors encountered during the run. The log files are labeled according to the RDR Tool Suite module they correspond to. The report is generated by the ‘o’ module. These output files provide detailed reporting on the tool run and can be used to troubleshoot any errors encountered by the user.

Appendix C: Glossary of Terms Relevant to RDR Tool Suite

Analysis period	Time period over which the project benefits accrue
Asset	A physical structure on which a project is implemented (e.g., bridge, highway)
Availability	Network link capacity to allow travel
Base run	A core model run without hazard disruption applied to the network
Base year	The year that the initial core model is run with base year trip tables (this can be different than the start year of the period of analysis)
Baseline	The baseline scenario is the scenario in which the hazardous event occurs but no project is deployed
Core model run	Scenario runs selected by the Latin Hypercube Sampling module to populate the regression that estimates network statistics for all scenarios in the scenario space
Damage	Damage refers to the physical and structural degradation or disrepair of a transportation asset
Discount/Dollar Year	The year that future monetary values will be discounted to
Discounting	The process of adjusting future time period values of cost and benefits to an equivalent value in the present period to account for the time value of money
Disrupt run	A core model run with hazard disruption applied to the network
Disruption	Loss of transportation asset operational capacity due to hazard exposure or due to damage
Economic scenario	The economic scenario refers to the different land-use and economic activity patterns that could emerge over the period of analysis
End year	The last year of the period of analysis
Exposure	The direct and immediate impact of a hazardous event on the transportation asset, e.g., in the case of flooding it is water inundation on the roadway surface
Future year	The year that the travel demand model trip tables and network are projected for
Hazard event	A single instance of a hazard such as a flood or a wildfire
Hazard level	The severity of a hazard (e.g., a 10 year flood or 100 year flood)
Hazard recession period	The period over which the hazardous event subsides in days, e.g., in a flooding event, it is the period over which the flood waters recede; also called hazard recovery in the RDR Tool Suite
Hazard severity	The highest level of the hazardous event, e.g., in the case of flooding, the highest inundation level
Latin Hypercube Sampling	Method to select the set of core model runs that populate the regression model in the RDRM
Metamodel	Method used to estimate potential conditions of the network not feasible to be estimated in a standard travel demand model
Mitigation	Reduction in disruption under a given hazard due to a resilience investment
Out year	A future year for which analysis is executed

Project group	A set of resilience projects grouped together either for analysis purposes or to represent a relationship among the projects
Recapitalization	Occurs when the project would be redeployed during the period of analysis because the project's useful life is shorter than the period of analysis
Recovery stage	The distinct levels of hazard exposure that occur as the hazardous event subsides, e.g., in a flooding event the flood waters recede from 12 ft to 10 ft to 8 ft and so forth
Regression	A function that describes the relationship between two variables (e.g., hazard severity versus network performance)
Repair cost	The cost of repairing the asset damage to its original condition prior to the hazardous event
Repair recovery period	The period over which repairs to an asset are performed
Repair time	The time in days that it takes to repair the asset to its original condition prior to the hazardous event
Resilience investment	An additional or unique project that is intended to reduce the impact of a hazard on the transportation system (see also resilience project)
Resilience project	An additional or unique project that is intended to reduce the impact of a hazard on the transportation system (see also resilience investment)
Scenario space	The range of conditions over which the resilience investment performance is estimated
Start year	The first year of the period of analysis
Trip loss elasticity	Factor defining the reduction in the number of trips based on the increase in travel time
Uncertainty	Factors in the analysis for which future conditions are only predicted based on probability but are not certain to occur
Useful life	The number of years the investment will last or be operational before needing to be replaced

Appendix D: Defining Exposure Data

The process for estimating exposure of transportation assets associated with the hazard scenarios depends on the data available and consensus on probability and severity. There are four main sources or types of data that can contribute to asset hazard exposure assessments (additional information can be found in Section 3 of FHWA's Framework[21]):

- Existing hazard exposure datasets and tools from federal or state agencies
- Existing scenario analyses
- Historical data
- Local/regional expert knowledge

Existing hazard exposure datasets and tools: There are a number of existing datasets from federal agencies that could be utilized in estimating exposure from a hazard scenario. The potential drawback to relying on national datasets is that they may not cover all areas of interest and/or the data may be too general for detailed analysis. For example, the Federal Emergency Management Agency's (FEMA) National Flood Hazard Layer[22] does not cover all U.S. counties, does not include detailed transportation infrastructure assets, nor does it provide inundation depths. In some cases, local agencies may have their own more detailed datasets regarding potential exposure to hazards that could be used to inform a hazard exposure analysis. Appendix E: Transportation Asset and Hazard Scenario Data Summary includes example datasets for flooding-related hazards. Some of the asset datasets contain detailed attributes that can help evaluate general susceptibility to flooding, and many of the available hazard layers provide detailed data on the potential impacts of various sea level rise and coastal flooding scenarios. However, the common limitations of the datasets analyzed include asset datasets that lack enough geospatial and attribute detail to identify specific levels of exposure and damage, and a lack of hazard datasets that provide flood inundation depth data for inland areas. Hazard datasets should be assessed for limitations when applying them to the analysis. Assets that might be initially characterized as exposed should be further evaluated to validate characteristics that may adjust the exposure estimation-- such as if the asset is elevated above grade-- so they are not improperly identified as vulnerable in the analysis.

