

Fuel and Emissions Calculator (FEC) Version 2.0

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A Summary Research Report from the National
Center for Sustainable Transportation

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List of Acronyms

AE	All-electric
ANL	Argonne National Laboratory
BEV	Battery electric vehicle
BRT	Bus rapid transit
CO	Carbon monoxide
CBD-SAE1376	Central Business District Cycle
CI	Compression ignition
CNG	Compressed natural gas
CO ₂ ,	Carbon dioxide
CO ₂ e	CO ₂ equivalent
DE	Diesel-electric
eGRID	Emissions and Generation Resource Integrated Database
FCEV	Fuel cell electric vehicle
FHWA	Federal Highway Administration, USDOT
g	Gram
GDOT	Georgia Department of Transportation
Georgia Tech	Georgia Institute of Technology
GIS	Geographic information system
GPS	Global positioning system
GREET	Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation
HD-UDDS	Heavy-Duty Urban Dynamometer Driving Schedule
HDV	Heavy-duty vehicle
HEV	Hybrid electric vehicle
hp	Horsepower
HVAC	Heating, ventilation, and air conditioning
ICE	Internal combustion engine
kg	Kilogram
kW	Kilo watt
kWh	Kilo watthour
LCA	Life-cycle assessment
LCCA	Life-cycle cost analysis
MARTA	Metropolitan Atlanta Rapid Transit Authority
CH ₄	Methane
MOVES	MOtor Vehicle Emissions Simulator
mph	Miles per hour
MWh	Mega watthour
NA	Not applicable
NaviGator	The intelligent transportation system operated by GDOT
N ₂ O	Nitrous oxide
NPV	Net present value
NYBC	New York Bus Cycle
NYCC	New York Composite Cycle

O&M	Operation and maintenance
OCTA	Orange County Transit Authority Cycle
opMode	Operating mode
ORNL	Oak Ridge National Laboratory
NO _x	Oxides of nitrogen
PFCEV	Plug-in fuel cell electric vehicle
PHEV	Plug-in hybrid electric vehicle
PM ₁₀	Particulate matter with a mean aerodynamic diameter of 10 μm
PM _{2.5}	Particulate matter with a mean aerodynamic diameter of 2.5 μm
PTW	Pump-to-wheel
SF	San Francisco (San Francisco Bus Cycle)
SI	Spark ignition
SHEV	Series-hybrid electric vehicle
SRTA	Georgia State Road and Tollway Authority
STL	Starting tractive load
STP	Scaled tractive power
SO ₂	Sulfur dioxide
FEC	Fuel and Emissions Calculator
TRB	Transportation Research Board
USB	Universal serial bus
USDOT	United States Department of Transportation
USEPA	United States Environmental Protection Agency
VOCs	Volatile organic compounds
VSP	Vehicle-specific power
WTP	Well-to-pump

Fuel and Emissions Calculator (FEC), Version 2.0

Summary Report

Executive Summary

The Fuel and Emissions Calculator (FEC) is an operating-mode-based, life-cycle emissions modeling tool developed by the Georgia Institute of Technology researchers. The primary purpose of the FEC is to assist fleet owners and managers, regulatory agencies, and policy analysts in assessing the energy and emissions impacts of fleet alternatives. The FEC's modeling approach estimates emissions as a function of engine load, which in turn is a function of vehicle service parameters, allowing modelers to account for local on-road operating mode conditions as model inputs. The functional modules are embedded in an Excel spreadsheet platform for all current model versions. The open platform allows users to see all input data and every calculation, which makes the model transparent and accessible for most users. With Version 2.0 of the model, an online Python version of the model has also been developed. The Python version enhances model performance, and provides functionality for advanced users who may wish to link the FEC with other modeling tools, such as travel demand or simulation models.

