CMAQ EMISSIONS CALCULATOR TOOLKIT

The purpose of the Congestion Mitigation and Air Quality Improvement Program Emissions Calculator Toolkit (CMAQ Toolkit) is to provide users a standardized approach to estimating emission reductions from the implementation of a CMAQ-funded project. The CMAQ Toolkit uses emission rates for highway vehicles based on a national-scale run of the Motor Vehicle Emission Simulator (MOVES) as well as other data sources. For each tool in the Toolkit, the inputs and methodology are described in user guides along with some example cases. Emission estimates from the CMAQ Toolkit are not intended to meet specific requirements for State Implementation Plans (SIPs) or transportation conformity analyses. Information regarding the development of default emission rates and guidance on incorporating user-supplied emission rates can be found in the accompanying documentation of the emissions data.

TRANSIT BUS SERVICE AND FLEET EXPANSION TOOL

The Transit Bus Service and Fleet Expansion Tool estimates emission reductions from diverting use of passenger vehicles to transit buses. It is suggested that users calculate related mode shifts through a travel demand model in advance of using this emissions calculator.[1]

This emissions calculator can model CMAQ-eligible transit improvement projects, including higher frequency scheduling, added routes and stops, and new vehicle procurement to support new or expanded bus service. Any project that demonstrates increased transit bus travel and decreased passenger vehicle activity may be modeled in this tool. This tool requires the user to provide vehicle miles travelled (VMT) for transit buses and passenger vehicle activity as number of trips or VMT, before and after the project. Project sponsors are welcome to use a preferred travel demand model to estimate the number of trips or VMT by mode. If such a model is unavailable, Appendix A in this document provides references to resources on travel demand modeling and model selection.

This document is organized into three sections – User Guide, Tool Methodology, and Examples – to aid the user in understanding and interpreting results from the calculator. The User Guide section directs the user to properly input values into the tool, and provides definitions of both user inputs and tool outputs. The Tool Methodology section outlines the steps taken by the tool to calculate emission reductions, as well as any assumptions made. This section includes all equations used within the tool. The Examples section provides several examples of how to use the tool for different types of analysis.

[1] The most current version of the tool is dated December 2021. To verify the version, check the date on the Introduction page of the tool. Release notes are included in the Change Log tab, which can be viewed by right-clicking on any tab in the tool, selecting “Unhide”, and revealing the tab.

Contents

USER GUIDE 3

User Inputs 3

Travel Demand Modeling 5

Data Conversion from TDM Outputs to Passenger Vehicle Miles Traveled 6

Converting Transit Bus Activity Data from TDM to CMAQ Tool Inputs .. **Error! Bookmark not defined.**

Time Aggregation and Day Operated Per Year 6

Information on Trip Linking: 7

Transit Bus Activity Allocations 7

Allocations of Model Years 8

Allocations of Fuel Types 8

Allocations of Road Types 9

Tool Outputs 10

Fleet Performance 10

Emission Reductions 10

Error Messages 10

TOOL METHODOLOGY 12

EXAMPLES 16

Example 1: Extended Bus Route 16

Example 2: Shorten the Headways 19

Example 3: 24

Example 4: A Growing Mid-sized City 28

APPENDIX A: Travel Demand Modeling Resources 33

TDM Concepts 33

Example Simplified Tools 34

TDM Best Practices and Practitioner Forums 35

Advanced TDM Resources 35

APPENDIX B: Alternative Fuels and Advanced Drivetrain Technology Definitions 36

USER GUIDE

This section describes each user input and the corresponding tool output. A description of emission reductions reporting and error messages, as well as other assumptions inherent in the tool, are also provided.

User Inputs

The interface of the Transit Bus Service and Fleet Expansion tool functions as a wizarding tool, with questions to help the user enter proper information for emission reduction calculations in a step-by-step process. Inputs for this tool should be specific to the CMAQ project, i.e. changes in service as a result of the project's fleet and/or route modifications (Table 1).

Table 1 User Inputs

Item	User Input	Units	Description
(1)	Project evaluation year	-----	Use the drop-down menu to choose a year between 2018 and 2040.
(2)	Days operated per year	Number of days	Input the number of days per year that the bus service operates. This input is 365 days per year by default. For weekdays only, input 260 days per year. For weekends only enter 105 days per year. Users can input any other value as well.
(3a)	Transit bus vehicle miles traveled before and after project completion	Miles	Enter the annual VMT by the transit bus fleet both before and after project completion. Both VMT estimates are required.
(3b)	Allocations of model years (button)	$\frac{Model\ Year\ VMT}{Total\ Fleet\ VMT}$ (All allocations must sum to 1)	Selecting this button brings the user to a separate tab to modify the fleet vehicle model year distribution. Input a distribution of the fleet's activity by model year before and after project completion. The model year cannot be later than the project year or more than 30 years prior to it. National average values are available in the tool if users do not have this information.
	Allocations of fuel types (button)	$\frac{Fuel\ Type\ VMT}{Total\ Fleet\ VMT}$ (All allocations must sum to 1)	Selecting this button brings the user to a separate tab to modify the fuel type distribution. Input a distribution of the fleet's activity using given conventional and

			alternative fuel types before and after project completion. National average values are available in the tool if users do not have this information.
	Allocations of road types (button)	$\frac{Road\ Type\ VMT}{Total\ Fleet\ VMT}$ (All allocations must sum to 1)	Selecting this button brings the user to a separate tab to modify the road type distribution. Input a distribution of the fleet's activity on the given road types before and after project completion. National average values are available in the tool if users do not have this information. National average values are available in the tool if users do not have this information.
(4a)	Passenger Vehicle Activity Type	-----	Choose an input for passenger vehicle activity as either VMT or number of trips.
	Passenger Activity	Trips or Miles	Enter either the annual VMT or the annual driven by passenger vehicles in the service area both before and after project completion. Both activity estimates are required.
	Average One-Way Trip Distance	Miles	Enter the average trip distance for passenger vehicles in the service area. Note that the default value for this input is 4.52 miles. For information on the source of this national average value, see the section on Travel Demand Modeling.
(4b)	Do you expect most passenger vehicle trips to be linked with bus trips as a result of the service or fleet expansion? (radio buttons)	----	Select whether service users will drive to transit hubs to use the bus service or not. If trips are linked, start emissions for passenger vehicles will not be reduced as a result of the transit project. If the project will reduce full passenger trips, start activity, and thus emissions, will also be reduced.

After making changes to the distributions in Question (3), return to the emissions calculation page by clicking the "Update Emissions Results" button.

Once inputs are filled, click the "Calculate Output" button to compute the scenario results. Emission results will not automatically update, so this button must be clicked to calculate updated emission reductions results each time parameters are modified. To return to default settings and clear inputs, click on the 'Reset to Default Values' button. Note that clicking on 'Reset to Default Values' will not clear inputs on the model year, fuel type, and road type VMT distribution tabs.

Travel Demand Modeling

Successful use of this tool relies on credible travel demand modeling (TDM) to provide VMT or Trip based mode shifts as passenger vehicle activity inputs. TDM can be a very complex computational process involving a great deal of effort. However, there are a number of simplified methodologies that enable agencies to conduct robust TDM analyses with fewer resources. A number of such materials are provided in Appendix A, including links to primers on travel behavior and travel modeling, as well as links to some simplified tools that may be useful.

Many travel models output changes in trips by mode rather than VMT. For this reason, the CMAQ tool provides an option to input passenger vehicle activity in either trips or VMT. This functionality requires that users input an average passenger vehicle trip distance as well as the activity before and after the project's implementation. While using local values of this average is preferred, if local data is not available,

Table 2 below provides average passenger trip distances by transit bus for different regions of the US, drawn from the 2017 National Household Travel Survey (NHTS).[2] Average trip distances by transit bus a used here because this roughly represents the distances that passengers are willing to travel by transit bus, and thus their current travel distance by passenger vehicle would need to be similar to induce mode shifts. These values can be used as inputs to the tool, or to convert travel demand modeling outputs manually to VMT for passenger vehicles. Note that the default input in the tool is the national average shown below in the leftmost column, or 4.52 miles.

Table 2: NHTS 2017 Average Regional Transit Bus Person Trip Distances (miles) for Bus Trips[3]

National	New England	Mid-Atlantic	East North Central	West North Central	South Atlantic	East South Central	West South Central	Mountain	Pacific
4.52	2.75	3.51	3.96	4.25	4.57	6.78	6.16	5.09	4.90

[2] U.S. Department of Transportation, Federal Highway Administration, 2017 National Household Travel Survey. URL: http://nhts.ornl.gov. Regional delineations are drawn from the US Census, and indicated in the NHTS Code Book, which can be found on the NHTS website.

[3] Note that that "Transit Bus" includes both commuter and local bus services.

Data Conversion from TDM Outputs to Passenger Vehicle Miles Traveled

For users who have trip-based TDM outputs, the CMAQ tool provides functionality to handle these trip-based inputs. The tool will automatically convert from trips to VMT, provided a valid average trip distance has been input into the tool. This conversion utilizes the following relationship to convert from trips to distance-based units for passenger vehicle activity:

$$VMT = Trips \cdot D \quad (1)$$

where

VMT = vehicle-miles traveled
$Trips$ = number of trips
D = typical average trip distance.

When VMT is used as the input unit for passenger vehicle activity, the inverse of the relationship shown in Equation 1 (i.e., Trips = VMT / D) is used to compute trip reductions for start activity reductions when full passenger vehicle trips are reduced and for the Fleet Performance parameters shown on the interface of the tool.

Some TDMs output results in person miles travelled (PMT). To be compatible with the inputs available in the CMAQ tool, these outputs must be converted to VMT of passenger vehicles. The following equation, which uses an average occupancy rate (OR) of passenger vehicles, can be used for this conversion:

$$VMT = \frac{PMT}{OR} \quad (2)$$

where

PMT = person miles traveled

OR = average occupancy rate in units of passengers (including driver) per passenger vehicle.

Days Operated Per Year

The tool requires users to provide annual activity inputs to calculate emissions benefits. The calculations require an input for the number of days of transit service operation to get daily emissions benefits from annual activity inputs as required by the tool. The default number of days of transit service operated per year assumes 365 days per year. For those who have daily activity data for a typical weekday or weekend day, users should multiply the daily activity by the number of week or weekend days in a year, 260 and 105 days respectively, and then input the appropriate value for the number of days operated per year. For projects where both weekday and weekend travel statistics or forecasts are available, users are recommended to report annual activity and input 365 days as the number of days operated. This ensures that the emission reductions will be representative of the project's full operations.

Information on Trip Linking:

Some transit projects aim to produce a reduction in passenger VMT by specifically promoting linked trips, or trips where passengers use personal vehicles for part of the trip, and public transit for the remainder. These projects only reduce running activity, and not a substantial amount of start activity. If passengers are expected to stop using personal vehicles entirely as a result of the transit project, this means trips are not expected to be linked, and both the start and running activity is reduced. If it is no known whether or not the project will reduce full passenger vehicle trips, answer "Yes" to question 4b, as this will produce a more conservative estimate of emissions benefits from the project.

Transit Bus Activity Allocations

Users can provide project-specific activity allocations for transit buses to improve their estimates of benefits. In the absence of user-supplied allocations, the tool provides MOVES3 national defaults.

This tool only considers the net emission reductions associated with increased transit bus travel and decreased passenger vehicle travel. The tool offers users the option of entering estimated effects of transit bus service and fleet activity allocations without needing to rerun MOVES. The national default passenger vehicle fleet distributions are used in the tool, regardless of user inputs. Since this tool focuses on transit improvements, any changes in passenger vehicle activity allocations must be imported from a local MOVES run.

A sample of the questions and buttons in the activity allocation tabs (model year, fuel type, road type) is provided below.

Questions

1. Enter the <model year, fuel type, road type> distribution of transit bus activity before and/or after completion (fractions for each distribution/column must sum to 1).
2. Use the button below to fill the table with national default model year distributions if desired. These distributions are specific to the year input on the "Transit Bus Service & Fleet Expansion" Tab.
    - Use the “Set to National Default Values” button to fill the table with the <model year, fuel type, road type> relevant to the year on the main interface tab.

Buttons

- Update Emission Results
    - This button will activate the main interface tab and calculate the emissions benefits from the transit bus project, provided the distributions sum to 1 and all other inputs on the main interface have been input correctly
    - After editing the <model year, fuel type, road type> distributions before and/or after project completion, this button brings a user back to the calculator

interface and will update the emission reduction results with the new allocation data.

- Set to National Default Values
  - This button will reset the fractions to the MOVES3 national <model year, fuel type, road type> default fractions.
- Clear Inputs
  - This button will clear all of the fractions in the table on the <model year, fuel type, road type> tab. It will not affect values input on any other tab in the tool.

Allocations of Model Years

By default, this tool applies MOVES3 national model year distributions of VMT to reflect emissions impacts of vehicle age.[4] Fleet age distributions change based on the evaluation year and locality, so users are encouraged to enter their own fleet activity characteristics where applicable. As with MOVES, this tool will only model vehicles up to 30 years older than the project evaluation year.