FEMA's publicly available tool Hazards U.S. Multi-Hazard (Hazus-MH) focuses on national exposure analysis and damage estimation. It provides a standardized methodology that estimates potential losses from earthquakes, floods, and hurricanes. Hazus uses GIS to estimate and illustrate physical, economic, and social impacts of disasters, and is focused on census blocks as the unit of analysis (rather than individual assets). The tool generates hazard maps (GIS shapefiles), physical damage estimates, and loss estimates including losses due to disruption. Although, Hazus does not calculate damage and losses to the transportation networks for events other than earthquakes, 30-meter resolution flood depth grids are available for all 50 states as an output from the tool. If no other data are available to conduct a flood analysis,[23] the depth grid dataset output from Hazus could provide the needed hazard input to conduct

[21] FHWA Office of Planning, Environment, & Realty. Vulnerability Assessment and Adaptation Framework. Third Edition. FHWA-HEP-18-020. https://www.fhwa.dot.gov/environment/sustainability/resilience/adaptation_framework/climate_adaptation.pdf

[22] FEMA. 2022. National Flood Hazard Layer [Online]. https://www.fema.gov/national-flood-hazard-layer-nfhl

[23] The Hazus depth grids can be used an as input into the RDR Exposure Analysis Tool.

the initial flood exposure analysis. Another national-level tool is USDOT's Coupled Model Intercomparison Project (CMIP) Climate Data Processing Tool and User Guide[24] that was developed to assist transportation professionals process downscaled climate projections into changes in the frequency of very hot days and extreme precipitation events that may affect transportation infrastructure and services.

Existing scenario analyses: For certain types of hazards (e.g., sea level rise, downscaled temperature data), scenarios may already be established for a given government agency or by a given modeling or analysis study, and these may be adapted for the purposes of analyzing transportation impacts (e.g., NOAA's Coastal Inundation Dashboard[25]). Some transportation agencies develop a GIS-based vulnerability analysis by collecting location-based GIS layers for hazards (e.g., extent of floodplain, sea level rise projections) and overlaying them with asset layers. The results of a GIS-based exposure analysis can be fed into a damage assessment and integrated into a TDM approach.

Historical data: Existing data sources either within an agency or in historical archives that track the occurrence of hazards relevant to a given region. For example, the U.S. Geological Survey[26] has an array of water data, including logs of stream gauge data. State and local agencies sometimes produce geospatial datasets documenting the extent of a historical hazard scenario, such as estimated flood inundation areas for August 2016 flooding in East Baton Rouge Parish, Louisiana.[27]

Local/regional data and expert knowledge: In many cases, even if no formal historical datasets exist, there may be expert and/or local knowledge of historical events that can inform assumptions about the probability and magnitude of potential future hazards. Such information can be used primarily in a binary analysis to inform an assumption about whether an asset is within or outside the exposure area.

Identify Relevant Individual Asset Data

Resilience investments are not needed for a given asset if the asset is not vulnerable to the hazard(s) of concern. In addition, it is not tractable to test every asset on the transportation network to determine if a resilience investment is worthwhile. Therefore, a screening approach is required to identify assets that may be considered for resilience investment, such that the impact of the hazard scenario(s) and the potential mitigation of that impact with a resilience investment can be assessed.

The selection of assets of interest for evaluating resilience ROI can be informed by expert knowledge as well as specific analyses (additional information can be found in Section 2 of FHWA's Framework[28]).

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[24] FHWA. 2021. Sustainability: Tools/Climate Change Adaptation. Accessed 26 July 2022 from: https://www.fhwa.dot.gov/environment/sustainability/resilience/tools/

[25] NOAA. 2022. Coastal Inundation Dashboard. Accessed 26 July 2022 from: https://tidesandcurrents.noaa.gov/inundationdb/

[26] USGS. 2022. Water Resources. Accessed 26 July 2022 from: https://www.usgs.gov/mission-areas/water-resources.

