Freight and Fuel Transportation Optimization Tool User Guide

FTOT 2025.3 Public Release Version

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13. ABSTRACT (Maximum 200 words)

Volpe created the Freight and Fuel Transportation Optimization Tool (FTOT) to support the FAA, DOE, and the U.S. Navy's Office of Naval Research to assess optimal transport options for freight and fuel supply chains. FTOT is a flexible scenario-testing tool that optimizes the transportation of materials for future energy and freight scenarios. FTOT models and tracks commodity-specific information and can take into account conversion of raw materials to products (e.g., crude oil to jet fuel/diesel) and fulfillment of downstream demand. This report documents how to use the FTOT public release version 2025.3. This documentation is updated quarterly and available on the Public FTOT GitHub repository: https://github.com/VolpeUSDOT/FTOT-Public

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1 INTRODUCTION

FTOT (https://volpeusdot.github.io/FTOT-Public) is a flexible scenario-testing tool that optimizes the transportation of materials for future energy and freight scenarios. FTOT models and tracks commodity-specific information and can take into account conversion of raw materials to products (e.g., crude oil to jet fuel and diesel) and the fulfillment of downstream demand. FTOT was developed at the US Department of Transportation's Volpe National Transportation Systems Center in support of the Federal Aviation Administration, the Department of Energy, and the Office of Naval Research.

This user guide document provides comprehensive details for how users can interact with FTOT to run their own scenarios. Section 2 explains how to install FTOT. Section 3 details how to customize FTOT inputs to run a basic scenario. Section 4 explains the configurations needed to run more advanced FTOT scenarios (e.g., customizing the GIS network, incorporating schedules). Section 5 guides the user through manually running an FTOT scenario. Section 6 describes the FTOT outputs and explains the interpretation of each output. Section 7 details the various FTOT tools that supplement the core tool. Section 8 provides a troubleshooting guide. Appendix A provides full documentation of the scenario XML input file. Appendix B provides full documentation of the FTOT network specification schema.

New FTOT functionalities and user materials are added every quarterly release. Specific details on updates associated with the latest release (and previous releases) can be found in the change log on the GitHub code hosting site at https://github.com/VolpeUSDOT/FTOT-Public/releases.

2 INSTALLATION

Current FTOT installation instructions can be found below. A demonstration video for how to install FTOT is also available on the Volpe Center YouTube channel here: https://youtu.be/VXay2v5KguA. **FTOT Version 2025.3** can be downloaded from the Public GitHub repository (https://github.com/VolpeUSDOT/FTOT-Public). Before running a scenario in FTOT, the following programs must be installed:

- **ESRI ArcGIS Pro** Version 3.0 or higher (a Geographic Information System (GIS) program) performs the geospatial analysis elements of the tool. The Advanced License level of ArcGIS Pro is required. While FTOT should function on ArcGIS Pro Version 3.0 or higher, please note that it has not been tested on every version of ArcGIS Pro.
- An installation of ArcGIS Pro is accompanied by a **base Python installation** (Version 3.9 or later), providing the majority of Python modules required for FTOT scripts to run. FTOT's installation process automatically generates a standalone FTOT Python environment based on the ArcGIS Pro default Python environment. Special attention should be paid to this Python environment. See the troubleshooting section for issues with pre-installed Python environments.
- **SQLite** is used to store scenario variables and results. In order for the user to fully explore SQLite-generated outputs, users are encouraged to install a SQLite database browser, such as DB Browser for SQLite.
- A **Tableau dashboard** is used to generate a suite of graphical outputs based on the optimal scenario solution. To view the Tableau dashboard, one can use either the free Tableau Reader or a full version of Tableau Desktop v2019.4 or higher.

During the FTOT installation process, the following packages are additionally installed and placed in the FTOT Python environment. Recommended package versions for use with FTOT Version 2025.3 are indicated below and have been tested with ArcGIS Pro Version 3.4.3:

- **NetworkX** [1] is an open-source Python-based suite of tools for manipulating and analyzing complex networks for which many publicly available algorithms and tools have been established. Version 2.8.4 or later is recommended with FTOT Version 2025.3.
- **PuLP** (Open Source Python Wrapper for Optimization Solvers) [2] is a linear programming module written in Python. Version 2.9.0 or later is recommended with FTOT Version 2025.3. In FTOT, PuLP is used to link the solvers in the Computational Infrastructure for Operations Research project (COIN-OR) [3]. The **COIN-OR** project maintains an archive of open-source software for operations research, including implementations of algorithmic solvers and modeling systems. This includes a number of open-source optimization models, including a branch and cut solver (CBC) for mixed integer programming.
- **HiGHS** [4] is an open-source solver for large-scale sparse linear optimization problems, including mixed integer programming problems, with a Python interface called highspy. Version 1.9.0 or later is recommended with FTOT Version 2025.3.

- **Pint** [5] is a Python package for unit conversions and dimensionality checks. It is used throughout FTOT to harmonize user input data into a common set of units for solids and liquid freight movements. Version 0.23 or later is recommended with FTOT Version 2025.3.
- **Imageio** [6] is a Python package required for creating animated graphics of FTOT mapping outputs. Version 2.9.0 or later is recommended with FTOT Version 2025.3.

2.1 Installing ESRI ArcGIS Pro

ESRI ArcGIS Pro Version 3.0 or higher (a Geographic Information System (GIS) program) performs the geospatial analysis elements of the tool.

FTOT requires the Advanced license level of ArcGIS Pro.

- Contact your system administrator for help in installing and licensing the software.
- All defaults can be accepted during installation. The process will involve installing two files—one exe file for the major version (e.g., ArcGIS Pro 3.0) and a patch/msp file representing the minor version (e.g., ArcGIS Pro 3.0.2).
- If you are upgrading from an earlier version of ArcGIS Pro, the upgrade will remove your old version automatically.
- After installation is complete, make sure you properly set up the license authorizing the software. Users should contact their system administrator for detailed instructions on activating the ArcGIS Pro license. Note that FTOT is only compatible with the Advanced license.

2.2 Installing FTOT

Download FTOT repository

1. To install FTOT, navigate to the FTOT repository on GitHub: https://github.com/VolpeUSDOT/FTOT-Public
2. Click the Code dropdown and select “Download ZIP” (Figure 1).

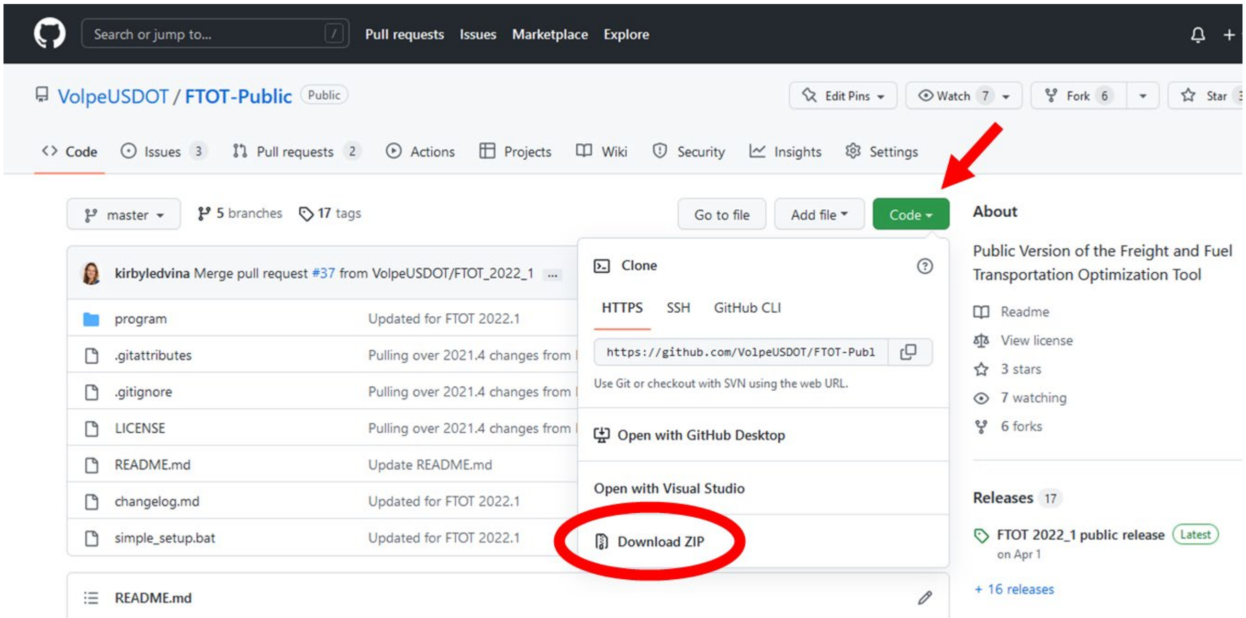


Figure 1: Screenshot of Download ZIP functionality on GitHub.

3. Extract the contents of the downloaded ZIP file into the following directory on your local machine: C:\FTOT
    - Note: On some systems the FTOT directory may need to be renamed from FTOT-Public-Master.
    - Ensure that the first layer inside C:\FTOT includes a subfolder called “program”, a file named “simple_setup.bat”, and two additional files named “.gitignore” and “.gitattributes” among other individual files. The contents may need to be moved into this configuration if they did not unzip this way automatically.

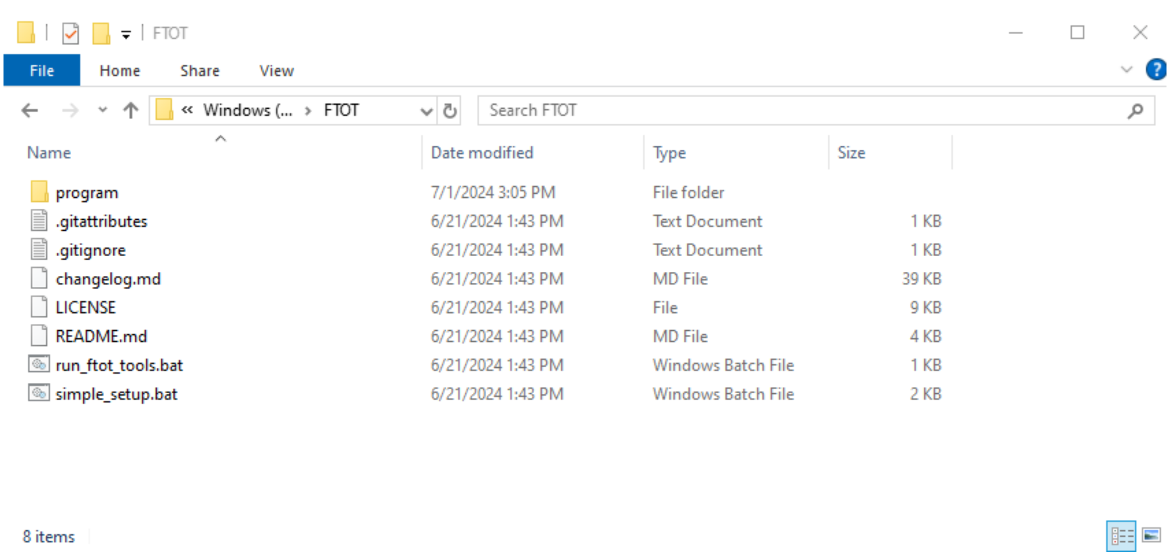


Figure 2: Screenshot of FTOT directory structure.

Install FTOT's Python dependencies

4. Open a command line window by clicking on the Windows Start Menu, searching for “Command Prompt”, and clicking on it.
5. Click and drag the file “simple_setup.bat” from the C:\FTOT folder to the command line window, and press enter in the command line window.
6. The script will create a new FTOT-specific Python 3 environment derived from ArcGIS Pro's installation of Python and install it in C:\FTOT\python3_env. Cloning the Python 3 environment (see screenshot in Figure 3) may take a few minutes.

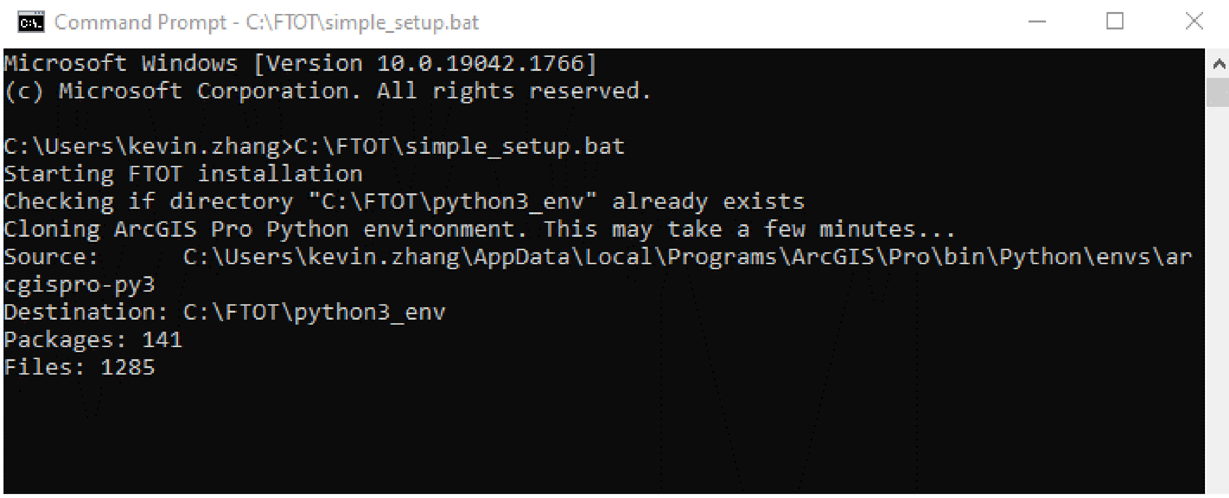


Figure 3: Screenshot of the command line window during setup of the FTOT Python environment.

7. When all dependencies are installed, the command line window will print “Complete” and prompt you to press any key to exit the installation. The Python executable file for the newly installed environment is located at C:\FTOT\python3_env\python.exe. If the “simple_setup.bat” script is unsuccessful, you can manually copy the ArcGIS Pro Python 3 environment into C:\FTOT\python3_env and “pip install” the remaining required packages listed in Section 2. More details are provided in Troubleshooting Notes in Section 8.

Note: Steps 4-7 above need to be re-run each time you install a new version of ArcGIS Pro. If the FTOT-specific Python 3 environment already exists, the setup script will ask to delete the existing C:\FTOT\python3_env directory before creating a new installation (see Figure 4 for message).

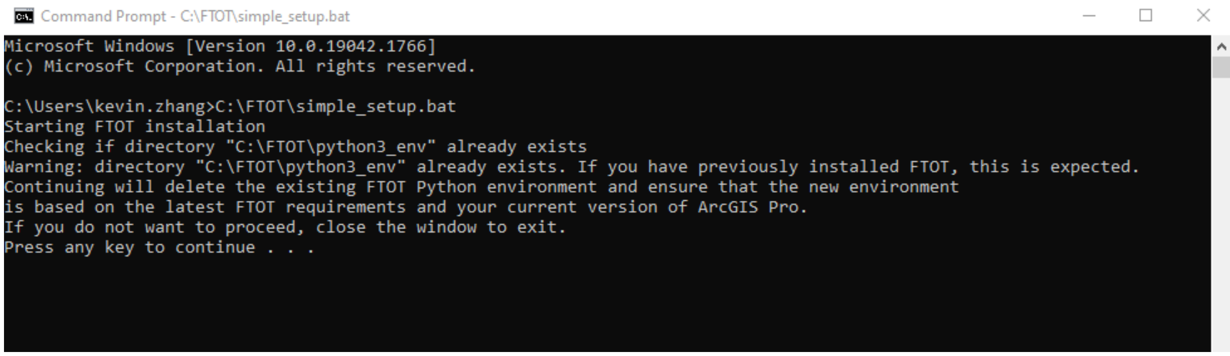


Figure 4: Screenshot of the command line window confirming deletion of previous Python environment.

Download FTOT datasets

8. Additional transportation GIS data are required to run FTOT. Default US-based transportation network and facility location data are provided with the FTOT installation. In addition, documentation and supplementary scenario data are provided to acclimate you to running FTOT. This geospatial, documentation, and scenario dataset can be downloaded directly from https://volpeusdot.github.io/FTOT-Public/data_download.html. Only the most recent version of the zip file needs to be downloaded. (To create custom transportation network and facility location datasets, refer to Sections 4.1.3 and 3.2.1, respectively.)
9. Extract the contents to within the C:\FTOT directory on your machine. After you download and save this data, your C:\FTOT directory should contain a scenarios folder and a documentation folder in addition to the existing folder and files.

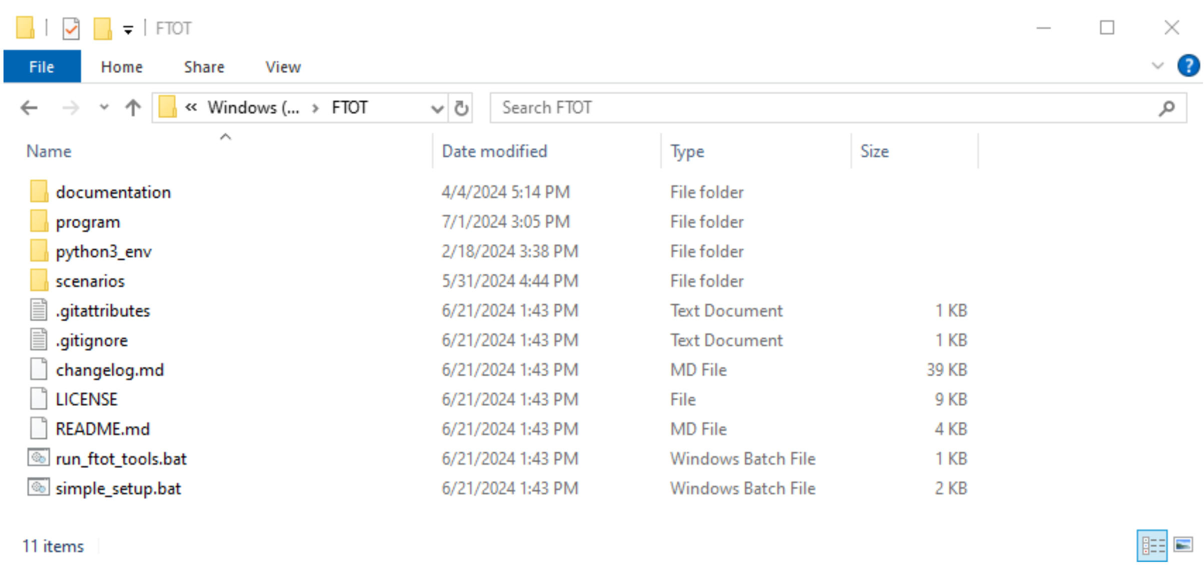


Figure 5: Screenshot of FTOT directory structure after download of documentation and scenario dataset.

Inside the scenarios folder should be a common_data folder along with directories containing quick start and reference scenarios. The user is strongly encouraged to walk through the Quick Start examples after installation and before creating their own scenarios in order to test that FTOT was installed correctly and to get used to the process and structure of an FTOT scenario. The Quick Start Tutorial document explains the inputs and outputs of both Quick Start scenarios. A demonstration video on how to run Quick Start 1 can also be found on the Volpe Center YouTube channel here: https://youtu.be/P__8oRHxuSc.

2.3 Installing Tableau

Tableau dashboard outputs (Section 6.2) will not be fully functional until you have installed Tableau Desktop or Tableau Reader. If Tableau is not available at your organization, install the free software, Tableau Reader, which can be downloaded here: https://www.tableau.com/products/reader. To install the software, follow the provided instructions.

3 SETTING UP A STANDARD SCENARIO

This section describes how to edit FTOT configuration files and inputs the user will need to create their own scenarios. Section 4 details how to configure FTOT inputs for more complex FTOT functionalities, which the user can reference as needed for their own scenario.

FTOT's Quick Start and Reference Scenarios datasets include several ready-to-use example scenarios and input files. See https://volpeusdot.github.io/FTOT-Public/data_download.html for the latest scenario and documentation files. In addition to demonstrating FTOT functionalities, the Quick Start and Reference Scenarios can also serve as templates for creating user-specified scenario configuration and input files. An introductory video for how to create a custom FTOT scenario is also available on the Volpe Center YouTube channel here: https://youtu.be/JmDtU_cKI1g. The FTOT Tools suite of supplementary materials also provides a Scenario Setup Template as well as a Sustainable Aviation Fuel (SAF)-specific Scenario Setup Template to help users input their supply chain data and create the input files required for an FTOT scenario; see Section 3.4 for more details.

Getting Started

FTOT's Quick Start and Reference Scenarios are stored in the C:\FTOT\scenarios\quick_start and C:\FTOT\scenarios\reference_scenarios folders, respectively, once downloaded. Each scenario includes its own dedicated subfolder for storing the scenario configuration, inputs, and outputs. Apart from the geospatial input data, which is shared in the common_data folder for the Quick Start and Reference Scenarios, each scenario folder comes with the minimum required files to run FTOT: a batch (.bat) file, a scenario XML file, and an 'input_data' directory with the relevant facility-commodity input CSV files.

A batch file is a file used to run FTOT in a command-line interface (see Section 5 for more information on this file and how it works). A scenario XML configuration file defines key input parameters applied to the network and optimization problem. FTOT scenarios also require geospatial information for the network itself (associated network attributes such as costs, impedances and weightings, movement restrictions, and schedules are specified in the scenario XML and CSV files). The FTOT network inputs must also include the facilities (origins, processors/waypoints, destinations) associated with the supply chain being analyzed, as well as their associated attributes such as facility minimum and maximum size, available supply/demand of input and output commodities, and associated efficiency/conversion to products. This facility-level supply chain data is defined in a set of comma-delimited files.

To ensure you have all necessary files to run a new FTOT scenario, the user can

1. Copy over a Quick Start or Reference Scenario folder based on the intended supply chain structure of the user's FTOT scenario, and then
2. Customize the copied starter files according to the user's specific scenario needs.

For example, use files from Quick Start 2 for a scenario where freight flows from a raw material producer (rmp) to a processor (proc) to a destination (dest); use Reference Scenario 2 as a template for a candidate processor generation scenario. To then adapt the starter scenario, the user will need to update the scenario XML (Section 3.1) and supply chain data (Section 3.3) at a minimum. Some custom scenarios will also require creating new facility-level GIS data (Section 3.2). Finally, customization of the scenario's batch file will also be necessary (discussed in detail in Section 5).

FTOT Use Cases and Corresponding Files

The Technical Documentation lays out several scenarios for which FTOT is particularly suited to evaluate the effects. To start creating custom scenarios for each of these use cases, these are the input files to pay particular attention to (beyond the usual editing of the scenario XML, supply chain data, and batch file):

- Changes in transportation infrastructure (e.g., gain or loss of transportation elements such as road links, bridges, etc.) or intermodal transfer points. This can include the assessment of hazard scenarios (e.g., flooding, etc.) based on loss of links in the network.
    - To explore loss of links in the network, the user should include a disruption data CSV as described in Section 4.1.2.
    - To identify network links affected by a certain hazard event, the user can use the network disruption tool in the FTOT Tools suite as described in Section 7.1.6.
    - To explore the impact of gaining a few key pieces of network infrastructure (e.g., roads, bridges), the user should add custom segments to the FTOT GIS network as described in Section 4.1.1.
- Changes in supply chain / industry infrastructure (e.g., gain or loss of specific facilities or facility types within the supply chain like a new processing location, or separating processing of materials into one or more steps), or changes in capacity at facilities (e.g., expanding a processor to enable more throughput).
    - To model changes in capacity at processor facilities or the gain/loss of processor facilities, the user should edit the processor and/or candidate processor facility-commodity CSV files as described in Section 3.3.1.
    - To incorporate new processor facilities into the scenario, the user may need to add facility location GIS data to the geodatabase as described in Section 3.2.1.
- Changes in supply of raw material from origins or demand at destinations (e.g., more agricultural production at origins, change in demand among destinations or overall).
    - To model changes in supply and/or demand at facilities, the user should edit the raw material producer and/or destination facility-commodity CSV files as described in Section 3.3.1.
- Effects of supply chain development options based on FTOT generation of potential processing facilities or inclusion of externally-generated candidate processing locations.
    - To explore the impact of variations in FTOT generation of candidate processors, the user should edit the candidate processor facility-commodity CSV file as described in Section 3.3.3.
    - To explore the impact of externally-generated candidate processors, the user should edit the processor facility-commodity CSV file as described in Section 3.3.4.
- Supply chain and optimal network resilience in the face of cumulative disruption.

    - To use the FTOT resilience tools, the user should follow the installation and usage instructions as described in Section 7.2 and the linked GitHub repositories.
- Changes in supply chain infrastructure availability and effects on transport / storage of materials over time.
    - To model changes in availability of raw materials, processing capacities, and product demanded across discrete time periods, the user should include a schedules CSV as described in Section 4.3.1.
- Consideration of the social cost of carbon dioxide (CO_2) emissions in the optimization.
    - To consider the routing impacts of incorporating CO_2 emissions costs in a scenario, the user should modify the scenario XML as described in Section 4.2.2.

3.1 XML Schema and Configuring FTOT Scenarios

A scenario configuration file, scenario.xml, is used to define the location of key input data such as the multimodal network, facility locations, and facility commodity information defined by the user, as well as key input parameters and assumptions for the run. More details on the XML configuration file are available in Section 3 of the FTOT Technical Documentation, particularly Section 3.10 which describes some of the default parameters and their sources.

The XML configuration file is a text-based file that can be modified in a text editor or an integrated development environment for software development. The user must update the placeholder values in the XML file with scenario-specific information, and the default values should be reviewed and adjusted by the user. The FTOT XML specifies input data file locations and user variables for the scenario.

3.1.1 Checklist of critical items to update for a new scenario

When creating a new scenario from an existing Quick Start or Reference Scenario, the user should modify the following XML elements (all line numbers below refer to the FTOT XML when all optional elements are included):

- \`Scenario_Name\` (line 3)
- \`Scenario_Description\` (line 4)
- \`RMP_Commodity_Data\` (line 22) – Confirm file path.
- \`Destinations_Commodity_Data\` (line 23) – Confirm file path.

Other optional items to update:

- \`Disruption_Data\` (line 13) – Change file path.
- \`Base_RMP_Layer\` (line 17) – Change geodatabase (GDB) layer if using your own GDB.
- \`Base_Destination_Layer\` (line 18) – Change GDB layer if using your own GDB.
- \`Base_Processors_Layer\` (line 19) – Change GDB layer if using your own GDB.
- \`Processors_Commodity_Data\` (line 24) – Change file path.
- \`Processors_Candidate_Commodity_Data\` (line 25) – Change file path.
- \`Schedule_Data\` (line 26) – Change file path.
- \`Commodity_Mode_Data\` (line 27) – Change file path.

- `Commodity_Density_Data` (line 28) – Change file path. Recommended if creating a scenario with liquid commodities.

Note that the file paths in XML lines 22-28 can be formatted as absolute paths or as paths relative to the scenario XML file location. For example, for the Quick Start 1 scenario, the 'RMP_Commodity_Data' file path can be entered as 'C:\FTOT\scenarios\quick_start\qs1_rmp_dest\input_data\rmp.csv' or as 'input_data\rmp.csv'.