Access the Model Year Distribution tab by selecting the button on the tool's interface. Both the distribution before and after the project evaluation year may be modified. The before and after project distributions must each sum to one. Users can choose to fill the table with the MOVES national default model year distribution.

Allocations of Fuel Types

The tool evaluates scenarios where transit buses are powered by conventional fuels and certain alternative fuels. Gasoline, diesel, and compressed natural gas (CNG) emission rates are from MOVES3. The tool also adjusts MOVES diesel transit bus emissions rates using the US Department of Energy's AFLEET alternative fuel factors in order to provide emissions estimates for fuel types not covered by MOVES, including battery electric, hybrids, renewable fuels, and other non-conventional fuels such as natural gas, propane, electricity, and hydrogen. Definitions of these alternative fuels and technologies are provided in Appendix B. The methodology for creating the AFLEET adjustment factors can be found in the AFLEET tool documentation.[5] The full list of available fuels can be found below:

- Gasoline,
- Diesel,
- Compressed natural gas (CNG),
- Liquefied natural gas (LNG),
- 20% biodiesel (B20),
- 100% biodiesel (B100),

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[4] US Environmental Protection Agency, *MOVES3: Population and Activity of On-road Vehicles*, https://cfpub.epa.gov/si/si_public_file_download.cfm?p_download_id=541815

[5] US Department of Energy, https://greet.es.anl.gov/afleet

- Dual fuel (natural gas/diesel),
- Hybrid electric (HEV),
- Hydraulic hybrid (HHV),
- Battery electric (BEV), and
- Hydrogen fuel cell (FCV).

Users can choose to fill the table with the MOVES national default fuel type distribution. The default distribution assumes market shares of the evaluation year for gasoline, diesel, and CNG. Users are similarly encouraged to input their fleet's characteristics by selecting the appropriate button on the main interface and entering the fuel type fraction representing the fleet. The before and after project distributions must each sum to one.

Allocations of Road Types

MOVES accounts for different emissions distributions based on the proportion of different road types. As described in the MOVES technical documentation[6], the following four road types are included in this tool:

- Rural Restricted Access: rural highways only accessible by on- or off-ramps,
- Rural Unrestricted Access: all other rural roads, including arterials, collectors, and local streets,
- Urban Restricted Access: urban highways that are only accessible by on- or off-ramps,
- Urban Unrestricted Access: all other urban roads, including arterials, collectors, and local streets.

Users are recommended to consider all road types in their analyses; road types should be determined using Highway Performance Monitoring System (HPMS) classifications[7] local to the jurisdiction. Users can choose to fill the table with the MOVES national default road type distribution. Users are encouraged to input locally representative road type fractions using a similar process as described in earlier sections. The before and after project distributions must each sum to one.

[6] US EPA, *MOVES3: Population and Activity of On-road Vehicles*, https://cfpub.epa.gov/si/si_public_file_download.cfm?p_download_id=541815

[7] US Department of Transportation, Federal Highway Administration (FHWA), Highway Performance Management System (HPMS), https://www.fhwa.dot.gov/policyinformation/hpms.cfm.

Tool Outputs

Fleet Performance

Table 3 below details the fleet performance (non-emissions) outputs for this type of project.

Table 3: Changes in Annual Vehicle Miles Traveled by Scenario Vehicles

Output	Units	Description
Transit Bus VMT Increase	Miles per year	The total change in annual vehicle miles traveled by the transit bus fleet.
Passenger Vehicle Trip Reduction	Trips per year	The total change in annual trips taken by passenger vehicles.
Passenger Vehicle VMT Reduction	Miles per year	The total change in annual vehicle miles traveled by passenger vehicles.

Emission Reductions

The Transit Bus Service and Fleet Expansion tool accounts for the changes in the underlying emission rates reflecting shifts from passenger vehicle to transit bus travel and changes to national default allocations for fleet activity. These include differences due to vehicle age, fuel type, and road type.

Emission reductions are calculated for five pollutants – carbon monoxide (CO), particulate matter with diameters of 2.5 microns or smaller (PM2.5), particulate matter with diameters of 10 microns or smaller (PM10), nitrogen oxides (NOx), and volatile organic compounds (VOC) – reported in kilograms per day based on the annualization factors specified.

This tool also outputs emissions reductions for CO_2 and CO_2 Equivalents (CO_2e) in kilograms per day and Total Energy Consumption (TEC) in British Thermal Units. These emissions benefits are only output when the emissions data are available from MOVES. This means that the tool will only output these reductions if gasoline, diesel, or CNG buses are part of project being assessed. If other fuel types are involved, the tool cannot estimate CO_2, CO_2e or TEC benefits for these outputs.

Error Messages

Table 4 below summarizes 1) error and warning messages associated with this tool, 2) the reasons for those errors, and 3) possible solutions. Once an error is corrected, please confirm the inputs and then click on 'Calculate Output' to estimate emissions reductions.

Table 4 Error Messages

Error Message	Reason for Error	Solution
ERROR: Please enter an appropriate project evaluation year.	Invalid input for project evaluation year	Input a year between 2018 and 2040
Please enter a non-zero number of days operated before calculating or updating outputs	Invalid input for the number of days operated per year	Input a positive integer value for the number of days operated per year
Please fill out bus activity data correctly before calculating or updating outputs	Invalid input for bus activity before or after values	Input valid values for the transit bus activity before and after the project's implementation.
Please choose a passenger activity type before calculating or updating outputs	The passenger vehicle activity units have not been selected	Select a passenger vehicle activity type (VMT or trips) to input into the passenger vehicle activity inputs
Please fill passenger activity data correctly before calculating or updating outputs	Invalid input for passenger vehicle activity before or after values	Input valid values for the passenger vehicle activity before and after the project's implementation
Please fill out average passenger trip distance before calculating updating outputs	Invalid input for passenger vehicle average trip distance	Input a valid value for the average trip distance that passengers take by passenger vehicle or by transit bus.
Please choose an option for linked or full passenger vehicle trips before calculating or updating outputs	An option for linked or full reductions of passenger vehicle trips must selected	Select an option to indicate if reduced passenger vehicle activity will consist of passengers driving to central hubs to use the transit service, or if full passenger vehicle trips will be reduced.
WARNING: The fractions in the before distribution do not sum to 1. Please review allocations prior to calculating emissions.	Activity distribution before project completion is not properly allocated.	Prepare a before distribution that sums to 1, within a tolerance of at least 3 significant digits (0.999 >= sum >= 1.0001)
WARNING: The fractions in the "after" distribution do not sum to 1. Please review allocations prior to calculating emissions.	Activity distribution after project completion is not properly allocated.	Prepare an after distribution that sums to 1, within a tolerance of at least 3 significant digits (0.999 >= sum >= 1.0001)

TOOL METHODOLOGY

This tool allows users to calculate emission reductions for a number of transit bus service and fleet expansion projects. There are equations below for transit bus emissions before and after project completion as well as passenger vehicle emissions before and after project completion. For passenger vehicles, there is potentially a reduction in start activity if the project is expected to reduce full passenger vehicle trips. The equations for calculating start emissions reductions for passenger vehicles are also shown here. The total emission reductions are calculated by finding the sum of the change in transit bus emissions and the change in passenger vehicle emissions before and after the project is completed. The emissions of a given pollutant reduced by diverting travel from passenger vehicles to transit buses and any associated transit bus activity allocations are reported in kilograms/day. Total Energy Consumption reductions are reported in million BTU (MMBTU).

The equations for transit bus emissions are defined below:

$$Bus\ emissions\ before\ project = \sum_{i\epsilon I, j\epsilon J, k\epsilon K, y, p} \left(e_{bus_{i,j,k,y,p}} \cdot Before\ VMT_{bus_{i,j,k,y}} \right) \quad (3)$$

$$Bus\ emissions\ after\ project = \sum_{i\epsilon I, j\epsilon J, k\epsilon K, y, p} \left(e_{bus_{i,j,k,y,p}} \cdot After\ VMT_{bus_{i,j,k,y}} \right), \quad (4)$$

where the transit bus activity before and after the project completion is defined as:

$$After\ VMT_{bus_{i,j,k,y}} = \left(f_{i_y} \cdot f_{j_y} \cdot f_k \right) \cdot After\ VMT_{bus_{user}} \quad (5)$$

$$Before\ VMT_{bus_{i,j,k,y}} = \left(f_{i_y} \cdot f_{j_y} \cdot f_k \right) \cdot Before\ VMT_{bus_{user}} \quad (6)$$

and the daily change in bus emissions is:

$$\Delta bus\ emissions\ per\ day = \frac{bus\ emissions\ before\ project - bus\ emissions\ after\ project}{days\ operated\ per\ year} \quad (7)$$

The terms in Equation 7 are defined as follows:

$bus\ emissions\ before\ project$ = the summation of the products of the appropriate MOVES emission rates and the corresponding portion of user-supplied transit bus activity before project completion,

$bus\ emissions\ after\ project$ = the summation of the products of the appropriate MOVES emission rates and the corresponding portion of user-supplied transit bus activity after project completion,

$e_{bus_{i,j,k,y,p}}$ = MOVES3 transit bus emission rate (sourceTypeID 42) according to a given model year *i*, fuel type *j*, road type *k*, evaluation year *y*, and pollutant *p*,

$Before\ VMT_{bus_{i,j,k,y}}$ = portion of transit bus activity before project completion for a given model year *i*, fuel type *j*, road type *k*, and evaluation year *y*,

$After\ VMT_{bus_{i,j,k,y}}$ = portion of transit bus activity after project completion for a given model year *i*, fuel type *j*, road type *k*, and evaluation year *y*,

$i \epsilon I$ = a specific model year *i* in the full 30-year distribution of model years *I,*

$j \epsilon J$ = a specific fuel type *j* in the full distribution of fuel types *J,*

$k \epsilon K$ = a specific road type *k* in the full distribution of road types *K,*

$Before\ VMT_{bus_{user}}$= annualized vehicle miles traveled (VMT) for transit buses before project completion within the input evaluation year *y*,

$After\ VMT_{bus_{user}}$= annualized vehicle miles traveled (VMT) for transit buses after project completion within the input evaluation year *y*,

f_{i_y}= VMT fraction for model year *i* in a specified evaluation year *y*,

f_{j_y}= VMT fraction for fuel type *j* in a specified evaluation year *y*,

f_k = VMT fraction for road type *k* (constant across each evaluation year *y*),

$\Delta bus\ emissions\ per\ day$ = delta of the transit bus emissions before and after project completion over the number of days operated per year, and

$days\ operated\ per\ year$ = number of days per year specified that transit service will be operated (may differ depending on weekday versus weekend versus annual service).

Methodologies for converting between the two types of passenger vehicle activity inputs were described previously (Equation 1). Passenger vehicle VMT values can be either directly input by the user, or calculated by the tool using the trip quantities and average trip distance input by

the user. Once VMT is obtained, the tool uses the following **equations for passenger vehicle running emissions**:

$$PV\ running\ emissions\ before\ = e_{LDV,Running_{y,p}} \cdot Before\ VMT_{LDV_{user}} \quad (8)$$

$$PV\ running\ emissions\ after\ = e_{LDV,Running_{y,p}} \cdot After\ VMT_{LDV_{user}} \quad (9)$$

When the project is expected to reduce full passenger trips and drivers are not expected to drive personal vehicles to central hubs to use the bus service, the amount of start activity for passenger vehicles will also be reduced. Passenger Vehicle Trips before and after the project are either input directly by the user, or calculated by the tool using the user input VMT and average trip distance. Shown below are the **equations for passenger vehicle start emissions**:

$$PV\ start\ emissions\ before\ = e_{LDV,Start_{y,p}} \cdot Before\ Trips_{LDV_{user}} \quad (10)$$

$$PV\ start\ emissions\ after\ = e_{LDV,Start_{y,p}} \cdot After\ Trips_{LDV_{user}} \quad (11)$$

When passengers are likely drive to central hubs when using the bus service, the following equation give the total change in passenger vehicle emissions.

$$\Delta PV\ emissions\ per\ day = \frac{PV\ running\ emissions\ before - PV\ running\ emissions\ after}{days\ operated\ per\ year} \quad (12)$$

When full passenger vehicle trips will be reduced:

$$\Delta PV\ emissions\ per\ day = \frac{(PV\ running\ emissions\ before + PV\ start\ emissions\ before) - (PV\ running\ emissions\ after + PV\ start\ emissions\ after)}{days\ operated\ per\ year} \quad (13)$$

The terms Equations 12 and 13 are defined as follows:

$PV\ running\ emissions\ before$ = the product between the appropriate MOVES running emission rate and the user-supplied or calculated passenger vehicle miles traveled before project completion,

$PV\ running\ emissions\ after\ project$ = the product between the appropriate MOVES running emission rate and the user-supplied or calculated passenger VMT after project completion,

$PV\ start\ emissions\ before$ = the product between the appropriate MOVES start emission rate and the user-supplied or calculated passenger vehicle trips taken before project completion,

$PV\ start\ emissions\ after\ project$ = the product between the appropriate MOVES start emission rate and the user-supplied or calculated passenger vehicle trips taken after project completion,

$e_{LDV,Running_{y,p}}$ = MOVES passenger vehicle running emission rate (composite of passenger car, sourceTypeID 21, and passenger truck, sourceTypeID 31) for a given model evaluation year *y* and pollutant *p*,

$e_{LDV,Start_{y,p}}$ = MOVES passenger vehicle start emission rate (composite of passenger car, sourceTypeID 21, and passenger truck, sourceTypeID 31) for a given model evaluation year *y* and pollutant *p*,

$Before\ VMT_{PV_{user}}$ = annual vehicle miles traveled (VMT) for passenger vehicles before project completion within the input evaluation year *y*,

$After\ VMT_{PV_{user}}$ = annual vehicle miles traveled (VMT) for passenger vehicles after project completion within the input evaluation year *y*,

$Before\ Trips_{PV_{user}}$ = annual passenger vehicle trips before project completion within the input evaluation year *y*,

$After\ Trips_{PV_{user}}$ = annual passenger vehicle trips after project completion within the input evaluation year *y*,

$\Delta PV\ emissions\ per\ day$ = delta of the passenger vehicle emissions before and after project completion over the number of days operated per year in either the central hub or full trip reduction scenario, and

$days\ operated\ per\ year$ = number of days per year specified transit service will be operated and associated mode shift occurs (may differ depending on weekday versus weekend versus annual service).