[27] USGS. 2019. August 2016 Louisiana Floods. https://www.usgs.gov/mission-areas/water-resources/science/august-2016-louisiana-floods

[28] FHWA Office of Planning, Environment, & Realty. Vulnerability Assessment and Adaptation Framework. Third Edition. FHWA-HEP-18-020. https://www.fhwa.dot.gov/environment/sustainability/resilience/adaptation_framework/climate_adaptation.pdf

Expert selection/knowledge: In many cases, local practitioners and other stakeholders may have knowledge of historical events, repair and maintenance of assets, or other data that can be leveraged to assess which assets have been affected by a hazard in the past and therefore may be vulnerable to future hazards. A stakeholder-based vulnerability assessment can include collecting expert information and institutional knowledge to rate the vulnerability of transportation assets. For example, maintenance and operations staff may be familiar with which roads are likely to flood under different conditions, and local residents may have an understanding of which roads provide critical access to community services. Using a workshop-based format to collect this type of information from staff and stakeholders and to discuss assets' expected performance under different hazard scenarios can help an agency identify at-risk assets and priorities for further analysis. This type of qualitative assessment would need to be translated into a format that can be used for a TDM-based damage analysis. Input from stakeholders could, for instance, drive configuration of the TDM network. Stakeholder engagement may also be leveraged to improve individual asset-level data.[29]

Existing vulnerability and risk assessments: Some agencies have performed vulnerability or asset risk assessments for anticipated hazards using their own tools or existing resources that take into account expert knowledge and historical information to rank and prioritize assets with high vulnerability (e.g., exposure, sensitivity, or adaptive capacity) to a set of predetermined hazards. One tool for conducting a vulnerability assessment is FHWA's Vulnerability Assessment Scoring Tool (VAST). VAST is a comprehensive spreadsheet-based tool that guides transportation professionals through a quantitative, indicator-based vulnerability screening process. The output of the tool is a vulnerability score (1-5).

[29] For example, the Maryland State Highway Administration (MDSHA) was having difficulty assessing the vulnerability of its transportation assets to climate variables and stressors due to limited data availability until they begin collecting the needed data by conducting workshops and interviews with maintenance staff. https://www.fhwa.dot.gov/environment/sustainability/resilience/pilots/2013-2015_pilots/maryland/final_report/mdpilot.pdf

Planned and proposed transportation projects: In some cases, a planned or proposed project can be enhanced with an added marginal cost to make the asset more resilient. Thus, one screening approach is to assume that resilience investments will occur in concert with other planned or proposed projects, and these assets can then be prioritized for resilience ROI analysis.

Criticality analysis: Existing designations of assets related to criticality may inform the practitioner of specific critical use assets that should be considered for resilience investments. Such critical uses may include designated evacuation routes, the Strategic Highway Network (STRAHNET), key access points for known isolated or economically critical facilities (e.g., ports), or results of past criticality analyses (e.g., DHS analysis[30]).

Network nodal/criticality analysis for key nodes: There are existing methodologies[31] for assessing the criticality of nodes in a network; however, these tend to be focused on connectivity by shortest paths and may not take into account rerouting or flow volume as factors in determining criticality.

Once the relevant asset data are identified, they must be incorporated into, or at least compatible with, the transportation network of interest, such as a TDM.

Agencies can use the scores from VAST to identify their most vulnerable assets. Indicator-based vulnerability assessments, like VAST, provide relative information about the most vulnerable assets, but do not give information about the extent of the vulnerability or potential damage to these assets. While the numerical scores from an indicator-based assessment may not be able to directly inform a damage/disruption analysis, some of the data collected for the vulnerability assessment may prove useful (e.g., data on exposure to flooding such as elevation or location in a floodplain). An indicator-based assessment can also be used as a screen to select assets for inclusion in a more detailed damage analysis.

[30] DHS/USDOT. 2015. Transportation Systems Sector-Specific Plan. https://www.cisa.gov/sites/default/files/publications/nipp-ssp-transportation-systems-2015-508.pdf

[31] e.g., Borgatti, Stephen P. 2006. Identifying sets of key players in a social network. Comput. Math Organiz. Theor. 12: 21-34 (DOI 10.1007/s10588-006-7084-x); Hillier B., Hanson J. 1984. The social logic of space. Cambridge University Press.

Appendix E: Transportation Asset and Hazard Scenario Data Summary

The table below lists data sets, covering both road networks and flooding, that could supply needed data for the RDR Tool Suite, with their strengths and limitations.

Table E-1: Transportation asset data resources for scenario development.