3.1.2 Additional variables for scenario configuration

The XML file includes 70 variables that can be modified by the user to customize the scenario, but many of these can be left as the default values, including (all line numbers below refer to the FTOT XML when all optional elements are included):

- **Choose default units:** In lines 33-34, solid and liquid phases are defined by `Default_Units_Solid_Phase` and `Default_Units_Liquid_Phase`. The user is free to specify facility-commodity data in any units they prefer, with the stipulation that solid materials must be defined in terms of mass and liquids must be defined in terms of volume. Units of length are defined in `Default_Units_Distance` on line 35. The default distance units must match the units used for link length in the GIS network. Finally, the default currency unit is defined in `Default_Units_Currency` on line 36. FTOT will convert each liquid/solid unit and distance unit record in the FTOT inputs to the specified default units using Pint, a Python module for converting units. However, FTOT does NOT convert currency, so the default currency must be the same units used in all other currency inputs in the FTOT inputs. For example, if modal costs are in "usd/tonne/mi" then the default currency unit must be set to "usd".
- **Set network impedances:** Impedance weights are used to discourage flow over portions of the road, rail, and water networks. The `Impedance_Weights_Data` element on line 88 can optionally contain a file path pointing to the impedance weights data CSV file. The networks subfolder in the common_data folder includes an example impedance CSV file populated with weights that correspond to FTOT's default U.S. multimodal network. Users supplying custom networks should update the impedance CSV file for their own custom network. If an impedance CSV file is not included, links will be equally weighted. See Section 4.2.1 for more information.
- **Include/exclude modes:** To exclude a network mode, the user can edit the Route_Optimization_Script section of the scenario XML file. For example, the road network can be excluded by setting line 123 in the scenario XML file (`Road` in the Permitted_Modes section) to False.
- **Enhance run time using network density reduction:** In the scenario XML file, enable the network pre-solve step by setting the `NDR_On` parameter to True (line 119) in order to improve runtime for larger scenarios. Enabling this functionality triggers a network density reduction (NDR) calculation using the NetworkX shortest path algorithm in the G step, which simplifies the optimization problem. Performing the optimization steps on the less dense shortest path network decreases the runtimes of the O steps. In addition, running an FTOT scenario with NDR will generate a supplementary output report and a Tableau routes dashboard describing characteristics (e.g., transport cost per unit of commodity flowed, routing cost per

unit of commodity flowed, length, CO_2 emissions per unit of commodity flowed, and travel time) of the routes considered in the optimal solution—this report can be useful for origin-destination route comparisons across disruption and other scenarios. For candidate generation or maximum transport distance scenarios, the G step includes an additional iteration through the NetworkX shortest path algorithm to identify the parts of the network that are reachable within the maximum transport distance. FTOT then excludes components of the network not reachable within the maximum transport distance prior to solving for routes between facilities. NDR cannot be used in combination with capacity constraints.

- **Specify liquid commodity densities:** FTOT allows users to specify density values for liquid commodities through a commodity-specific density input file (line 28) and/or a default density value (line 71) in the scenario XML file. Commodity densities are used to convert liquid commodities from units of volume to units of mass, as well as convert vehicle specification parameters as needed. See Section 4.4.1 for more information.
- **Configure artificial links:** FTOT automatically constructs artificial links to connect facilities to each modal network based on an artificial link distance parameter, which the user can set for each mode in lines 101 to 105 of the scenario XML file (e.g., `Road_Max_Artificial_Link_Distance` for the road network). See Section 4.2.3 for more information on how FTOT constructs and uses artificial links. In addition, on line 108 the user can set `Report_With_Artificial_Links` to True to include artificial links when calculating summary metrics. By default, transportation on artificial links is treated like local road transportation; users may also set custom transportation costs on artificial links using the optional `Artificial_Link_Cost` field.
- **Set short-haul penalties to reduce spurious mode switching:** The short haul penalties `Rail_Short_Haul_Penalty` and `Water_Short_Haul_Penalty` on lines 114-115 are used to prevent very short movements by rail and water (as road is much more commonly used for short freight movements). By default, short haul penalties are applied as a function of the minimum distance desired for movements on the rail or water mode. The default short haul penalty, entered by the user as a distance, is equivalent to the cost to travel over 100 miles of network. Decreasing this distance allows for shorter movements by rail and water, while increasing the distance further discourages short movements by rail and water. Section 4.2.4 provides additional information on the application of short haul penalties.
- **Apply capacity constraints to routing:** The Capacity_Options section of the scenario XML file starting at line 129 can be modified to set `Capacity_On` to True (which turns on capacity for all links) and to set Background_Flows for each modal network to True (which prompts FTOT to use existing transportation network flows to limit the usable capacity of the network). Both capacity and background flows are based on daily flows, so using capacity in a scenario implies that flows are all happening in a day. Background flows can be turned on by mode, although the public version of FTOT only contains background flows for road, water (through the locks feature class), and a subset of crude pipeline modes. More details on where background flows data are sourced from can be found in the Technical Documentation. Note that the default 2025 version of FTOT's Public U.S. Contiguous Network does not contain capacity data for the road network, so users are directed to use the FAF4 Capacity version (referring to the Freight Analysis Framework Version 4 roadway data) for capacity-constrained scenarios. The Capacity_Options

section also includes the field `Minimum_Capacity_Level`, which is a fraction between 0 and 1 representing the minimum available capacity that FTOT should give any link in the scenario when `Capacity_On` is set to True. When set above 0, this property allows FTOT to flow freight on links that are at or near capacity. When the allowable capacity is 0, this means that FTOT can only use the currently available capacity of the network and cannot route goods along any link that is at or over capacity. A minimum capacity level of 0.25 sets the available capacity of each link in the network to at least 25% of its normal capacity, even for links that would normally be unavailable or capacity constrained based on their capacity and existing background flows. Links with more than 25% available capacity are unaffected.

- **Enable CO_2 optimization:** FTOT can solve for an optimal routing solution based on a combination of scaled transport cost and CO_2 emissions cost. The parameters for this functionality are found in the optional CO2_Optimization section of the scenario XML file; see Reference Scenario 8 for an example. The scaling factors Transport_Cost_Scalar and CO2_Cost_Scalar accept values between 0.0 and 1.0 and control how much each cost element is considered in the optimization. The CO2_Unit_Cost will be applied to each unit of CO_2 emissions; cost should be entered in default currency units per mass unit of CO_2. The XML parameters related to CO_2 optimization are optional—in absence of these elements, FTOT will default to using the full value of impeded transport cost (scaling factor of 1.0) and to zero out CO_2 emissions cost (scaling factor of 0.0), which leads to a transport cost-only optimization approach. However, if CO2_Cost_Scalar is greater than 0, then CO2_Unit_Cost must be provided. Be aware that while FTOT will not consider CO_2 costs in the optimization and reporting if CO2_Cost_Scalar is nonexistent or set to 0, helper tables in the SQLite database will still list CO_2 cost for each link assuming a default unit cost of 191 USD per ton of CO_2 (and will not account for currency conversions).
- **Set solver configuration:** FTOT relies on open-source solvers to find the optimal solution to the supply chain routing problem. There are two solvers enabled for use with FTOT: (1) the COIN-OR branch and cut (CBC) algorithm, (2) HiGHS. The optional XML parameter Solver can be used to specify the algorithm to use. Users can also specify a maximum time limit for the solver to run before terminating with the best solution found so far using the optional XML parameter Solver_Time_Limit. More guidance on how to set these parameters can be found in Section 8.3.
- **Penalize unmet demand:** The default unmet demand penalty (e.g., `Unmet_Demand_Penalty`) is a fixed penalty per unit of unmet demand (in default solid units) at the destination facilities of the FTOT scenario. The unmet demand penalty can be further customized in the facility-commodity input CSV files, see Section 3.3.1. This cost penalty is used to drive commodity flow over the network. See Troubleshooting Notes in Section 8 for common issues with the unmet demand penalty. The unmet demand penalty can be set in a number of ways for different scenario objectives. If set significantly higher (e.g., by a factor of 10 to 50) than average transportation cost for the scenario, FTOT will aim to maximize demand fulfilled regardless of cost. If set at values near actual average transportation cost, the user can evaluate the trade-off between demand fulfillment and cost of transport. It is advised to run scenarios with multiple

unmet demand penalties to explore the sensitivity of a given analysis. In doing so, the user can fine tune the actual transport cost of the optimal routing solution within a desired range.

3.1.3 Updating FTOT scenarios from older release versions

The FTOT team often introduces optional XML elements as new features are added to FTOT, so older versions of Quick Start and Reference Scenario XML files may not have all available scenario elements. The quickest way to update an existing, older scenario is to manually add any additional elements needed. For reference, the master XML template saved at `C:/FTOT/program/lib/v8_temp_Scenario.xml` contains all required and optional XML elements.

When updating the XML, the user does NOT need to include any comments from the original XML or in the template XML, but the elements do need to be in the same order as seen in the template.

3.1.4 Tools for Updating XML Files

Several tools can help the user efficiently and thoroughly update their new scenario XML (and to a lesser extent, the batch files described further in Section 5). Text file comparisons can help the user recognize items that still need updating. Consider comparing new scenario files to the following:

- **FTOT's template XML**, located in the `C:/FTOT/program/lib` sub-directory. This file (named `v8_temp_Scenario.xml`) can help the user identify missing scenario elements or differences from the Quick Start or Reference Scenario defaults. The file is also used as the template for an FTOT Tool that creates new scenario files from scratch.
- **Previously-created versions** of the scenario being run, including any template Quick Start or Reference Scenario files. This comparison is especially helpful to verify scenario variations and new file paths. Note that previously-created versions may rely on an older XML schema and may not be compatible with current versions of FTOT without modification.

Listed below are just a few tools to update scenario files:

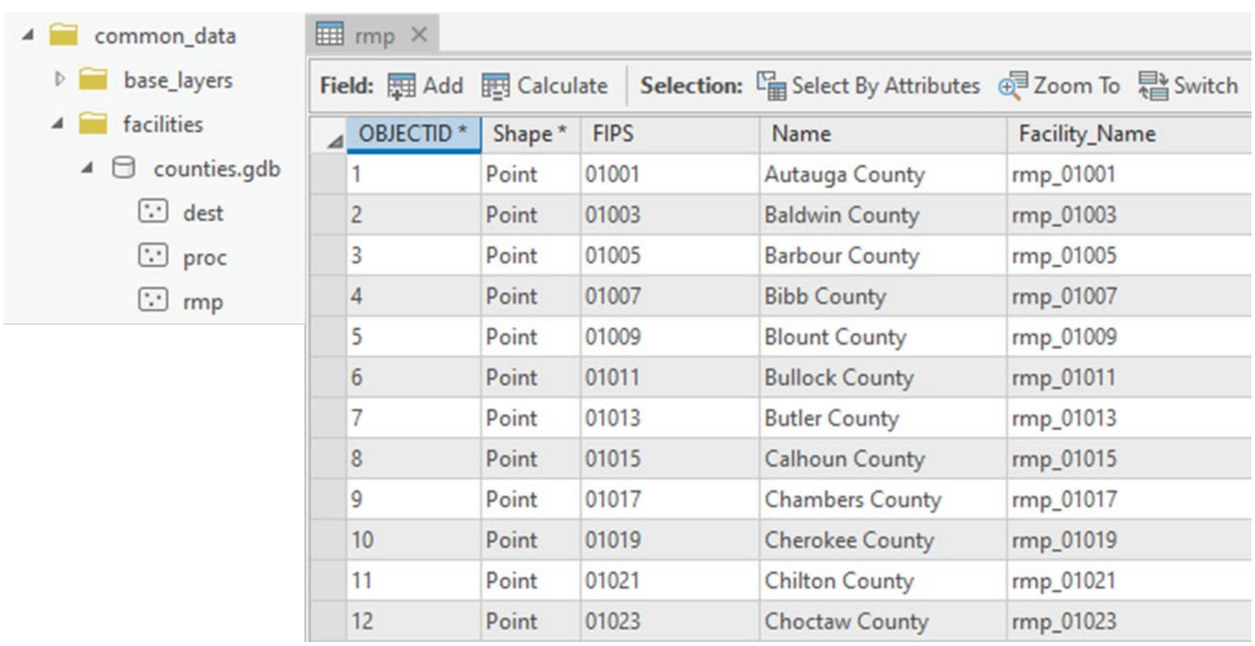
- **FTOT Tools.** The XML tool in ftot_tools.py can create a new, blank scenario XML from the template XML, or update an existing XML to the most recent schema. Make sure to manually check all element values if using this tool since default values generated by the tool may still require user input. See Section 7.1.1 for guidance on running this tool.
- **Text editor.** Any text editor, such as Windows Notepad, can be used to directly edit XML element values (e.g., file paths).
- **BeyondCompare.** Using the BeyondCompare (https://www.scootersoftware.com/) application, the user can "copy section to right/left" using arrows in the side bar and highlight differences in text (red lines) and in spacing (purple lines). Make sure to separate out distinct sections before copying over to avoid unintentional overwriting. Note: Requires a paid license after a trial period.
- **Visual Studio.** In Visual Studio, go to Tools > Command Line > Developer Command Prompt, and in the window that appears enter `devenv.exe /diff list1.txt list2.txt` replacing list1.txt and list2.txt with the XML or other files the user wishes to compare. The user can drag and drop files to paste in the full file path. A comparison window will open in Visual Studio. See a related Stack

Exchange post (https://stackoverflow.com/questions/13752998/compare-two-files-in-visual-studio).

3.2 Facility Location GIS Data

FTOT requires GIS-based input datasets containing the facility names and locations of raw material producers (rmp), processors (proc), and destinations (dest). These GIS feature classes (FC) must contain facility names and point locations for each facility. **Note: facility names must be unique**, e.g., Middlesex County CT must be differentiated from Middlesex County MA. FTOT will automatically match the geospatial location specified in the FC to the facility-commodity relationships specified in the CSV files defined below (Section 3.3) using the Facility_Name fields.

There are many sources of GIS data an FTOT user can leverage to represent the locations of a scenario's facilities. FTOT comes with one preexisting facility location geodatabase included in FTOT's common data subdirectory—point-based representations of every county in the United States located at the centroid of the most populated place within each county. All of the Quick Start and Reference Scenarios utilize this data as proxies for hypothetical facility locations. If FTOT was installed in the default location (including the separate download of documentation and scenario datasets available at https://volpeusdot.github.io/FTOT-Public/data_download.html), the county-based facility location geodatabase is stored in the following location: C:\FTOT\scenarios\common_data\facilities\counties.gdb (in previous versions of FTOT this was known as facilities.gdb). The facility location geodatabase included with FTOT is a useful facility location dataset to start with for users working with county-based commodity data who quickly want to get up and running with FTOT. One feature class is provided for each facility type (raw material producers, processors, and destinations) with unique county-facility names. The structure of the geodatabase and an example of the records are shown below.



OBJECTID *	Shape *	FIPS	Name	Facility_Name
1	Point	01001	Autauga County	rmp_01001
2	Point	01003	Baldwin County	rmp_01003
3	Point	01005	Barbour County	rmp_01005
4	Point	01007	Bibb County	rmp_01007
5	Point	01009	Blount County	rmp_01009
6	Point	01011	Bullock County	rmp_01011
7	Point	01013	Butler County	rmp_01013
8	Point	01015	Calhoun County	rmp_01015
9	Point	01017	Chambers County	rmp_01017
10	Point	01019	Cherokee County	rmp_01019
11	Point	01021	Chilton County	rmp_01021
12	Point	01023	Choctaw County	rmp_01023

Figure 6: Screenshot of the FTOT counties geodatabase.

Users basing facility locations on the default data that come packaged with FTOT do not need to move or copy over those data into a new scenario directory; they can continue to be read from their default location (in the `C:/FTOT/scenarios/common_data/facilities` subdirectory). Users who want to create their own customized facility location GIS data should read the next section for guidance on leveraging other facility location data and creating custom facility location data—either based on the default facility location data or built entirely from scratch.

3.2.1 Creating Custom Facility Location Data

In some cases, existing GIS-based facility location data relevant to an FTOT scenario may not already exist. The sections below walk the FTOT user through ArcGIS Pro functionality and workflows that help the user build custom facility location data.

Accessing and Viewing the Template Facility Location Data in ArcGIS Pro

- Users who installed FTOT in the default location can find the default facility location database in C:\FTOT\scenarios\common_data\facilities\counties.gdb.
- The facilities contained in this geodatabase can easily be viewed, queried, and subset within ArcGIS Pro. Open ArcGIS Pro and create a blank map template, saving the project in a directory of your choice.

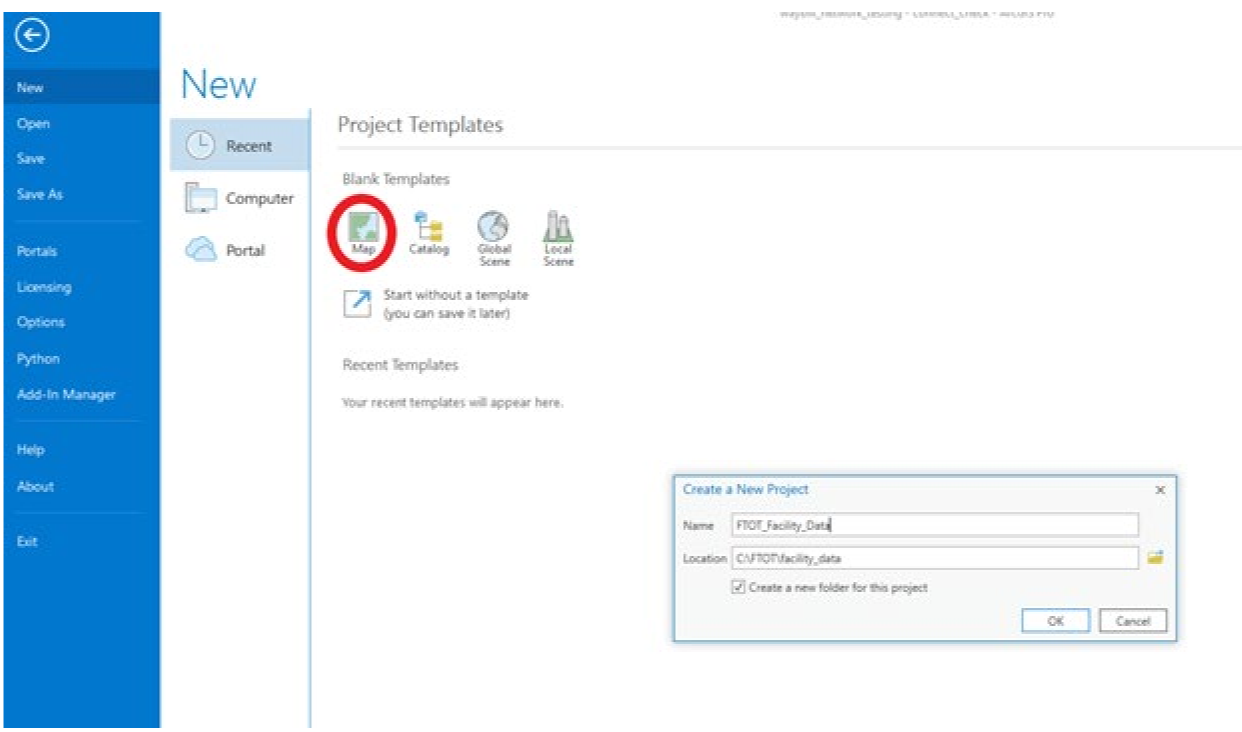


Figure 7: Screenshot of a new ArcGIS Pro project for facility location data.

- The three feature classes inside this geodatabase can be added to a blank map using the Add Data button.

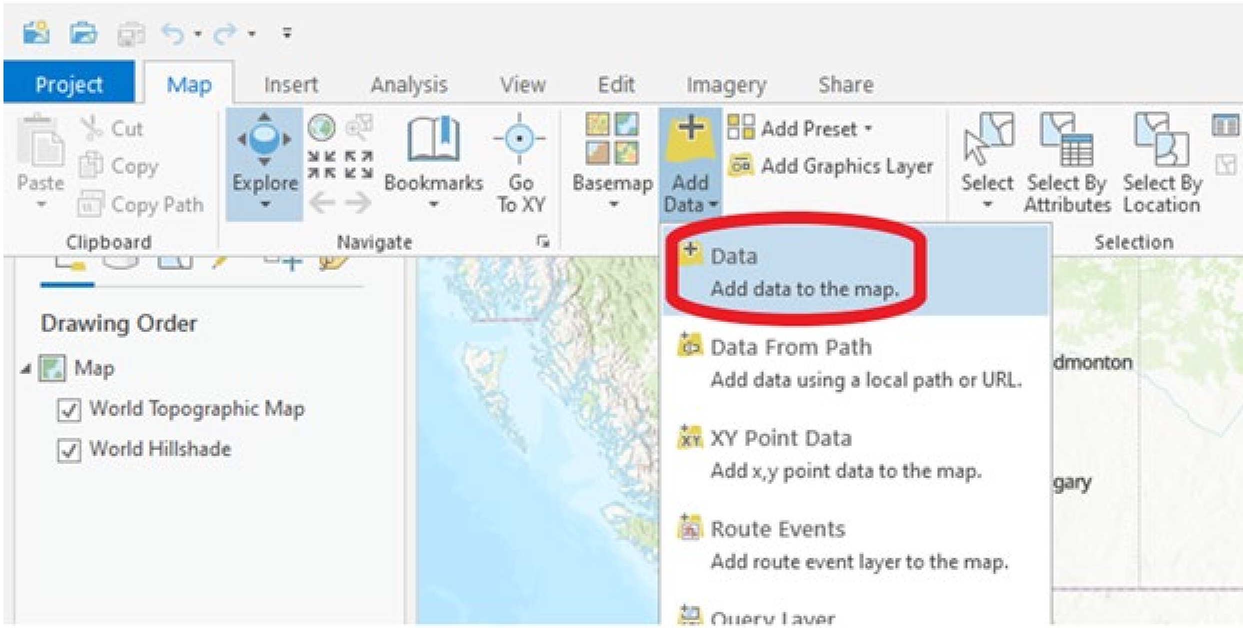


Figure 8: Screenshot of ArcGIS Pro demonstrating how to add data to a map.

- Right click on each feature class within the map's Table of Contents to open the associated attribute table. The attribute table contains the Federal Information Processing Standards (FIPS) code for each county, the county name, and a unique facility name. Each feature class (rmp, proc, and dest) is identical except for the facility names (i.e., Autauga County, Alabama has a facility name of 'rmp_01001' in the rmp feature class, a facility name of 'proc_01001' in the proc feature class, and a facility name of 'dest_01001' in the dest feature class).
- The default facility locations may be sufficient for certain FTOT scenarios, but if not, these feature classes can be used as templates for a custom facility location dataset.

Building Custom Facility Location Data from the Template in ArcGIS Pro

- Users who wish to add their own unique facility locations to an FTOT scenario should start with a copy of the default facility location data template feature classes, rather than the original data that is stored in the common_data folder. The template feature classes can be copied into a working directory using Windows Explorer or within ArcGIS Pro using the 'Export Features' tool by right clicking on each feature class and selecting Data→Export Features to save them into a working directory. Users who wish to only bring a subset of the default facilities into their customized feature class should establish that subset using ArcGIS Pro before exporting with the "select interactively," [7] "Select by Attribute," [8] or "Select by Location" [9] tools.
- The new user-created facility location feature classes do not need to have the same names as the template feature classes, but it is best to continue using a unique feature class name for each facility type (raw material producers, processors, and ultimate destinations). Users will

need to know the full path to these feature classes so that they can be referenced in the FTOT scenario's XML configuration file.

- Using the Export Features tool will automatically add these new feature classes to the ArcGIS Pro map. If the template data were instead copied using Windows Explorer, make sure to add the newly copied feature classes to the ArcGIS Pro map. The old (original copies) of the feature class can be removed from the map.
- FTOT users who wish to start with a blank template can select all the existing facilities and delete them within an ArcGIS Pro Edit session. For more information on deleting feature classes, consult the ArcGIS Pro documentation. [10] Deleting facilities is optional—users can add facilities without removing existing facilities as long as each added facility has a unique facility name.

Building Facility Location Data from Scratch using ArcGIS Pro

- More experienced GIS users can build their own facility location data from scratch (rather than from the template that comes with FTOT). The data must be in a standard GIS data format, each facility type must have its own uniquely named feature class, and each feature class must contain a field called "Facility_Name" (case-sensitive) with a unique identifier for each facility that does not repeat across the FTOT scenario. ArcGIS Pro has documentation on building point feature classes from scratch. [11]

To populate custom facility locations using ArcGIS Pro:

- Under the ArcGIS Pro Map tab, there is a Locate button that can be used to access an interface to help locate facilities based on a name, address, or other identifying information. If this brings up a facility of interest, right click on the result, select Add to Feature Class, and then select the appropriate feature class (rmp, proc, or dest). Press OK. You may need to log in to your ArcGIS account for this functionality to work properly.
- Alternatively, if you've already located where the facility is and you'd like to add a location to your feature class without searching first, navigate to the Edit tab in ArcGIS Pro, select the Create button, and then select the feature class to which you are adding facilities. Ensure that the 'Point' icon is selected and then click on the location on the map where you wish to create a facility. A new facility will be added to the last row in the feature class's attribute table. Open the attribute table and fill in any appropriate fields. As previously mentioned, the only field that must be included is "Facility_Name", but you may wish to create new fields or populate existing fields to include additional information about the facility.

3.2.2 Finding Existing Facility Location Data

- Any standard GIS-formatted point feature class (e.g., shapefile, file geodatabase, etc.) is acceptable to generate facilities for FTOT. The key requirements are that:
    - There should be distinct feature classes representing each FTOT facility type (e.g., raw material producers, processors, and ultimate destinations).

   - The feature classes must contain a “Facility_Name” attribute (note: attribute name is case-sensitive) populated with unique facility names for each facility. Facility names cannot repeat across the FTOT scenario. These facility names must be the same facility names represented in the scenario's commodity CSV input files.
- In the likely event that the "Facility_Name" field name is not included with a pre-existing GIS feature class, use ArcGIS Pro to add a new field [12] and then calculate the contents of that new field based on another existing field. [13] Alternatively, rename an existing attribute to “Facility_Name” (case-sensitive) using the “Alter Field” tool. [14]

A few potential facility data sources include:

- U.S. Energy Information Administration Map Data [15]: Contains shapefiles with the locations of biodiesel plants, power plants, and other energy-related facilities.
- Bureau of Transportation Statistics Open Data [16]: Facility location information includes airports, ports, air-to-truck intermodal freight facilities, and other facilities.
- U.S. Environmental Protection Agency Facility Registry Data. [17]
- Joint BioEnergy Institute (JBEI) BioSiting Tool [18]: Facility location information includes ethanol biorefineries, renewable diesel and SAF plants, biosolids facilities, biodiesel plants, and livestock anaerobic digesters in the continental U.S., as well as sub-county point source estimates of various bio-based feedstocks.

3.3 FTOT Supply Chain Data

3.3.1 Facility Characteristics Data Input Files

In addition to the XML scenario file and facility location data, FTOT requires a set of comma-separated-values (CSV) files, which define facility-commodity information (e.g., supply/demand amounts, product slates and conversion efficiency, and minimum/maximum facility size, among other elements).

The facility-commodity data are specified in a series of CSV files located within the specific scenario’s input_data folder. Four comma-separated-values input files are available for facility definitions in FTOT. These files contain information for each facility type: raw material producers (RMPs, which are the supply origin locations in the scenario), processors (which are waypoints or processing locations in the supply chain), candidate processors (to be used in a candidate generation scenario), and destinations (which are locations of demand for the final commodities).

Each facility input file includes the following fields:

- **facility_name**; used to match the facility-commodity data to locations in the scenario geodatabase. NOTE: the facility_name in the input data CSV file must match the records in the Facility_Name field of the GIS feature class. Facility names should be unique and not duplicated. Care should be taken when using county or city names as these are often repeated across states. Additionally, take care that extra trailing whitespace is not included, as “Whitewater” and “Whitewater ” will not match.