The first Fuel and Emissions Calculator (Version 1.0), known as 'FEC for transit fleets,' was originally developed by Georgia Tech researchers in 2013-2014 for transit bus, shuttle bus and rail systems (ORNL and Georgia Tech, 2014). This report first summarizes the FEC Version 2.0 model's main features. The generic methodology that is applied to all transportation modes is introduced in Chapter 2, which includes modules for scenario setting, energy consumption, on-road emission rates, life-cycle assessment, and cost-effectiveness. The model specifications for individual transportation modes are introduced in Chapter 3, and case study examples are provided to help users prepare customized analysis for their own fleets. The key considerations for establishing the online FEC are discussed in Chapter 4. Current research achievements and ongoing work to update and improve the FEC are provided in the final Chapter.

1. Introduction

The Fuel and Emissions Calculator (FEC) is an operating-mode-based, life-cycle energy and emissions modeling tool developed by Georgia Tech research team. The FEC was originally designed to assist transit agencies in evaluating the purchase of new transit bus and rail technologies, but has been expanded over time to other on-road fleets. The model provides support to regulatory agencies and policy analysts interested in assessing various transit fleet and powertrain options based on energy savings, emission reduction, and life-cycle cost-effectiveness. The FEC compares the performance of multiple alternative fuels and powertrains across a range of operational characteristics and conditions. The FEC facilitates customized and flexible assessments that account for local conditions. The FEC has been applied in a number of published applications, helping researchers assess transit purchase and operations decisions, and the energy and environmental impact of alternative fuel and powertrain options (Xu, et al., 2013; Gbologah, et al., 2014; Xu, et al., 2015). Originally developed as an Excel spreadsheet, Version 2.0 has also been prepared in Python code to facilitate external model integration.

The FEC's modeling approach estimates emissions as a function of engine load, which is in turn a function of transit service parameters, including duty cycle (idling and speed-acceleration profile), road grade, and passenger loading (Xu, et al., 2015). However, the original model algorithms, embedded emission rates, and model settings in FEC Version 1.0 needed to be updated for Version 2.0, with latest research findings, for following reasons:

- Version 1.0 was only designed to support transit fleets. The FEC framework can facilitate the integration of all transportation modes, given that the overall model structure and algorithms are also suitable for processing other vehicle fleets. Expansion of the model to support heavy-duty truck evaluations was a natural improvement.
- The Excel spreadsheet tool is too cumbersome and too slow to support large numbers of scenario analyses. As an interim solution, the Excel approach in Version 2.0 has been decomposed into separate spreadsheets for each mode, so that emission rates can be expanded. A separate transit bus calculator and a heavy-duty truck calculator have been developed for Version 2.0 (version 1.0 still applies to rail). Individual Excel spreadsheet calculators for other applicable transportation modes are being developed. Eventually, all transportation modes will be supported in separate spreadsheets that can be updated as new data become available.
- With Version 2.0, the researchers have moved toward the support of real-time analyses and direct linkages between the FEC and travel demand and traffic simulation models. An online version of Version 2.0 is written in Python, which provides the same functionality as the Excel spreadsheet calculators. All the existing Excel Version 2.0 functions have been scripted in Python and are hosted on a Georgia Tech server.
- Finally, online documentation and a model tutorial have been made available for potential users to help them setup their own model runs and obtaining emission results for their fleet. An official website for the FEC is now online, sharing share the latest resources of the tool, and assisting in deploying the tool (<http://fec.ce.gatech.edu/>). The

website contains the tool overview, latest updates, publications, tutorials, and contact information for technique issues. The website is being updating to better assess users in using the tool.

This report provides a brief overview of the FEC, including the basic model structural methodologies that apply to all modes, tool specifications that apply to specific transportation modes, and the structure of the online version. After the methodologies that apply to each mode are described, the report provides a case study to help users understand the information needed and procedures of conducting analysis with the FEC for various purposes. Finally, current achievements and future development plans will be summarized to provide the comprehensive scope of the tool.