Dataset	Source	Data Type (Transportation Asset, Hazard Data)	Strengths	Limitations
Travel demand model road networks	State DOT or regional MPO	Transportation Asset— Road network data exportable as GIS data	Represents best knowledge of state/regional transportation assets, travel demand, asset vehicle capacity and travel speed, and may include planned /proposed asset investment projects.	No mechanism to incorporate hazard data and impacts on assets, nor mitigation of hazard impacts. Attributes relevant to hazard (e.g., elevation, scour vulnerability) not included, requiring incorporation of data from other sources.
National Bridge Inventory	FHWA	Transportation Asset— Database with location information and bridge attributes	National level bridge inventory with rich attribute data: waterway adequacy, scour critical, bridge condition.	Poor geospatial representation (single point rather than representing full bridge span), no elevation data. Does not cover bridges less than 20 feet in length.
National Tunnel Inventory	FHWA	Transportation Asset— Database with location information and tunnel attributes	National level tunnel inventory.	Poor geospatial representation (single point rather than representing full tunnel span), few attributes relevant to hazard scenarios (other than detour length).
Highway Performance Monitoring System (HPMS) and All Roads Network Of Linear	FHWA	Transportation Asset— GIS Road Network and Attributes	Detailed attributes including surface type AADT, pavement condition, climate zone, soil type, and terrain type that could be	Not flowable, no elevation data.

Dataset	Source	Data Type (Transportation Asset, Hazard Data)	Strengths	Limitations
referenced Data (ARNOLD)			useful to help estimate high-level flood risk and impacts. Can be easily overlain on top of hazard data.	
Freight Analysis Framework (FAF)	FHWA	Transportation Asset— GIS Road Network and Attributes	Flowable road network.	Only covers major freight corridors, not local roads.
Freight and Fuel Transportation Optimization Tool (FTOT) multimodal, flowable transportation network	Volpe	Transportation Asset— Flowable multimodal transportation network	Flowable multimodal dataset and optimization module provide ability to assess network disruptions and rerouting.	Does not include local roads, no attributes related to hazards.
Coastal Inundation Dashboard and Sea Level Rise, Sea Level Rise Depth, Mapping Confidence, DEM, and Flood Frequency Data	NOAA	Hazard Data— flooding scenario datasets	Detailed data for coastal areas.	Does not cover inland flooding.
Global Ensemble Forecast System (GEFS) and NOAA Operational Model and Archive Distribution System (NOMADS)	NOAA	Hazard Data— weather forecast model	May be useful at local scales to determine the probability that a set of conditions will occur.	Not useful for regional/national analysis.
National Flood Hazard Layer	FEMA	Hazard Data— flooding	Determines flood zones, base flood elevation and floodway status across large portions of the U.S.	Does not cover all counties, does not provide inundation depth associated with various flooding scenarios. Flood zones may not be relevant for transportation assets that are elevated (e.g., bridges, causeways).
FLDPLN	University of Kansas	Hazard Data— inland flooding	Outputs from this tool could be overlain on transportation assets	Not currently publicly available.

Dataset	Source	Data Type (Transportation Asset, Hazard Data)	Strengths	Limitations
			to quantify exposure to inland flooding.	
Current Water Data for the Nation	USGS	Hazard Data—inland flooding	Real-time, detailed flood information at flood gauge sites across the country.	Does not provide enough information to determine flooding impact on nearby transportation assets.
Flood Inundation Mapper	USGS	Hazard Data—inland flooding	Can help provide detailed information on the extent and depth of inland flooding.	Limited in scope to relatively small geographic areas immediately surrounding a small subset of river gauges throughout the country.
Hydraulic Engineering Circular No. 20 (HEC 20)	USACE	Hazard Data—flooding/stream stability	Details procedure for evaluation of stream stability problems.	No ready-made data for helping assess bridge vulnerability.

Appendix F: RDR Exposure Analysis Tool

Exposure Grid Overlay Helper Script Documentation

Introduction

The goal of this script (`exposure_grid_overlay.py`) is to automate the process of assessing disruption to a road network based on exposure to a hazard, using Geographic Information Systems (GIS). If the road network is a GIS export of a Travel Demand Model (TDM), the output from this tool can be fed back into the TDM to be leveraged by the Resilience and Disaster Recovery Metamodel (RDRM). Additionally, it can also be used as a standalone script; it can be useful for creating, analyzing, and visualizing specific exposure and disruption scenarios without running the full tool. The script is written to work on a Windows computer in conjunction with an installation of ArcGIS (v 10.x) or ArcGIS Pro. The script is designed for an intermediate or advanced GIS user who is already familiar with running custom Python scripts. The script must be run using Windows Command Prompt or PowerShell. The analyst may also wish to use an Integrated Development Environment (IDE) such as IDLE (which is provided with ArcGIS) or PyCharm to make custom, optional modifications to the code.