- **facility_type**; specifies the type of facility (e.g., “raw_material_producer”, “processor”, “ultimate_destination”).
- **commodity**; a unique name for the commodity. FTOT will create origin-destination pairs by matching commodity names across facilities. For example, if an RMP specifies commodity_A as an output and a destination specifies commodity_A as an input, FTOT will try and flow material from the RMP to the Destination. Through these origin-destination pairs, commodity names imply the structure of the supply chain. Unlike with facility names, commodity names are converted to lowercase and stripped of leading/trailing whitespace when read into FTOT. Thus, “Blueberries” and “blueberries” will be treated as the same commodity.
- **value**; the quantity of the commodity. Use of this field varies by facility type: for RMPs, it is the maximum available material; for destinations, it is the total demand; for processors, it defines how much output is created by the specified quantity of input. If a processor has more than one input (output) commodity listed, FTOT requires the commodities to be used (produced) in the specified ratio. For “total” rows for processors, which are used to specify total facility input/output capacity in the “max_capacity” or “min_capacity” column, the quantity in the “value” field is ignored and may be left blank.
- **units**; the units of the quantity for the commodity. Solid commodities must be specified in units of mass; liquid commodities must be specified in units of volume.
- **phase_of_matter**; solid or liquid, (gas is not currently supported).
- **io**; specifies if the commodity is an input (i) into the facility, or an output (o) out of the facility. RMPs by definition ONLY have outputs, and destinations by definition ONLY have inputs. Each processor must have at least one input commodity AND at least one output commodity.
- **schedule** (optional); a user specifies the name of the availability schedule that each facility follows. The schedule name provided in the facility CSV should match one provided in the schedule CSV input file. The amount of material supplied or demanded at the facility on each day of the scenario is equal to the product of the commodity quantity and the fraction availability provided in the schedule. Candidate processors specified in the proc_cand.csv input file described in Section 3.3.3 are also able to be assigned availability schedules using an optional field.
- **access_cost** (optional); a cost associated with movements into or out of a user-defined facility, in addition to base transportation costs associated with the network. Access cost can be specified per facility, commodity phase (liquid or solid), and in or out movement. The access cost units are assumed to be in default currency units (from the scenario XML file) per commodity unit from the CSV line where access cost is provided. If multiple access costs are provided for the same facility, phase, and in or out movement, the largest value entered in the CSV file is used. Access costs are not compatible with candidate processors. The field is useful for reflecting facility and/or commodity-specific transportation or facility operation costs, such as additional costs associated with remote facilities or facilities in congested urban environments.

For raw material producer facilities and (when NDR is enabled) processors, there is one additional optional field allowed in the input CSV file:

- **max_transport_distance** (optional); a user-specified maximum transport distance that this commodity can travel. When FTOT is generating candidate processors, this value is required for any commodity that is an input to a candidate process. This field should be excluded from scenario runs where it is not needed for performance reasons. The maximum transport distance has units specified by the default distance unit in the scenario XML.

For destination facilities, there is one additional optional field allowed in the input CSV file:

- **udp** (optional, facility-specific); a user-specified unmet demand penalty (UDP) that applies to destination facilities that do not meet the amount of commodity demanded. This field can be manually set for each destination facility and commodity. The UDP units in the destination CSV file are assumed to be in default currency units (from the scenario XML file) per commodity unit from the CSV line where UDP is provided. If this field is not added as an optional column, FTOT uses the default unmet demand penalty specified in the scenario XML for all destination facilities and commodities in the optimization step. The field is useful to prioritize demand fulfillment at specific locations or for specific commodities. It is also recommended for scenarios with multiple end products, particularly if those commodities are different phases of matter.

For processors, there are three additional optional fields allowed in the input CSV file:

- **max_capacity** (optional); here the user can specify the maximum amount of material a processor can handle. This property is often taken from real-world constraints; lower values may drive the optimal solution for the scenario to utilize more processor facilities than just the one on the lowest cost route, resulting in higher transportation costs or even more unmet demand at the destination. If this column exists, the value provided in each row corresponds to a maximum capacity for the commodity (either input or output) in the row. Capacity values specified for a commodity must be in the same units as the quantity. Additionally, a maximum capacity for the entire processor facility can be specified by including an additional row in the CSV file with commodity set to 'total' and 'io' set to 'i' for input or 'o' for output. To allow backwards compatibility with older scenario files, the column max_processor_input can still be used. Any value in it is treated as an overall facility capacity, handled the same as the 'total' row. The max_capacity or max_processor_input field can be left blank for some or all processors; these processors will have no upper restriction on the amount of material they process, though the processing ratio is still defined by the 'value' field. If a max_capacity or max_processor_input column does not exist, processor upper capacity is unbounded for all processors specified in proc.csv.
- **min_capacity** (optional); here the user can specify the minimum amount of material a processor can handle if it is utilized. If this column exists, the value provided in each row corresponds to a minimum capacity for the commodity (either input or output) in the row. Capacity values specified for a commodity must be in the same units as the quantity. Additionally, a minimum capacity for the entire processor facility can be specified by including an additional row in the CSV file with commodity set to 'total' and 'io' set to 'i' for input or 'o' for output. To allow backwards compatibility with older scenario files, the column min_processor_input can still be

used. Any value in it is treated as an overall facility capacity, handled the same as the 'total' row. The min_processor_input or min_capacity field can be left blank for some or all processors; blank values are interpreted as a minimum capacity of zero. If none of the columns exist, processor lower capacity is unbounded for all processors specified in proc.csv.

- **build_cost** (optional); to indicate that a processor is a candidate facility as opposed to an existing facility, the user must add the build_cost field in the processor commodity input file and specify a positive fixed build cost. Processors for which this field is 0 or missing are considered existing facilities. To use the optional build_cost field, the user should enter numbers representing the amortized cost of building the facility across the given time period. If this column exists, it should be the same for all rows of a single processor. Note that this is a separate functionality from candidate generation, which is specified in Section 3.3.3.

Processor facility input files are also able to specify conversions with multiple input commodities and multiple output commodities. For example, in cases where the processor requires two inputs (e.g., blueberries and sugar) and one output/product (e.g., jam), the two raw materials are specified as inputs to the same processor, and the output quantity is specified as a ratio of the two inputs. If capacity values are specified for a commodity, they must be in the same units as the quantity. If a 'total' row is included for capacity, its units must be specified. Units for the 'total' row must be of solid phase unless all commodities being totaled (input or output) are liquid phase; only in this case can the 'total' row have liquid units. Note that FTOT requires all input commodities to be available in order to generate the outputs. FTOT will not use the facility if one commodity is missing. If one of the input commodities is limited, then FTOT will generate up to the limiting amount of input material.

Candidate processor facility input files require a few additional fields used by FTOT's candidate generation process, which are described in Section 3.3.3.

3.3.2 Commodity Mode Input File

This optional input file allows the user to toggle different modes on and off for individual commodities. Users can also assign specific truck, railcar, or barge types to a commodity. This CSV file can be stored in the same place as the other scenario input data, for example the facility commodity CSV files, are stored.

The file name and file path should be added to the `Commodity_Mode_Data` element in the scenario XML.

<Commodity_Mode_Data>YOUR_SCENARIO_FOLDER_HERE\commodity_mode.csv</Commodity_Mode_Data>

The commodity mode CSV file must be included in order to include pipelines in the solution. Both a crude pipeline network and a petroleum product pipeline network are included in the FTOT network but disabled for all commodities by default. This is to allow users to have flexibility in naming commodities while preventing commodities that are not supposed to flow on pipeline from utilizing it in the optimal scenario since it is usually the least expensive mode. In modeling real-world scenarios, the user should note that most commodities are not allowed to flow on both the crude and petroleum product pipeline networks, though these commodity-mode decisions are left up to the user as best fit their scenario.

As depicted below in Table 1, users can input a Y for yes or an N for no within the CSV file to toggle a mode on or off for a commodity. Commodity-mode pairs with a Y are assigned the default vehicle type for that mode as defined in the scenario XML file. Users can alternatively specify a vehicle label selected from the ‘vehicle_types.csv’ file in the ‘lib’ folder of the project code repository (e.g., C:\FTOT\program\lib) to permit travel via a custom vehicle. Changing the vehicle type for a commodity updates the post-processing and reporting for that commodity and mode but does not affect the optimization.

Table 1: commodity_mode.csv for two commodities: crude oil, and a generic petroleum product (pet_prods).

commodity	road	rail	water	pipeline_crude	pipeline_prod
crude_oil	N	Y	Y	Y	N
pet_prods	small_truck	Y	Y	N	Y

By default, FTOT comes with a small_truck option pre-populated in vehicle_types.csv. This truck type represents a single-unit truck and can be assigned in the commodity mode input file as a ready-to-use option for commodities traveling on road. The vehicle_types.csv structure and small_truck attributes are presented below in Table 2. The small_truck vehicle includes a row with the element and value for each road-related payload, fuel efficiency, and CO_2 emissions entry in the XML file. Vehicle cost is not included since only the default vehicle defined in the scenario XML file is used for the optimization. Note the vehicle types functionality is not compatible with CO_2-based optimization.

In Table 1, crude oil is only allowed to flow on the crude pipeline network (pipeline_crude), and not allowed in the petroleum products pipeline (pipeline_prod). Similarly, the generic petroleum product (pet_prods, e.g., gasoline, diesel, jet fuel) commodity is not allowed to flow on the pipeline_crude network but is allowed to flow on the pipeline_prod network. Additionally, crude_oil travels by road using the default truck defined in the scenario XML file while pet_prods travels on small_truck as specified in vehicle_types.csv.

Table 2: vehicle_types.csv with the pre-populated small_truck vehicle for road.

vehicle_label	mode	vehicle_property	value
small_truck	road	Truck_Load_Solid	8.8 ton
small_truck	road	Truck_Load_Liquid	2.5 thousand_gallon
small_truck	road	Truck_Fuel_Efficiency	106.5 ton-mi/gallon
small_truck	road	Truck_CO2_Emissions	845.41 g/mi

Users can also edit the vehicle_types.csv file to create custom vehicles for the road, rail, and water modes. When adding a custom vehicle to vehicle_types.csv make sure to include all solid payload, liquid payload, fuel efficiency, and CO_2 emissions elements for the corresponding mode as specified in the scenario XML file.

3.3.3 Candidate Generation Option

FTOT can generate screening-level processor candidate locations to convert raw material to commodities demanded by the destinations. Candidate generation requires the user to specify the input and output commodity relationship, as well as the facility maximum and minimum size, minimum aggregation size for generating a candidate processor, and the amortized capital cost as a function of size. As of version 2024.4, FTOT allows candidate generation at any step of supply chain scenarios with multiple processor steps when NDR is enabled; when NDR is not enabled, FTOT is limited to generating candidates only for the first processor in a supply chain.

- In order to run a candidate generation scenario, the user must add the max_transport_distance field for a candidate process's input commodity in the RMP or processor commodity input file. This field is mandatory for FTOT runs with candidate generation. See the end of this section for a note about how to set maximum transport distance for different scenarios.
- A new facility-commodity CSV file is used in this scenario: proc_cand.csv. It contains six attributes per type of processor, listed as six rows in the CSV file: one for the input commodity and one for the output commodity, as usual, plus minimum and maximum facility sizes (minsize and maxsize, respectively), minimum amount of material aggregation on the network to place a candidate facility (min_aggregation) and cost_formula. The relationship between input and output commodities is stored in FTOT per unit of input material. Therefore, the user is free to use whatever commodity values are convenient for them, as long as the ratio is correct. Candidate generation processes can have multiple output commodities, but only one input commodity. All six attributes are required inputs except for min_aggregation; if min_aggregation is left blank, it defaults to one-fourth the minsize.
- The candidate processor facility-commodity CSV file has the same fields as the other facility-commodity CSV files: facility_name, facility_type, commodity, value, units, phase_of_matter, io. For the minsize, maxsize, cost_formula, and min_aggregation rows, the 'io' field should be left blank. For the cost_formula row, the 'phase_of_matter' field should be left blank.
- The candidate processor size is limited by the minsize and maxsize parameters. The minsize of the facility is the minimum amount of material that must flow through the facility during the optimization for FTOT to utilize it as a candidate. The maxsize is the largest size facility (defined by input commodity) that FTOT will generate. The max_capacity field will be populated with this maxsize value when the ftot_generated_processor_candidates.csv file is generated as an intermediate output file by FTOT. The min_aggregation is the quantity of material that must flow over a given link on the network to generate a candidate node.
- The cost formula defines the amortized capital cost for candidate processors. This is specified as a formula in units of currency per input material amount, with the maxsize value used as the processor capacity.

In the first step of the candidate generation process, FTOT optimizes the flow of commodities from raw material producers to destinations, automatically converting the input commodity of the candidate process to the output commodity at (1) the max transport distance, or (2) intermodal facilities. Based on this initial optimization, FTOT identifies candidate nodes at source facilities, at points on the network where raw material flows aggregate, and at points where candidate process inputs were converted to outputs (e.g., at the max transport distance or intermodal facilities). These nodes are treated as possible processor facility locations in the second optimization. A candidate processors feature class is generated in the scenario GDB, and an FTOT-generated candidate processors facility-commodity CSV file (e.g., ftot_generated_processor_candidates.csv) is stored in the .\debug folder.

FTOT now processes the new facilities in the same fashion as other known locations. It will rerun the facility, connectivity, and graph steps (this time with the number 2 appended for logging purposes, e.g., f2, c2, g2). The candidate processors are added into the list of all processors considered by FTOT during the supply chain optimization. At this point, the scenario is functionally the same as in scenarios where existing / known processor candidates are used.

As of version 2022.4, FTOT supports the network density reduction (NDR) pre-solve step for scenarios with candidate generation. While the overall approach when NDR is enabled is the same as the default approach, this new NDR functionality runs significantly faster than the default method (e.g., Reference Scenario 2 finishes in 20 minutes with NDR enabled and 3-4 hours with NDR disabled).

Users should take particular care around setting maximum transport distance parameters when NDR is not enabled, as there is a known issue that makes FTOT sensitive to the maximum transport distance applied. For scenarios not using NDR, the apparent maximum transport distance may be less than what the user specifies. Users are recommended to add an additional buffer (e.g., 40 miles) to the maximum transport distance to ensure FTOT can route commodities through all processors.

3.3.4 User-Provided Candidate Processor Option in Optimizer

FTOT can evaluate user-defined candidate processors in addition to FTOT-generated candidates. In order to use candidate processors not generated by FTOT (e.g., identified by a siting tool), the user will need to execute the following steps:

- Specify candidate processor locations in the processor feature class layer within their facilities GDB file. The feature class includes the ‘Facility_Name’ field, which is a unique identifier for each facility that matches with the facility-commodity CSV file.
- Specify user-provided candidate processors in the “Processors_Commodity_Data” CSV file named “proc.csv”. In order to indicate that a processor is a candidate facility as opposed to an existing facility, the user must add the build_cost field in the processor commodity input file and specify a **positive** fixed build cost. Processors for which this field is 0 or missing are considered existing facilities. To use the optional build_cost field, the user should enter numbers representing the amortized cost of building the facility across the given time period. Note that this amortized cost is **not** per unit but for the entire facility, unlike for FTOT-generated candidate processors. This cost should be included on all rows for a candidate processor; it will only be counted once.
- If desired, set the max_transport_distance field in the RMP commodity input file.

These facilities are added to the main.db and main.gdb just as the known and existing RMPs, Processors, and Destinations are. If by chance a candidate processor generated in the OC step is also an externally-generated candidate processor (e.g., build_cost > 0 in proc.csv), then the build cost from proc.csv is used.

3.4 Scenario Setup Template

Starting with the 2023.3 release of FTOT, the suite of supplementary FTOT tools includes an Excel-based Scenario Setup Template file that serves as a user-friendly aid for creating FTOT scenario files for certain types of scenarios. In the 2025.1 release, an additional setup template specific to regional sustainable aviation fuel (SAF) scenarios was added. Both templates are located in the C:\FTOT\program\tools directory. Examples of filled out template files are also included in the C:\FTOT\program\tools directory. The user should copy the template into a directory of their choice, give the file a relevant name, and input their scenario data, following the directions in the file.

The Scenario Setup Template is intended for use in most common FTOT scenarios; it does not cover all possible FTOT functionalities and input files. A video tutorial of how to fill out the Scenario Setup Template and how to run the Scenario Setup Conversion Tool can be found on the FTOT landing page.

The SAF Scenario Setup Template prompts users for basic information on a SAF supply chain—specifically consisting of feedstock suppliers, refineries, blenders, and as a final destination, airports—and upon import into the Scenario Setup Conversion Tool, queries relevant feedstock data and aggregates to the county-level and generates necessary spatial data and other input files to run the scenario.

Note that several fields in the template use drop down lists or other forms of data validation to help the user appropriately enter their supply chain data. If copy-pasting data into the template, please be careful to “Paste Values” (right click a cell or range and select the Paste Values icon) to avoid overwriting cell formatting and validation. Note that the template file uses FILTER functions which are only available in later Excel releases including Excel for Microsoft 365 and Excel 2021.

A Scenario Setup Conversion tool in the FTOT Tools suite can be run to convert a filled-out template file into FTOT scenario input files (e.g., a batch file, a scenario XML, and facility-commodity CSV files). The resulting files can be used to run the FTOT scenario corresponding to user inputs in the template file. See Section 7.1.8 for further details.

4 ADVANCED SCENARIO OPTIONS

4.1 Customizing the FTOT GIS Network

After installing FTOT, two multimodal networks representing the contiguous United States are available for download with all the other supporting data and scenarios on the FTOT GitHub site (note that a third draft North American network with some modal coverage of Canada and Mexico is available by request). For most scenarios occurring within the contiguous U.S., users should plan on using the default version of the network named FTOT_Public_US_Contiguous_Network_v2025.gdb. However, users running capacity-constrained scenarios with the road network should utilize the FAF4 Capacity version of the network, named FTOT_Public_US_Contiguous_Network_v2025_FAF4_Capacity.gdb, as it is the only version of the default network that currently includes road capacity data. Scenarios that try to use the default version of the network for a capacity-constrained analysis will automatically default back to the FAF4 Capacity version of the network. The feature classes included with each network are shown in Figure 9 and are available in the scenarios/common_data/networks subdirectory. Full metadata for the multimodal network can be accessed in ArcGIS Pro. Additional technical discussion of the FTOT GIS Network is provided in Section 2.2 of the FTOT Technical Documentation.

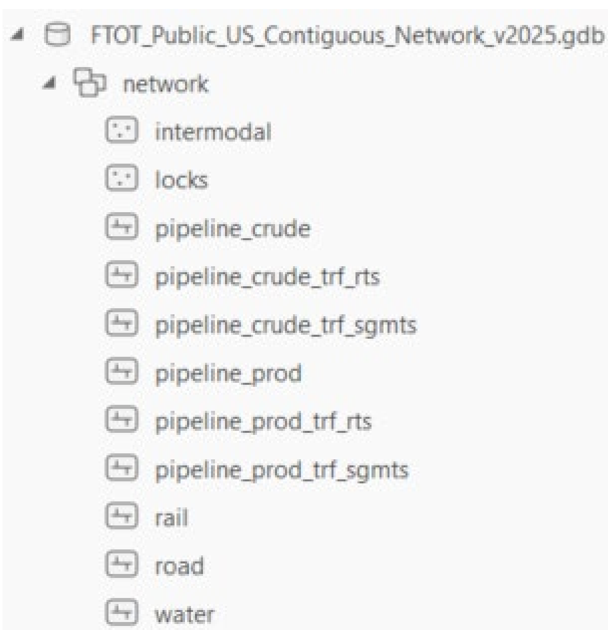


Figure 9: Default multimodal network feature classes included in base FTOT network.

For most contiguous U.S. scenarios, users can use the default multimodal GIS networks provided with FTOT. In some circumstances, an FTOT user may wish to customize an existing default FTOT multimodal network. For example, a user may wish to add an additional network segment (or handful of new network segments) to the network. This is achievable provided the FTOT user has some existing GIS experience and the patience to customize the GIS layers provided by FTOT, as the process is not automated. Adding network segments is not recommended if the user intends to add more than a dozen or so additional network segments, due to the complexity of integrating new data into an existing network. Section 4.1.1 walks through this process in detail.

In addition, segments can be automatically removed from the default FTOT network (i.e., 'disrupted') through the creation of an optional disruption data CSV. The process for this is described in Section 4.1.2.

Beginning with the 2023.1 release, FTOT is able to work with custom transportation networks that align with the FTOT network specification. Users who wish to use an alternative network rather than the default multimodal FTOT network can structure their network file to match the network specification schema and specify its file location in the scenario XML file. Section 4.1.3 and Appendix B provide more detail on this process.

4.1.1 Adding Segments to the Default FTOT GIS Network

Adding segments to the existing default FTOT multimodal network may be useful in scenarios in which a key link is missing from the default FTOT network, or if you wish to include a proposed or under construction link in your analysis. Similar steps may be followed for other FTOT GIS networks that match the FTOT network specification schema.

Note that for pipeline, the process is somewhat more complicated—feel free to skip the **PIPELINE NOTE ONLY** sections if adding segments to other modes in the FTOT network (road, rail, and water).

1. Make a copy of the default FTOT multimodal network geodatabase (e.g., C:/FTOT/scenarios/common_data/networks/FTOT_Public_US_Contiguous_Network_v2025.gdb). You can save it in the same directory, but make sure to rename it to distinguish it from the default network.
2. Open your GIS software of choice (e.g., ArcGIS Pro) and navigate to the copy of the network geodatabase you just made. Identify the mode for which you wish to add additional network segments (road, rail, water, crude pipeline, or petroleum product pipeline). If not pipeline, finding the right feature class to modify is simple—choose the 'road', 'rail' or 'water' feature class and add it to an existing map. If pipeline, read the following note.

PIPELINE NOTE ONLY: There are three pipeline feature classes provided for each of the crude oil and petroleum products networks. The reason for the added complexity is due to the unique nature of the pipeline network—unlike the other modes, FTOT limits possible movements along the pipeline to known origin-destination pairs for which tariffs have been designated and does not allow commodities to flow freely on or off the network as it does for other modes. To help enforce that restriction, FTOT utilizes three different feature classes for each commodity. Section 2 of the main FTOT documentation provides a brief description of how each feature class differs. Once you determine the commodity you are utilizing (crude or petroleum product), you should focus on the feature class ending in "trf_rts". The FTOT team currently does not support the modification of the other two pairs of feature classes (pipeline_crude and pipeline_crude_trf_sgmts / pipeline_prod and pipeline_prod_trf_sgmnts), which are only utilized in capacity-constrained scenarios. As a result, we only recommend adding additional pipeline movements to the FTOT network in scenarios where the capacity constraint and background flows are disabled.

3. Once you have opened your desired network mode's GIS feature class, use your GIS functionality to digitize new segments where necessary. When adding new segments, use your GIS to draw a new connection between an origin and destination. For guidance on creating polyline features in ArcGIS Pro, refer to the ArcGIS Pro documentation. [19] For road, rail, and water, ensure that any new segments are snapped into the existing network. [20] You will also need to split the existing network at any new junctions in the network that are made. [21] [22] If you do not split existing segments where your new segments intersect the existing network, they will be unreachable from the rest of the network. In most cases, this prevents them from being utilized in FTOT scenarios.

PIPELINE NOTE ONLY: Make sure to start drawing at the origin and end at the destination of a particular pipeline movement—the order matters, as two-way movements along pipelines are not allowed as is the case for the other modes.

4. Once you have completed generating your new feature geometry, you will need to specify the new feature attributes.

For road, attributes that must be populated include:

- Link_Type—distinguishes unique categories of road segment. FTOT's default network uses the FHWA approved Functional Classification System. [23]
- Urban_Rural—set to 1 if a link is urban, 0 if rural, or <Null> if unknown. This attribute in the FTOT default network is based on U.S. Census Urban Area Code. [23] When in doubt, utilize the same urban code that is entered for existing road segments in the surrounding area. This attribute is necessary to determine whether the roadway is classified as urban or rural, which impacts emissions reporting.
- Limited_Access—set to 1 if a link has limited access (e.g., FHWA's functional class 1 and 2), 0 if non-limited access, or <Null> if unknown. This attribute is needed for emissions reporting.
- Artificial—should be set to 0 for all added segments.
- Mode_Type—should be set to 'road'.
- Length—select any new or modified road segments (including any segments that you split in order to connect in new road segments) and use the Calculate Geometry [24] tool to calculate the length of each road segment. The default distance units in the scenario XML must match the units of the Length attribute. FTOT's default network uses miles (Statute Miles).
- Additionally, volume, capacity, and VCR (volume capacity ratio) must be populated if capacity or background flows are enabled. Volume and capacity must be entered in terms of vehicles per day and volume capacity ratio simply needs to be entered as volume divided by capacity.
- All other attributes are optional.

For rail, attributes that must be populated include:

- Link_Type—distinguishes unique categories of railway. In FTOT's default public networks, density codes are based on the following rules (see Section 3.10 of the FTOT Technical Documentation for more details):
    - Density Code 7—STRACNET (Strategic Rail Corridor Network) - Class 1 Ownership
    - Density Code 6—Other STRACNET (non-Class 1 Ownership)
    - Density Code 5—Class 1 Ownership (non-STRACNET)
    - Density Code 4—Class 1 Rights (non-STRACNET)
    - Density Code 3—Non-Class 1 (non-STRACNET)
- Artificial—should be set to 0 for all added segments.
- Mode_Type—should be set to 'rail'.
- Length—select any new or modified rail segments (including any segments that you split in order to connect in new rail segments) and use the Calculate Geometry [24] tool to calculate the length of each rail segment. The default distance units in the scenario XML must match the units of the Length attribute. FTOT's default network uses miles (Statute Miles).
- Additionally, capacity must be populated if you plan to use the network for capacitated scenarios. Capacity must be entered in terms of train cars per day. The public FTOT network does not have background flow data available—therefore, the volume and VCR fields for new segments can be left blank.
- All other attributes are optional.

For water, attributes that must be populated include:

- Link_Type—distinguishes unique categories of waterway. In FTOT's default public networks, link type is based on the tonnage of any freight that flows on the segment—this data is populated in other segments by the U.S. Army Corps of Engineers (USACE) National Waterway Network and can be estimated or based on nearby segments.
- Artificial—should be set to 0 for all added segments.
- Mode_Type—should be set to 'water'.
- Length—select any new or modified water segments (including any segments that you split in order to connect in new water segments) and use the Calculate Geometry [24] tool to calculate the length of each water segment. The default distance units in the scenario XML must match the units of the Length attribute. FTOT's default network uses miles (Statute Miles).
- Additionally, volume, capacity, and VCR (volume capacity ratio) can be added via two methods if capacity or background flows are enabled: (1) these attributes can be populated directly in the water feature class, (2) the existing locks point feature class can be modified to add, remove, or modify lock volume and capacity information. Locks must be nodes located at the intersection of two waterway segments; lock volume and capacity data are evenly split across the segments coming into the node (e.g., for locks that divide two different segments of a waterway, the upstream and downstream sections each inherit 50% of the lock capacity and volume). Volume and capacity must be entered in terms of barges per day and volume capacity ratio simply needs to be entered as volume divided by capacity.
- All other attributes are optional.

For pipeline, attributes that must be populated include:

- base_rate—this is the cost to flow this particular movement in currency units per barrel.
- Tariff_ID—sequential unique number—use any number that is not already used.
- Artificial—should be set to 0 for all added segments.
- Commodity—should be set to ‘Crude Oil’ or ‘Petroleum Products’ depending on the commodity.
- Mode_Type—should be set to ‘pipeline_crude_trf_rts’ or ‘pipeline_prod_trf_rts’ depending on the commodity.
- Length—select any new or modified pipeline segments (including any segments that you split in order to connect in new pipeline segments) and use the Calculate Geometry [24] tool to calculate the length of each pipeline segment. The default distance units in the scenario XML must match the units of the Length attribute. FTOT’s default network uses miles (Statute Miles).
- All other attributes are optional.

Following Steps 1-4 above will allow scenarios to utilize these new segments—except in cases where these new segments need to be directly connected to existing intermodal facilities (e.g., to allow for multimodal movements). For enabling multimodal movements with these new segments, continue on with steps 5-6 below. Otherwise, skip to Step 7.

5. In some cases, particularly in situations where you have added new pipeline tariffs, you may need to add additional intermodal facilities to the network. Open your custom network’s ‘intermodal’ feature class. GIS functionality can be used to create new point features for each desired facility. Note that they should ideally be offset slightly from the rest of the network. Artificial links (described further in the next step) are used to control access to the relevant modes that the intermodal facility serves. Modify the attributes of these new intermodal facilities off of the attributes provided for the other intermodal facilities. The essential columns to populate for each new intermodal facility are those indicating which modes the intermodal facility is supposed to connect to. Indicate a connection with a “Y”.
6. Artificial links will need to be manually added to connect any relevant modes to these new intermodal facilities. This involves opening the relevant mode feature class and tracing new connections between the intermodal facility and the mode’s closest existing segment. It is easiest to trace these connectors so they connect into existing nodes (intersections) in the mode’s network. Otherwise, you will have to split the existing network at these new nodes to ensure that the artificial links are actually accessible from the rest of the mode’s network. The Split tool [21] or Line Intersection tool [22] can help with that functionality in ArcGIS Pro. If you do split features in the existing network, you’ll need to recalculate the “Length” field with updated distance. Once the new artificial segment is digitized, assign each new artificial link an “Artificial” attribute of 2 and a MODE_TYPE consistent with the other features in the layer (e.g., ‘road’ for the road feature class). Also, calculate “Length” for the new segment using “Calculate Geometry”. Other attributes can be left blank.
7. Modify your scenario files accordingly to reference your new network. You are now ready to run scenarios using the network.