2. Base FEC Methodology

The FEC estimates energy consumption and emissions using an activity-based, bottom-up modeling approach. Travel activity is based upon vehicle operating mode data (second-by-second speed profiles) input by users, or driving cycle defaults selected by the user. The FEC modeling framework is illustrated in Figure 1 below. Energy consumption, emissions, and cost-effectiveness are estimated via four steps:

- Users set the scenarios and provide on-road operating mode conditions to the tool. The inputs are pre-processed automatically by the model (input processors). Rail modules use a separate scenario-creation process.
- The scaled tractive power (STP) or vehicle-specific power (VSP), depending on vehicle type, hybrid vehicle modules, and rail-cycle modules estimate energy consumption for the selected vehicle type and powertrain options.
- The direct emissions from tailpipe (pump-to-wheel) are estimated by matching STP/VSP operating mode bins with emissions rates from U.S. Environmental Protection Agency's (USEPA's) MOVES (MOTOR Vehicle Emissions Simulator) model (USEPA, 2014).
- Emissions generated from fuel production and transmission (well-to-pump) are estimated with energy and emission rates from the GREET (Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation) model developed by Argonne National Laboratory (ANL, 2015). Upstream emission rates for electric vehicle are from the Emissions and Generation Resource Integrated Database (eGRID), developed by the U.S. EPA (USEPA, 2015a). The GREET fuel-cycle emission rates, eGRID electric emission rates, the cost-effectiveness, and summary modules link to all of the aforementioned modules and provide tabulated results.

Each of the steps described above are detailed in the report sections that follow:

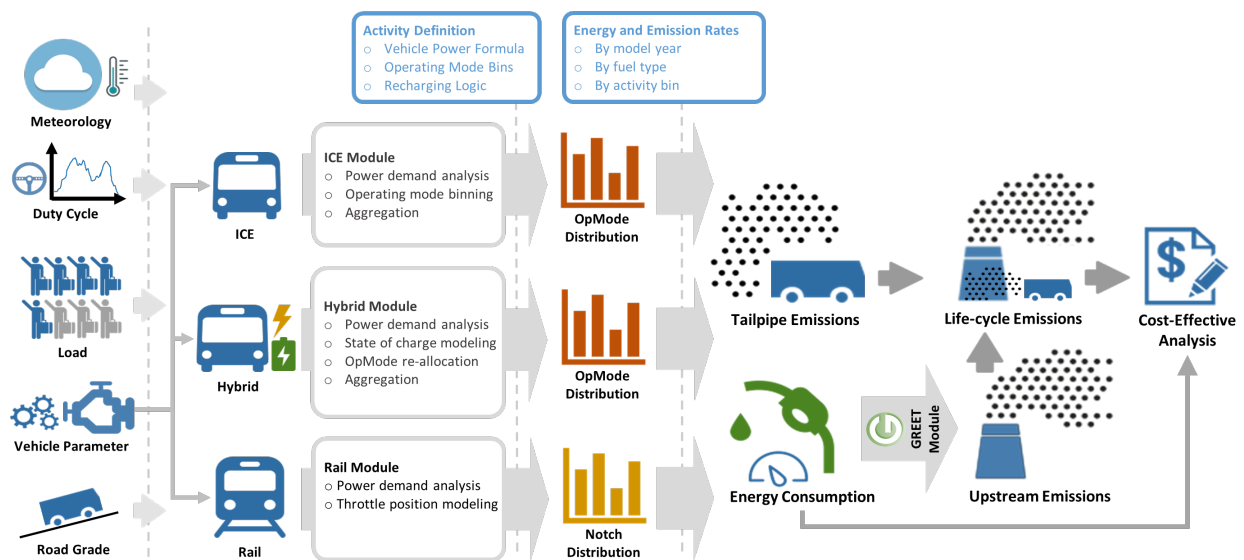


Figure 1. Calculator Structure

2.1 Scenario Setting Module

In the scenario setting module, the key descriptors of local fleet operation are input by users, and automatically processed by the tool. Factors with significant impact on energy consumption, emissions, and costs were identified through previous analysis and embedded in the FEC (ORNL and Georgia Tech, 2014). The FEC allows users to specify customized geographic, meteorological, and operational parameters. For all of the transportation modes embedded, except rail (most rail inputs will be introduced separately in following chapters), the following information must be prepared to run the model:

Geographic Boundary: The geographic input is city and state for all modeling. The geographic boundary is used to select a terrain roughness. Location also impacts the power generation mix employed in life-cycle emissions estimates for electricity production. The FEC does not currently account for county-level inspection and maintenance and fuels programs because the emission rate matrices would be too large for practical application in the spreadsheet format. However, the MOVES-Matrix model (as will be described later) has been run for 12 representative counties (those counties were also used to define 12 representative meteorology scenarios, introduced below) and each scenario does account for the local inspection and maintenance and fuel programs. Transit emission rates are not very sensitive to fuel and inspection and maintenance programs across these twelve locations, meaning that the differences across regions reflect primarily the differences in meteorology. The online FEC version will ultimately be linked to region-specific MOVES emission rates in a future model version to allow any fuel composition and inspection and maintenance program to be reflected in the vehicle emission rates.

- **Calendar Year:** Emission rates are affected by calendar year of analysis because emission standards for new vehicles entering the fleet are more stringent (overall fleet emissions decline with fleet turnover). The Calculator currently includes single years between 2015 and 2025. For projects that need to assess the impacts of older transit vehicles, the applicable emission rates for these model years can be integrated directly into the FEC from MOVES-Matrix.
- **Terrain Roughness:** Terrain roughness is tied to considerations of road grade in the estimation of direct emissions. Based on the U.S. physiographic divisions, the Calculator automatically classifies each city as one of four terrain roughness categories (flat, low, medium, and high), but users can opt to override the default classification. For example, if a location has mountainous terrain and is designated “high” for terrain roughness by the FEC, a user may choose to override the value to “medium” when analyzing freeway operations. This will account for the fact that freeways and major arterials have considerable amount of cut and fill, and therefore do not closely follow local topography.
- **Meteorological Settings:** Meteorology plays an important role in energy consumption and emissions due to increased cooling loads from air conditioning usage and seasonal differences in fuel composition. Users can choose to model either a winter or a summer

scenario. Moreover, the severity of season, ranging from 1 to 6 to indicate mild to severe, is also defined follow the season to provide additional information of local meteorology.

- **Fleet Size:** Fleet size is used to project the unit energy consumption and emissions to the total fleet. Fleet size includes number of vehicles (for rail, it is represented by number of cars in each train), average route length, and annual number of runs to define the scale of the service.
- **Duty-cycle:** The on-road speed-acceleration profile and the frequency of stops both affect engine load and energy losses. The FEC includes many built-in duty cycles that are representative of routes that traverse different areas, ranging from high-density urban cores to suburbs. However, one of the most important features of the FEC is that users can enter their own second-by-second duty-cycle collected using a GPS device.
- **Vehicle Loading:** The weight of the transit vehicle can be significantly affected by vehicle occupancy, which impacts engine load. Users can set default passenger loading or enter passenger loading data from fare analysis or onboard passenger counting data streams.
- **Propulsion and Fuel Options for Selected Vehicle Types:** The fuel and powertrain options used by the vehicle types serve as a model input. For on-road vehicles (bus, car, truck, etc.), users choose from internal combustion engine (ICE); hybrid electric vehicle (HEV), parallel or series; plug-in hybrid electric vehicle (PHEV); battery electric vehicle (BEV); and fuel cell electric vehicles (FCEV). Fuel options include conventional diesel, gasoline, compressed natural gas (CNG), as well as 2%, 5%, 10%, 20%, and 100% biodiesel. For rail, users can select all-electric (AE) or diesel-electric (DE) trains. The ICE category includes spark ignition (SI), gasoline vehicles, and compression ignition (CI), diesel vehicles. SI and CI engines operate very differently, and emissions and fuel consumption are significantly different across these engines. In MOVES, SI and CI vehicles use the same STP calculation equation and vehicle-specific model coefficients, but the energy consumption and emission rates are different across these engine types.
- **Transportation Mode-specific Settings:** Specific inputs are applied to specific vehicle types or powertrain options. Because different vehicle types may have different configurations and operating conditions, mode-specific inputs are provided in the tool for each transportation mode, such as idling hours of heavy-duty truck, and charging strategies of all-electric rails. Details of mode-specific settings are provided in Chapter 3.