Setting up the Analysis

The analyst will need to modify certain configuration parameters within a standalone configuration file in order to get the script up and running. A template configuration file (“`exposure_grid_sample.config`”) accompanies the tool, but the file can be edited and renamed as appropriate for the specific region and hazard scenario. These customizable parameters include the following:

- **Input Exposure Grid** (input_exposure_grid)—the full path to the raster formatted input exposure grid associated with the hazard scenario of interest. One hazard for which these sorts of datasets are commonly available is flooding, but any GIS-formatted gridded dataset representing exposure to a hazard (in which higher numeric values represent higher levels of exposure to a hazard) can be utilized. In the case of flooding, depth grids may be published by government entities, such as NOAA, FEMA, states, and local Metropolitan Planning Organizations (MPOs) or created as an output of modeling tools such as FEMA’s HAZUS tool.
- **Input Road Network** (input_road_network)—path to the input road network GIS-based feature class (shapefile, file geodatabase feature class, etc.).
- **Output Directory** (output_dir)—the folder where outputs will be stored. The output directory will be created if it does not exist. If the directory does exist, any existing outputs in this directory will be overwritten.
- **Run Name** (run_name)—scenario name with no spaces used to name all file outputs. Choose a descriptive run name that distinguishes it from other hazard scenarios (i.e., “100_yr_flood_hazard_scenario”).
- **Link Availability Approach** (link_availability approach)—the approach used to convert exposure into a corresponding level of disruption for each individual segment in the road network. The current options are:
    - ‘Binary” where any value above 0 is considered full exposure and link will not be available. Other links will remain fully available. This method is used when detailed

information about the relationship between the level of hazard exposure and disruption is unavailable or the analyst wants a “worst case” estimate of disruption.
    - ‘Default_Flood_Exposure_Function’—utilizes depth-disruption function adapted from an existing function (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.[32] If this option is chosen, the exposure_unit must be defined so that units can be properly converted to millimeters. 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.
    - ‘Manual’—analyst-defined bins representing the conversion of exposure into link availability. If this option is chosen, the link_availability_csv path must be defined. This method is used when the analyst does not have a specific exposure-disruption function but can still estimate categories of disruption based on exposure.
    - ’Beta_Distribution_Function’-- allows the analyst to define a custom exposure-damage function for any hazard for which severity grids exist. The goal is to give the analyst flexibility in determining how link availability could change in a non-linear fashion due to varying levels of exposure. Due to the complexity of this approach compared to the others, there are several additional configuration parameters that must be defined if this approach is selected. These fields include ‘alpha’, ‘beta’, ‘lower_bound’, ‘upper-bound’ and ‘beta_method’ (described in further detail below). The Keisan Online Calculator can be used to help the analyst test different alpha and beta parameters which define the shape of the customized beta distribution. The analyst must define the bounds of values where link availability is expected to be partially impacted by a particular hazard (values outside these bounds will default to 0% availability or 100% availability depending on the beta method chosen).
- **Exposure Field** (exposure_field)—this is the field name associated with the exposure level for each grid cell in the exposure grid. The most common field name associated with gridded GIS-data is ‘Value’ but depending on the specific exposure grid, it may differ. Confirm by examining the details of the exposure grid within ArcGIS.
- **Search Distance** (search_distance). Search distance for determining the maximum exposure along a road segment (include units—e.g., feet, meters, or yards)—the analyst is strongly encouraged to define a search distance that is half of the raster’s grid size, to ensure that all overlapping exposure levels are taking into account.
- **Road Network Fields to Keep** (fields_to_keep). The fields/column names that the analyst would like to keep in the final csv output. If using the results of this tool as an input for the RDR Metamodel, ensure that this includes a unique ID field called ‘link_id’. If this does not exist already, create it before running this tool.
- **Comment Text** (comment_text)—text to describe the hazard scenario. If not needed, this can be left blank.

[32] 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

- **Evacuation** (evacuation)—indicates whether or not the analyst wishes to flag evacuation routes as part of the analysis. Needs to be set to True or False.
- **Evacuation Input** (evacuation_input)—if evacuation is set to True, then this parameter defines the path to the GIS feature class representing evacuation routes.
- **Evacuation Route Search Distance** (evacuation_route_search_distance)—a distance in which to search around evacuation routes in order to identify evacuation routes in the input road network. Any roadways existing completely within the search distance of the evacuation input will be flagged as evacuation routes.
- **Emergency (**emergency)—indicates whether or not the analysis represents emergency vehicle and/or high clearance exposure/disruption scenario. Needs to be set to True or False. If True, this simply modifies the format of the output to make it clear that the link availability calculated is for emergency vehicles.

The following parameters are located in the configuration file but only need to be defined if the relevant link availability approach is selected.