4.1.2 Disruption Data

The user can populate an optional disruption data CSV in order to disrupt (i.e., make unavailable) certain segments in the input FTOT multimodal network. The CSV consists of three columns in which the mode, unique link ID, and level of link availability are identified for each segment of interest. An example of the specific schema for the disruption data CSV can be found in Reference Scenario 4. The first three columns must consist of "mode", "unique_link_id" (which refers to the OBJECTID associated with each network link in the corresponding GIS feature class) and "link_availability". Only segments that will be disrupted need to be included in this CSV. Segments not included in the table will not be disrupted. To identify the segment IDs to be disrupted, the user will need to open up the input FTOT network in GIS software and identify the segment IDs manually. There is an FTOT supplementary tool (see Section 7.1.6) that can help with this process if appropriate input data are available.

At this time, only a link availability of 0 (fully disrupted) in the disruption data CSV is recognized by FTOT. In these cases, the links will be completely removed from the network and unavailable for use in any optimal solution. This is useful in cases when the user would like to model a scenario in which a certain segment or corridor is unavailable due to some sort of hazard (e.g., flooding, earthquake) or other form of disruption (construction, motor vehicle crash).

4.1.3 Creating a Custom FTOT GIS Network

This section walks the FTOT user through the workflow for creating a custom FTOT network that aligns with the FTOT network specification. The FTOT network specification leverages a standardized network modeling format for sharing routable road networks called the Generalized Modeling Network Specification (GMNS). [25] In order for a custom network to work with the FTOT codebase, it must contain all required fields defined in the schema found in Appendix B as well as:

- Each mode (e.g., road, water, etc.) must be saved in a distinct feature class inside a feature dataset named 'network' located within a single ESRI File GDB.
- Each feature class must be in a consistent meters-based coordinate system appropriate to the region (e.g., USA Contiguous Lambert Conformal Conic is used for the default FTOT U.S. network). Note: When using UTM zones or other regional coordinate systems, take care to ensure that all geospatial data included in the network is appropriate for that particular coordinate system. For example, a UTM zone appropriate for the Pacific Northwest (e.g., UTM Zone 10 or 11) should not contain network features for areas in the Eastern United States, as this could cause issues when calculating distances and processing the network in FTOT.
- All features should be digitized in a way that makes them fully connected and routable (e.g., grade separation should be honored, no gaps should exist between different features). This is often the most challenging requirement for a network to fulfill, as many GIS-based road, rail, and waterway networks are designed more for visualization and less for routability. If an authoritative routable GIS-based network does not exist, one potential source is OpenStreetMap (OSM). There are various tools that can be utilized for accessing GIS-based versions of OSM data, but one particular Python package that is useful for extracting routable, GIS-based road networks is osmnx [26]. As an example, a Jupyter notebook using the osmnx package to extract a regional road network is available in C:\FTOT\program\tools for the user's

reference. Create a copy of this notebook, and follow the included instructions to download a different road network of interest. Note that this notebook does NOT transform the downloaded network into FTOT's network schema. Refer to Appendix B for details on FTOT's network schema.

- Any intermodal facilities must be directly connected to the network associated with each relevant mode through a segment in the mode's feature class (artificial links with the Artificial field of the feature class set to 2).

The two default FTOT networks available for download with all the other supporting data and scenarios on the FTOT GitHub site follow the FTOT network specification and provide examples for how to create a custom FTOT network. A third draft North American network which also follows the FTOT network specification includes additional modal coverage for Canada and Mexico and is available by request from the FTOT Team. FTOT's supplementary network validation tool (see Section 7.1.7) can be used to confirm custom networks meet some of these requirements. In particular, the tool checks whether feature classes use a meters-based coordinate system, follow the correct naming conventions, and include the required data fields as described in the schema. In addition, the tool can optionally evaluate the connectivity of the network in order to identify disconnected subcomponents that could potentially lead to stranded FTOT flows. Once the network has been created, the user should specify the path of the network GDB in their scenario XML file in order for the scenario to run on the new network.

4.2 Customizing the Routing Optimization Problem

4.2.1 Transport Cost Impedances

In FTOT, a series of weights known as impedances modify the transport costs associated with flowing commodities over the transportation network (see Technical Documentation, Section 3.10). Transport costs being equal, segments with lower weights have a lower routing cost and are favored over segments with higher weights. Ultimately, both the transport and routing costs are reported in the scenario results.

The networks subfolder in the common_data folder includes the file default_impedance_weights.csv, which is prepopulated with recommended weights corresponding to FTOT's default U.S. Contiguous network. In this file, default road impedance categories are based on Freight Analysis Framework (FAF) [27] Functional Class (e.g., interstates versus local roads). Default rail impedance categories are based on publicly available rail ownership data and whether the rail segment is part of STRACNET. Default water impedance categories are based on publicly available USACE freight volumes over the national waterway network. The optional artificial link impedance (specified with mode "allmodes" and link type "Artificial: 1") applies to all modes on the artificial link connecting a user-specified facility to the network. The default value is based on the default local road impedance value.

Users can modify these default weights when exploring different exercises and other scenario variations. In general, a larger increase in weights between categories of the same mode will lead to bigger differences in routing costs between categories; optimal routing will hew closer to lower weighted categories.

Users providing custom networks should modify the impedance weights CSV file or update the file path in the `Impedance_Weights_Data` XML element if creating a new file, to match the Link_Type names and preferred weights for their custom network. If an impedance weights CSV file is not provided, FTOT will apply equal weight to all links within the modal network.

4.2.2 Incorporating CO_2 Costs in Optimization

FTOT uses the routing cost of each network segment to select the best paths for commodities to flow along the network. Starting with the 2023.3 release, FTOT enables users to incorporate the cost of CO_2 emissions in routing cost. The updated routing cost is comprised of a transport cost component and a CO_2 cost component with user-specified scalars for each. Transport cost incorporates the impedance weights described above to encourage use of main freight corridors, such as the interstate highway network, over minor routes. CO_2 cost is calculated as the product of the CO_2 unit cost parameter from the scenario XML and the CO_2 emissions associated with transporting materials along a given segment. Routing cost is the weighted sum of transport costs and CO_2 costs multiplied by their respective scalars. In default FTOT scenarios, the routing cost only incorporates impeded transport cost, as described in Section 4.2.1, and does not include CO_2 cost.

Users can modify the default scalars in the scenario XML to weigh transport and CO_2 costs at different levels of importance. Both scalars are adjustable between 0.0 and 1.0 (inclusive). Note that setting the CO_2 cost scalar to 1 will include the full cost of CO_2 emissions in the optimization but will not cause FTOT to consider transport and CO_2 impact equally, since CO_2 cost on a network segment only ranges between 4% (for road) and 20% (for water) of impeded transport cost for the same segment. A user may also set the transport cost scalar to 0 to optimize only on CO_2 costs, but the resulting routes will differ significantly from those selected when transport cost is included and may not perfectly reflect the real-world route with the lowest CO_2 emissions.

4.2.3 Artificial Links

FTOT automatically constructs artificial links to connect facilities to each mode in the multimodal network when possible. Facilities will only be connected to the road (or rail, water, pipeline) network if there is a road (or rail, water, pipeline) network link within the user-defined artificial link distance from the facility point; this distance threshold can be adjusted in the scenario XML. With a larger artificial link distance, FTOT is more likely to find a network link to which to connect the facility. If an artificial link distance is too small, facilities can potentially become stranded and unusable, with no network connections in the scenario. The summary text report generated at the end of an FTOT run will indicate if any user-provided facilities were stranded.

Due to artificial links being constructed only to the nearest link of each mode, the process may interact adversely with dual carriageway specifications found in the default FTOT GIS network and can lead to unintuitive and circuitous routing (e.g., traveling in the wrong direction for a number of miles before turning around). The user is recommended to examine optimal routing in their scenarios around facilities and adjust facility locations if needed to address these issues.

FTOT also uses artificial links to represent first-mile/last-mile movements in a supply chain. In calculating the transport cost, the (optional) CO_2 cost, and the routing cost (which is used in FTOT's optimization problem), artificial links are assigned the same per-distance cost as a highly impeded local road by default. The local road impedance weight is assumed to be the highest defined road impedance value in the impedance weights CSV file. Users may specify alternate transport costs for artificial links using the optional `Artificial_Link_Cost` parameter in the XML and may specify alternate impedance for artificial links in the impedance weights CSV file in a row with `allmodes` in the mode column and `Artificial: 1` in the link type column.

By default, artificial links are not included in calculations of summary metrics in FTOT reports, with the exception of routing cost which always includes artificial links as they factor into the optimization. Optionally, users can set the `Report_With_Artificial_Links` scenario XML element to True to include artificial links in the calculation of transport cost, length of network used, vehicle-distance traveled, emissions, and fuel burn.

Artificial links are also used to implement facility-, commodity phase- and in-/out-specific access costs specified in the facility-commodity CSV files.

4.2.4 Short Haul Penalties

FTOT uses short haul penalties to discourage short movements on the rail and waterway networks, as roads are more commonly used for short freight movements. These penalties are applied as an additional routing cost on the artificial links connecting facilities to the rail and waterway networks. A fixed penalty is calculated as the difference between a highly impeded (i.e., local) road cost and the base cost for rail or water transport cost, multiplied by a user-specified number of units of distance (e.g., 100 miles), which can be adjusted in the scenario XML. Users can adjust the short haul distance parameter in the scenario XML to increase or decrease the penalty. The default short haul penalty, entered by the user as a distance, is equivalent to the cost to travel over 100 miles of network. Decreasing this distance allows for shorter movements by rail and water, while increasing the distance further discourages short movements.

4.3 Modeling Time and Schedules in FTOT

FTOT is primarily a supply chain optimization tool focused on high-level commodity and flow planning with limited time analyses. In particular, FTOT does not explicitly model travel time in its route optimization. [1] As such, FTOT is not meant to act as a substitute for travel demand models.

For the majority of FTOT scenarios, the supply chain model is time agnostic. As long as user inputs (e.g., commodity supply and demand amounts, processor capacities) are provided at the same scale, FTOT will optimize and report scenario results at that scale. This remains true when considering capital cost of building candidate facilities (build cost) as input by the user in either processor input CSV file. The user should specify the build cost as an amortized cost based on the time period of the scenario they are

[1] While travel time is not explicitly modeled within FTOT's optimization algorithm, the routing cost does include user-defined weights to prioritize flow on network segments with higher capacity / flow / traffic (e.g., larger roadways over smaller), which often is correlated with faster travel time.

modeling, but the time step determination is left to the user to best serve the scenario. For example, for a scenario looking at yearly feedstock data, the build cost for a processing facility should be provided as an annual amortized cost from the facility's lifetime capital cost.

There are two types of FTOT scenarios with explicit time units. First, schedules for facility availability are denoted in days by default. More information can be found below in Section 4.3.1. Second, capacity and background flow data associated with the default FTOT multimodal network are provided in per-day units. To run a capacity-constrained FTOT scenario with the default network, the user must provide commodity inputs in daily amounts to be at the same scale as capacity data.

4.3.1 Schedule Input File

Schedules can be used to run scenarios that span multiple time steps (the default and recommended time step is in days). This optional input file allows the user to define schedules of facility availability for each day in a scenario. An availability of 1 indicates that the facility produces or demands the same amount of the commodity as in the "quantity" column of the facility input file. An availability of 0 indicates the facility does not produce or demand any product on that day, and an availability of 1.5 indicates the facility produces or demands 1.5 times the amount in the "quantity" column in the facility input file.

The schedule input file includes three columns: schedule, day, and availability. Each schedule's default value is indicated by day '0' and any days with a different availability must be specified. All schedules for a scenario are the same length. The scenario schedule length is determined by the highest value in the 'day' column. FTOT forces all schedules for a scenario to be the same length to avoid mismatch issues between facilities with schedules of different lengths. An example of a schedule input is shown in Table 3.

Table 3: Example of schedule input file containing two 7-day schedules.

Schedule	day	availability
weekdays	0	1
weekdays	1	0.5
weekdays	7	0.5
exceptDay3	0	1
exceptDay3	3	0

The table has two schedules. The 'weekdays' schedule has an availability of 0.5 on days 1 and 7 and availability of 1 on days 2 through 6. Since the largest value in the day column is 7, that is the scenario schedule length. As a result, the exceptDay3 schedule is also 7 days long even though only the default value, and day 3 value are specified. The 'exceptDay3' schedule has an availability of 0 on day 3 and an availability of 1 on days 1-2 and 4-7. Reference Scenario 3 provides another example schedule file.

The file name and file path should be added to `Schedule_Data` element in the scenario XML.

4.3.2 Estimating Route Travel Times

Starting with the 2025.2 release, users may specify an optional CSV input file setting default travel speeds for transportation network links by mode and/or link type and default travel/transloading times for transportation network nodes by node type. These values are used to calculate total travel time between facility pairs when the NDR_On XML parameter is set to True. Link-level travel times for all routes are calculated based on link length and the default speed for the link's mode and/or link type. Routes that pass through locks and/or intermodal facilities (including between consecutive pipeline tariff movements) incur additional travel time based on those corresponding default times. Route-level travel times are reported in the all_routes CSV report.

The travel speeds and times CSV file can be customized for the user's FTOT network and should be specified using the Speed_Time_Data parameter in the XML's Assumptions section. The file should include columns "type" (link or node), "mode" (road, rail, water, pipeline_crude, pipeline_prod, locks, or intermodal), "link_type" (left blank to define the default speed for links; no impact for nodes), "speed" (populated for links in units of default distance units per hour), and "time" (populated for nodes in units of hours). FTOT provides an example travel speeds and times CSV for the default FTOT network in the directory scenarios/common_data/networks.

4.4 Customizing Emissions Outputs

4.4.1 Commodity Density Input File

This optional input file allows the user to specify each commodity's density. Currently, density values are used (1) for converting liquid commodities and associated costs from units of volume to units of mass and vice versa for the FTOT optimization module, (2) for calculating emissions from the transport of liquid commodities on rail, water, and pipeline modes, (3) for calculating fuel burn from the transport of liquid commodities on road, rail, and water modes, (4) for calculating vehicle loads for liquid commodities in capacity-constrained scenarios, and (5) for calculating per-commodity capacities from a total facility capacity for a processor with a mix of solid and liquid commodity inputs (or outputs). This CSV file is optional and can be stored in the same place as the other scenario input CSV files. The user is highly recommended to supply this input file if running a scenario with liquid commodities.

Once this CSV file is created, the user-specified file name and file path should be added to the `Commodity_Density_Data` element in the scenario XML:

<Commodity_Density_Data>YOUR_SCENARIO_FOLDER_HERE\commodity_density.csv</Commodity_Density_Data>

The commodity density CSV is structured as in Table 4, with the first column titled "commodity" containing a commodity's name and the second column titled "density" containing a string with a density value and units, expressed as a unit of mass per unit of volume. FTOT will automatically process and convert the density to the necessary units for the emissions and capacity calculations.

Table 4: Commodity density CSV for two example commodities: ethanol and water.

commodity	density

ethanol	0.79 kg/liter
water	1.0 g/cm^3

Densities for solid commodities or unrecognized commodity names are accepted (no error is flagged) but disregarded. The default density specified in the scenario XML's `Density_Conversion_Factor` parameter will be assigned to any liquid commodity not included in the commodity density CSV.

4.4.2 Detailed Emissions Factors Input File

FTOT automatically calculates CO_2 emissions for the optimal solution using default emissions factors for each mode in the scenario XML. However, the user can optionally calculate and report additional emissions information using detailed CO_2 emissions factors (for road) as well as non-CO_2 emissions factors for all modes. Users should review the optional detailed emissions factors CSV file and update the `Detailed_Emissions_Data` element in the scenario XML with this file's path; FTOT will then generate a supplementary emissions report upon finishing a scenario run.

The common_data folder (networks subfolder) comes with a default detailed_emissions_factors.csv file prepopulated with several emissions factors for FTOT's default vehicles (as specified in the scenario XML) for transport on road, rail, and water modes as well as for the "small_truck" that is provided in vehicle_types.csv. The default emissions factors will be used for all commodities on a mode *except* in the case that a custom vehicle is assigned to a commodity (see Section 3.3.2). If users create a new custom vehicle, they will need to (1) assign that vehicle to a commodity in the commodity mode CSV and (2) add custom emissions factors to the detailed emissions factors CSV to include that vehicle in the detailed emissions report. Note that while detailed emissions factors are compatible with CO_2-based optimization, custom vehicle types currently are not.

The detailed_emissions_factors.csv file contains the following fields:

- vehicle_label – set to "Default" for the default vehicles assigned in the scenario XML. You can alternatively enter a vehicle label that matches the name of a custom vehicle in vehicle_types.csv. Note: The vehicle label is case-sensitive.
- mode – set to road, water, or rail.
- urban – set to 1 if the emissions factor applies to urban road links, 0 if it applies to rural roads, or "NA" to not distinguish road types. Also set to "NA" if emissions factor is for water or rail.
- limited_access – set to 1 if the emissions factor applies to limited access roads, 0 if it applies to non-limited access roads, or "NA" to not distinguish road types. Also set to "NA" if emissions factor is for water or rail.
- pollutant – can be set to one of the following values: CO2, CO, CO2e, CH4, N2O, NOx, PM10, PM2.5, VOC. Note: pollutant is NOT case sensitive.
- value – emissions factor for this entry. Emissions factors must be in grams per unit distance for road entries (e.g., g/mile) and in grams per unit of commodity mass per unit distance (e.g., g/ton/mile) for rail and water. The vehicle emissions portion of Section 3.10 of the Technical Documentation provides additional information on the prepopulated pollutant emissions factors.

Note that emissions factors for road CO_2 with “NA” in the urban and limited_access columns will override the default CO_2 factor in the XML. In contrast, providing additional information (0 or 1) in the urban and limited_access columns will enable more targeted calculations when this information is also available in the road network. If a network includes information on urban/rural and limited/nonlimited links, but the detailed emissions file doesn’t have corresponding emissions factors, FTOT will use the XML default CO_2 emissions factor in place of the missing values.

In contrast, for non-CO_2 emissions factors, which do not have general default values in the scenario XML, FTOT will calculate the average of any provided emissions factors for a given mode and pollutant and use that average in place of missing values.

5 RUNNING A SCENARIO

5.1 FTOT Scenario Sequence

FTOT is a command line tool that runs in a sequence of steps. Each component of an FTOT run represents a generalized step within the scenario that the user can review in corresponding log files generated during each step. Each component in this sequence can be run as part of a full FTOT run (this is applicable to most users' scenarios) or in isolation (for debugging or advanced FTOT scenario testing). The basic FTOT sequence for a standard scenario is:

1. S – setup; prepare the scenario files and transportation network
2. F – add the facility GIS and facility-commodity data to the scenario files
3. C – connect the facilities to the transportation network
4. G – export a NetworkX graph for the optimization
5. O1 – prepare the optimization problem
6. O2 – setup and solve the optimization problem
7. P – post process the optimal solution
8. D – generate reports for the run
9. M – generate maps for the run

For candidate processor generation scenarios, several additional steps (highlighted in **bold**) are run during the FTOT sequence:

1. S – setup; prepare the scenario files and transportation network
2. F – add the facility GIS and facility-commodity data to the scenario files
3. C – connect the facilities to the transportation network
4. G – export a NetworkX graph for the optimization
5. **OC – pre-candidate generation optimization**
6. **F2 – add generated facility locations and commodity data to the scenario (specified as F2 to distinguish from pre-defined processor facilities)**
7. **C2 – connect the new facilities to the transportation network**
8. **G2 – export a new NetworkX graph for the optimization**
9. O1 – prepare the optimization problem
10. O2 – setup and solve the optimization problem
11. P – post process the optimal solution
12. D – generate reports for the run
13. M – generate maps for the run

Further details on candidate generation can be found in Section 3.3.3.

5.2 Batch (BAT) File

Each scenario contains a batch file called **run_vX.bat** where X specifies the version (current version is run_v8.bat). A batch file is used to automatically run the sequence of steps necessary for a complete FTOT scenario. An advanced user can also manually modify the batch file to only run certain steps necessary for testing or debugging purposes. The batch file references the scenario XML configuration file, which is loaded at runtime during each step. The file also references the Python path and FTOT directory. If a user has based their scenario off an existing quick start or reference scenario, they must modify the batch file ahead of running their own customized scenario.

- `set XMLSCENARIO={}` - Replace existing path inside brackets with full file path to the new scenario XML file.
- NOTE: If you have stored your FTOT installation anywhere other than "C:\FTOT" or your FTOT Python environment anywhere other than "C:\FTOT\python3_env" (these are the defaults as defined in the FTOT installation instructions), then you will also need to modify these paths for each batch script that you run to appropriately reflect the actual paths on your machine.

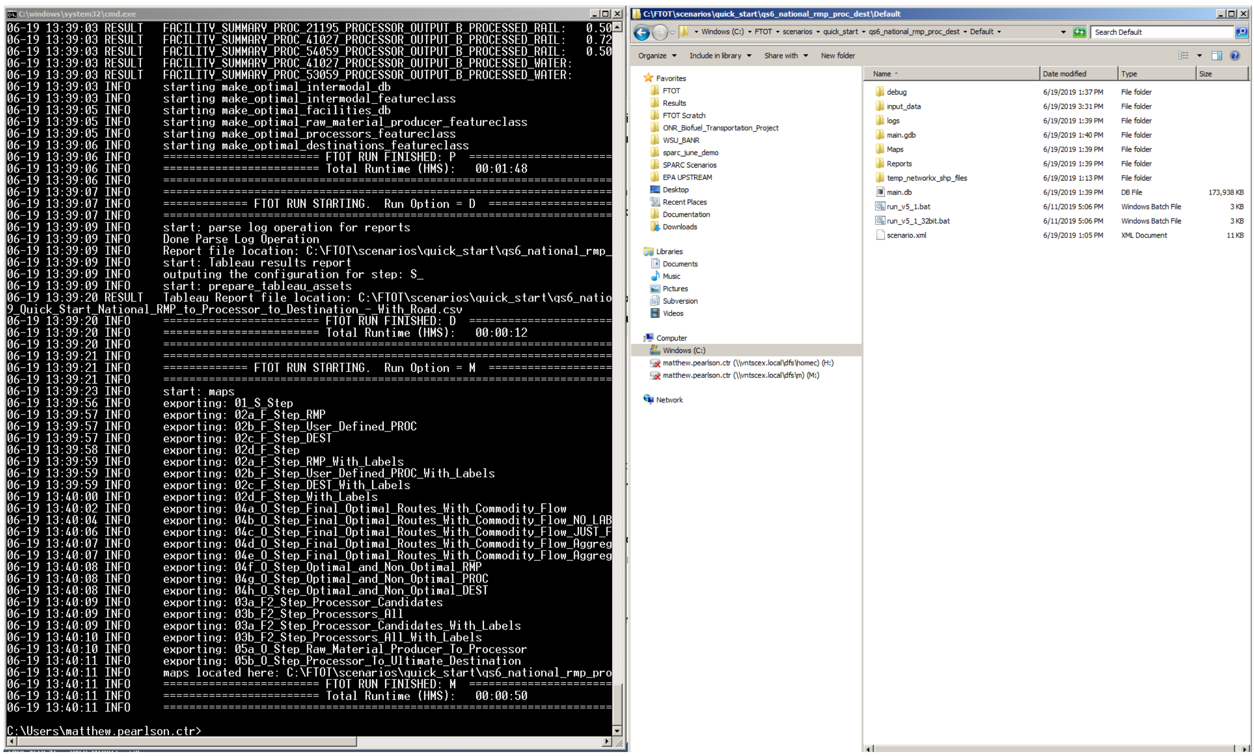


Figure 10: Split screen practice for running an FTOT scenario. The command line is on the left, and the scenario opened in the Windows Explorer is on the right.

The FTOT supplementary tool for generating batch files is described in Section 7.1.2. The FTOT supplementary tool for converting a general or SAF-specific Scenario Setup Template into FTOT input files also creates the required batch file; see Section 7.1.8.

5.3 FTOT Scenario Execution

FTOT is a command line program that executes in the Windows shell. It is a recommended practice to run the scenarios with a command line window on the left and the scenario folder opened in an explorer window on the right (Figure 10). This will allow the user to see that the scenario running in the appropriate folder.

A scenario can be started by dragging the batch file located in the scenario folder into the command line and hitting the [enter] key in the command line window. Alternatively, the user can run the batch script by double clicking it. As new files are created in the various FTOT steps, they will become visible in the explorer window on the right.

Informational logging is available in the command shell during the run. Detailed log files are created for each step in the **.\logs** folder. The logs are prefixed with a letter and suffixed with a timestamp indicating the FTOT step and time the log was generated. The user is encouraged to read the logs to familiarize themselves with the FTOT operations occurring during each step.

See the troubleshooting guide in Section 8 for tips on how to resolve common issues like runtime dependency errors (missing software), missing input data, and missing base maps. The troubleshooting guide also contains guidance on actions to take if the user's FTOT scenario fails to find an optimal solution or the solver fails to terminate.

6 ANALYZING A SCENARIO

6.1 Results

FTOT generates four main types of outputs described in detail below. Three different sets of reporting outputs (items 1-3) are generated in the D Step and maps (item 4) are generated in the M step.

1) **A human-readable text report (.txt)** shows a summary of the results for each step in the analysis. The report is broken into the following sections: runtime summary of each step, intermediate calculations and optimal results, configurations, warnings, and errors. This is saved in the **.\Reports** directory of the scenario.
2) **A CSV file report (.csv)** that can be used to generate graphical dashboards showing summary statistics for the scenario, such as relative contributions of commodities and mode to cost, emissions, and vehicle-distance traveled, amount of supply utilized and demand met in the scenario, and other elements. The CSV file can be used as an input to Excel, Tableau, or other data analysis programs. This is saved in the **.\Reports** directory of the scenario. The CSV report includes multiple groups of results: the scenario configuration, the commodity-specific summary results, the facility summary results, and the scenario summary results.
    a. The scenario configuration reports out the scenario name, description, and various input parameters from the XML, as well as the name and location of the GIS layers used to define the network and the facilities included in the scenario.
    b. The commodity summary results include the following data by commodity and mode:
        i. Mass and/or volume movements
        ii. Cost of movements
        iii. Fuel burn
        iv. Length of network segments used in the solution
        v. Number of vehicles, counted by distinct loading events, used for transport
        vi. Vehicle-distance traveled
        vii. CO_2 emissions
        viii. Social cost of CO_2 emissions (when enabled)
        ix. Percent of routing cost from impeded transport costs (when enabled)
    c. The facility summary results include
        i. Facility size (available supply, total demand, or processor capacity)
        ii. Facility utilization (amount of supply utilized, demand met, or processor capacity used)
        iii. Facility utilization fraction (relative to total supply, demand, or processor capacity)
        iv. Facility access costs
        v. Processor build costs
    d. The scenario summary results include the following data by mode (aggregated across commodities):
        i. Cost of movements
        ii. Fuel burn

iii. Length of network segments used in the solution
iv. Number of vehicles, counted by distinct loading events, used for transport
v. Vehicle-distance traveled
vi. CO_2 emissions

3) **A packaged Tableau workbook (.twbx)** that contains all the geospatial and summary result information required to display a Tableau dashboard in the free version of the Tableau Reader software. This is saved in the **.\Reports** directory of the scenario.
4) **Maps** from each step of the analysis, including the network, facilities, candidate processing locations, and the optimal solution (optimal facilities, optimal flows, non-optimal facilities, etc.) are saved in the **.\Maps** directory of the scenario. FTOT generates a series of maps for each FTOT step to help the user see what happens during the scenario.