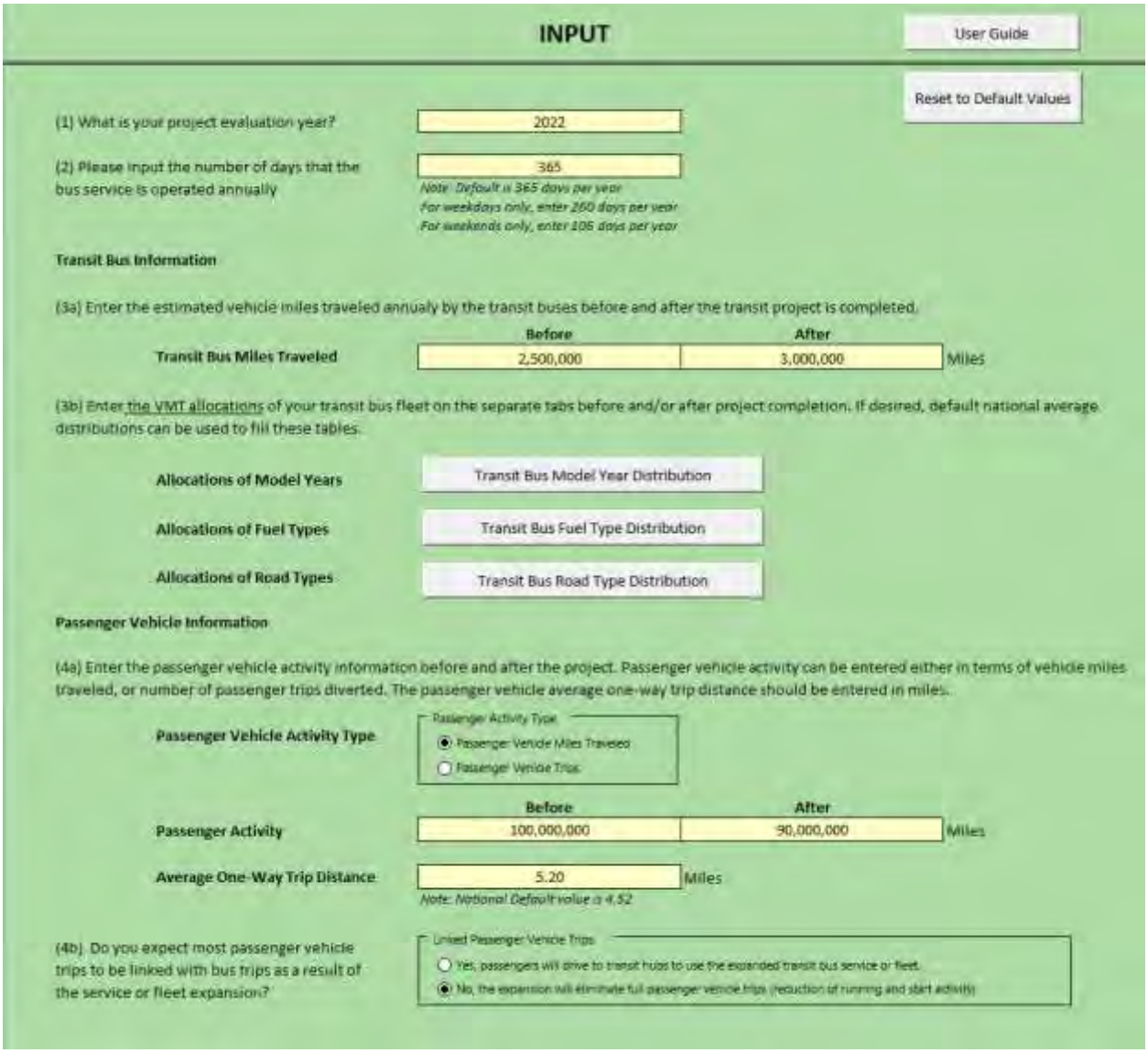
Finally, the **total emissions reduced** is calculated as the sum of change in emissions for passenger vehicles and transit buses before and after project completion, as denoted in the equation below:

$$total\ emissions\ reduced = \Delta PV\ emissions\ per\ day + \Delta bus\ emissions\ per\ day. \quad (14)$$

EXAMPLES

Example 1: Extended Bus Route

A transit authority operates a number of bus lines throughout a municipality. After new development in a previously unserved area, they have identified sufficient demand to warrant extending a nearby line to access it. The authority will not be adding new vehicles to their relatively new fleet, but has sited the route and can provide changes in VMT for their fleet based on these route changes, and changes in passenger vehicle VMT based on their local travel demand model. Those who utilize the new bus service in the area are expected to completely shift travel modes and are unlikely to drive to a transit hub. In the tool, the user would select the following inputs, shown in the image below:



Project year: 2022

Number of days operated: 365

Before transit bus VMT: 2,500,000

After transit bus VMT: 3,000,000

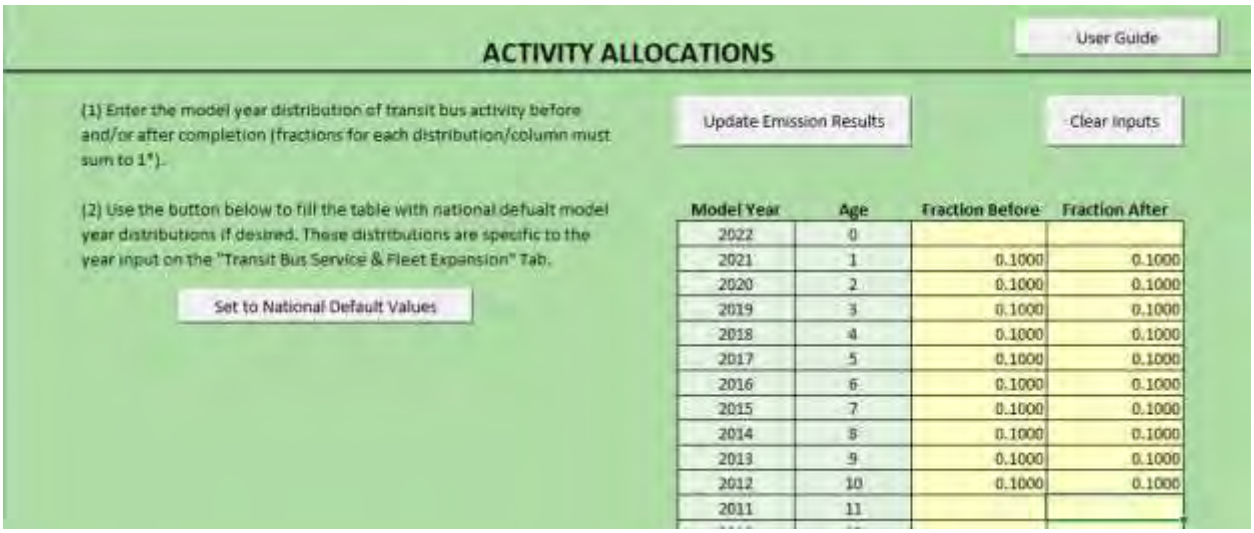
Passenger vehicle activity type: Passenger Vehicle Miles Traveled

Before passenger vehicle VMT: 100,000,000

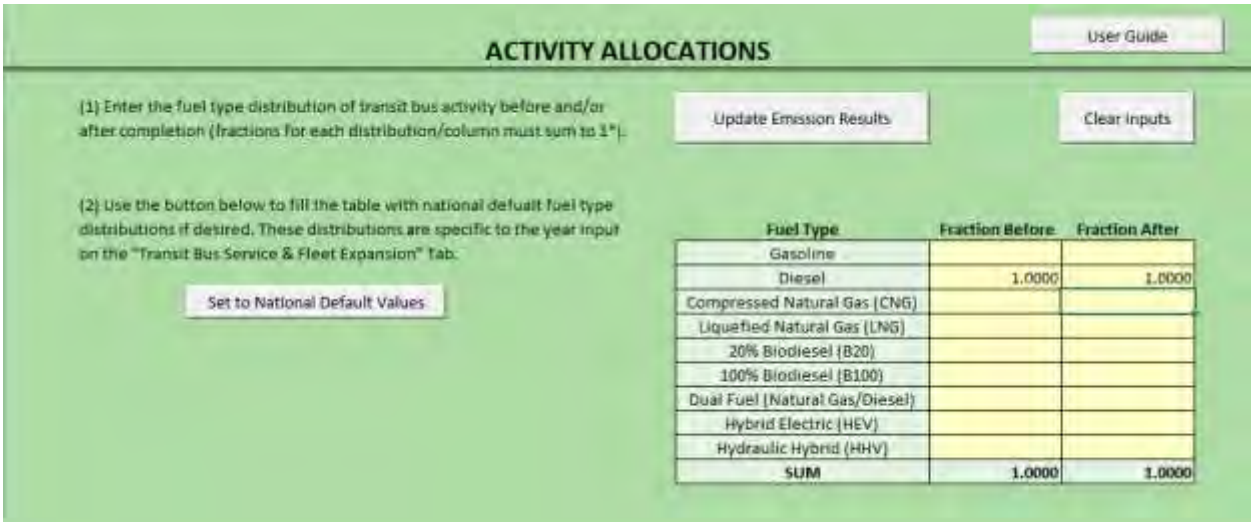
After passenger vehicle VMT: 90,000,000

Average one-way trip distance: 5.2 miles

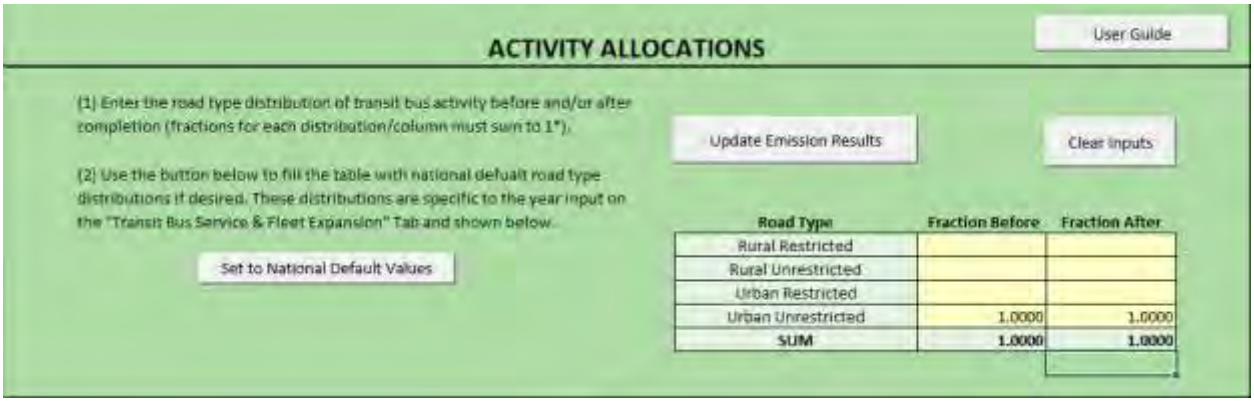
Since the fleet is relatively new, the user should choose to edit the transit bus activity distribution tabs by selecting the buttons from the home screen and modifying the inputs accordingly. For the **model year** distribution, the fleet has ten percent fleet from each model year from 2012 to 2021 both before and after, so the user should input "0.1" for each applicable model year. Since the fleet is not changing, the values should be identical in the before and after columns. Make sure the total across all model years sums to one.