- **Specific Configuration Parameters for 'Manual' Link Availability Approach**
  - **Link Availability CSV** (link_availability_csv)—must be defined if manual link availability approach is being utilized. The analyst should base this off of a template csv ("`exposure_grid_key.csv`") that accompanies the script.
- **Specific Configuration Parameters for 'Default_Flood_Exposure' Link Availability Approach**
  - **Exposure Unit** (exposure_unit)—must be defined if default flood exposure link function is being utilized. Compatible units are feet, yards, and meters.
- **Specific Configuration Parameters for 'Beta_Distribution_Function' Link Availability Approach**
  - **Alpha** (alpha)—a number greater than 0 that helps define the shape of the beta distribution.
  - **Beta** (beta)—a number greater than 0 that helps define the shape of the beta distribution.
  - **Lower Bound** (lower_bound)—the exposure value where link availability reaches 0% (if lower cumulative beta distribution function is utilized) or 100% (if upper cumulative beta distribution function is utilized).
  - **Upper Bound** (upper_bound)—the exposure value where link availability reaches 100% (if lower cumulative beta distribution function is utilized) or 0% (if upper cumulative beta distribution function is utilized).
  - **Beta Method** (beta_method)—analyst can select 'lower cumulative' or 'upper cumulative'. If 'lower cumulative', link availability reaches 0% at lower bound and 100% at upper bound. If upper cumulative, link availability reaches 100% at lower bound and 0% at upper bound. The shape of the curve defining link availability between the lower and upper bounds is determined by the alpha and beta parameters. For either method, link availability will always be 100% for links with no hazard exposure.

In order for the script to run most efficiently, the analyst should define local paths for all inputs and outputs, rather than remote network paths.

Analysis Process

In order to run the tool once the configuration file is prepared, the "`exposure_grid_overlay_run.bat`" file must be edited to point to the following three files:

1. The Python executable associated with the analyst's installation of ArcGIS or ArcGIS Pro (e.g., C:\Python27\ArcGIS10.8\python.exe in the case of ArcGIS 10.8)
2. The location of the script on the analyst's machine
3. The location of the specific configuration file on the analyst's machine

The analyst can then open the Windows Command Prompt interface or Windows PowerShell. For instance, for the Command Prompt, go to the Windows Start Menu, type Command Prompt in the search bar, click on the Command Prompt icon and a new Command Prompt will open. Then drag the bat file into the shell, and press enter to run (you may need to press enter more than once).

Once the tool begins to run it will leverage a series of geoprocessing tools built into ArcGIS. The script will print several brief log messages to document its status. The full process is summarized below:

- Prepares the output directory and geodatabase, deleting any existing outputs.
- Extracts the exposure grid raster values that overlap the road network.
- Converts these raster cells into vector-based point data.
- Associates the maximum exposure grid point within the analyst-specified search distance of each road segment.
- Depending on the link availability approach set by the analyst, the code will convert exposure levels to a value which determines how much of each link's capacity is available given the hazard.
    - 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).
    - If the default flood exposure function is selected, then the exposure values will be computed using the function as defined earlier in this documentation.
    - If the manual approach is selected, the link availability CSV is read and processed to convert values that fall between each pair of min_inclusive and max_exclusive values into their corresponding link_availability value. For example, in the example CSV provided below, exposure values greater than or equal to 0 and less than 0.1 will be converted to a link availability value of 1 (no disruption). Subsequent ranges of values will be converted to lower values of link availability until exposure values greater than or equal to 1 are converted to a link availability of 0 (fully disrupted).

	A	B	C
1	min_inclusive	max_exclusive	link_availability
2	0	0.1	1
3	0.1	0.2	0.8
4	0.2	0.5	0.5
5	0.5	1	0.1
6	1	999999	0

Figure F-0-1: An example of a manual link availability CSV file

    - If the beta distribution function is selected, the specific beta distribution parameters are processed to convert values that fall within the lower and upper bounds to their corresponding lower or upper cumulative distribution function of the beta distribution. Values that fall outside of the bounds will convert to 0 or 1 depending on whether the lower or upper cumulative distribution function is selected. For either method, link availability will always be 100% for links with no hazard exposure.
- The tool outputs a GIS feature class of each road segment with its corresponding link availability and exposure value.
- If evacuation is set to True, an additional column of data (evacuation_route) is output which indicates for each road network segment whether or not the segment is part of an evacuation route. (1 indicates that it is part of evacuation route, 0 indicates that it is not). If evacuation is set to True, then an evacuation input and evacuation route search distance must also be defined. Alternatively, if the input road network already has information as to whether or not each segment is part of an evacuation route, the analyst can feel free to calculate the evacuation_route column on their own (ensuring each segment is represented by a 1 or 0 indicating whether or not it is part of an evacuation route), and simply carrying through evacuation_route field as one of the "fields_to_keep" defined in a separate parameter. In this case, the analyst can set evacuation to False, as there is no need for the tool to make the evacuation route determination again.
- If emergency is set to True, then the "link_availability" field in the output is modified slightly to read "link_availability_emergency", indicating that this is an emergency vehicle/high clearance vehicle scenario.
- A simple comma-separated values (CSV) file is also generated which provides the exposure level and link availability for each road segment in the road network. The analyst can join this back to the original network for more comprehensive analysis or feed this CSV into the RDR Metamodel.