Note that by default, all summary metrics except routing cost exclude artificial links. Users can optionally include artificial links in calculations of transport cost, length of segments used, vehicle-distance traveled, CO_2 emissions, and fuel burn by setting the `Report_With_Artificial_Links` scenario XML element to True.

Supplementary reports on the scenario results are also generated alongside the other main outputs in the **.\Reports** folder:

- Artificial links – the artificial_links_TIMESTAMP.csv output file summarizes the artificial links used to connect facilities to the multimodal network. Each row of the file specifies a facility (e.g., RMP, proc, or dest) in the scenario, a permitted mode in the scenario, a commodity, and a measure. The measures reported are artificial link length, transport cost, routing cost, access cost, CO_2 emissions, fuel burn, vehicle-distance traveled, and network used. Length is the only measure reported for all facility-mode combinations; the remaining metrics are only reported for artificial links contained in the scenario's optimal solution. The network used metric is identical to the length metric. To model first/last mile considerations, artificial link measures are calculated using local roads cost methodology by default for transport cost, routing cost, and CO_2 emissions, regardless of what mode the artificial link is connecting to; users may specify a custom transport cost for artificial links in the scenario XML using the optional `Artificial_Link_Cost` element. Facility, commodity phase, and in or out movement specific access costs are implemented as an additional cost associated with an artificial link. The other measures assume the vehicle load attributes of the modal network to which the artificial link connects. For the length measure, each entry in the table is the artificial link length if the facility is successfully connected to that mode, or "NA" if the facility is unable to connect to that mode within the artificial link distance parameter specified in the scenario XML file. Note that stranded facilities (those that fail to connect to the multimodal network at all) are not included in the artificial links CSV file.
- Costs – the costs_TIMESTAMP.csv output file breaks out the cost components that feed into the objective function of the optimization problem. Cost components are grouped by cost family, namely movement (transport, transloading, first-mile last-mile costs, impedances, access costs,

and mode short haul penalties), emissions (CO_2 cost of transport on network links and first-mile last-mile CO_2 cost of transport on artificial links), build cost, and unmet demand penalty. The costs report includes both the unscaled and scaled values, where scaled values account for the user-provided transport and CO_2 scaling factors that enable both transport cost and CO_2-based optimization, respectively. The objective value found in the main text report equals the sum of all scaled cost components.

- Routes - when network density reduction (NDR) is enabled to calculate shortest paths (see Section 3.1.1.2), an additional all_routes_TIMESTAMP.csv file is generated containing information for potential routes considered in the optimization problem. For each origin-destination pair's shortest path, the routes report presents the associated mode and commodity, route length, transport cost per unit of commodity flowed, routing cost per unit of commodity flowed, access cost per unit of commodity flowed, CO_2 emissions per unit of commodity flowed, travel time (based on speeds and travel times CSV file specified in XML), and whether the route is in the optimal solution. Information provided by this report can be used to compare scenario results across FTOT runs (e.g., between a baseline and disruption scenario). The user is free to create their own analysis or tools for reviewing these data.
- Detailed emissions – when the file path to a detailed emissions factors CSV is entered in the XML, the detailed_emissions_TIMESTAMP.csv report is generated with total emissions for several pollutants. Emissions are reported by commodity, mode, and pollutant. Set the `Report_With_Artificial_Links` scenario XML toggle to True to include artificial links in detailed emissions calculations.

Reports and maps are stored in timestamped folders within their respective directories and are re-generated (not overwritten) after each successful run. Beyond the reports and maps, the full set of FTOT results are stored in a SQLite database (main.db) and geospatial data underlying the maps are stored in the scenario geodatabase (main.gdb). Both of these datasets are saved in the scenario's main directory. These datasets are overwritten for each run.

6.1.1 Understanding Costs Reported by FTOT

Of particular note when interpreting FTOT reporting are the various types of costs associated with a scenario. The main costs reported by FTOT for the optimal solution are:

1) Transport Cost—the actual cost of the transportation flows in the optimal solution based on the modal costs. For road, rail, and water modes, these are per-distance costs that are constant across the entire network. For example, the transport cost of travel on one mile of a local roadway is identical to the transport cost of travel on one mile of interstate highway. These costs are defined in the scenario XML. Intermodal movements are assigned a unit-based transloading cost, which is also defined in the scenario XML, in addition to the per-distance costs for road, rail, and water modes. Artificial links, which represent first/last mile movements on the network to/from facilities, have a default distance-based modal cost associated with them corresponding to transport via local road, regardless of mode they connect to; users can alternately specify an artificial link transportation cost in the scenario XML. Users may specify

additional costs associated with a specific facility, phase, and in/out movement in the facility-commodity CSV files, which are incorporated in the artificial link cost. As noted below, in the routing cost, these transport costs are adjusted based on weights and other factors; therefore, the route with the lowest transport cost is not always chosen as the optimal route.

2) CO_2 Cost—the cost associated with CO_2 emissions from transportation in the optimal solution. CO_2 cost is calculated by multiplying the CO_2 emissions associated with transportation by the CO_2 unit cost parameter specified in the scenario XML file. CO_2 cost is not reported if the scalar for CO_2 cost is set to 0, but the cost can be calculated from the CO_2 emissions report item.
3) Routing Cost—the generalized cost used to pick the lowest cost routes. This is a weighted sum of impeded transport costs (described in Section 4.2.1) and CO_2 costs multiplied by their respective scalars as specified in the scenario XML. The routing cost is intended to incorporate several factors that impact routing decisions beyond transport cost, including use of major links in the network, mode choice for shorter routes, and cost externalities like emissions. FTOT will always select optimal routes that lead to the lowest routing cost, which may not match the lowest transport cost or carbon cost routes. Routing costs for artificial links include transport and CO_2 costs associated with movement via local road by default, regardless of mode they connect to. As noted above, transport costs on artificial links can be customized using the scenario XML and facility-commodity input files, though neither impacts artificial link CO_2 costs. When connecting to rail or water facilities, artificial link routing costs also include short haul penalties which encourage FTOT to avoid unrealistically short movements on those modes; these penalties only impact routing cost (not transport cost).
4) Routing Cost from Transport—a fraction representing the portion of Routing Cost that reflects impeded transport costs for a scenario. This metric is only included for scenarios where the CO_2 Cost Scalar is greater than 0.
5) Optimal Objective Value (Total Routing Cost + Unmet Demand Penalty + Amortized Cost of Constructing New Candidate Processors)—this is the full cost that the optimizer considers in solving for the optimal routing solution. In many FTOT scenarios, the routing cost is the only contribution to the optimal objective value if no candidate processors with build costs are used and all of the demand at the destination was met.

The optimal objective value is reported during the O2 step in the text report. Transport costs and routing costs (i) for the scenario, (ii) by mode, (iii) by commodity, (iv) by commodity and mode are reported in the text report and CSV file report and are visualized in the Tableau workbook. A Cost Breakdown dashboard in the Tableau workbook presents both scaled and unscaled costs contributing to the objective function value by component (transport cost, transloading cost, first-mile last-mile cost, impedances, short haul penalties, CO_2 costs, build costs, unmet demand penalties). Transport costs, access costs, and routing costs for individual routes are reported in the optimal routes report, which is generated when network density reduction is enabled.

Note that FTOT's reported routing costs always include costs from artificial links as these costs affect optimization; to also include artificial links in reported transport costs and other metrics, set the `Report_With_Artificial_Links` scenario XML element to True.

6.1.2 Interpreting Flows

The FTOT-generated Tableau workbook and maps help visualize flows within an FTOT scenario. Advanced users can also use the raw GIS data provided in the main.gdb to generate customized maps, if desired. Commodities with multimodal optimal flows (e.g., optimal routes between facilities that utilize more than one mode of transport) are noted in the CSV file report and can be visually examined in the output maps and Tableau workbook. Additionally, if network density reduction is enabled, the Tableau workbook will populate an interactive dashboard with summary information on all shortest paths, including the count, cost per unit of commodity flowed, and length of available routes. Shortest path routing information is additionally stored in the SQLite database in the route_edges and od_pairs tables; this route data can be combined with the routes CSV file to fully characterize flows in the optimal solution.

6.1.3 Emissions

The FTOT reports and Tableau dashboard include total CO_2 generated from transport. This value is CO_2 generated from end use combustion only, i.e., from fuel burned by the vehicle. Total CO_2 from movements on road depends on vehicle-distance traveled while total CO_2 from movements via rail, water, and pipeline depend on commodity weight and length of network traveled. In addition, commodity density is used in the total CO_2 calculation for liquid commodities on non-road modes. The optional detailed emissions report presents similar information for CO_2 as well as non-CO_2 emissions, specifically carbon monoxide (CO), methane (CH_4), nitrous oxide (N_2O), nitrogen oxides (NOx), particulate matter (PM10 and PM2.5), volatile organic compounds (VOCs), and carbon dioxide equivalent (CO_2e). Emissions associated with first/last mile movements are assumed to be via transport on local roads but are reported in the mode category the first/last mile movement connects to. Inclusion of metrics associated with first/last mile movements, including emissions, can be toggled on or off using the `Report_With_Artificial_Links` element in the scenario XML input file. Note that CO_2 emissions for movements on road are calculated using partial truckloads, while non-CO_2 emissions for movements on road are calculated using nearest full truckload. For justification of this methodology, refer to the Technical Documentation.

6.2 Graphics Dashboard

FTOT outputs include a packaged Tableau workbook (.twbx file) to visualize the CSV report results and the facilities and routes from the analysis. The workbook includes a Tableau "story" with dashboards presenting facility, commodity, mode, and route-level results as well as information on quantities of material moved, utilization levels, CO_2 emissions, vehicle-distance traveled, fuel burn, and costs. This workbook is created from FTOT's Tableau template file, located at `C:/FTOT/program/lib/tableau_dashboard.twb`.

To view the Tableau story, navigate to the **.\Reports** sub-directory in the scenario folder and select the latest timestamped report folder. Double click on the tableau_dashboard.twbx file to open it in Tableau. Note you will need to have Tableau Desktop or Tableau Reader installed.

6.2.1 FTOT Tableau Dashboard Features

At the top of the workbook are navigation buttons to bring the user to the various dashboards within the scenario story. The story includes seven dashboards:

1. Supply Chain Summary includes a map and data chart with user inputs on facility locations and available supply, demand, and processing capacity.
2. By Commodity & Mode includes a map with the optimal routes and a graph pane presenting key scenario measures from the optimal solution, such as transport cost, vehicle-distance traveled, and CO_2 emissions.
3. By Supply & Demand includes a map and graph pane presenting facility utilization under the optimal solution.
4. Cost Breakdown presents the various costs considered and reported by FTOT as both unscaled and scaled versions (i.e., those included in the objective function of the optimization problem).
5. Routes includes graphs describing the shortest paths linking each available origin and destination facility, including paths selected in the optimal solution. *Note: This dashboard populates only for scenarios run with NDR_On set to True.*
6. Runtimes displays the time used to run each FTOT step.
7. Parameters Table lists input values from the scenario XML.

Dashboard functionality

The first five dashboards listed above include a Legend panel on the left side of the page and a Filters panel on the right side:

- The Legend panel includes color and size legends. The By Commodity & Mode and Routes dashboards additionally present symbology options.
- The Filters panel lets users select which elements—such as modes, commodities, and facility types—to display on the dashboard.

Selected filters and toggles in these panels will apply to all maps, data tables, and graphs on a dashboard. *Note: Depending on the scenario, some facility quantities or cost categories may dwarf other facilities or costs. Uncheck the filter box for these larger facilities or cost categories to see smaller items at a larger scale.*

In addition, some dashboards contain buttons, toggles, and input fields that let you update the data views for graphs:

- By Commodity & Mode includes buttons beneath the map that will update the graphs for different results breakdowns and measures.
- By Supply & Demand includes a switch beneath the map that toggles the graphs between facility utilization and demand/supply utilization.
- Routes includes text boxes for user-specified bin sizes for histograms of route length, cost, and CO_2 emissions.

On any dashboard, hover over an item on a map or chart (e.g., bar, icon, point, etc.) to display a tooltip which contains additional data.

Resolving dashboard display issues

Users may notice display issues in FTOT's Tableau outputs where dashboard text is too big or disappears altogether. Try the following steps to resolve display issues:

- Go to the folder that contains the tableau.exe file. This file is located in a folder like C:\Program Files\Tableau\Tableau 2020.3\bin.
- Right-click on tableau.exe, open "Properties," and go to the "Compatibility" tab.
- Click the "Change high DPI settings" button.
- Check the box to override high DPI scaling behavior. Set the "Scaling performed by" drop-down box to "System."
- Restart Tableau.

6.2.2 FTOT Tableau Dashboard Panels

The first story point (Figure 11) is the supply chain summary which indicates the locations and relative size of the facilities in the supply chain. Demand centers are displayed with orange squares. The supply centers have green circles. The user can filter the facilities shown on the right-hand side under the Facility Type and Commodity filters. Hovering over an individual icon will provide a tooltip with a list of commodities and quantities for an individual facility, and the quantity of material available by facility type is shown in the table below the map.

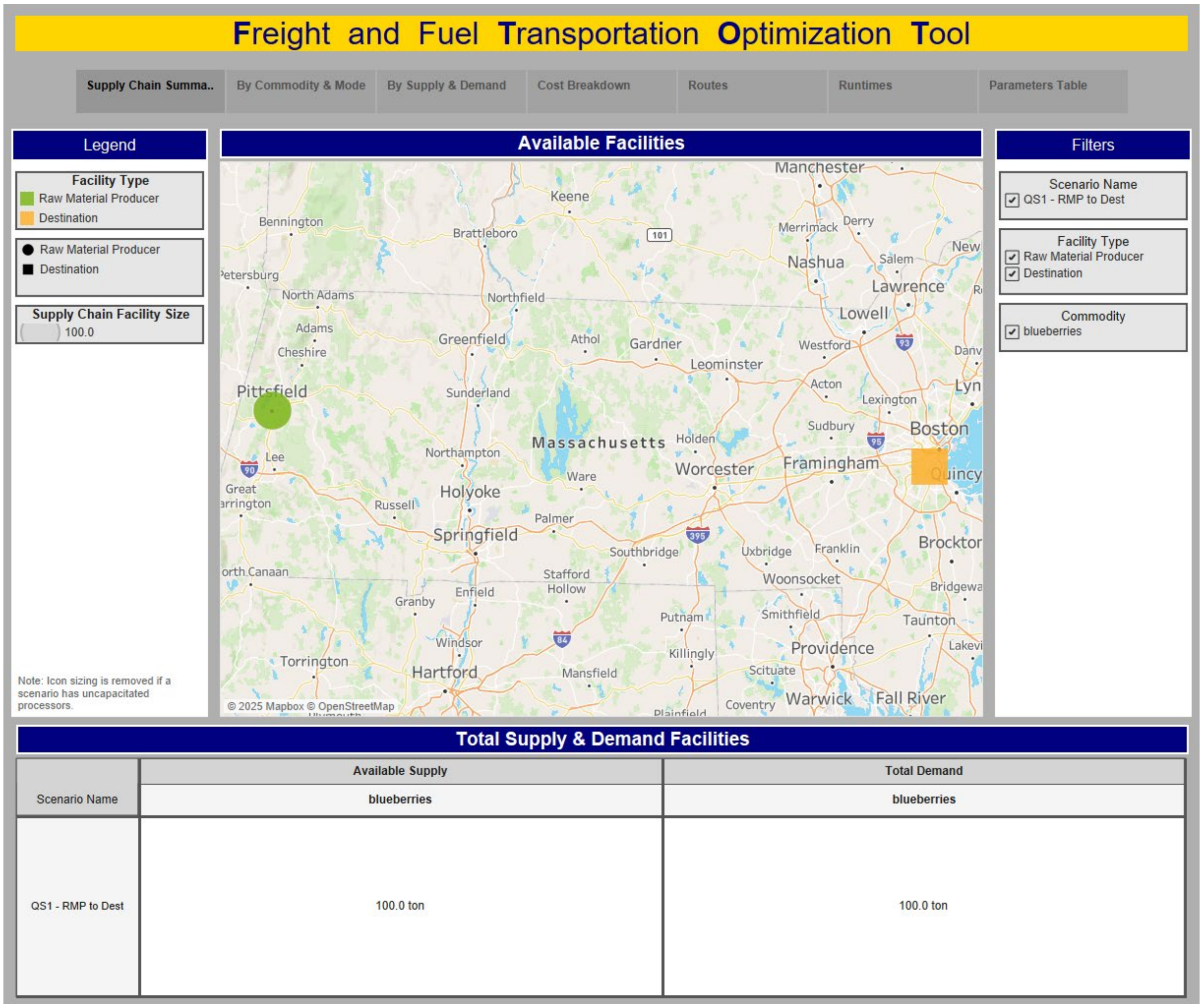


Figure 11: Tableau Story – Supply Chain Summary Dashboard

The By Commodity & Mode story point (Figure 12) shows the routing results for the optimal solution. Routes can be colored using the legend options on the left-hand side of the screen. Options include coloring by mode (as shown), commodity, and scenario name (this becomes more useful when comparing multiple scenarios). The filters on the right-hand side allow the user to turn various elements on or off, and it applies to both the map and the results summary chart at the bottom of the dashboard. Scenario filters include scenario name, mode, commodity, and time period. [2] Results reported by FTOT include transport cost, vehicle-distance traveled, fuel burn, and CO_2 emissions. The results can be graphed and grouped by commodity or by both commodity and mode.

[2] The time period filter affects the map only. It does not affect the summary tables.

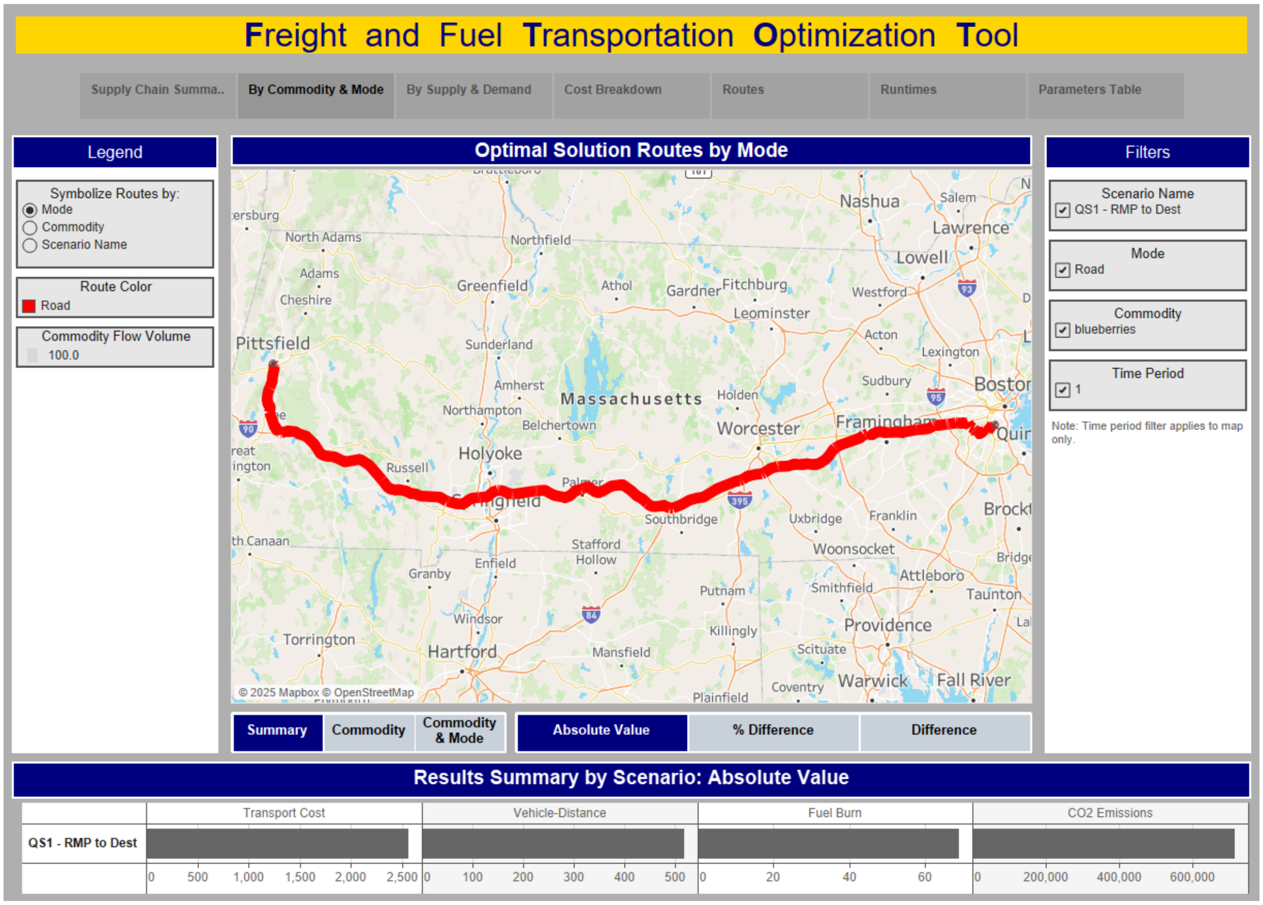


Figure 12: Tableau Story - By Commodity & Mode Dashboard

The By Supply & Demand story point (Figure 13) summarizes the optimal results by facility. The Size & Utilization of Facilities map shows the relative size of supply and demand facilities, as well as the utilization of those facilities. The user may toggle between facility counts and total quantities using the slider under the map.

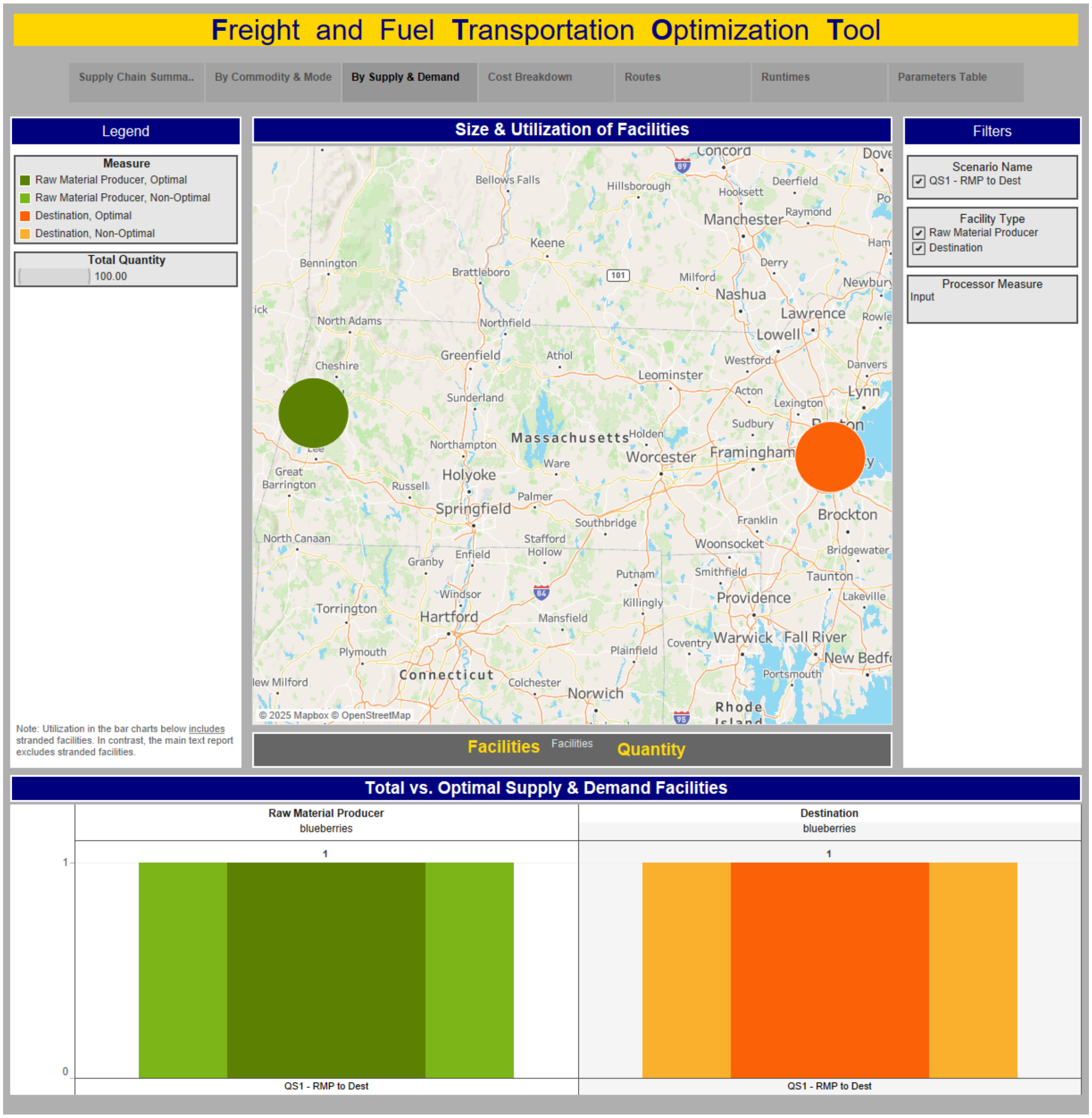


Figure 13: Tableau Story - By Supply & Demand Dashboard

The Cost Breakdown dashboard (Figure 14) presents the various costs considered and reported by FTOT. Separate bar charts illustrate the unscaled and scaled versions of these costs. The scaled versions are costs included in the objective function of the optimization problem and account for user-provided transport and CO_2 scaling factors. Costs are symbolized as individual cost components, which are organized into cost families. The dashboard can be filtered by scenario name, mode, commodity, and cost family.

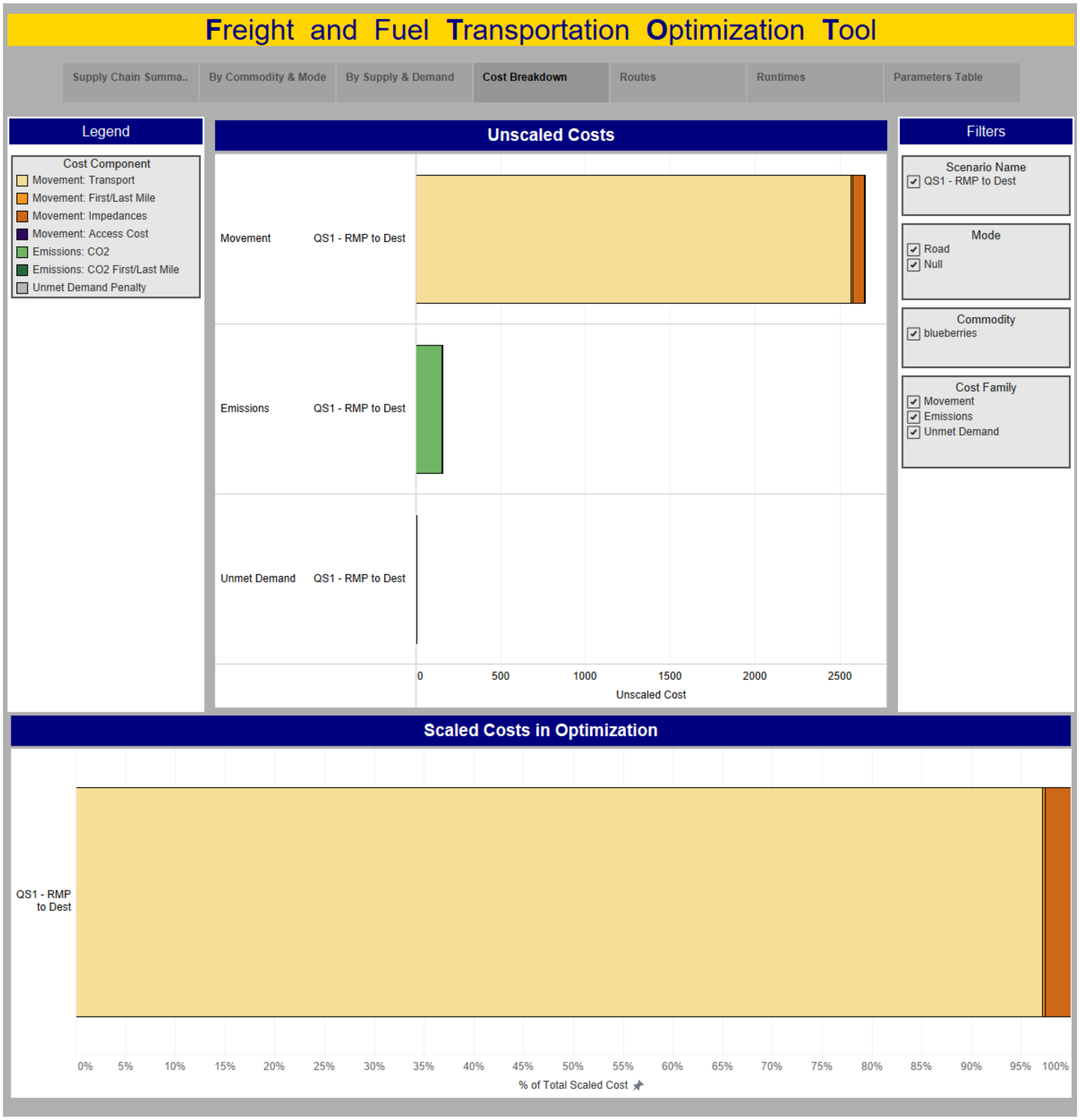


Figure 14. Tableau Story – Cost Breakdown Dashboard

The Routes dashboard (Figure 15) populates only for scenarios run with network density reduction (NDR) enabled. To enable NDR for a scenario, set the NDR_On element in the scenario XML file to True (see Section 3.1.1.2). The Routes dashboard summarizes the count, length, per-unit cost, and CO_2 emissions associated with the shortest paths linking each available origin and destination facility. Graphs can be filtered to show only the routes associated with particular modes, commodities, or facilities, or only the routes selected for the optimal solution.