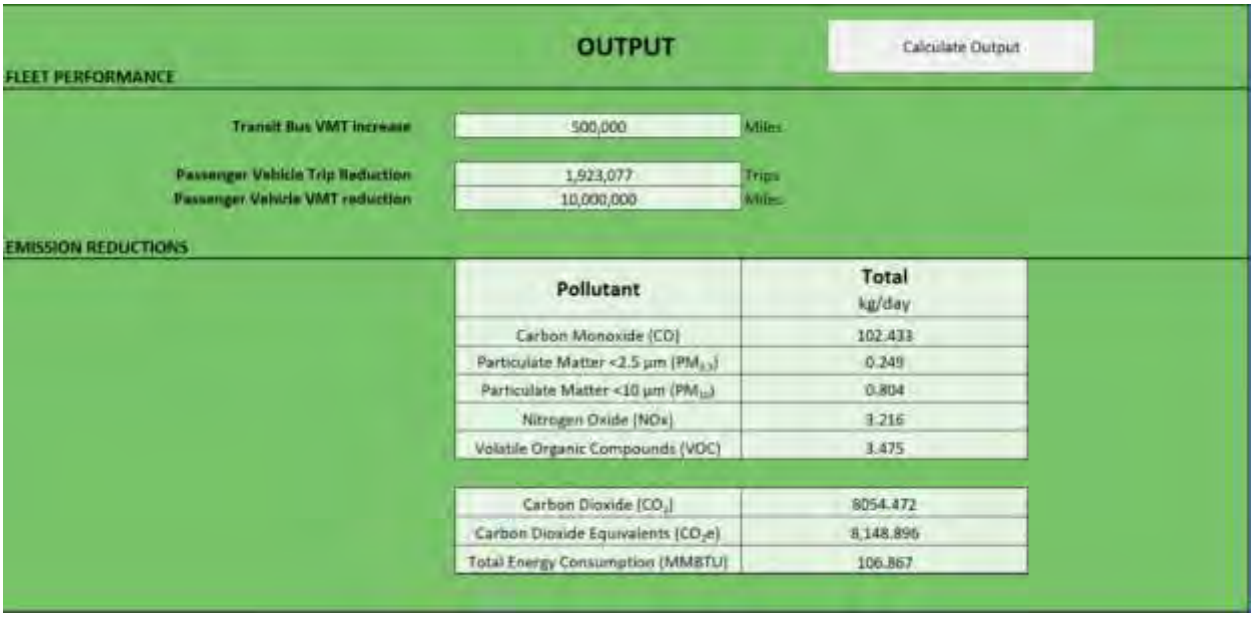
Next, the user should enter the **fuel type** distribution by navigating to the "Fuel Type Dist" tab or using the links in the navigator on the left of the interface. This municipality uses only diesel busses, so the user should input "1" for both before and after columns in the "Diesel" row of the table. Again, confirm the inputs sum to 1.



Finally, the user should input the **road type** distribution by navigating to the "Road Type Dist" tab or using the links in the navigator on the left of the interface. Since the municipality is designated as an urban area, and the service does not use any restricted access freeways or interstates in the routes, the user can input "1" for the before and after cells in the "Urban Unrestricted" row of the table.



At this point, the user can click the "Update Emission Results" button to return to the main interface page and calculate emission reduction results.



OUTPUT

Calculate Output

FLEET PERFORMANCE

Transit Bus VMT increase	500,000	Miles
Passenger Vehicle Trip Reduction	1,923,077	Trips
Passenger Vehicle VMT reduction	10,000,000	Miles

EMISSION REDUCTIONS

Pollutant	Total kg/day
Carbon Monoxide (CO)	102.433
Particulate Matter <2.5 μm ($PM_{2.5}$)	0.249
Particulate Matter <10 μm (PM_{10})	0.804
Nitrogen Oxide (NOx)	3.216
Volatile Organic Compounds (VOC)	3.475

Carbon Dioxide (CO_2)	8054.472
Carbon Dioxide Equivalents (CO_2e)	8,148.896
Total Energy Consumption (MMBTU)	106.867

The emission reductions in kg/day for all seven pollutants are:

Carbon Monoxide (CO): 102.433

Particulate Matter (PM2.5): 0.249

Particulate Matter (PM10): 0.804

Nitrogen Oxide (NOx): 3.216

Volatile Organic Compounds (VOC): 3.475

Carbon Dioxide (CO_2): 8,054.472

Carbon Dioxide Equivalents (CO_2e): 8,148.896

Total Energy Consumption (TEC): 106.867 MMBTU

Example 2: Shorten the Headways

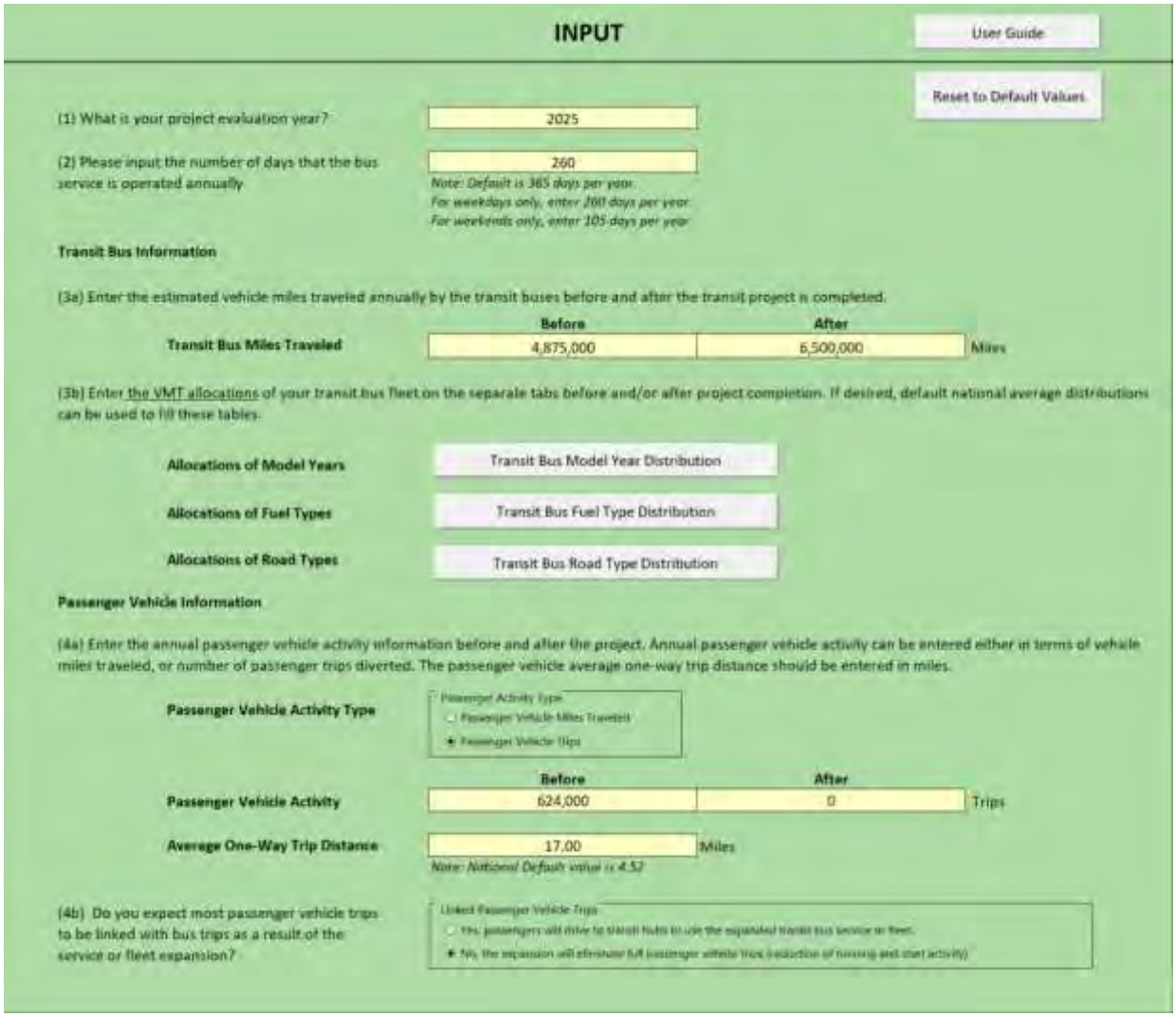
A Snowbelt county operates bus service during weekdays along a corridor that has recently become more densely populated, and seen growth in transit-dependent residents as well as choice riders[8]. This is putting pressure on the bus route's level of service, especially in winter months. To increase reliability and user satisfaction, the county wants to reduce the distance and time between busses (the headway) by 25 percent for their one-hundred vehicle fleet, and so have purchased an additional twenty five vehicles to serve passengers along the route. The

[8] Passengers who own personal vehicles but choose to use transit services anyway.

new buses use CNG fuel, while the existing fleet uses diesel. Most of the transit-dependent passengers live within walking distance of the corridor along which the service operates.

The county has estimated passenger vehicle trip reductions based on current ridership data giving an average number of passengers per bus. By assuming that this average ridership per bus will likely will remain constant with the fleet expansion, the country can obtain an estimate for the increase in overall service usage by multiplying the average passengers per bus by number of new busses being added to the fleet. Note that the required input to the CMAQ tool is the before and after values for passenger vehicle trips, but the county has estimated reductions in passenger vehicle activity based on an increase in ridership of the existing service. This can be input into the tool as a "before" passenger activity value, with 0 as the "after" activity value, indicating that the increase in ridership was the direct result of a shift away from passenger vehicle usage.

In the tool, the user would select the following inputs, shown in the image below:



Project year: 2025

Days Operated Per Year: 260

Before transit bus VMT: 4,875,000

After transit bus VMT: 6,500,000

Passenger Vehicle Activity Type: Passenger Vehicle Trips

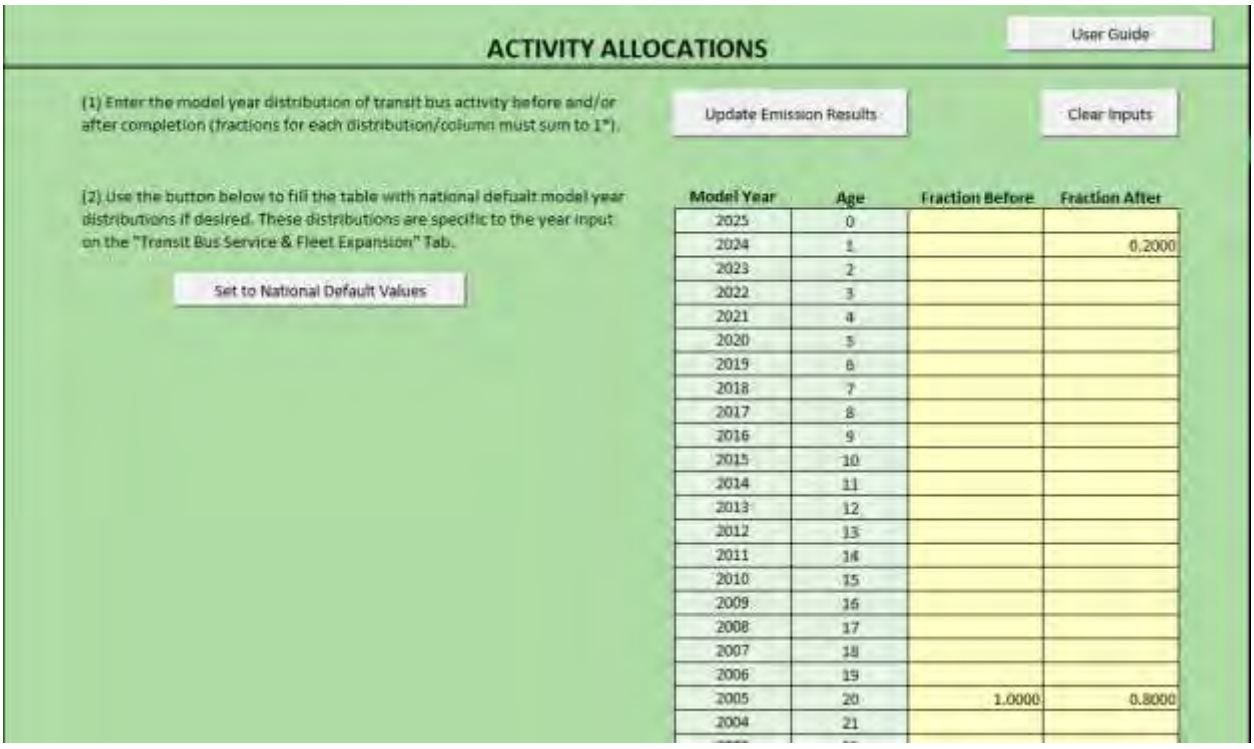
Before passenger vehicle activity: 624,000

After passenger vehicle activity: 0

Average one way trip distance: 17.00 miles

Linked Passenger vehicle trips: No, expansion will eliminate full passenger vehicle trips

As the fleet now has buses of different ages and fuel types, the user should edit the model year and fuel type distributions by selecting each button from the home screen and modifying the inputs accordingly. For the model year, the fleet's "Fraction Before" was entirely from 2005, and the "Fraction After" is comprised of 0.80 from model year 2005 and 0.20 from model year 2024. The total across all years must sum to one, as shown below.



ACTIVITY ALLOCATIONS

User Guide

(1) Enter the model year distribution of transit bus activity before and/or after completion (fractions for each distribution/column must sum to 1*).