Depending on the size of the inputs, the final run time may vary from a few minutes to more than an hour.

Limitations

- This script has been tested on several combinations of GIS datasets (including depth grids published by Hampton Roads Transportation Planning Organization (HRTPO) and the Federal Emergency Management Agency (FEMA), and road networks provided by both HRTPO and the State of North Carolina). However, the script is not guaranteed to work on every combination of road network and exposure grid. An advanced GIS user with coding experience may need to make adjustments to the script in order to get the script working with their specific datasets.
- The output generated by the script is limited by the precision of the input datasets. For example, if the exposure grid is not high-resolution (e.g., 30-meter resolution) than the exposure values for each road segment are likely to be less reliable.
- The analyst may wish to manually edit the output to adjust the link availability in areas where the exposure grid is not accurately determining the availability of a link (e.g., bridges may be elevated above the inundation)

- Depending on the size of the road network and exposure grid, this process may take several minutes or hours to run. It is recommended that exposure grids and road networks are clipped beforehand to the area of interest to minimize run time. For large regional networks and detailed exposure datasets, run times could be upwards of an hour, but the script will run much faster with smaller networks.
- The script is currently designed to be run in its entirety with one command. Analysts with some basic Python experience may wish to only run portions of the script and are welcome to comment out or otherwise separate or modify portions of the code in order to—for example—run the first part (exposure piece) or second part (the link availability/disruption piece) in isolation.
- Ensure that all relevant GIS data used as inputs in this tool is not actively open within ArcGIS or ArcGIS Pro before running.

The RDR Exposure Analysis Tool can be found at https://github.com/VolpeUSDOT/RDR-Public/tree/master/helper_tools/exposure_grid_overlay.

Appendix G: Base Year Run Helper Tool

The base year run helper tool is designed to automate the production of base year AequilibraE core model runs ahead of a full run of the RDR Metamodel. Base year core model runs are required as input to the ROI Analysis Module so that they can be interpolated with the future year core model runs to provide metrics across the entire ROI performance period. The base year run helper tool leverages the same functionality of the core tool suite but allows the base year run outputs to be prepared separately in a quick and efficient standalone tool. The tool automatically runs base year AequilibraE model runs for every combination of hazard and recovery parameters supplied by the analyst. All AequilibraE base year model outputs are consolidated into one comma-separated (CSV) file.

Base Year Run Helper Tool Required Inputs

The base year run helper tool leverages the same configuration file used for a full RDR Metamodel run. Specifically, the configuration parameters that must be defined include input directory, output directory, AequilibraE Model Run Type, and Mini-Equilibrium Run. The following list of input files (stored within the input directory) are leveraged by the base year run helper tool and must be prepared and stored in the correct locations prior to running the tool. Users can consult Section 4.1 for more information on each of these configuration parameters, along with the standalone Run Checklist.

The following input files are required:

1. Model parameters XLSX file (in main input directory) - `"Model_Parameters.xlsx"`. This is where each hazard and recovery parameter utilized in a scenario is defined.
2. Trip table OMX file (in `AEMaster/matrices` sub-directory) - `"baseyear_demand_summed.omx"`. This provides the daily average trip table for the base year.
3. SQLite database (in `AEMaster` sub-directory) – `"project_database.sqlite"`. This provides the network structure and disruption information to AequilibraE.
4. Exposure CSV file(s) (in Hazards sub-directory) - one for each hazard, `"{HAZARD_RUN_NAME}.csv"`
5. Network links CSV file (in `Networks` sub-directory) - `"baseyear.csv"`
6. Network nodes CSV file (in `Networks` sub-directory) - `"node.csv"`

The following parameters are optional:

7. True shapes CSV file (in `LookupTables` sub-directory) - `"TrueShape.csv"`

Running the Tool

To run the base year helper tool, ensure that all files listed in 1-6 above are fully prepared and saved in the designated locations. Once the relevant parameters within the configuration file are prepared, the `"base_year_run.bat"` file (located within `RDR/helper_tools/base_year_run`) must be edited to point to the following three files:

1. The Python executable associated with the analyst's RDR Python environment (RDRenv)
2. The location of the `"base_year_run.py"` script on the analyst's machine
3. The location of the scenario's configuration file on the analyst's machine

The analyst can then open the Windows Command Prompt interface or Windows PowerShell. For instance, for the Command Prompt, go to the Windows Start Menu, type Command Prompt in the search bar, click on the Command Prompt icon, and a new Command Prompt will open. Then drag the bat file into the shell, and press enter to run (you may need to press enter more than once).