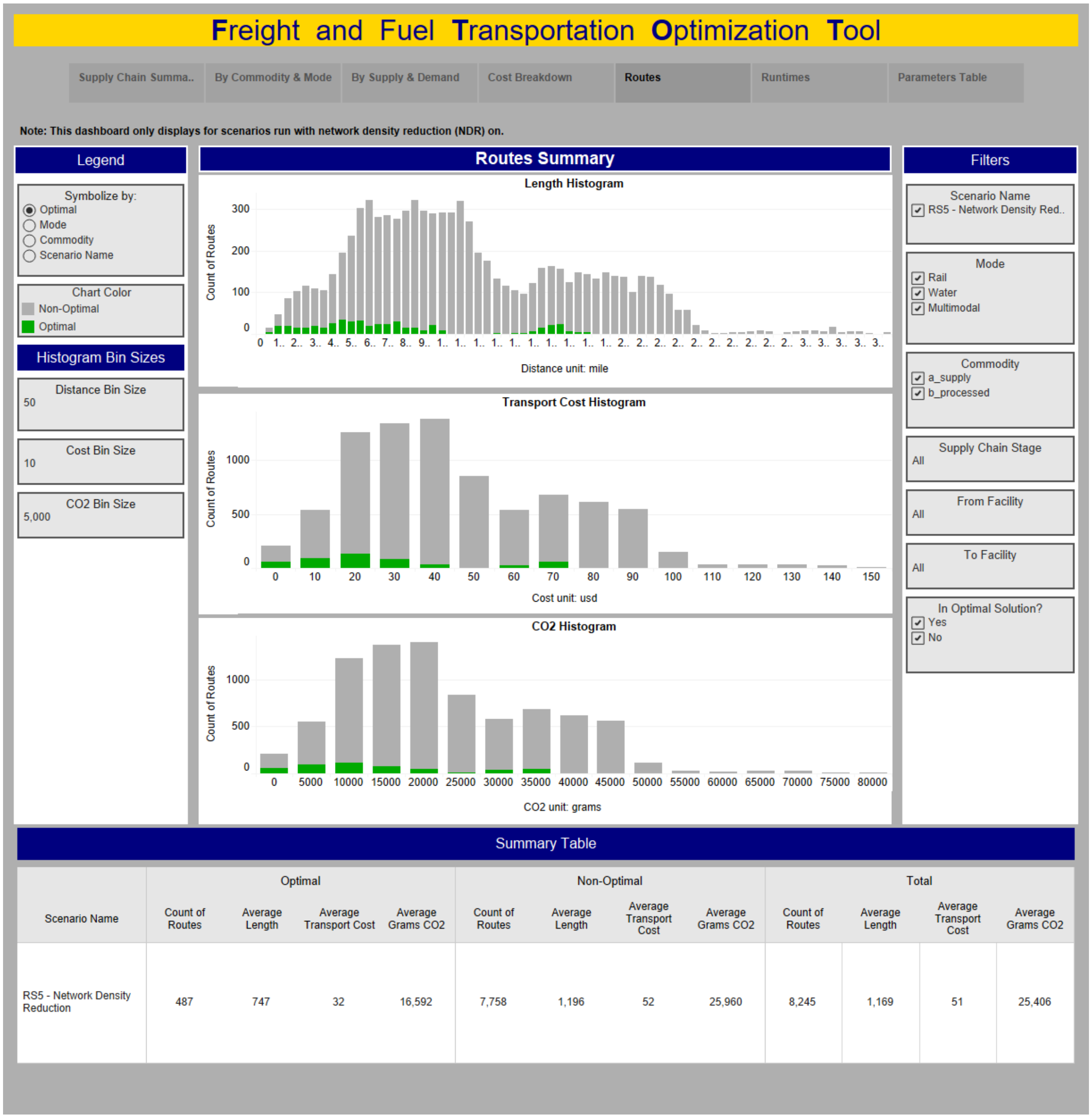


Figure 15: Tableau Story - Routes Dashboard (Reference Scenario 5)

The Runtimes story point (Figure 16) summarizes the runtimes of each step in the run, as well as the cumulative total runtime. Hovering over an individual color will provide a tooltip with additional information.

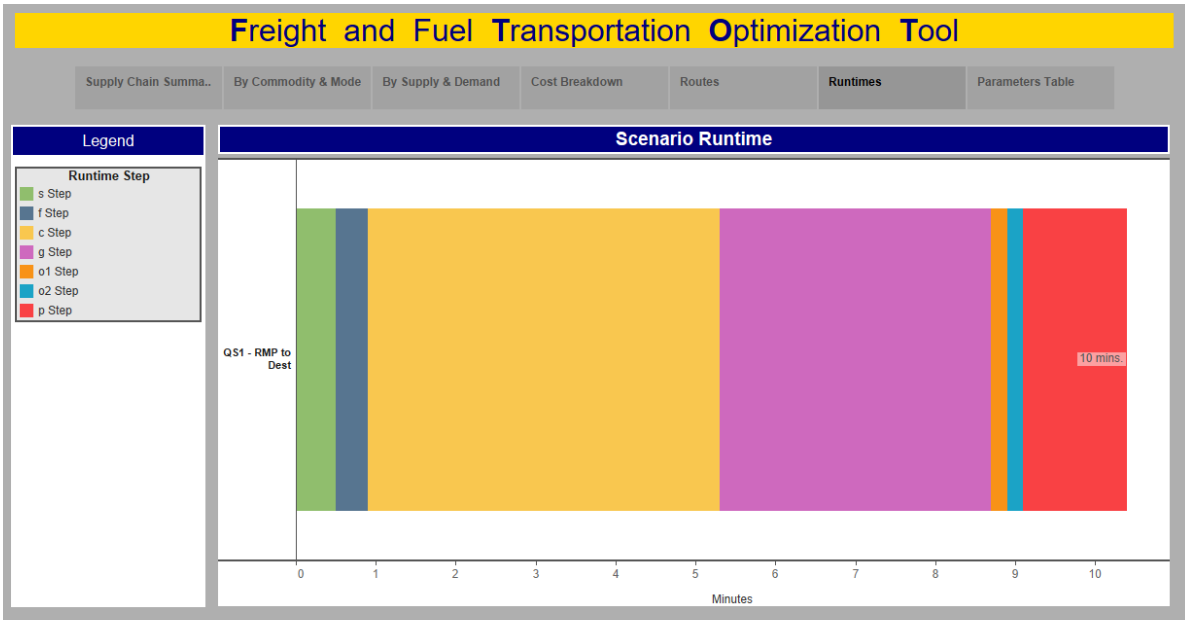


Figure 16: Tableau Story – Runtimes Dashboard

The Parameters Table dashboard is the last story point (Figure 17). It shows the parameters used in the scenario. Parameters are grouped together by sections, such as cost per mode, emissions factors, and vehicle load sizes.

Freight and Fuel Transportation Optimization Tool

Supply Chain Summa.. | By Commodity & Mode | By Supply & Demand | Cost Breakdown | Routes | Runtimes | **Parameters Table**

Scenario	Scenario Name	QS1 - RMP to Dest	QS1 - RMP to Dest
	Scenario Description	QS1 - RMP to Dest	This scenario demonstrates simple movements from a RMP to a destination.
	Scenario Directory	QS1 - RMP to Dest	C:\FTOT\scenarios\quick_start\qs1_rmp_dest
	Schema Version	QS1 - RMP to Dest	8.0.1
	Common Data Folder	QS1 - RMP to Dest	C:\FTOT\scenarios\common_data
Default Units	Solid Units	QS1 - RMP to Dest	ton
	Liquid Units	QS1 - RMP to Dest	thousand_gallon
	Distance Units	QS1 - RMP to Dest	mile
	Currency Units	QS1 - RMP to Dest	usd
Network-Specific Data	Base Network GDB	QS1 - RMP to Dest	C:\FTOT\scenarios\common_data\networks\FTOT_Public_US_Contiguous_Network_v2025.gdb
	Disruption Data	QS1 - RMP to Dest	None
	Impedance Weights Data	QS1 - RMP to Dest	C:\FTOT\scenarios\common_data\networks\default_impedance_weights.csv
	Speed Time Data	QS1 - RMP to Dest	C:\FTOT\scenarios\common_data\networks\default_speeds.csv
Facility Location Data	Base RMP Layer	QS1 - RMP to Dest	C:\FTOT\scenarios\common_data\facilities\counties.gdb\rmp
	Base Processor Layer	QS1 - RMP to Dest	None
	Base Destination Layer	QS1 - RMP to Dest	C:\FTOT\scenarios\common_data\facilities\counties.gdb\dest
Facility & Commodity Information	RMP Commodity Data	QS1 - RMP to Dest	C:\FTOT\scenarios\quick_start\qs1_rmp_dest\input_data\rmp.csv
	Processor Commodity Data	QS1 - RMP to Dest	None
	Candidate Processor Slate Data	QS1 - RMP to Dest	None
	Destination Commodity Data	QS1 - RMP to Dest	C:\FTOT\scenarios\quick_start\qs1_rmp_dest\input_data\dest.csv
	Schedule Data	QS1 - RMP to Dest	None
	Commodity Mode Data	QS1 - RMP to Dest	None
	Default Density Factor	QS1 - RMP to Dest	3.33 ton / thousand_gallon
	Commodity Density Data	QS1 - RMP to Dest	None
Vehicle Load Size	Truck Load (Solid)	QS1 - RMP to Dest	26 ton
	Truck Load (Liquid)	QS1 - RMP to Dest	8 thousand_gallon
	Railcar Load (Solid)	QS1 - RMP to Dest	100 ton
	Railcar Load (Liquid)	QS1 - RMP to Dest	30 thousand_gallon
	Barge Load (Solid)	QS1 - RMP to Dest	1500 ton
	Barge Load (Liquid)	QS1 - RMP to Dest	454 thousand_gallon
	Pipeline Load - Crude (Liquid)	QS1 - RMP to Dest	3150 thousand_gallon
	Pipeline Load - Product (Liquid)	QS1 - RMP to Dest	3150 thousand_gallon
Emissions & Fuel Use	Truck Fuel Efficiency	QS1 - RMP to Dest	195.2 mile * ton / gallon
	Railcar Fuel Efficiency	QS1 - RMP to Dest	471.0 mile * ton / gallon
	Barge Fuel Efficiency	QS1 - RMP to Dest	618.3 mile * ton / gallon
	Default Truck CO2 Emissions Factor	QS1 - RMP to Dest	1384.06 gram / mile
	Default Railcar CO2 Emissions Factor	QS1 - RMP to Dest	21.54 gram / mile / ton
	Default Barge CO2 Emissions Factor	QS1 - RMP to Dest	34.72 gram / mile / ton
	Default Pipeline CO2 Emissions Factor	QS1 - RMP to Dest	0.0 gram / mile / ton
	Detailed Emissions Data	QS1 - RMP to Dest	None
Network Costs	Truck Base Cost	QS1 - RMP to Dest	0.19050879540000001 usd / mile / ton
	Railroad Class I Cost	QS1 - RMP to Dest	0.04354486752000001 usd / mile / ton
	Barge Base Cost	QS1 - RMP to Dest	0.029029911680000006 usd / mile / ton
	Transloading Cost	QS1 - RMP to Dest	11.203731539000001 usd / ton
	Artificial Link Cost	QS1 - RMP to Dest	0.19050879540000001 usd / mile / ton
Short Haul Penalties	Rail Short Haul Penalty	QS1 - RMP to Dest	100 mile
	Water Short Haul Penalty	QS1 - RMP to Dest	100 mile
Artificial Links	Road Max Artificial Link Distance	QS1 - RMP to Dest	5 mile
	Rail Max Artificial Link Distance	QS1 - RMP to Dest	5 mile
	Water Max Artificial Link Distance	QS1 - RMP to Dest	5 mile
	Pipeline (Crude) Max Artificial Link Distance	QS1 - RMP to Dest	5 mile
	Pipeline (Product) Max Artificial Link Distance	QS1 - RMP to Dest	5 mile
	Report with Artificial Links	QS1 - RMP to Dest	False
Route Optimization	Permitted Modes	QS1 - RMP to Dest	['road', 'rail', 'water', 'pipeline_crude_trf_rts', 'pipeline_prod_trf_rts']
	NDR On	QS1 - RMP to Dest	True

Figure 17: Tableau Story - Parameters Table Dashboard

6.3 Maps

The FTOT map outputs are saved in a timestamped folder within the scenario's **.\Maps** directory and include the following:

- The multimodal network used in the optimization (01_S_Step)
- Raw Material Producers (02a_F_Step_RMP, 02a_F_Step_RMP_With_Labels)
- User Defined Processors (02b_F_Step_User_Defined_PROC, 02b_F_Step_User_Defined_PROC_With_Labels)
- Ultimate Destinations (02c_F_Step_DEST, 02c_F_Step_DEST_With_Labels)

- All Facilities (02d_F_Step, 02d_F_Step_With_Labels)
- Processor Candidates (03a_F2_Step_Processor_Candidates, 03a_F2_Step_Processor_Candidates_With_Labels)
- All Processors (03b_F2_Step_Processors_All, 03b_F2_Step_Processors_All_With_Labels)
- Final Optimal Routes (04a_O_Step_Final_Optimal_Routes_With_Commodity_Flow, 04b_O_Step_Final_Optimal_Routes_With_Commodity_Flow_NO_LABELS, 04c_O_Step_Final_Optimal_Routes_With_Commodity_Flow_JUST_FLOW)
- Optimal and Non-Optimal Raw Material Producers (04d_O_Step_Optimal_and_Non_Optimal_RMP)
- Optimal and Non-Optimal Processors (04e_O_Step_Optimal_and_Non_Optimal_PROC)
- Optimal and Non-Optimal Ultimate Destinations (04f_O_Step_Optimal_and_Non_Optimal_DEST)

All map names are suffixed with the following text—"default_basemap, "gray_basemap", "topo_basemap", or "streets_basemap"—based on the version of the mapping that is specified in the run.bat file for the scenario.

Running the default "m" step produces maps utilizing the default FTOT basemap, replacing "m" with "mb" produces maps utilizing the Esri light gray basemap, replacing "m" with "mc" produces maps utilizing the Esri topographic basemap, and replacing "m" with "md" produces maps utilizing the Esri streets basemap. In general, the default basemap is adequate for national and large regional scenarios, while the gray, topographic, and streets basemaps are more appropriate for smaller regional and local scenarios. Base layers (countries, states, counties) provided by the US Census Bureau and Esri's Living Atlas are also shown by default in each mapping output.

Note that many maps include variations that include/exclude labels. Since each scenario is different and all the maps are automated, some variations may work better than others depending on the scenario.

The user can manually develop their own maps within ArcGIS Pro leveraging the project file automatically generated in each scenario's output. To produce customized maps that are automatically output directly to the maps folder within an FTOT scenario, the user must edit the ftot_maps.aprx provided in the FTOT common_data folder and add user-specified and user-symbolized map data within the group layers located under the "CUSTOM_USER_CREATED_MAPS" section of the project file's Table of Contents. If these group layers are populated with actual data, FTOT will export these maps when the mapping step is run.

If the optional m2 step of FTOT is run, additional time period and commodity specific mapping is output into the scenario's **.\Maps_Time_Commodity** folder. Time step mapping is applicable for scenarios which include schedules. These map outputs include:

- Maps showing location of flows for each commodity in the scenario
- Maps showing location of flows for each time step in the scenario
- Maps showing location of flows for each commodity/time step combination in the scenario

- An animation (.gif) representing flows for all time steps in the scenario

Like the m step, alternative basemaps can be run by replacing the m2 step in the bat file with m2b (gray basemap), m2c (topographic basemap), and m2d (streets basemap).

6.4 Tableau Scenario Comparison Dashboard

The scenario comparison dashboard provides the ability to compare multiple scenarios in the Tableau dashboard. Functionality includes options to change the color of mapping route results by mode, commodity, and scenario name, as well as a Tableau Story format that allows users to step through each of the following dashboards:

- Supply Chain Summary
- Optimal Routes by Commodity and Mode
- Facility Results by Supply and Demand
- Cost Breakdown of the Optimal Routing Solution
- Routes Summary for All Shortest Paths (if run with NDR enabled)
- Runtimes
- Parameters

The scenario comparison dashboard can be created using the Scenario Compare Tool detailed in Section 7.1.5. The Scenario Compare Dashboard resembles the individual scenario dashboard with a few notable differences detailed in the following subsections.

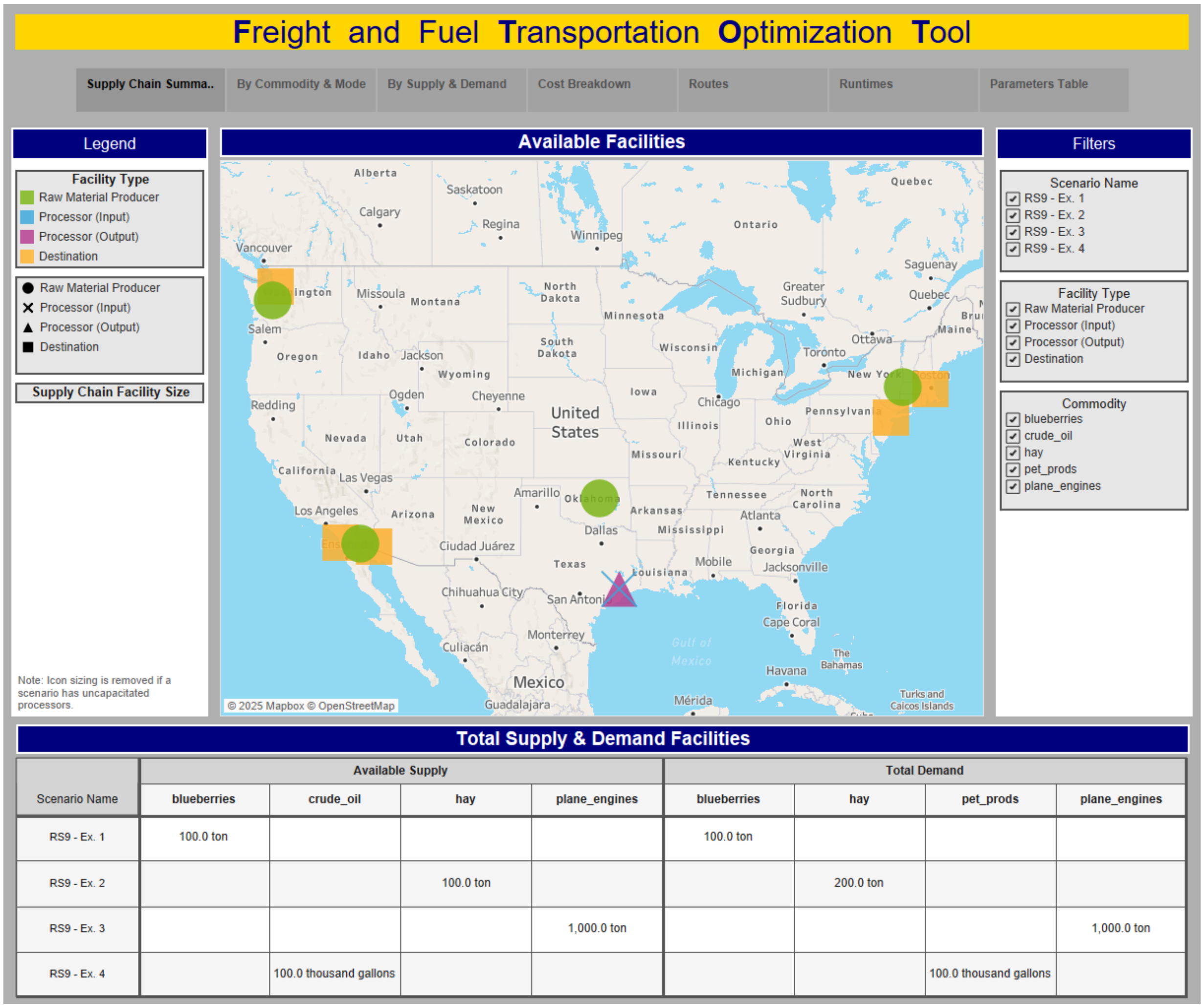
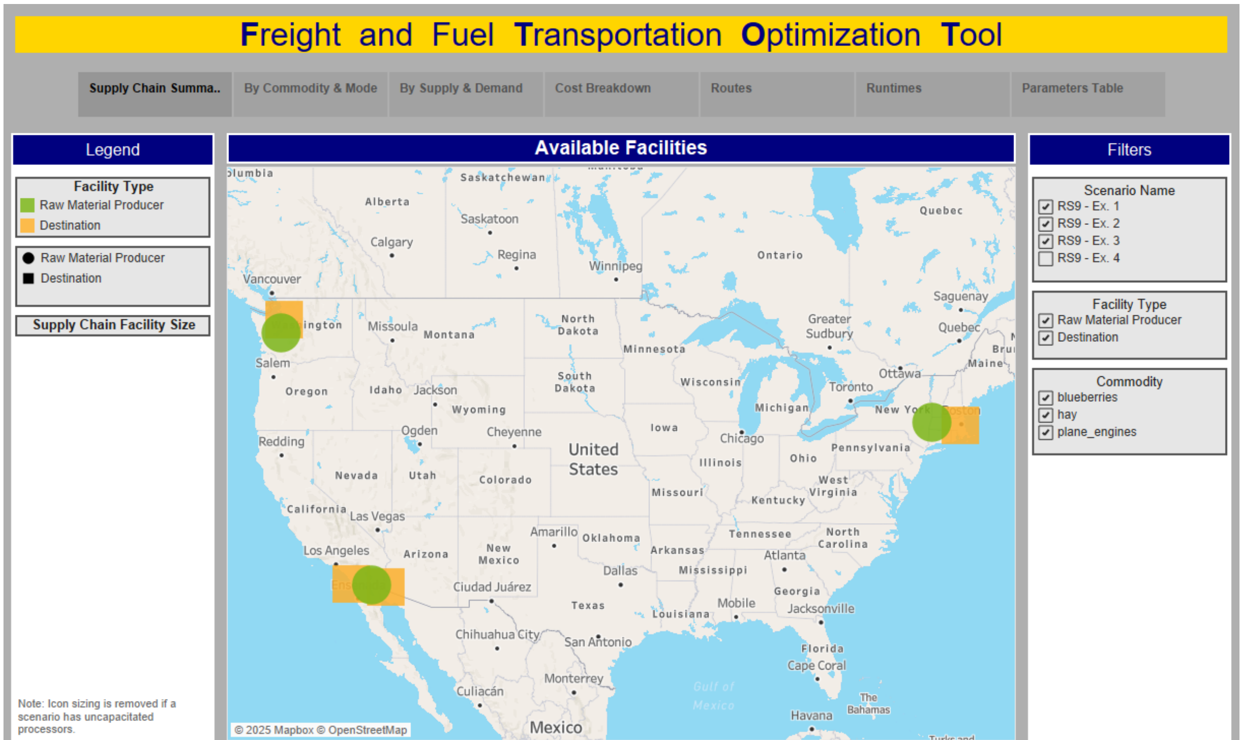


Figure 18: Supply Chain Summary on a scenario comparison dashboard (Reference Scenario 9)

6.4.1 Filtering Results

The filters are located on the right-hand side of the dashboard. The filters turn off the scenario results from the graphs, maps, and charts throughout. When Reference Scenario 9 - Ex. 4 is disabled in the filter, the map and supply chain table update automatically.



Total Supply & Demand Facilities

Scenario Name	Available Supply			Total Demand		
	blueberries	hay	plane_engines	blueberries	hay	plane_engines
RS9 - Ex. 1	100.0 ton			100.0 ton		
RS9 - Ex. 2		100.0 ton			200.0 ton	
RS9 - Ex. 3			1,000.0 ton			1,000.0 ton

Figure 19: Supply Chain Summary for subset of Exercises 1, 2, and 3 (Reference Scenario 9).

6.4.2 Optimal Route Results

Returning to all four exercises again, the optimal route results are displayed in the By Commodity & Mode dashboard. A high-level scenario summary indicating the percent difference of transport cost, vehicle-distance traveled, fuel burn, and CO_2 emissions are displayed relative to the first (“Baseline”) scenario. The results can be investigated in more detail and visualized in a number of different ways. The left-hand side legend provides three options for the route colors including mode, commodity, and scenario name. Additional graphs of the data can be visualized by selecting the different buttons below the maps. There is a high-level summary by scenario, a commodity summary, and a commodity & mode summary. The legend coloring options on the left-hand side and the filters on the right-hand side also change the result tables below.