Update Emission Results

Clear Inputs

(2) Use the button below to fill the table with national default model year distributions if desired. These distributions are specific to the year input on the "Transit Bus Service & Fleet Expansion" Tab.

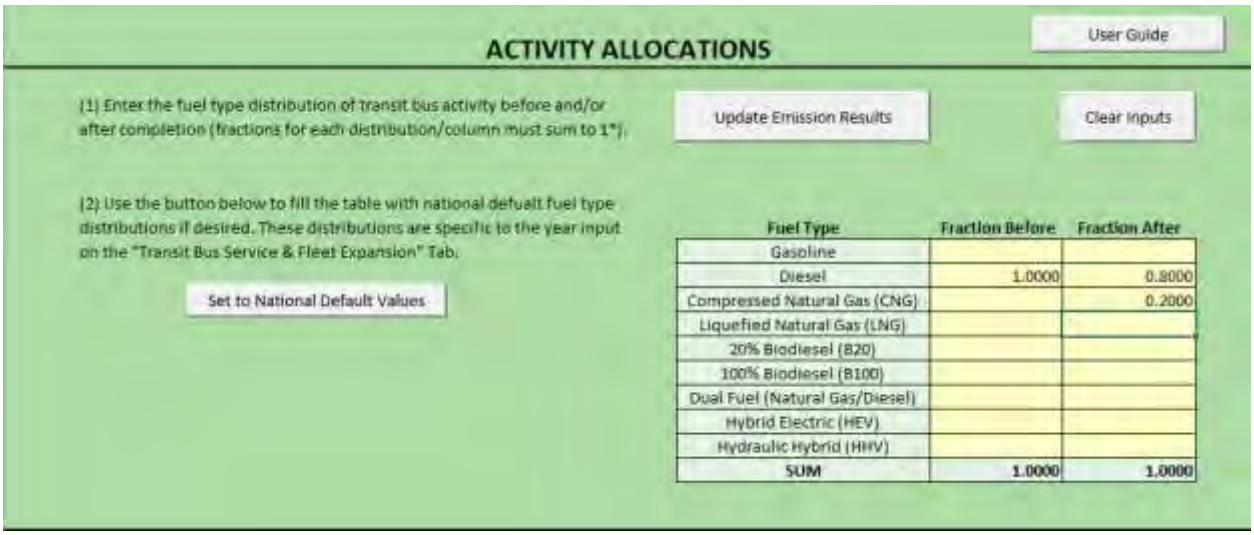
Set to National Default Values

Model Year	Age	Fraction Before	Fraction After
2025	0		
2024	1		0.2000
2023	2		
2022	3		
2021	4		
2020	5		
2019	6		
2018	7		
2017	8		
2016	9		
2015	10		
2014	11		
2013	12		
2012	13		
2011	14		
2010	15		
2009	16		
2008	17		
2007	18		
2006	19		
2005	20	1.0000	0.8000
2004	21		

Fraction Before: 1.0 for year 2005

Fraction After: 0.8 for year 2005, 0.2 for year 2024

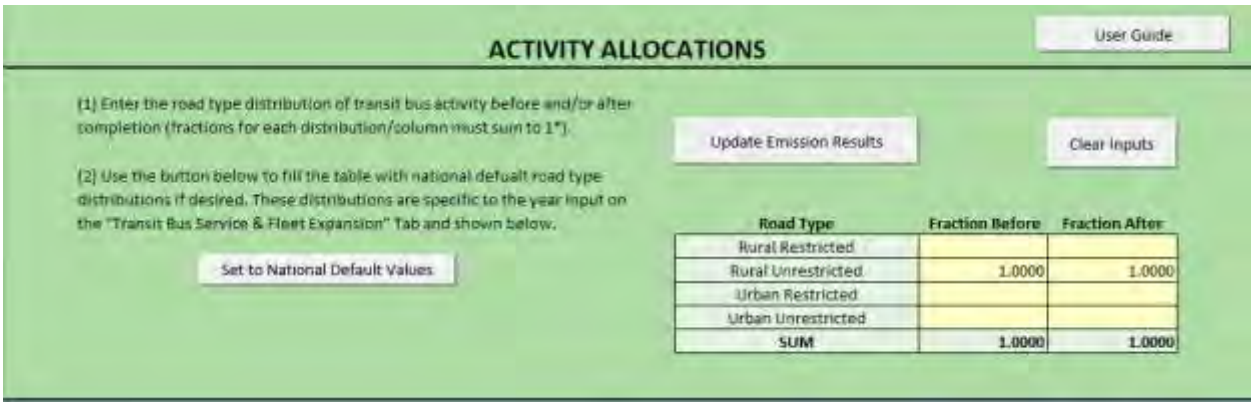
The process for the fuel type distribution is similar to that of the model year distribution:



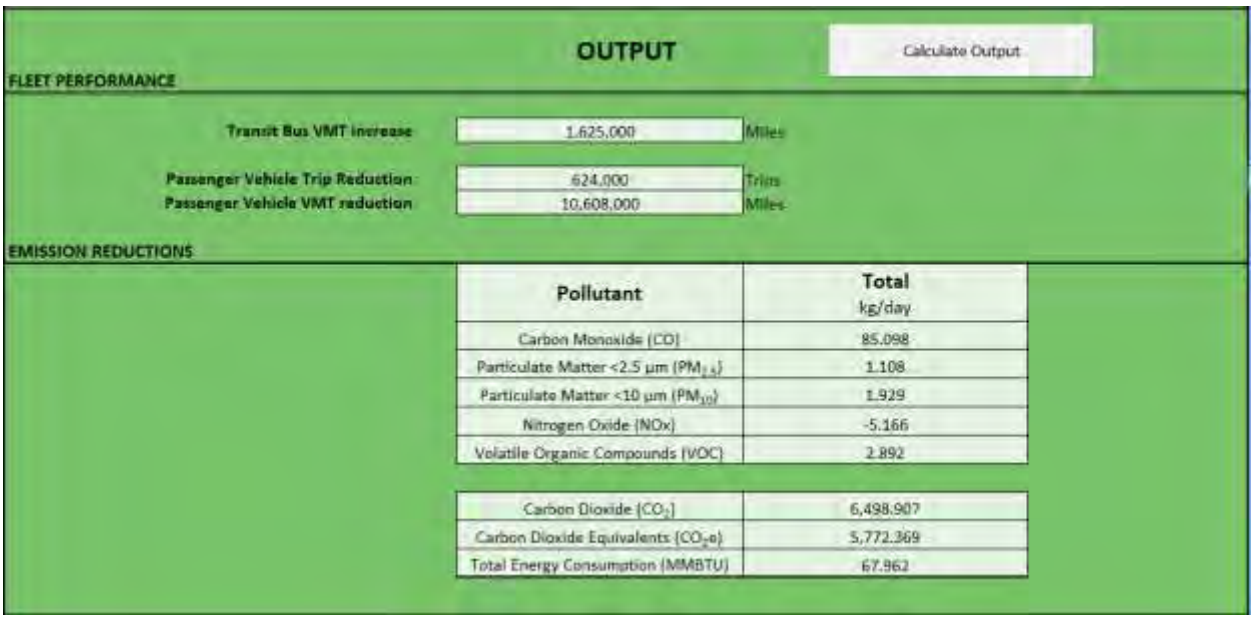
Fuel for older fleet: Diesel

Fuel for newer fleet: CNG

On the road type tab, input 1 before and after the project for rural unrestricted roads, as the service is in a rural area and does not include freeways or interstates in its route.



At this point, the “Update Emission Results” button can be pressed to return to the front interface and estimate emission reductions from the additional buses and resulting mode switch from passenger vehicle to transit bus, as shown below:



OUTPUT

Calculate Output

FLEET PERFORMANCE

Transit Bus VMT increase	1,625.000	Miles
Passenger Vehicle Trip Reduction	624.000	Trips
Passenger Vehicle VMT reduction	10,608.000	Miles

EMISSION REDUCTIONS

Pollutant	Total kg/day
Carbon Monoxide (CO)	85.098
Particulate Matter <2.5 μm ($PM_{2.5}$)	1.108
Particulate Matter <10 μm (PM_{10})	1.929
Nitrogen Oxide (NOx)	-5.166
Volatile Organic Compounds (VOC)	2.892

Carbon Dioxide (CO_2)	6,498.907
Carbon Dioxide Equivalents (CO_2e)	5,772.369
Total Energy Consumption (MMBTU)	67.962

The emission reductions in kg/day for all seven pollutants are:

Carbon Monoxide (CO): 85.098

Particulate Matter (PM2.5): 1.108

Particulate Matter (PM10): 1.929

Nitrogen Oxides (NOx): -5.166

Volatile Organic Compounds (VOC): 2.892

Carbon Dioxide (CO_2): 6,498.907

Carbon Dioxide Equivalents (CO_2e): 5,772.369

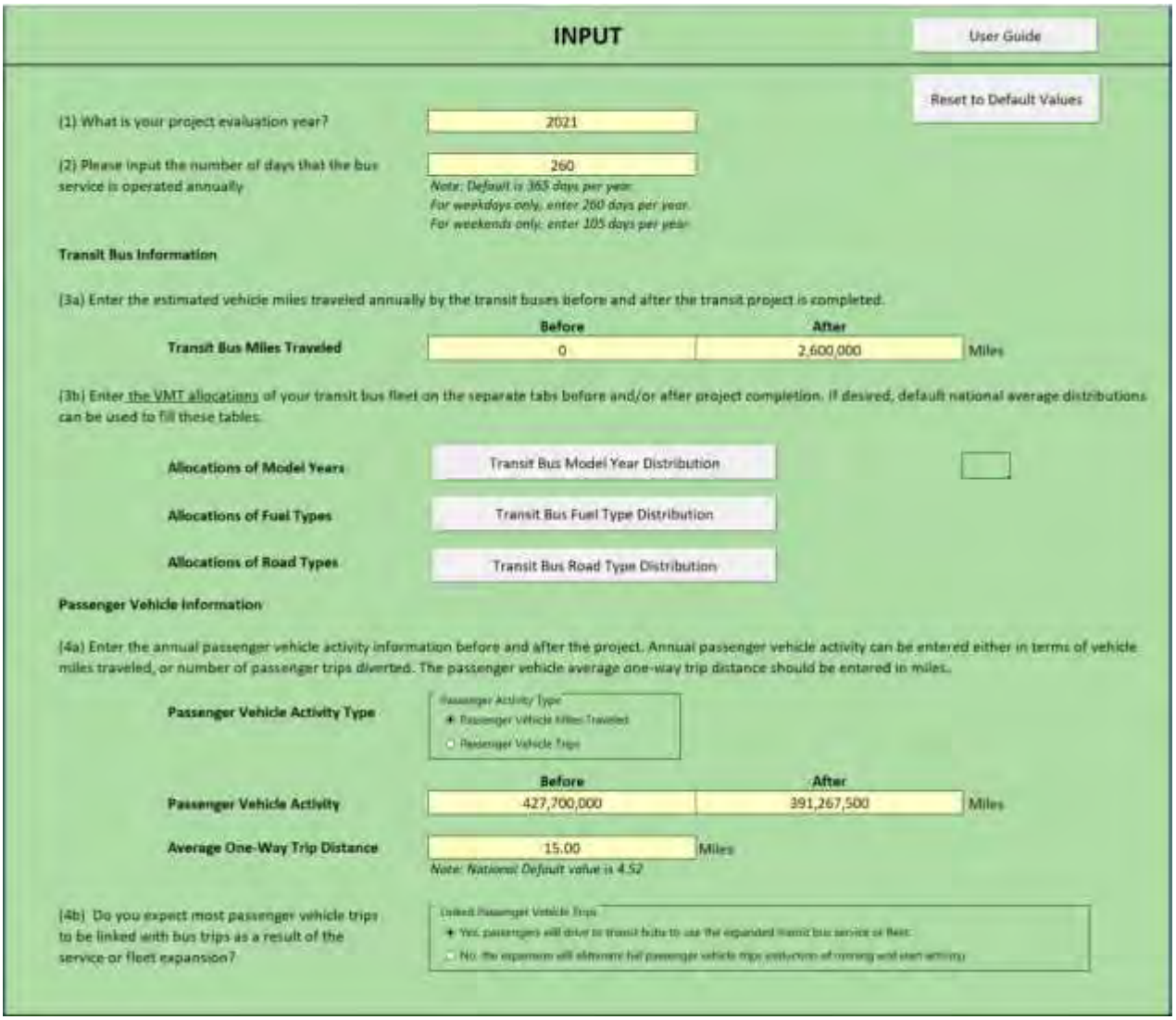
Total Energy Consumption (TEC): 67.962 MMBTU

Note here that NOx shows a value less than zero for this example, or a disbenefit for this specific pollutants. At the same time, there are positive benefits output for the other pollutants. This is a result of the combinations of transit bus emission rates as well as the passenger vehicle emission rates. Since there are multiple vehicle types involved in these calculations, final emissions results may show benefits for some pollutants but not others, due to the mathematical relationships between activity reductions and emission rates for the different modes and fuels involved.