The output of a run is either "`Metamodel_scenarios_SP_baseyear.csv`" if the AequilibraE run type is set to 'SP' or "`Metamodel_scenarios_RT_baseyear.csv`" if the AequilibraE run type is set to 'RT'.

Appendix H: Capital Cost and Residual Value Helper Tool

The capital cost helper tool is designed to automate the calculation of the discounted total capital costs of the projects accounting for the period of analysis, the lifespan of the project, and discounting. On the 'Capital Costs and & Residual Value' sheet of the "`resiliency_cost_residual_calculator.xlsx`" workbook, users can calculate the discounted capital costs and residual value of the project. Up to five projects can be calculated at the same time. If the analysis includes more than five projects, the columns can be reused. Green cells show where users need to provide information. The user must provide the discount rate, the discount year, the analysis period start year and end year, the total project costs (in 2020$ dollars) and the useful life of the project. The tool will automatically calculate the total discounted costs of the project including any recapitalization required based on the period of analysis and the useful life of the project. For example, as shown below in Figure H-0-1, Project 1 has a useful life of 17 years, but the period of analysis is 20 years in length, meaning that the project would need to be recapitalized over the period of analysis. The 'Annual Cost (disc.)' shows that in year 2039, the project would need to be recapitalized at a discounted value of $2.8 million. The helper tool also calculates the discounted residual value of the project which accounts for the useful life and any recapitalization of the project.

Discount Value	0.07
Discount Year	2020
Analysis Period Start	2022
Analysis Period End	2041

ResiliencyProjectName	**Project 1**		**Project 2**	
Project Costs ($2020)	$ 10,000,000		$ 35,000,000	
Useful life	17		21	
Analysis Period	**Reconstruction Counter**	**Annual Costs (disc.)**	**Reconstruction Counter**	**Annual Costs (disc.)**
2021	17	$ 9,345,794	21	$ 32,710,280
2022	0	$ -	0	$ -
2023	1	$ -	1	$ -
2024	2	$ -	2	$ -
2025	3	$ -	3	$ -
2026	4	$ -	4	$ -
2027	5	$ -	5	$ -
2028	6	$ -	6	$ -
2029	7	$ -	7	$ -
2030	8	$ -	8	$ -
2031	9	$ -	9	$ -
2032	10	$ -	10	$ -
2033	11	$ -	11	$ -
2034	12	$ -	12	$ -
2035	13	$ -	13	$ -
2036	14	$ -	14	$ -
2037	15	$ -	15	$ -
2038	16	$ -	16	$ -
2039	17	$ 2,765,083	17	$ -
2040	0	$ -	18	$ -
2041	1	$ -	19	$ -
0	0	$ -	0	$ -
0	0	$ -	0	$ -
0	0	$ -	0	$ -
0	0	$ -	0	$ -
0	0	$ -	0	$ -
0	0	$ -	0	$ -
0	0	$ -	0	$ -
0	0	$ -	0	$ -
0	0	$ -	0	$ -
0	0	$ -	0	$ -
Total Disc. Costs	**$ 12,110,878**		**$ 32,710,280**	
Residual	**$ 2,273,064**		**$ 805,044**	

Figure H-0-1: Capital Cost and Residual Value Helper Tool

Appendix I: Safety and Emissions Benefits

The safety and emissions benefits can be calculated on a per-mile basis based on the change in VMT compared to the no-action baseline. This assumes the safety and emissions per-mile costs are not impacted by the hazard itself, and that the project does not provide safety or emissions countermeasures. Total change in VMT relative to the baseline for each project can be calculated using the `‘tableau_input_file.xlsx’` which includes fields for the change in VMT relative to the baseline for each project for each period of the analysis, the initial, exposure, and damage periods. To get the sum of ‘initVMTvsBase’, ‘expVMTvsBase’, and ‘damVMTvsBase’ columns to get total difference in VMT for each project scenario compared to the baseline without the project.

Users should consult the USDOT BCA Guidance for how to calculate safety benefits and emissions benefits based on changes in VMT.[33]

[33] US DOT OST. “Benefit Cost Analysis Guidance for Discretionary Grant Programs.” February 2021. Accessed from: https://www.transportation.gov/office-policy/transportation-policy/benefit-cost-analysis-guidance-discretionary-grant-programs-0