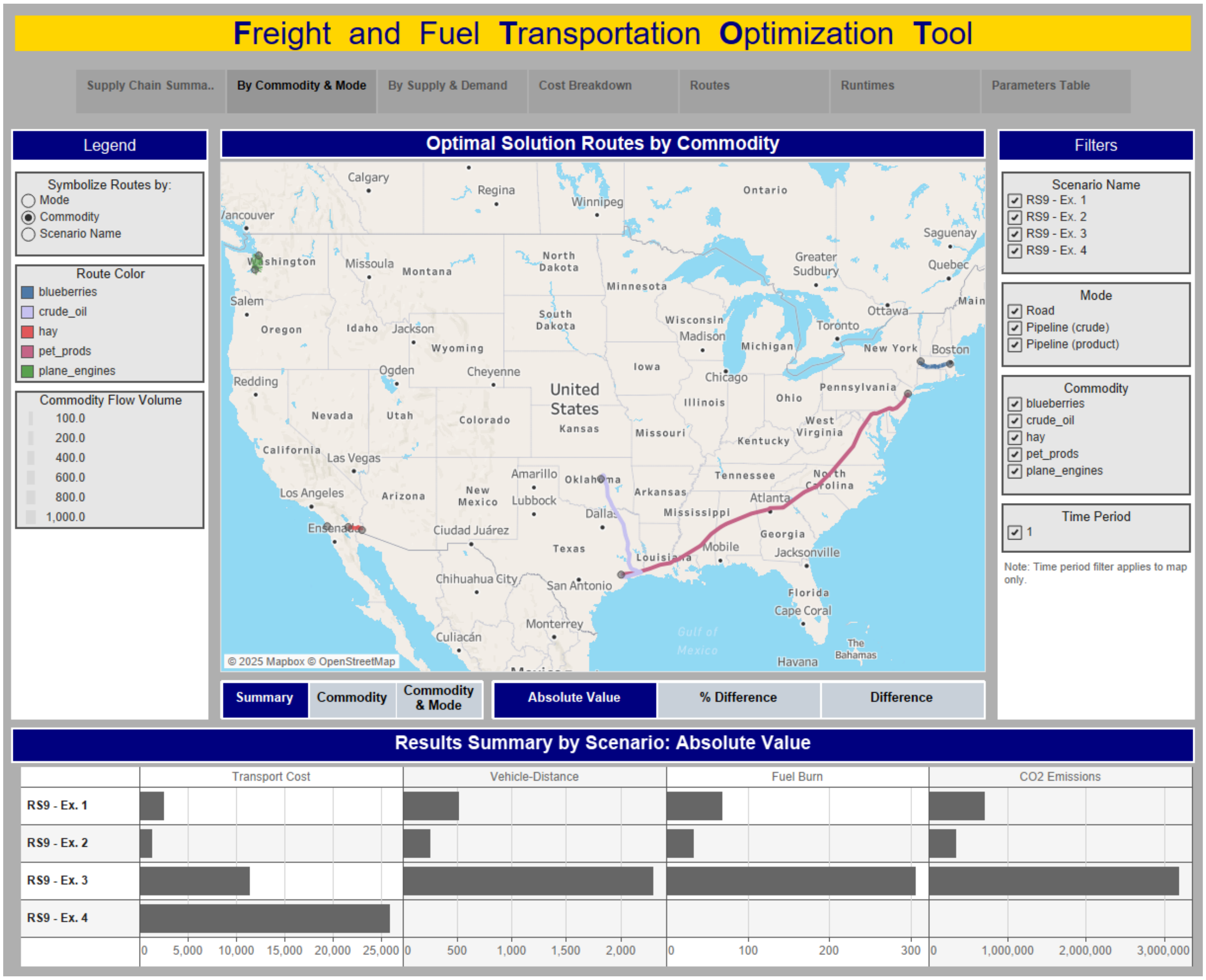


Figure 20: By Commodity & Mode results for Exercises 1, 2, 3, and 4 (Reference Scenario 9).

7 SUPPLEMENTARY TOOLS

7.1 FTOT Tools

A set of supplementary FTOT tools is provided to assist the user with a variety of common tasks. These tools include the following:

- **xml_tool:** Generates an updated XML scenario file based on either 1) the current FTOT template XML with default values, or 2) an existing, older user-generated XML file. See Section 7.1.1.
- **bat_tool:** Generates a bat file for running a new FTOT scenario based on user-provided inputs. See Section 7.1.2.
- **generate_template_csv_files:** Generates a set of input data CSV files for RMPs, processors, candidate processors, and destinations as user requested. See Section 7.1.3.
- **replace_xml_text:** Batch replaces XML configuration elements recursively through a top-level directory. See Section 7.1.4.
- **scenario_compare_tool:** Concatenates the results from one or more scenarios into a packaged Tableau workbook. See Section 7.1.5 for running the tool and Section 6.4 for usage.
- **network_disruption_tool:** Generates a network disruption CSV associated with a hazard scenario (e.g., NOAA sea level rise data, HAZUS data, etc.). See Section 7.1.6.
- **network_validation_tool:** Allows users to conduct preliminary validation on custom networks. Given a GDB file path, this tool confirms the contained feature classes use a meters-based system, have the correct mode-based naming convention, and contain all required data fields with the correct data types. This tool also summarizes mileage, segment counts, and link type counts, and optionally checks network connectivity (both across modes and within a mode). See Section 7.1.7.
- **scenario_setup_conversion_tool:** Converts a copy of the Scenario Setup Template file or the SAF Scenario Setup Template file, as filled out by the user to match their scenario specifications, into the bat file, XML scenario file, and input data CSV files required to run an FTOT scenario. See Section 7.1.8.
- **udp_sensitivity_tool:** Runs a sensitivity analysis for a user-provided FTOT scenario around the unmet demand penalty (UDP) parameter. Given a desired range for the transportation cost to deliver a unit of the finished product to its destination, the tool runs a series of scenarios varying the UDP parameter to find the level of supply chain utilization that meets that desired delivery cost.

You can access the suite of FTOT tools by double clicking the run_ftot_tools.bat file in the C:\FTOT folder.

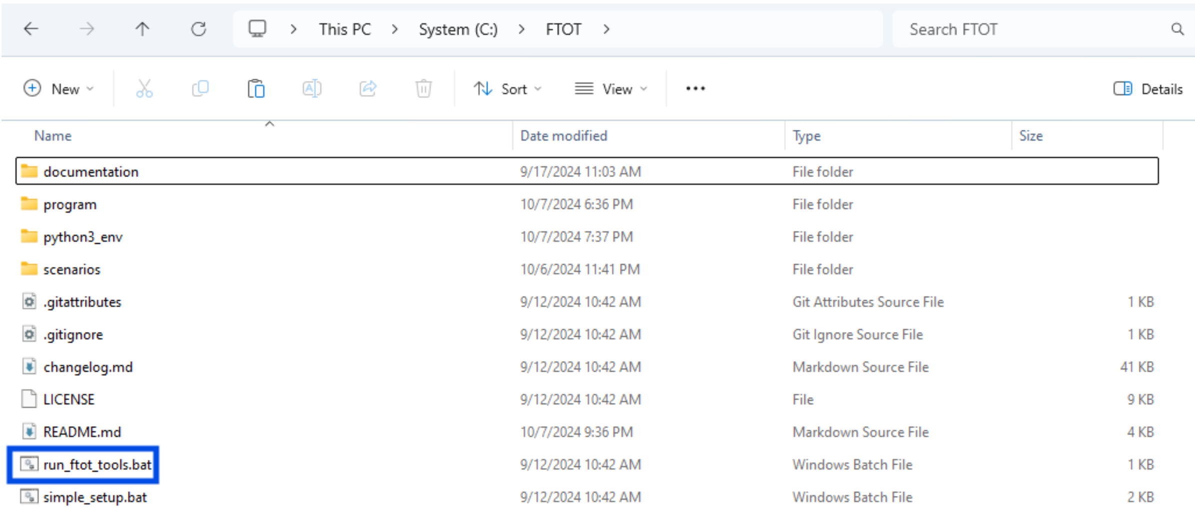
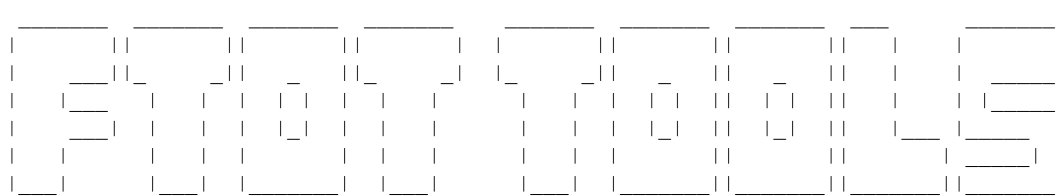


Figure 21: Location of BAT file used to launch FTOT Tools.

Alternatively, you can manually run FTOT Tools by typing the following line of code in a command-line window, where %python_path% should be replaced by the full path to the user's Python executable associated with FTOT:

```
%python_path% C:\FTOT\program\tools\ftot_tools.py
```

Users who set up FTOT using the simple_setup.bat script can replace the %python_path% environment variable with the Python path: *C:\FTOT\python3_env\python.exe*. After pressing enter, the user should see the following menu of FTOT tools:



```
Version Number: 2025.3, (9/30/2025)
-----------------------------------------
[1]  xml_tool
[2]  bat_tool
[3]  generate_template_csv_files
[4]  replace_xml_text
[5]  scenario_compare_tool
[6]  network_disruption_tool
[7]  network_validation_tool
[8]  scenario_setup_conversion_tool
[9]  udp_sensitivity_tool
[10]  help
[11]  exit
-----------------------------------------
Enter a number below to activate a tool
>>
```

The remainder of this section documents some of these tools in more detail.

7.1.1 XML Tool

This tool has two options. The user can either generate a default XML scenario file from scratch or update an old XML scenario file to the current schema version. Note: Make sure to confirm the correct scenario values are included in the XML if updating from an older XML file. For more information on the XML configuration file, see Section 3.1.1.

Input

The required user input for this tool is a directory in which to save the new scenario XML file, a name for the scenario XML file, and optionally a path to an existing scenario XML file to upgrade.

Output

The output is a prepopulated XML file in the directory specified by the user. The XML file contains all elements of the current XML schema with values set to defaults or migrated from the older existing XML file.

7.1.2 Bat Tool

This tool generates a default batch (.bat) file based on the inputted scenario XML file. The user can choose whether to include candidate generation steps. For more information on the batch file, see Section 5.2.

Input

The required user input for this tool is a path to the scenario XML file associated with the new batch file, a determination of whether candidate generation steps should be included in the batch file, and a directory in which to save the new batch file.

Output

The output is a batch file referencing the user-specified scenario XML file.

7.1.3 Generate Template CSV Tool

This tool generates facility CSV templates (e.g., rmp.csv). The user can specify which facility types to generate. The user also has the option to include optional fields (e.g., max_transport_distance). For more information on the facility-commodity input CSV files and their corresponding fields, see Section 3.3.1.

Input

The required user input for this tool is a list of facility CSV files to generate, a determination of which optional fields to include, and a directory in which to save the new facility CSV templates.

Output

The output is a set of facility-commodity input CSV files. Note that the user still needs to manually input the facility and commodity data; only the headers of the CSV files are automatically generated.

7.1.4 Replace XML Text Tool

This tool modifies specific XML fields for scenarios in a specified folder. If XML files with different schema versions are in the same folder, only files sharing the schema version of the first file alphabetically will get modified. This tool is useful for making changes to a number of scenario files, such as changing the base network geodatabase location.

Input

The required user input for this tool is a directory containing the XML files to modify, the specific XML element to update, and the new text to replace the element's existing text in each of the XML files found.

Output

There are no new files output by this tool. Instead, existing XML files within the directory are modified according to the XML element tag and new text provided by the user.

7.1.5 Scenario Compare Tool

The Scenario Compare tool is a supplemental FTOT Tool used to concatenate the results from one or more scenarios in a list. The scenario compare tool automates the process of creating a Tableau Scenario Comparison Dashboard (see Section 6.4 for more details). To run the tool, run FTOT Tools and select Option 5 (scenario_compare_tool).

The tool has two steps: (i) the user specifies an output directory where the concatenated results workbook will be stored, (ii) the user specifies the input directories which contain the results to be concatenated. The tool has two modes to generate the list of scenarios to concatenate: an automatic recursive search, and a user-specified search. In the recursive mode, the user provides a high-level directory and FTOT returns all sub-directories within it. In the manual mode, the user specifies which scenario folders should be added to the list until specifying the "done" keyword.

After the list is established (either automatically with the recursive search, or manually) the tool will search for Tableau workbooks within each .\Reports subfolder, find the latest version, and concatenate the tableau_report.csv, the all_routes.csv (if available), and tableau_output.gdb.zip records into the compare files. Any subfolders without a Reports folder are skipped.

Once the data is concatenated, the tool zips the workbook, CSV report(s), geodatabase, and supplemental files into a packaged workbook file (.twbx). The user can open this packaged workbook using Tableau Reader, which is available as a free download. The comparison dashboard allows the user to select one or more scenarios to compare against.

For more specific steps:

- Select the `Scenario Compare Tool` from the FTOT Tools menu and follow the prompts. First specify an output folder for the tool to put the concatenated results and packaged Tableau workbook. If the folder does not exist, FTOT will create it, place temporary files, and open the window for you. For example:

`C:\FTOT\scenarios\reference_scenarios\rs9_scenario_compare_dashboard\compare`

```
You called the scenario compare tool

FTOT scenario comparison tool

-------------------------------

scenario comparison tool | step 1/2:

-------------------------------

scenario comparison output directory:

---------------------->
C:\FTOT\scenarios\reference_scenarios\rs9_scenario_compare_dashboard\compare
```

- Next, FTOT needs to generate a list of directories to search for the individual Tableau reports. The user can select two modes: (i) a recursive sub-folder search, or (ii) manually providing the paths to the scenarios. Select the recursive search (option 1) for this exercise, and then specify the RS9 directory (note: this is **not** the compare directory!)

`C:\FTOT\scenarios\reference_scenarios\rs9_scenario_compare_dashboard`

```
scenario comparison tool | step 2/2:

-------------------------------

Option 1: recursive directory search

Option 2: user-specified directories

Enter 1 or 2 or quit: >> 1

enter top level directory

---------------------->
C:\FTOT\scenarios\reference_scenarios\rs9_scenario_compare_dashboard
```

- Once the list of scenarios is created, the tool will loop through each subdirectory under the RS9 suite, search for the .\Reports folder, and find the latest reports_YYYY_MM_DD_HH-MM-SS folder. If there are no .\Reports folders, then the tool skips that folder.

- The records in the tableau_report.csv, all_routes.csv, and tableau_output.gdb files from the latest report are then concatenated into the comparison files stored in the output directory.

When all of the scenario directories have been searched, the concatenated results files are zipped up into a packaged workbook. Open the scenario compare dashboard by double clicking the `tableau_report.twbx` file newly created in the output directory.

Input

The required input for this tool is a set of at least two already run FTOT scenarios. The paths to each scenario must be defined manually or the parent path containing all scenarios to be compared must be defined (and the scenarios will be identified through a recursive search). The user must also define an output directory to store the scenario comparison dashboard.

Output

The output is a Tableau workbook providing tables and visualizations comparing each scenario. More information on interpreting the Scenario Comparison Dashboard is provided in Section 6.4.

7.1.6 Network Disruption Tool

The network disruption tool helps automate the process of creating a network disruption dataset for an FTOT scenario (see Section 4.1.2). To run the tool, run FTOT Tools and select Option 6 (network_disruption_tool).

Input

The required input for this tool is a GIS-based raster dataset representing exposure data (e.g., due to a hazard such as flooding, earthquakes, etc.). The user also specifies the name of the dataset's attribute which specifies the exposure level and defines a search tolerance and the modes to which they want to apply disruption (currently limited to road and rail). The tool then automatically finds the maximum exposure level within the specified tolerance (distance) for each network segment.

Output

The output is a comma-delimited file (CSV) defining the unique segment IDs which are disrupted by the relevant exposure data, in the format FTOT can process. This disruption file can then be referenced in the relevant scenario's configuration XML.

7.1.7 Network Validation Tool

This tool allows users to conduct preliminary validation on custom networks. Given a GDB file path, the tool confirms the contained feature classes use a meters-based system, have the correct mode-based naming convention, and contain all required data fields with the correct data type.

Input

The required user input for this tool is a GDB with modal network feature classes to validate. The user also optionally selects whether or not to evaluate the network connectivity.

Output

The tool prints validation findings to the command prompt window. If network connectivity is being evaluated, the tool also creates a copy of the network containing connectivity-related feature classes along with a summary table listing the number of connected feature groups by mode. The output files are saved in the same directory containing the original network. The copy of the network contains feature classes that can be used to visualize disconnected parts of the network.

Note that a fully connected network will only contain one group of features. However, in many instances, disconnected features are expected (and thus the number of connectivity groups can be greater than one). This includes rail networks that are disconnected from the main network, roads that are on islands or separated from the rest of the network due to topography, or navigable waterways separated from other navigable waterways due to dams or variations in control depth.

7.1.8 Scenario Setup Conversion Tool

The Scenario Setup Conversion tool is a supplemental FTOT Tool that helps users create input files required to run an FTOT scenario, based on the Excel-based Scenario Setup Template or SAF Scenario Setup Template (Section 3.4) filled out by the user according to their scenario specifications. To run the tool, launch FTOT Tools and select Option 8 (scenario_setup_conversion_tool). The tool asks for the template file and an output directory, and primary FTOT input files will be generated by the tool.

Input

The required user input for this tool is a directory in which to save the generated FTOT scenario files and a path to the user-completed scenario setup template file.

Output

The output is a set of FTOT scenario files: a bat file for running the scenario, an XML scenario file with user-defined parameters and relevant file paths, and a set of facility-commodity CSV files (e.g., rmp.csv, proc.csv, proc_cand.csv, dest.csv) containing the user-defined supply chain data. Of the optional CSV input files (e.g., the commodity mode input file, schedules, disruption data, density), the SAF setup template creates only a commodity mode and density file. The general template does not create any of the optional files.

7.1.9 Unmet Demand Penalty Sensitivity Tool

The Unmet Demand Penalty (UDP) sensitivity analysis tool helps users find unmet demand penalty value(s) corresponding to optimal routing solutions that meet user-specified bounds for the metric of cost per unit of commodity delivered, for a user-specified commodity and unit relevant to the scenario. The tool performs multiple iterations of FTOT scenarios, with each iteration involving a scenario run with updated UDP value(s). The iterations are performed according to a binary search to identify the optimal UDP by lowering the UDP if the metric exceeds the user-specified upper bound and raising the UDP when the metric falls below the user-specified lower bound. This process helps users determine the most optimal UDP value(s) that achieve the desired metric within the bounds.

Input

There are six required user inputs for this tool:

1. File path to the scenario the user wishes to run
2. Name of the commodity for which to obtain metrics
3. Lower bound for the metric
4. Upper bound for the metric
5. Unit of the finished product delivered to the destination
6. Maximum number of scenarios run

Output

The output is saved as a CSV file named “Results.csv” in the scenario’s base directory. The CSV file includes five columns:

1. **Scenario_run_number**: The number of scenarios run using the tool.
2. **Total_transport_cost**: The transport cost extracted from the results of each scenario run.
3. **Total_flow_delivered**: The amount of flow delivered from the results of each scenario run.
4. **Metric**: The objective metric value found during the process of optimizing the UDP value to achieve the desired outcome. The metric is calculated by dividing the total_transport_cost by the total_flow_delivered and converting the result into the user-specified final product units.
5. **Scaling_factor**: The multiplier applied to the original UDP value(s) to generate the new UDP value(s) for each scenario run.

The user should expect the metric to approach the range defined by the user-specified lower and upper bounds. If the metric falls within the bounds, additional scenario runs will aim to find a higher metric that exceeds the current value within these bounds. These additional runs will continue until the user-specified maximum number of scenario runs is reached or the metric falls within the range three times. By examining the metric, the user can determine if the goal is reached. If the goal is reached, the user can determine the optimal UDP value by multiplying the scaling factor by the original UDP value(s) in the scenario.

Note that reaching the goal metric is entirely scenario-dependent, so there may not always be an optimal solution that achieves the desired metric bounds. Note that blank entries for some rows in the results CSV file occur when a scenario run results in a no-flow solution with the given UDP value. This prompts the next scenario run to have a higher set UDP value to incentivize more commodity flow. Also note for candidate generation scenarios, the randomness in the candidate generation process may cause some variability in the metric calculations.

7.2 Resilience Tools

7.2.1 Network Resilience Tool

The Network Resilience Tool (saved in repository FTOT-Resilience-Link_Removal) is a modification of the base FTOT program to assess the resilience of a **road-only** FTOT optimal solution to disruption. The link removal resiliency testing process works as follows: (1) a baseline FTOT run is completed using a modified version of FTOT, (2) network edges are ranked by a user-selected importance metric (either betweenness-centrality [28] or the volume of background flows), (3) links are iteratively removed in order of importance and FTOT is re-run to create new optimal solutions for the resulting disruption scenarios, and (4) total scenario costs are calculated and compared.

To install the Network Resilience Tool code, follow the instructions available here on the GitHub repository. The tool is run through a Jupyter notebook and generates an interactive report of the resilience results. A video for how to install and run the Network Resilience Tool is also available on the Volpe Center YouTube channel here.

7.2.2 Supply Chain Resilience Tool

FTOT-Resilience-Supply_Chain is a modification of the base FTOT program to support analysis of supply chain resilience. The supply chain resilience assessment includes two parts: integrated risk assessment to capture the combined effects of multiple risk factors on supply chain performance, and resilience assessment to calculate the long-term supply chain resilience in planning horizon. The supply chain methodology and modifications to the FTOT code were developed at Washington State University (WSU).

To install the FTOT-SCR code, follow the instructions available here on the GitHub repository for the modified tool. After installing, follow the instructions in the “Running the Scenario” section to run the two batch files to generate input data and analyze the resilience of the supply chain. The repository also contains two additional documents developed by the WSU team about the methodology used to create input data for the tool as well as the analysis performed in the tool.

8 TROUBLESHOOTING

Issue	Action
The user encounters SSL and/or module download errors during installation when running the simple_setup.bat file.	The user's security settings may be blocking download of certain file types used by required modules in the FTOT ArcGIS Pro Python environment (e.g., tar files). A workaround for the simple_setup.bat file is (1) locating the arcgispro-py3 folder path within the user's ArcGIS installation, (2) manually copying that folder and renaming to python3_env within C:\FTOT, (3) pip installing the remaining packages specified in simple_setup.bat.
When running FTOT in a command line window, the user immediately receives the following message: "The system cannot find the path specified."	Confirm that the paths defined in the scenario's batch file are appropriate. This issue is usually due to the user having an FTOT Python environment stored somewhere other than the default location (C:\FTOT\python3_env\python.exe). If so, the Python environment variable needs to be adjusted to reflect the path to the user's version of Python. The user should also confirm that the XMLSCENARIO and FTOT paths are set appropriately.
When running FTOT in a command line window, the user receives the following error towards the beginning of an FTOT run: "You will need ArcGIS Pro 3.0 or later to run this script. Exiting."	Assuming the user does indeed have ArcGIS Pro 3.0 or higher installed, confirm that the license to use ArcGIS Pro is available (try opening up ArcGIS Pro in its own window). If not, the user may need to connect to their work network or a VPN in order to access the license—contact the ArcGIS Pro license administrator for further details.
The user receives a RuntimeError indicating "The Product License has not been initialized" or similar.	Ensure that you have a license to use ArcGIS Pro. Some users may need to be connected to their organization's network directly or through a VPN in order to access the ArcGIS Pro license. In some cases, the user might receive this error even when they do have access to a license. This may be due to a number of factors including: • License server connectivity issues (borrowing an ArcGIS Pro license can resolve this issue, through the Licensing area of the ArcGIS Pro application). • Being logged into your Esri account within ArcGIS Pro (try logging out and rerunning the FTOT scenario). FTOT has better reliability with a Concurrent Use license as opposed to a Named User license. • Running more than one FTOT scenario at a time (try running one at a time to see if the error disappears). Named User licenses are limited to three concurrent uses at one time. • A license seat being unavailable (e.g., if your organization has five licenses for ArcGIS Pro and all are in use, then there may not be a license available for FTOT to use).
The user encounters an import error where Python is missing a required module.	See the installation guide in Section 2 and verify that the required modules are installed in the FTOT Python environment.

The user encounters a compatibility error for a Python module version. The user may have recently run the simple_setup.bat file, and would receive the following message upon running a scenario: “Import Error: cannot import name ‘___’ from ‘{module name}’ (C:\FTOT\python3_env\lib\site-packages\{module name}.py”	FTOT requires additional Python modules that are not part of the default ArcGIS Pro Python environment. These are automatically installed by the simple_setup.bat file, but only certain versions of each module are compatible with FTOT. See Section 2 for the list of recommended versions. Report any version compatibility issues to the FTOT team via the GitHub Issues page.
The user is unable to run the batch file (run.bat).	Running a batch file downloaded from a public source 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.
The user encounters a thrown exception error and exits the program because FTOT cannot find a GIS feature class or facility commodity CSV file.	Ensure that the appropriate scenario assets exist, and the path is properly specified in the scenario XML configuration file.
The user encounters an error during the O2 step with an “IOError: [Errno 13] Permission denied” message and FTOT fails.	This may be due to specific constraints within the user’s work network or VPN. Try running FTOT on a different network and/or off the VPN to see if it resolves the issue.
The user encounters a runtime error related to accessing a “read only” file or failing to execute a Copy command.	FTOT references several databases and geodatabases throughout a scenario run. Occasionally these files or directories are locked for use by another process or a prior processing step. Try running the scenario again with few competing computing processes.
The user receives a MemoryError during the G step and FTOT fails.	If the user is running a scenario w/ a large maximum transport distance (e.g., 500 miles) and/or a large number of RMPs (e.g., several hundred), consider either: • Reducing the number of RMPs either by aggregating RMPs that are close to each other (e.g. by zip code, county, or region), or by separating RMPs into separate scenarios to run in parallel. • Reducing the maximum transport distance.
The user finds a no-flow solution in the FTOT scenario run results.	Potential causes: • The unmet demand penalty (UDP) is too low. Adjust the unmet demand penalty in the scenario XML configuration file. In general, it may be necessary to raise this penalty when any other cost (e.g., rail transport) is raised, or else the optimizer will conclude that it is more optimal to transport less material. As a general guide, the unmet demand penalty will likely work best if set to be 10-50

	times the average actual transportation cost. It is advised to run scenarios with multiple unmet demand penalties to explore the sensitivity of a given analysis. • The candidate processing facility capital cost is too high. Increase the unmet demand penalty in the scenario configuration file or decrease the capital cost in the candidate processors commodity CSV file. • The processing facility lower bounds are too high for the amount of supply available. Adjust the minimum processor size in the facility commodity CSV file. • No-flow solutions are possible if facilities are not located close enough to segments in the FTOT transportation network. To address, raise the artificial link distances specified in the scenario's XML to ensure facilities connect to the network (for most modes, the default artificial link distance is 5 miles). Lack of connectivity is unlikely unless facilities are located far away from populated areas. • For capacity-constrained scenarios where existing background flows are being considered, no-flow solutions are possible when facilities are not accessible due to capacity constraints. Turn off the capacity constraint or increase the minimum available capacity in the scenario XML to address this issue. • When including both transport and CO_2 cost in a scenario, UDP may need to be set ~25% higher to account for higher routing costs.
The user notices dashboard text is too big or disappears altogether in the Tableau workbook.	• Go to the folder that contains the tableau.exe file. This file is located in a folder like C:\Program Files\Tableau\Tableau 2020.3\bin. • Right-click on tableau.exe, open "Properties," and go to the "Compatibility" tab. • Click the "Change high DPI settings" button. • Check the box to override high DPI scaling behavior. Set the "Scaling performed by" drop-down box to "System." • Restart Tableau. • Note that older versions of Tableau Reader may not be able to render all graphics (e.g., lines) in the dashboard.
The user is not able to view the expected dashboards in a scenario comparison Tableau workbook, or the comparison dashboards do not include the expected features associated with the FTOT release.	FTOT uses one of the existing scenarios' generated Tableau workbook as the template for the scenario comparison workbook. • If the scenario(s) were run with a previous FTOT version, the out-of-date Tableau workbook will propagate to the scenario comparison workbook. • Re-run the full scenarios using the same version of FTOT. To access the latest version of the Tableau workbook, re-run all scenarios with the latest FTOT release.

The user encounters the error message “database alias name 'dbXXXX' already in use” when opening the Tableau workbook.	• Exit out of the error and use the dashboard as normal. Visualizations will not be impacted. • This is a known issue in Tableau Desktop, found in Tableau Desktop 2023.1.0 and resolved in later versions. See Salesforce documentation for issue W-13598143.
In the Tableau workbook facilities on the maps are oversize and overlapping.	• The Tableau workbook is sensitive to the scale of commodity quantities and choice of commodity units. Consider modifying the scenario XML file to use different default units that represent commodity amounts at a smaller magnitude and in a similar range with other commodities in the scenario.
In the Tableau workbook filter boxes at the right side of a dashboard are empty.	• This issue is intermittent and isn’t often repeatable for the same workbook. • The reason is unknown but it is suspected to be due to delays in loading large datasets within the workbook. • Try re-opening the workbook, or navigate to other dashboards within the workbook to give the full file more time to load.