Example 3:

A county wants to decrease congestion on a freeway which serves as the major route into a central business district from a group of surrounding suburban areas. The planning organization's proposal includes new commuter bus routes that use park-and-ride locations throughout the suburban region that offer service into the central business district. After planning the routes and scoping the purchase of 50 new diesel buses, the county estimates annual bus VMT to be 2.6 million miles per year. Since this is a new service, the VMT of buses before the project should be zero (0).

The county hopes to see a 10% reduction in overall weekday traffic in the inbound direction, and a 7% overall reduction in the outbound direction, and would like to roughly estimate corresponding emissions benefits for these traffic reductions. Based on AADT counts along this major corridor, the county can roughly estimate VMT before and after the project for passenger vehicles. Since the service primarily focusses on park-and-ride lots as central pickup locations, passengers must still drive their personal vehicles on local roads before using the transit service. The inputs on the main interface of the tool are as shown below:



Project year: 2021

Days Operated Per Year: 260

Before transit bus VMT: 0

After transit bus VMT: 2,600,000

Passenger Vehicle Activity Type: Passenger Vehicle Miles Traveled

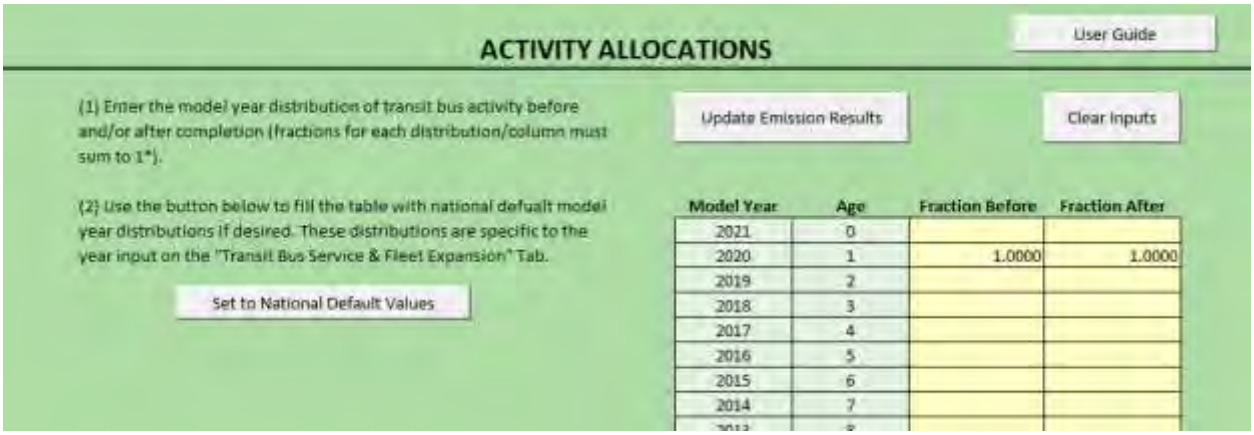
Before passenger vehicle activity: 427,700,000

After passenger vehicle activity: 391,267,500

Average one way trip distance: 15.00 miles

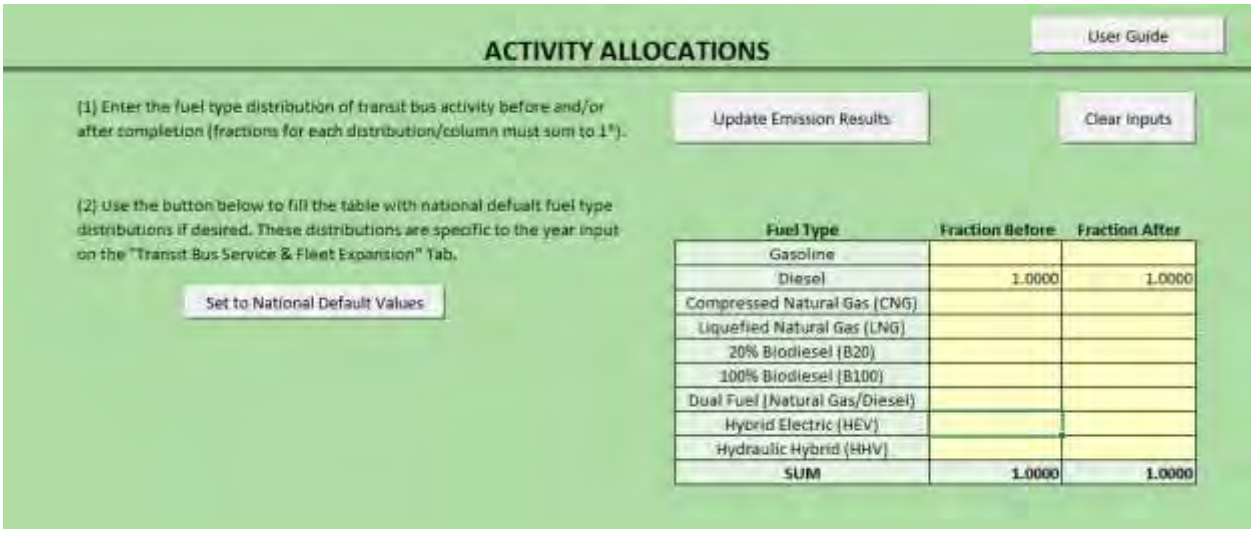
Linked Passenger vehicle trips: Yes, passengers will drive to transit hubs to use the expanded transit bus service or fleet

The distributions for the new bus fleet should now be input in the relevant tabs. For the model year distribution, since the county will buy all new buses, the fleet will be made up of all model year 2020 buses after the project is complete. Since the VMT of buses before the project is 0, the fraction inputs in the before column do not have an effect on the tool's calculations. However, the sum of the fractions still needs to equal 1, so we will input "1" for 2020 buses, like the after column, for simplicity.



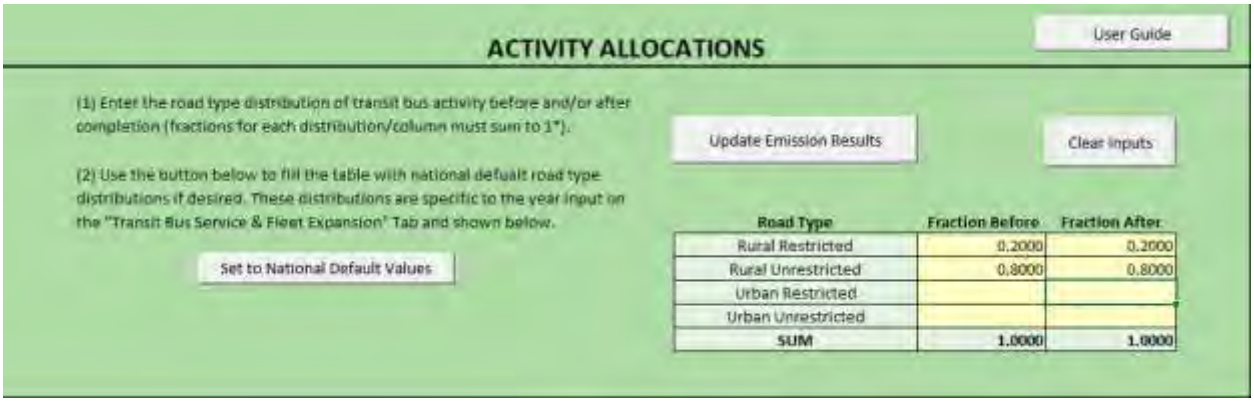
Model year 2020 buses: 1 before and after project

The fuel type distributions, like the model year distributions, should be 1 for diesel buses in the after column. Because the before column does not matter in this case, we will again input 1 for simplicity in the diesel fuel row.



Diesel Fuel: 1 before and after project

Finally, for the road type distributions, the service will run mostly on rural unrestricted roads. However, some parts of the routes will use freeways. Again, only the “after” column is significant due to the lack of bus VMT before the project. The following inputs are used here:



ACTIVITY ALLOCATIONS

User Guide

(1) Enter the road type distribution of transit bus activity before and/or after completion (fractions for each distribution/column must sum to 1*).

(2) Use the button below to fill the table with national default road type distributions if desired. These distributions are specific to the year input on the "Transit Bus Service & Fleet Expansion" Tab and shown below.

Set to National Default Values

Update Emission Results

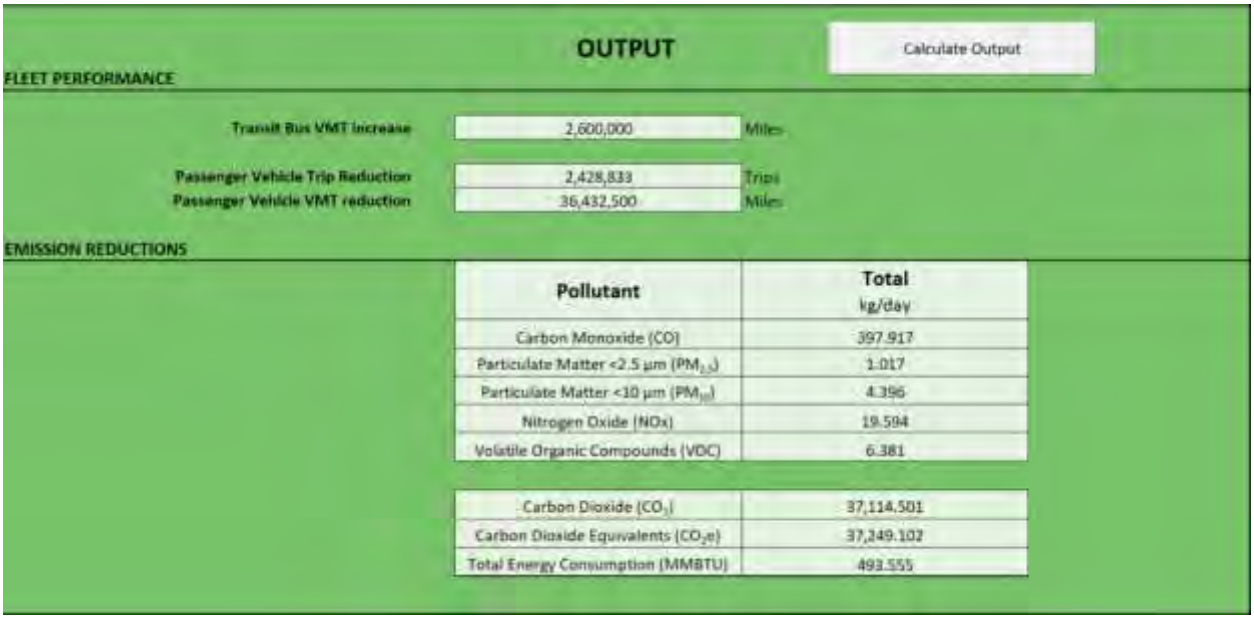
Clear Inputs

Road Type	Fraction Before	Fraction After
Rural Restricted	0.2000	0.2000
Rural Unrestricted	0.8000	0.8000
Urban Restricted		
Urban Unrestricted		
SUM	1.0000	1.0000

Rural Restricted: 0.2 before and after project

Rural Unrestricted: 0.8 before and after project

Finally, the “Update Emission Results” button can be pressed to return to the front interface and calculate emissions benefits. The outputs are shown below:



OUTPUT

Calculate Output

FLEET PERFORMANCE

Transit Bus VMT increase	2,600,000	Miles
Passenger Vehicle Trip Reduction	2,428,833	Trips
Passenger Vehicle VMT reduction	36,432,500	Miles

EMISSION REDUCTIONS

Pollutant	Total kg/day
Carbon Monoxide (CO)	397.917
Particulate Matter <2.5 µm ($PM_{2.5}$)	1.017
Particulate Matter <10 µm (PM_{10})	4.396
Nitrogen Oxide (NOx)	19.594
Volatile Organic Compounds (VOC)	6.381

Carbon Dioxide (CO_2)	37,114.501
Carbon Dioxide Equivalents (CO_2e)	37,249.102
Total Energy Consumption (MMBTU)	493.555

The emission reductions in kg/day for all seven pollutants are:

Carbon Monoxide (CO): 397.917

Particulate Matter (PM2.5): 1.017

Particulate Matter (PM10): 4.396

Nitrogen Oxides (NOx): 19.594

Volatile Organic Compounds (VOC): 6.381

Carbon Dioxide (CO_2): 37,114.501

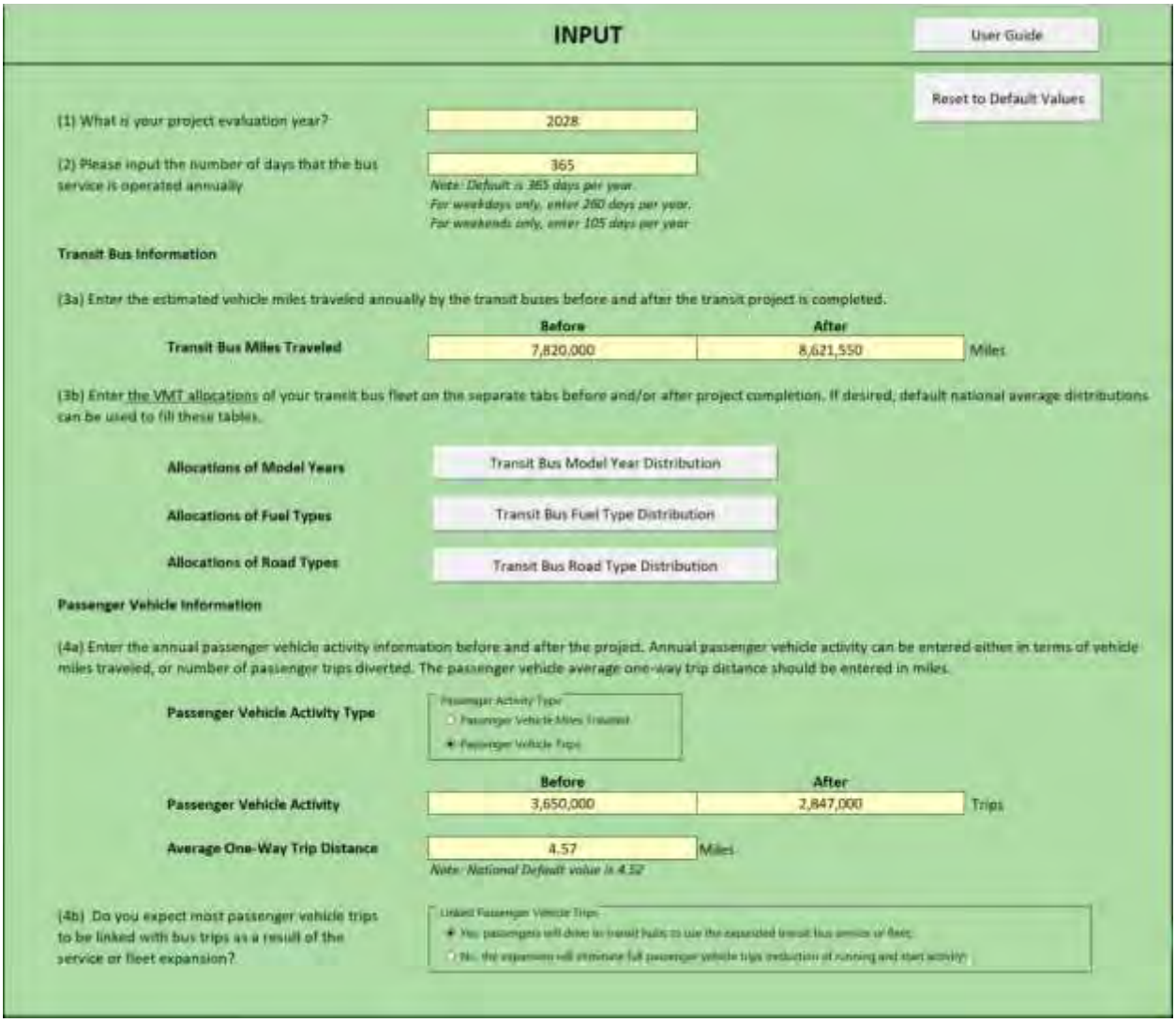
Carbon Dioxide Equivalents (CO_2e): 37,249.102

Total Energy Consumption (TEC): 493.555 MMBTU

Example 4: A Growing Mid-sized City

A transit authority's service area spans three counties in a mid-Atlantic state, but its buses primarily serve a medium-density core. The constituent counties have approved additional operational funding to expand service to the outlying, lower-density areas. After performing trip-based TDM and additional analyses, the authority's staff have determined how many new buses and new routes are required to meet the new riders' needs. The new routes will involve additional road types. The fleet will increase by 5%, and while all older buses use diesel fuel, the new buses will be hybrid electric vehicles. The new routes will also increase the fleet VMT by 5 percent. Based on a fleet VMT estimate before the project of 7,820,000 miles per year and the expected increase in fleet and route distances, the transit authority estimates a fleet VMT after the project of 8,621,550 miles.

The agency's TDM analyzed a number of modes, giving values of passenger VMT before and after project implementation as 10,000 miles and 7,800, respectively. The authority does not have detailed information on average trip distances, so they decide to use the reference table of National Household Travel Survey data for South Atlantic Region (Table 2) as an input to the CMAQ tool. Since the service expansions are wide and varied, the agency does not know if full passenger trips will be diverted, or if people will drive to central transit hubs to use the service. Therefore, the agency will choose to estimate emissions benefits with linked passenger trips to obtain a more conservative estimate of emissions benefits. The inputs are as shown in the figure below:



Project year: 2028

Days Operated Per Year: 365

Before transit bus VMT: 7,820,000

After transit bus VMT: 8,621,550

Passenger Vehicle Activity Type: Passenger Vehicle Trips

Before passenger vehicle activity: 3,650,000

After passenger vehicle activity: 2,847,000

Average one way trip distance: 4.57

Linked Passenger vehicle trips: Yes, passengers will drive to transit hubs to use the expanded transit bus service or fleet

Next, as described in earlier examples, modify the model year distribution to account for the 5% increase in the fleet:

ACTIVITY ALLOCATIONS

User Guide

(1) Enter the model year distribution of transit bus activity before and/or after completion (fractions for each distribution/column must sum to 1*).

Update Emission Results

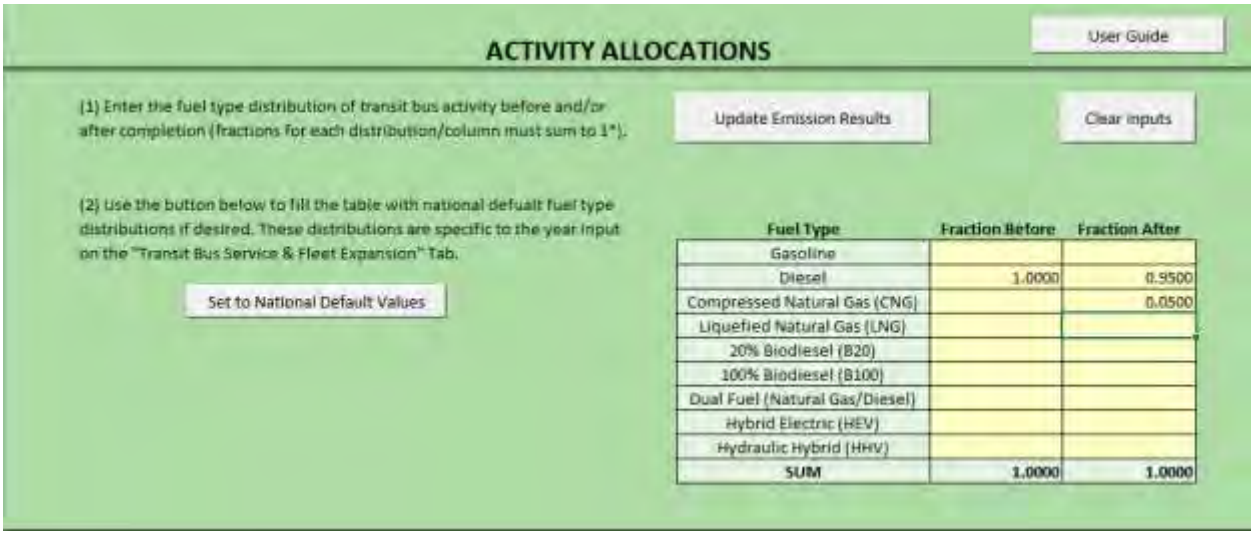
Clear Inputs

(2) Use the button below to fill the table with national default model year distributions if desired. These distributions are specific to the year input on the "Transit Bus Service & Fleet Expansion" Tab.

Set to National Default Values

Model Year	Age	Fraction Before	Fraction After
2028	0		0.0500
2027	1	0.2000	0.1900
2026	2	0.2000	0.1900
2025	3	0.2000	0.1900
2024	4	0.2000	0.1900
2023	5	0.2000	0.1900
2022	6		
2021	7		
2020	8		
2019	9		
2018	10		
2017	11		
2016	12		

Modify the fuel type distribution:



ACTIVITY ALLOCATIONS

User Guide

(1) Enter the fuel type distribution of transit bus activity before and/or after completion (fractions for each distribution/column must sum to 1*).

Update Emission Results

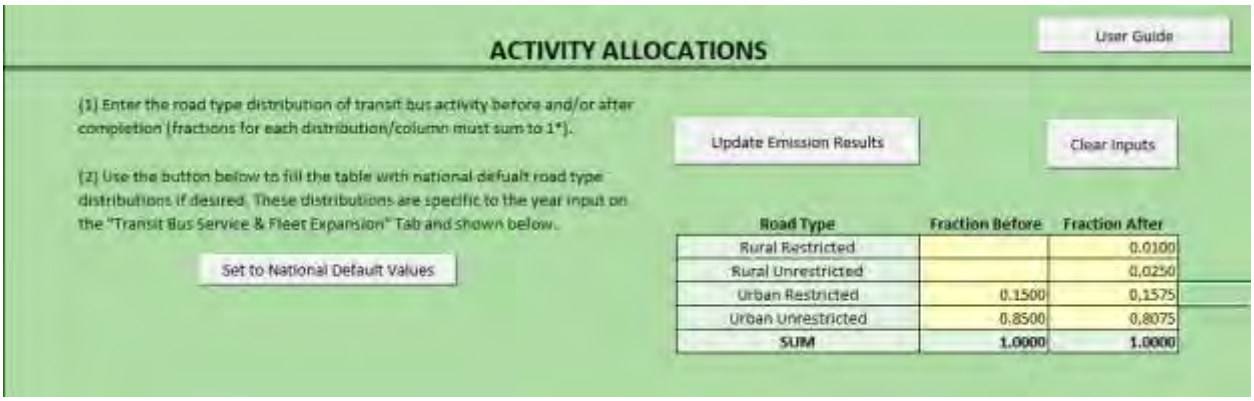
Clear Inputs

(2) Use the button below to fill the table with national default fuel type distributions if desired. These distributions are specific to the year input on the "Transit Bus Service & Fleet Expansion" Tab.

Set to National Default Values

Fuel Type	Fraction Before	Fraction After
Gasoline		
Diesel	1.0000	0.9500
Compressed Natural Gas (CNG)		0.0500
Liquefied Natural Gas (LNG)		
20% Biodiesel (B20)		
100% Biodiesel (B100)		
Dual Fuel (Natural Gas/Diesel)		
Hybrid Electric (HEV)		
Hydraulic Hybrid (HHV)		
SUM	**1.0000**	**1.0000**

Finally, modify the road type distribution to account for the new routes. The procedure is conceptually identical to the fuel type distribution modifications:



Rural Restricted before: 0

Rural Unrestricted before: 0

Urban Restricted before: 0.15

Urban Unrestricted before: 0.85

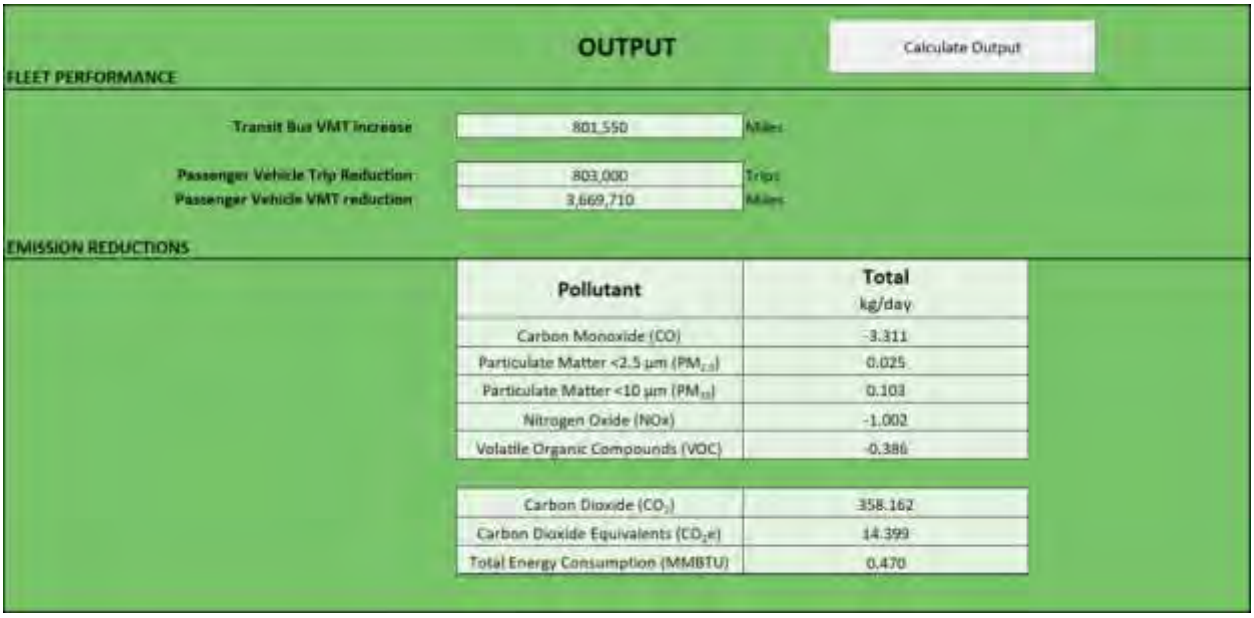
Rural Restricted after: 0.01

Rural Unrestricted after: 0.025

Urban Restricted after: 0.1575

Urban Unrestricted after: 0.8075

Select the Update Emission Results button in the distribution tabs and the Calculate Output button in the main tab to estimate emission reductions from the new vehicles and routes, as shown below:



OUTPUT

Calculate Output

FLEET PERFORMANCE

Transit Bus VMT Increase	801,550	Miles
Passenger Vehicle Trip Reduction	803,000	Trips
Passenger Vehicle VMT reduction	3,669,710	Miles

EMISSION REDUCTIONS

Pollutant	Total kg/day
Carbon Monoxide (CO)	-3.311
Particulate Matter <2.5 µm ($PM_{2.5}$)	0.025
Particulate Matter <10 µm (PM_{10})	0.103
Nitrogen Oxide (NOx)	-1.002
Volatile Organic Compounds (VOC)	-0.386

Carbon Dioxide (CO_2)	358.162
Carbon Dioxide Equivalents (CO_2e)	14.399
Total Energy Consumption (MMBTU)	0.470

The emission reductions in kg/day for all seven pollutants are:

Carbon Monoxide (CO): -3.311

Particulate Matter (PM2.5): 0.025

Particulate Matter (PM10): 0.103

Nitrogen Oxides (NOx): -1.002

Volatile Organic Compounds (VOC): -0.386

Carbon Dioxide (CO_2): 358.162

Carbon Dioxide Equivalents (CO_2e): 14.399

Total Energy Consumption (TEC): 0.470 MMBTU

There is a slight increase in emissions of CO, NOx, and VOC. This is due to the interplay and mathematical relationships between the different vehicle types, and fuel types involved in the calculation. Diesel transit buses have a higher NOx emission rate than passenger vehicles relative to other pollutants, so NOx is more likely to show disbenefits when transit bus activity increases.

APPENDIX A: Travel Demand Modeling Resources

Successful use of this CMAQ calculator relies on credible travel demand modeling (TDM) to provide VMT-based mode shifts as activity inputs. TDM can be a complex computational process involving a great deal of effort. However, there are a number of simplified methodologies that enable agencies to conduct robust TDM analyses with fewer resources. A number of such materials are provided below, including primers on travel behavior and travel modeling, as well as links to some simplified tools that may be useful to agencies.[9] Any additional questions about the resources should be directed to their respective authors.

TDM Concepts

The following provide an overview of travel demand core concepts, both theoretical and practical.

Integrating Demand Management into the Transportation Planning Process: A Desk Reference (FHWA 2012) was prepared to assist transportation officials' incorporation of TDM into policy and implementation. It characterizes a number of ways TDM relates to policies regularly considered by state and local governments, including air quality and environment. It also includes a chapter on TDM strategies and tools available to the transportation community.

Transportation Research Board Special Report 288 (TRB 2007) is the product of several years of dedicated research to evaluate the state of TDM practice among American MPOs and State DOTs. The report includes the history and statutory origins of travel modeling in the United States, and gives a plain language overview of the economic principles informing its applications to planning a transportation system. It also discusses the technical and resource considerations for various modeling scales i.e., Federal, state, and local.[10]

Understanding Transport Demands and Elasticities (Litman 2017) describes the relationship between travel behavior and the demographic, geographic, and economic factors that lead to mode choice. The paper gives an assessment of theoretical bases for travel behavior, and emphasizes the role of total cost pricing when modeling transportation scenarios. In addition, the author describes a computationally light modeling strategy involving demand elasticities, which are provided in tables summarizing other economic research.[11]

[9] Note that the CMAQ program does not endorse the use of any particular tool, and provides this list as a starting point for agencies without their own preferred modeling approach. It is incumbent upon the user to ensure they can defend their TDM analysis used in conjunction with a CMAQ calculator.
[10] Transportation Research Board (TRB), http://onlinepubs.trb.org/onlinepubs/sr/sr288.pdf.
[11] Victoria Transportation Policy Institute, www.vtpi.org/elasticities.pdf.

Example Simplified Tools

The three tools listed below provide simplified methodologies for estimating shifts in travel demand for a number of modes as a result of level of service, land use, pricing, and infrastructure changes; each account for non-motorized as well as motorized changes.

Trip Reduction Impacts of Mobility Management Strategies (TRIMMS) is a spreadsheet tool developed by the Center for Urban Transportation Research (CUTR) at the University of South Florida that evaluates transportation and land-use impacts of policy scenarios. TRIMMS[12] has a built-in TDM calculator, which uses a demand elasticity methodology to calculate shifts in trips by mode resulting from changes in the time/money costs of each mode.[13] Note that users must convert these outputs into distance-based units using known typical trip distances.[14] TRIMMS comes pre-loaded with default values that the user may modify at their discretion. Depending on input data availability, a simple run of the tool might take less than one day.

Rapid Policy Analysis Tool (RPAT) is a graphical user interface (GUI)-based transportation scenario planning software package developed by the American Association of State Highway and Transportation Officials (AASHTO) in partnership with FHWA and the second Strategic Highway Research Program (SHRP2).[15] RPAT's six internal models use inputs on local household dynamics, economics, urban form, and transportation characteristics to evaluate regional land use and transportation policy scenarios; this includes a TDM which gives outputs in VMT. RPAT provides modifiable default input data, and its user guide provides step-by-step instructions for obtaining data and constructing scenarios. RPAT is expressly designed to be accessible for users with no prior modeling experience. However, due to its comprehensiveness and ability to consider multiple scenarios at once, using RPAT with local data may require 1-2 days if the needed inputs are not readily available.

Simplified Trips-on-Project Software (STOPS) is a standalone software package developed by the Federal Transit Administration.[16] STOPS applies a set of travel models to predict detailed transit travel patterns using a modified approach to the conventional "four-step" method. STOPS uses the Census Transportation Planning Package (CTPP) to describe the local travel market, and replaces the traditional coded transit network with transit services in the General Transit Feed Specification (GTFS) framework. STOPS outputs include a prediction of changes in the automobile mode person-miles of travel (automobile mode trips plus auto access to transit

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[12] TRIMMS is available at www.trimms.com/download/

[13] Florida Department of Transportation hosts the TRIMMS user manual at www.fdot.gov/research/Completed_Proj/Summary_PTO/FDOT_BDK85_977-27_UserManual.pdf

[14] For an example of a simplified methodology extracting typical commute distances, see www.brookings.edu/wp-content/uploads/2016/07/Srvy_JobsProximity.pdf

[15] RPAT is available at www.planningtools.transportation.org/551/rapid-policy-analysis-tool.html

[16] For the latest information about STOPS, and to obtain the latest software and documentation, please visit www.transit.dot.gov/funding/grant-programs/capital-investments/stops

trips) that can be converted into a VMT change. Note that using the software requires a background in applying travel models to project-specific forecasts, as well as familiarity with GIS and the other data required for the analysis, including GTFS and zonal transportation characteristics. Depending on the availability of data and skilled personnel, successful use of STOPS for project analysis may take several weeks.

TDM Best Practices and Practitioner Forums

There are a vast number of resources on TDM, and many are internet-accessible including some useful items here:

The Transportation Modeling Improvement Portal is the long-term home for the Travel and Freight Modeling Improvement Programs (TMIP/FMIP) that came out of SHRP2. Supported by TRB and FHWA, their website includes a library of hundreds of documents, datasets, and an archive of webinar presentations by private and public transportation professionals over the course of the programs (2007-2016).[17]

Travel Forecasting Resource (TFR) is the long-term home of the community that produced the aforementioned TRB Special Report 288. TFR's website includes a curated resource library with documents and webinar recordings, an active user forum, and information on their annual Innovations in Travel Modeling Conference.[18]

The Victoria Transport Policy Institute (VTPI) is an independent think tank in Victoria, British Columbia. VTPI regularly publishes white papers, topical policy analyses, and evaluation references for free. Their website houses the Online TDM Encyclopedia, a comprehensive resource for travel modeling information.[19]

Advanced TDM Resources

For those interested in expanding their modeling capacity beyond trip-based and simplified methods, the following documents provide guidance and instruction in activity-based modeling.

Activity-Based Travel Models: A Primer (FHWA 2015) is a report prepared by FHWA and AASHTO to serve as a practical guide for understanding activity-based travel modeling, and considerations applying this kind of modeling to transportation system planning.[20]

A Self Instructing Course in Mode Choice Modeling: Multinomial and Nested Logit Models (Koppelman and Bhat 2006) is a manual written for the Federal Transit Administration. It instructs the reader in the fundamentals of discrete choice probabilistic modeling, as well as model construction using recommended software.[21]

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[17] Transportation Modeling Improvement Portal, www.tmip.org
[18] Travel Forecasting Resource (TFR), www.tfresource.org
[19] VTPI, Online TDM Encyclopedia, www.vtpi.org.
[20] FHWA, https://planningtools.transportation.org/files/108.pdf
[21] Koppelman and Bhat, www.caee.utexas.edu/prof/bhat/COURSES/LM_Draft_060131Final-060630.pdf

APPENDIX B: Alternative Fuels and Advanced Drivetrain Technology Definitions

A **hybrid electric vehicle (HEV)** uses a combination of an electric motor and an internal combustion engine to propel the vehicle. Usually hybrids have downsized engines, this coupled with power from an on-board battery system to the electric drivetrain, leads to better fuel efficiency than non-hybridized models.[22] The most common example of a gasoline HEV is a Toyota Prius, which charges its batteries through regenerative braking. At low speeds, a Prius is powered entirely by its batteries and electric motor. Specialized designs such as plug-in hybrid electric vehicles (PHEVs) and extended range electric vehicles (EREVs) are part of this broader hybrid electric category.

A **hydraulic hybrid vehicle (HHV)** utilizes a pressurized fluid system rather than batteries for chemical energy storage but operates much in the same way as a hybrid electric vehicle. Hydraulic hybrids, like HEVs, capture energy for storage through regenerative braking.[23] Hydraulic hybrids also offer better fuel economy and often lower emissions than comparable non-hybridized vehicles.

A **battery electric vehicle (BEV)**, or an all-electric vehicle, uses a battery pack to store electrical energy that powers the motor entirely. EVs are charged through plugging the vehicle into an electric power source, and even though electricity production may contribute to air pollution based on the power source makeup of the electrical grid, the EPA classifies EVs as zero-emission vehicles due to their lack of direct exhaust and tailpipe emissions.[24] Any emissions associated with EVs come from brakewear and tirewear particulate matter emissions.

A **hydrogen electric vehicle (FCV)** also uses an electric motor instead of an internal combustion engine and therefore has no smog-related or greenhouse gas tailpipe emissions. FCVs are not recharged through plugging in to a power source like EVs, instead generating electricity through the combination of hydrogen (H_2) gas from the fuel tank and oxygen (O_2) from the air. The only byproducts of this process are water and heat. FCVs can be refueled at designated hydrogen dispensers at public stations and refill within 5 minutes. The fuel economy of FCVs can be close to 70 miles per gasoline gallon equivalent (MPGe). Similar to EVs, emissions associated with FCVs come from brakewear and tirewear particulate matter emissions.[25]

Natural gas is increasingly being used as a transportation fuel. Most commonly natural gas is distributed as a pressurized gas or in liquid form. Some original equipment manufacturers (OEMs) produce natural gas vehicles like the now discontinued Honda Civic GX that ran on

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[22] US Department of Energy, http://www.afdc.energy.gov/vehicles/electric_basics_hev.html
[23] US Environmental Protection Agency, https://archive.epa.gov/otaq/technology/web/html/research-hhvs.html
[24] US Department of Energy, Alternative Fuels Data Center: All-Electric Vehicles (energy.gov)
[25] US EPA, Hydrogen Fuel Cell Vehicles | US EPA

compressed natural gas (CNG), but many natural gas vehicles are retrofitted conventional fuel vehicles with aftermarket conversion kits. These vehicles may be either dedicated for natural gas or use a system that runs on a conventional fuel and natural gas. A **dual fuel vehicle** uses diesel for pilot ignition and natural gas for propulsion. CNG is dispensed at 3000 or 3600 pounds per square inch (psi) and stored on the vehicle in high-pressure fuel tanks. **Liquefied natural gas (LNG)** is super-cooled and then stored at extremely cold temperatures in cryogenic fuel tanks.[26] Natural gas has a lower energy density than either gasoline or diesel, which results in less range for natural gas vehicles across equivalent fuel volumes.

Renewable fuels such as soy biodiesel are also included in the CMAQ tool. **Biodiesel** comes in two blends for this tool, either 20 percent biodiesel and 80 percent petrol-based diesel (**B20**) or 100 percent biodiesel (**B100**).[27]

[26] DOE, http://www.afdc.energy.gov/fuels/natural_gas_basics.html
[27] DOE, http://www.afdc.energy.gov/fuels/biodiesel_basics.html