8.1 Known Bugs and Issues

- Errors with very large and very small numbers:
    - If it seems like numbers are being capped or cut off in unexpected ways, the most likely cause is an improperly set constraint—double check the upper and lower bounds on processor facility capacity, transportation and transloading costs, and demand vs. production values. If none of those address the problem, it is possible that limitations of the programming language in handling very large numbers are having an impact. The COINMP_DLL solver is written in C++, which limits values depending on the data type to ±2,147,483,647 (Integer), 38 places (Float), 308 places (Double).
    - Very small numbers (particularly when specifying cost parameters and/or using very large default solid or liquid units) can hit limitations associated with the optimization problem. The optimization algorithm terminates once changes in the objective function value fall below a threshold parameter; very small (e.g., 1e-10) objective function values may lead to the algorithm terminating before the true optimal solution has been found.
- On machines running ArcGIS Pro 3.2.x and 3.3.x, the optional M2 step (time and commodity mapping step) will crash with an error indicating “Cannot get exclusive schema lock.” At present, the only known solution is to run FTOT on a different version of ArcGIS Pro, such as version 3.4. This error does not impact the main maps (M step) and the generation of Tableau dashboards.
- Candidate generation scenarios and maximum transport distance:
    - FTOT does not support scenarios with candidate processes involving multiple inputs or for multiple processes with overlapping input or output commodities.
    - When NDR is disabled, in scenarios with a maximum transport distance, FTOT may limit how far commodities can travel from the RMPs to a shorter distance than specified by the user.

To ensure processing facilities are reachable, set a max transport distance 40 miles higher than the actual distance desired from RMP to processor.

- In some limited situations when scenario facilities are located close together, a facility may unexpectedly hook into a limited access roadway when it should instead hook into a non-limited access roadway. To work around this issue, ensure that scenario facility locations are located correctly and consider consolidating into one any scenario facility locations that are located adjacent to one another.
- For capacity-constrained scenarios using the default US FTOT network, the set of locks provided below are listed in the original USACE dataset as having zero capacity but existing barge volumes. If the Minimum Capacity Level parameter in the scenario XML is set to 0, these locks will not be traversable in the routing solution. To allow consideration of waterway routes crossing these locks in a capacity-constrained scenario, set the Minimum Capacity Level parameter to a value greater than zero.
    - USACE locks with zero capacity and positive volume values: 1 MISSISSIPPI; 7 ALLEGHENY; BERWICK; CANAVERAL; CLAIBORNE; FELSENTHAL; HILDEBRAND; JULIAN KEEN, JR.; LOWER SAINT ANTHONY FALLS; MILLERS FERRY; ROBERT F. HENRY; SCHOONER BAYOU; W. P. FRANKLIN; WILLIAM O. HUSKE
- If using a custom network with FTOT, note that locks in the feature class located more than 0.1 meters in either latitude or longitude from a node in the water feature class will not be associated with the waterway network. To prevent unanticipated omissions in capacity-constrained scenarios, snap the locks feature class to vertices of the waterway network when preparing the custom network.
- In the By Supply & Demand Tableau dashboard, facility utilization in the pie charts calculates percent utilization as a simple average across commodities when there are multiple commodities at a facility. In contrast, the tooltips for the bar charts on that dashboard calculate average utilization as a weighted average across commodities. For all calculations, units are ignored, and only commodity volume magnitudes are used without reconciling solid or liquid phases.

8.2 Known Functionality Dependencies and Incompatibilities

As the complexity of FTOT has grown, some optional features and scenario capabilities have been added that are incompatible with other optional features and capabilities, or depend on other features. Here are the current known dependencies and conflicts:

- Candidate Generation option requires a Maximum Transport Distance to be specified in the rmp.csv or (if NDR is enabled) proc.csv file for input commodities specified in the proc_cand.csv file.
- NDR On cannot be used with route capacity. The route sparsification methodology implemented by NDR On prevents route capacity from being implemented properly, as it removes routes that might receive overflow.
- Pipeline On requires a commodity-mode specification file. Pipeline usage defaults to "Off" for all commodities; for pipeline to be effectively enabled, a commodity-mode specification must be

included that lists the commodities allowed to use pipeline. This is done to prevent non-liquid commodities from appearing on pipelines.

- FTOT does not support scenarios with candidate processes involving multiple inputs or for multiple processes with overlapping input or output commodities.
- Custom vehicle types require a commodity-mode specification file.
- Using NDR On, Candidate Generation, and Max Transport Distance together introduces some complexities which are laid out in detail in Section 3.3.3.
- Custom vehicle types are not compatible with CO_2-based optimization.
- In order to avoid complete overlap of candidate processor locations with other supply chain elements (e.g., RMPs, processors, etc.), FTOT adds a randomized offset to FTOT-generated candidate processor locations that can change the specifics of how these facilities get connected to the network. For this reason, repeated runs with the Unmet Demand Penalty (UDP) Sensitivity Tool for scenarios with Candidate Generation can lead to variations in routing and transportation costs even for scenarios with the same candidate processing locations.
- The UDP Sensitivity Tool does not support scenario XML files with relative file paths.

8.3 Optimization Problem and Solver Guidance

For larger scenarios, the FTOT optimizer can take significant time to find an optimal solution or may not terminate in a reasonable time. These runtime issues are often due to (1) very large facility build costs or unmet demand penalties in the objective function, particularly compared to transportation routing cost values, (2) large numbers of candidate processor variables in the optimization problem, (3) many routes between facilities with similar costs to select among. In these situations, users should check a few characteristics of their supply chain optimization problem:

- Check that total commodity flow amounts (e.g., supply in rmp.csv, demand in dest.csv) are comparable numbers. If the amount of potential supply provided by the user does not align with other user inputs like minimum processor capacity or demand requested at the destinations, this can cause issues with the optimization problem formulation. If demand is exceedingly high and unmet demand penalties are significantly larger than other components of the objective function, the solver may not distinguish between differences in facility selection or transportation routes due to their relative scale and impact on the overall objective value. Modeling the demand at destinations to more closely match the technical potential of the supply to meet demand can mitigate any outsize impact of unmet demand penalties causing issues with solver convergence.
- Check that any maximum transport distance set in the rmp.csv or proc.csv files is reasonable for the number of raw material producers specified. A large number of RMPs combined with a high maximum transport distance can hit hardware constraints or lead to massive optimization problem formulations.
- Consider down-selecting or aggregating the facilities in the FTOT scenario and/or running multiple scenarios in parallel and aggregating results in post-processing. If evaluating several candidate processors, consider filtering the ftot_generated_processor_candidates.csv file in the “debug” folder via other criteria (e.g., location analysis) before re-running the O1 and O2 steps.

If considering supply across multiple geographies, consider breaking the rmp.csv file into several different scenarios by geographic region to run separately with FTOT.

The user can also adjust the optimization solver settings using the FTOT XML input file. FTOT is compatible with two open-source solvers, CBC and HiGHS, which may have different performance for different supply chain configurations. In testing across a range of FTOT scenarios, the convergence behavior for CBC has been more varied, with some test scenarios finding an optimal solution within a minute and several similar test scenarios failing to close the convergence gap after multiple days. HiGHS has more consistent behavior, though on average it has a slower runtime than CBC when convergence is fast. In instances where the two solvers find different optimal solutions, the solution found by HiGHS is generally more optimal, though only by a small amount.

The user can also set a maximum time limit for the solver in the XML file. Setting a solver time limit is useful for large scenarios if the user does not require an absolutely optimal solution, but rather can accept something close to optimal. It is recommended that the user check the gap between objective function values for the current best lower bound and best solution if running with a specified time limit to evaluate the optimality of the solution; this information can be found in the probsolve_capture.txt file in the “debug” folder. If the user finds CBC is not converging, they should try running the same FTOT scenario with HiGHS and a time limit set to several hours up to two days.

9 References

[1] NetworkX, "Network Analysis in Python v. 2.7," 2022. [Online]. Available: https://networkx.org/.

[2] S. Mitchell, A. Kean, A. Mason, M. O'Sullivan, A. Phillips and F. Peschiera, "PuLP: Optimization with Pulp," 2009. [Online]. Available: https://coin-or.github.io/pulp/.

[3] COIN-OR, "COIN-OR Linear Program Solver," 2007. [Online]. Available: https://www.coin-or.org/Clp/.

[4] Q. Huangfu and J. A. J. Hall, "Parallelizing the dual revised simplex method," *Mathematical Programming Computation,* vol. 10, no. 1, pp. 119-142, 2018.

[5] "Pint," [Online]. Available: https://pint.readthedocs.io/en/stable/.

[6] "imageio," [Online]. Available: https://imageio.readthedocs.io/en/stable/.

[7] ESRI, "Select features interactively," [Online]. Available: https://pro.arcgis.com/en/pro-app/latest/help/mapping/navigation/select-features-interactively.htm.

[8] ESRI, "Select features using attributes," [Online]. Available: https://pro.arcgis.com/en/pro-app/latest/help/mapping/navigation/select-features-using-attributes.htm.

[9] ESRI, "Select features by location," [Online]. Available: https://pro.arcgis.com/en/pro-app/latest/help/mapping/navigation/select-features-by-location.htm.

[10] ESRI, "Delete features and parts of features," [Online]. Available: https://pro.arcgis.com/en/pro-app/latest/help/editing/delete-features-and-parts-of-features.htm.

[11] ESRI, "Create point and multipoint features," [Online]. Available: https://pro.arcgis.com/en/pro-app/latest/help/editing/delete-features-and-parts-of-features.htm.

[12] ESRI, "Add field," [Online]. Available: https://pro.arcgis.com/en/pro-app/latest/tool-reference/data-management/add-field.htm.

[13] ESRI, "Calculate field," [Online]. Available: https://pro.arcgis.com/en/pro-app/latest/tool-reference/data-management/calculate-field.htm.

[14] ESRI, "Alter field," [Online]. Available: https://pro.arcgis.com/en/pro-app/latest/tool-reference/data-management/alter-field-properties.htm.

[15] EIA, "U.S. Energy Atlas," [Online]. Available: https://atlas.eia.gov/search.

[16] BTS, "Geospatial at BTS: Open Data Catalog," [Online]. Available: https://data-usdot.opendata.arcgis.com/.

[17] EPA, "Facility Registry Data," [Online]. Available: https://www.epa.gov/frs/geospatial-data-download-service.

[18] T. Huntington, N. Baral, M. Moore, S. Nordahl, T. Hendrickson, H. Breunig, O. Kavvada, M. Yang, X. Cui and C. Scown, "Biositing Webtool, v2," USDOE, 2024.

[19] ESRI, "Create Polyline Features," [Online]. Available: https://pro.arcgis.com/en/pro-app/latest/help/editing/create-polyline-features.htm.

[20] ESRI, "Snap to specific features," [Online]. Available: https://pro.arcgis.com/en/pro-app/latest/help/editing/snap-while-creating-geometry.htm.

[21] ESRI, "Split a feature," [Online]. Available: https://pro.arcgis.com/en/pro-app/latest/help/editing/split-a-feature.htm.

[22] ESRI, "Split lines at an intersection," [Online]. Available: https://pro.arcgis.com/en/pro-app/latest/help/editing/split-lines-at-an-intersection.htm.

[23] FHWA, "Highway Performance Monitoring System Field Manual: Chapter 4," [Online]. Available: https://www.fhwa.dot.gov/policyinformation/hpms/fieldmanual/page04.cfm#toc249159687.

[24] ESRI, "Calculate geometry attributes," [Online]. Available: https://pro.arcgis.com/en/pro-app/latest/tool-reference/data-management/calculate-geometry-attributes.htm.

[25] "Generalized Modeling Network Specification (GMNS)," 30 03 2023. [Online]. Available: https://github.com/zephyr-data-specs/GMNS .

[26] G. Boeing, "Modeling and Analyzing Urban Networks and Amenities with OSMnx," *Working paper,* 2024.

[27] FHWA, "Freight Analysis Framework Version 5," USDOT, 2022. [Online]. Available: https://ops.fhwa.dot.gov/freight/freight_analysis/faf/.

[28] L. C. Freeman, "A Set of Measures of Centrality Based on Betweenness," *Sociometry,* vol. 40, no. 1, pp. 35-41, 1977.

[29] "lxml," 2022. [Online]. Available: https://lxml.de/.

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Appendix A. Scenario XML Elements

The following is a description of each element and parameter in the scenario XML input file. Default values for several XML parameters and their sources can be found in Section 3.10 of the FTOT Technical Documentation.

1. <Scenario xmlns="Schema_v8.0.0"> - the namespace used by the XML schema. This should not be modified by the user. The latest version of the XML schema is not compatible with FTOT 2025.1 or earlier versions.
2. <Scenario_Schema_Version> - the version of the schema. Used to verify against changes to the XML schema, and code changes. The convention is: version X.Y.Z, where X = major version of FTOT, Y = breaking change to XML/Schema/Code, Z = non-breaking change to XML/Schema/Code. If a breaking change is made to the schema or code, the user must upgrade their XML file to meet the new schema standard. Users can use FTOT's scenario update tool to generate the latest version of the default XML file or use one of the latest Quick Start scenario files as a template.
3. <Scenario_Name> - a short string used to identify the scenario in the reports and logs. Scenario Names should be descriptive but no more than about ten characters long. Note: scenarios names should be differentiated for purposes of analyzing results with the Tableau workbooks.
4. <Scenario_Description> - a string used to describe the scenario. This is printed out in the reports and useful to quickly determine what is different between otherwise similar scenarios. For example, if the unmet demand penalty is increased in a sensitivity analysis, or if the road network is shut off in the permitted mode list, the description is a great place to note this. Keep descriptions under 500 characters.
5. <Scenario_Inputs> - contains the following elements:
    a. <Common_Data_Folder> - contains several files that are required by FTOT to run including the default national multimodal networks and ftot_maps.aprx, which is used for generating maps. The files listed in the common data folder are not modified by FTOT. Instead, FTOT copies a local copy to the scenario folder and modifies that version.
    b. <Base_Network_Gdb> - a string specifying the full path to the network geodatabase FTOT will set up and use for the scenario. FTOT will copy the base version to the local scenario. Therefore, a single base network can be used across multiple scenarios without impacting the base version.
    c. <Disruption_Data> - an optional string specifying the full path to the network disruption CSV that the scenario will leverage. If a disruption CSV exists, then the scenario will read it and remove any segments from the network identified in the table with a link availability of 0.
    d. < Base_RMP_Layer>, <Base_Destination_Layer>, <Base_Processors_Layer> - strings specifying the full paths to the feature classes (FC) containing the respective facilities that FTOT will use for routing. Again, FTOT will create a copy of the base FC to the local scenario geodatabase and leave the base version untouched. In the case of the <Base_Processors_Layer>, it should be noted that these are user specified processor locations, and not candidates generated by the tool.

e. <RMP_Commodity_Data>, <Destinations_Commodity_Data>, <Processors_Commodity_Data>, <Processors_Candidate_Commodity_Data> - paths to the CSV files that are used to define the commodity-facility relationships. The RMPs by definition only have "output" commodities that define the available supply from the facility. Destinations only have "input" commodities that define the total demand of a commodity at the destination. Processors have both "input" and "output" commodities that define the facility size and product-slate/processing ratio. The Processor Candidates commodity data file defines the maximum and minimum facility size, minimum aggregation threshold, processing ratio, and cost formula for the amortized capital cost of the facility.
f. <Schedule_Data> - an optional string specifying the full path to the schedules CSV file.
g. <Commodity_Mode_Data> - an optional string specifying the full path to the commodity mode CSV which allows the user to specify which commodities can travel on each mode, and by which vehicle type. This file is necessary to permit movement by pipeline.
h. <Commodity_Density_Data> - an optional string specifying the full path to the commodity density CSV which allows the user to specify commodity-specific density values. For more information see Section 4.4.1. If this parameter is omitted from the XML, the Density_Conversion_Factor parameter value (see below) will be applied to all liquid commodities.
i. <Default_Units_Solid_Phase>, <Default_Units_Liquid_Phase>, <Default_Units_Distance>, and <Default_Units_Currency> - strings used to specify the units in which FTOT will report the results. The Pint python module is used to convert the quantities and units specified in the input files into the default units specified in these tags. The default distance units must match the units used in the Length attributes of the network GDB—note that FTOT does NOT check this. Also, FTOT does NOT convert currency; all XML elements involving cost must use the default currency units. At run time, FTOT will process the default units and raise an error if it cannot use the user specified values because of a typo or other failed validation check.

6. <Assumptions> - contains the vehicle load, fuel efficiency, and CO_2 emissions factors for each mode and phase of matter.
   a. Vehicle loads - quantities with units for the maximum load as defined for each mode and phase of matter (Truck_Load_Solid, Railcar_Load_Solid, Barge_Load_Solid, Truck_Load_Liquid, Railcar_Load_Liquid, Barge_Load_Liquid, Pipeline_Crude_Load_Liquid, Pipeline_Prod_Load_Liquid).
   b. Fuel efficiencies - rates with units of distance per volume as defined for each mode (Truck_Fuel_Efficiency, Railcar_Fuel_Efficiency, Barge_Fuel_Efficiency).
   c. CO_2 emissions factors - rates with units of mass per distance (for road) or units of mass per weight per distance (for non-road) as defined for each mode (Truck_CO2_Emissions, Railcar_CO2_Emissions, Barge_CO2_Emissions, Pipeline_CO2_Emissions).
   d. <Detailed_Emissions_Data> - an optional file path for detailed emissions factors. If a sufficient file is provided, FTOT will generate a separate, detailed emissions report that includes non-CO_2 emissions.

e. <Density_Conversion_Factor> - an optional number with units specifying the default density value used. The default density will be used for any liquid commodity not specified in the commodity density CSV input file. If this parameter is omitted from the XML, a default density value of 3.33 tons per thousand gallons is used, as it is the density of kerosene, a proxy for sustainable aviation fuel.

f. <Speed_Time_Data> - an optional file path for link speed and node travel time. If provided and if NDR_On parameter is True, FTOT will tabulate total travel time for each facility pair and include the results in the routes CSV report. The FTOT data package includes a sample file for the default FTOT network.

7. <Create_Network_Layer_Script> - updates each network link with the cost functions defined for each mode and link type by the user.

   a. <Network_Costs>

      i. <Modal_Costs> - The GIS module assigns costs to each link in the multimodal network based on the transport costs specified in the XML Scenario file. The transport costs on the GIS network are the costs required to transport material over each particular link depending on mode and commodity phase. The default costs are defined in USD/metric ton-mile for all commodities. Commodity densities are used to convert liquid commodities from units of volume to units of mass. The default cost values come from the US BTS average freight revenue per Ton-Mile. The 2020 data was used because it is the latest complete year reported in the table.

      ii. <Intermodal_Transloading_Costs> - Intermodal costs specify the cost of switching from one mode on the network to another (e.g., rail -> road). Intermodal transfers can only take place as specified intermodal facilities on the network. A cost for solid material and a cost for liquid material transloading is specified by the user.

      iii. <Artificial_Link_Costs> - Optional section specifying cost for artificial link movements. If omitted, truck transport cost on local roads is used.

      iv. <Impedance_Weights_Data> - optional file path to a CSV with weights for different categories of road, rail, and waterway links. These weights discourage flows over portions of the networks by scaling up the routing cost over certain links.

   b. <Artificial_Links> - Since facilities are not always located directly on the multimodal network, artificial links must be used to connect facilities to the network. A reasonable default is 5 miles, though longer artificial link distances can be conceivably used, particularly for the pipeline network where there is the least amount of detail. Shorter artificial link distances can be used when the facilities are known to be located directly on or adjacent to the relevant network modes. Artificial links are only created for the permitted modes defined in the XML scenario file. In addition, this XML section includes an element with a True/False flag for whether to include artificial links in calculations for report metrics.

   c. <Short_Haul_Penalties> - FTOT applies a penalty to rail and water artificial links to discourage short movements on those networks. Inputting a higher penalty value will further discourage transport by rail and waterway.

8. <Route_Optimization_Script>

a. <NDR_On> - The True/False flag determines whether the network presolve step using the NetworkX shortest path algorithm is enabled. The default is for the presolve step to be disabled.
b. <Permitted_Modes> - The following True/False flags determine whether or not a particular mode should be allowed for routing any flows in the scenario. The default is for all modes to be on.
c. <Capacity_Options> - contains the following elements:
    i. <Capacity_On> - The True/False flag determines whether network capacity should be considered as a constraint for flowing in the scenario. The default is for capacity to be off.
    ii. <Background_Flows> - The following True/False flags determine whether or not a particular mode should have its existing (background) flows considered. If True, then background flows (e.g., existing movements of freight on the network) will be considered. The default is for all modes to NOT have their background flows considered.
    iii. <Minimum_Capacity_Level> - The setting (0-1) determines the minimum fraction of daily capacity that must be available for each network segment in the scenario. Setting a value above 0 allows network segments that are already at capacity due to existing flows, to be traversable in this scenario up to the minimum capacity level.
d. <CO2_Optimization> - contains the following elements:
    i. <Transport_Cost_Scalar> - This scaling factor determines what share (0-1) of transport routing cost is considered in the optimization.
    ii. <CO2_Cost_Scalar> - This scaling factor determines what share (0-1) of CO_2 emissions cost is considered in the optimization. Setting this element to a decimal value greater than 0 will yield additional output metrics specific to CO_2-based optimization scenarios.
    iii. <CO2_Unit_Cost> - This cost is applied to each unit of CO_2 emissions for the purpose of CO_2-based optimization. The cost should be entered in default currency units per mass unit of CO_2.
e. <Solver_Options> - contains the following elements:
    i. <Solver> - solver used by FTOT to find an optimal solution to the routing problem. The options are CBC (default) or HIGHS.
    ii. <Solver_Time_Limit> - maximum amount of time given for the solver to find an optimal solution. If the optimal solution has not been proven optimal by the time limit, the current best solution is returned by the solver. The parameter is specified as a number and time unit (e.g., “2 hours”). To set no time limit, set to “None”, which is the default.
f. <Unmet_Demand_Penalty> - This parameter sets the default cost in default units of mass applied to each unit of demand at a destination that is not fulfilled. It is used to drive flow in the scenario.

Appendix B. FTOT Network Specification Schema

The following tables show the field names and data types for each component of the network specification, along with a short description of each field. Note that in all cases, additional fields are acceptable in a network used by FTOT, as no error will be generated, but additional fields will not be used.

While FTOT does not utilize attributes beyond those included in the network specification, it does retain these attributes in the scenario network constructed by the program, in case the user would like to access the additional attributes for user-generated reporting, mapping, or analysis. Note, however, that attributes not contained in the network specification are passed along to the modified scenario network 'as is' and are not re-calculated when links are split to allow scenario-specific facilities to be attached the network in the C step. For this reason, users are discouraged from including non-network specification attributes that would need to be recalculated if network segments are split. For example, if the user includes count or density link attributes within their network, these feature attributes may not be valid when the scenario network is processed to flow an FTOT scenario, as split segments will retain the same (and potentially inaccurate) counts and densities as the parent link. Each of the feature classes described in the following tables must be saved inside a feature dataset named 'network' located within a single ESRI File Geodatabase. The file path to the geodatabase is specified by the user in the scenario XML file.

FTOT's supplementary network validation tool (see Section 7.1.7) can be used to help confirm that custom geodatabase files meet important structural and schema requirements.

Table 5: Roadway Network Schema – Line feature class named 'road'

Field Name	Field Type	Description/Example
OBJECTID	Object ID/Unique identifier (Required)	Automatically included with Esri file geodatabase features
Shape	Geometry (Required)	Automatically included with Esri file geodatabase features
Mode_Type	Text (Required)	'road'
Artificial	Integer (Required)	2 = intermodal (connectors to intermodal facilities), 1 = artificial (connectors to facilities), 0 = actual network link
Length	Numeric (Required)	Length of segment in default distance units
Link_Type	Text (Optional but highly encouraged for impedances)	Category used for setting impedance weights
Dir_Flag:	Integer (Optional)	1 = one-way in the direction of digitization (from-to node); 0 = two-way; -1 = one-way (to-from node)
Urban_Rural	Integer/Boolean (Optional)	1 = Urban, 0 = Rural
Limited_Access	Integer/Boolean (Optional)	1 = Limited Access, 0 = Non-Limited Access
Volume	Numeric (Optional)	Volume in vehicles per day (per direction)
Capacity	Numeric (Optional)	Capacity in vehicles per day (per direction)
VCR	Numeric (Optional)	Volume to Capacity Ratio
Name	Text (Optional)	Descriptive Name for the segment
Free_Speed	Numeric (Optional)	Free Flow Speed (distance unit per hour)

Table 6: Rail and Water Network Schema – Line feature classes named ‘rail’ and ‘water’

Field Name	Field Type	Description/Example
OBJECTID	Object ID/Unique identifier (Required)	Automatically included with Esri file geodatabase features
Shape	Geometry (Required)	Automatically included with Esri file geodatabase features
Mode_Type	Text (Required)	'rail' or 'water'
Artificial	Integer (Required)	2 = intermodal (connectors to intermodal facilities), 1 = artificial (connectors to facilities), 0 = actual network link
Length	Numeric (Required)	Length of segment in default distance units
Link_Type	Text (Optional but highly encouraged for impedances)	Category used for setting impedance weights
Dir_Flag:	Integer (Optional)	1 = one-way in the direction of digitization (from-to node); 0 = two-way; -1 = one-way (to-from node)
Volume	Numeric (Optional)	Volume in vehicles per day (per direction)
Capacity	Numeric (Optional)	Capacity in vehicles per day (per direction)
VCR	Numeric (Optional)	Volume to Capacity Ratio
Name	Text (Optional)	Descriptive Name for the segment

Table 7: Pipeline Tariff Routes Schema – Line feature class named 'pipeline_prod_trf_rts' or 'pipeline_crude_trf_rts'

Field Name	Field Type	Description/Example
OBJECTID	Object ID/Unique identifier (Required)	Automatically included with Esri file geodatabase features
Shape	Geometry (Required)	Automatically included with Esri file geodatabase features
Tariff_ID	Integer (Required)	Unique Tariff ID
base_rate	Numeric (Required)	Tariff Cost in default currency to traverse the pipeline
Mode_Type	Text (Required)	'pipeline_prod_trf_rts' or 'pipeline_crude_trf_rts'
Dir_Flag	Integer (Required)	Most if not all pipeline tariffs should be one-way in the direction of digitization (Dir_Flag = 1)
Artificial	Integer (Required)	2 = intermodal (connectors to intermodal facilities), 1 = artificial (connectors to facilities), 0 = actual network link
Length	Numeric (Required)	Length of segment in default distance units
Commodity	Text (Optional)	'Petroleum Products' or 'Crude Oil'
Name	Text (Optional)	Descriptive Name for the segment

Volume, Capacity, and Volume Capacity Ratio (if needed) must be provided in a separate Pipeline Tariff Segments feature class (the individual segments making up overlapping tariffs). These tables must be linked via the unique Tariff_ID. Refer to the default FTOT network of the contiguous United States for more information.

Note: Separate feature classes for crude and product pipelines.

Due to the unique nature of the pipeline data, we strongly encourage users to utilize the default FTOT data unless custom data is necessary. Sources for these data are limited.

Table 8: Intermodal Facility Schema – Point feature class named 'intermodal'

Field Name	Field Type	Description/Example
OBJECTID	Object ID/Unique identifier (Required)	Automatically included with Esri file geodatabase features
Shape	Geometry (Required)	Automatically included with Esri file geodatabase features
Name	Text (Optional)	Descriptive Name for the intermodal facility

Each intermodal facility must be physically connected to each relevant mode through an artificial link in the mode's feature class. This might be aided by fields in the intermodal feature class that indicate Y/N whether a mode is relevant to that intermodal facility, but these attributes are not required.

Table 9: Locks Schema – Point feature class named 'locks'

Field Name	Field Type	Description/Example
OBJECTID	Object ID/Unique identifier (Required)	Automatically included with Esri file geodatabase features
Shape	Geometry (Required)	Automatically included with Esri file geodatabase features
Volume	Numeric (Optional)	Volume in vehicles per day
Capacity	Numeric (Optional)	Capacity in vehicles per day
VCR	Numeric (Optional)	Volume to Capacity Ratio
Name	Text (Optional)	Descriptive Name for the lock

Each lock must be located at a node (start and/or endpoint) connecting up to two segments in the water link network. The locks feature class is solely used by FTOT to assign barge background volumes and capacities to adjacent links in the water network (and for mapping purposes). They are not a required component of a FTOT network that contains water links. Lock background volumes and capacities are halved and attributed to the adjacent waterway segments. Note that lock volumes and capacities will override any volumes or capacities that might be enumerated for adjacent links in the waterway network. Note that the default water network for FTOT only defines volumes and capacities at the lock level and not at the waterway (link) level.