After setting up the input scenarios, two pre-processors run automatically before energy and emission calculations begin. The Meteorology Processor finds the temperature and humidity for each of the 12 combinations of season and severity. The terrain roughness processor looks up the applicable terrain roughness coefficient for the selected city.

2.2 Energy Consumption Module

The energy consumption module calculates energy use for each second of vehicle operation for the selected powertrain and fuel options. Several processors are dedicated to different vehicle

types and powertrain options. An operating mode bin processor (bin processor) applies to conventional SI/CI vehicles. A hybrid processor applies to hybrid electric vehicles. An extended idling processor is used for heavy-duty trucks. All-electric (AE) and diesel-electric (DE) calculators are applied to trains.

In each energy consumption processor, the tractive power is estimated as a function of operating condition, which normally includes duty-cycle, road grade, and vehicle loading. The FEC calculators estimate energy consumption and emissions as a function of engine-load, using scaled tractive power (STP) for heavy-duty vehicles and vehicle-specific power (VSP) for light-duty vehicles. The FEC directly integrates the STP/VSP modeling approach that is employed in the current EPA regulatory emissions rate model known as MOVES (USEPA, 2016). That is, all of the calculation structures are exactly the same, just the inputs and coefficients vary.

The FEC first calculates STP (heavy-duty vehicles) or VSP (light-duty vehicles) for each second of on-road operation. The FEC then uses the calculated STP/VSP value and vehicle speed to assign each second of on-road operation to a MOVES operating mode bin (opMode bin). Once the operating mode bin is known, the MOVES emission rate can be found in the corresponding energy and emission rates tables for that vehicle type. Because the FEC employs MOVES fuel rates for light-duty and heavy-duty vehicles, the differences between SI and CI engines are reflected in the corresponding MOVES fuel and emission rates for diesel, gasoline, and CNG fuels. In the rail calculators, total tractive power (or total tractive power by notch for trains) is used in energy and emission calculations. The details of operating mode processors are introduced by mode in Chapter 3.

2.3 On-road Emission Rate Module

The on-road emissions are selected and applied to each second of on-road operation by matching the calculated operating mode bin (based upon vehicle-specific power or scaled tractive power and speed as outlined above) to the applicable emission rate from MOVES. For all vehicle types except rail, emissions are estimated by using MOVES-Matrix (Guensler, et al., 2016). MOVES-Matrix is a multi-dimensional lookup matrix containing energy consumption and emission rates (in grams/second or joules/second) for all applicable vehicle types, model years, fuel types, and operating mode bins for 12 meteorology scenarios. The vehicle model years are currently set to the same as calendar year for emission rates because the FEC is designed for assessing the impacts of new fleets. The current emission estimation includes three steps:

- Second-by-second operating mode (opMode) bins are aggregated to obtain the opMode distribution for ICE, parallel-hybrid, and series-hybrid vehicles respectively.
- The energy consumption and emissions per driving cycle (including idling) are calculated by matching the opMode bin distributions with the operating mode bin emission rates for the specific meteorology scenario (temperature/humidity), vehicle type, and calendar year. The energy consumption per route is calculated by multiplying the cycle energy consumption with total operating hours.

- The energy consumption and emissions of BEV and FCEV are derived by adjusting the outputs of series-hybrid vehicles.

The FEC model outputs include energy consumption, atmospheric CO₂, methane (CH₄), nitrous oxide (N₂O), elemental carbon, CO₂ equivalent, carbon monoxide (CO), volatile organic compounds (VOCs), oxides of nitrogen (NO_x), total primary exhaust PM_{2.5}, total primary exhaust PM₁₀, and sulfur dioxide (SO₂).

For rail technologies, EPA provides various locomotive standards which apply to all new and existing locomotives at the time of manufacture and remanufacture, respectively (USEPA, 2009). The average emission rates for six of these standards have been incorporated into the rail module and users do not have to input or modify them. The six standards are; uncontrolled; Tier 0+; Tier 1+; Tier 2+; Tier 3; and Tier 4. For any selected standard, the EPA average emission rate for pollutants is used in the “on-road” emission rate module to estimate notch-specific emission rates. Analysts can also provide their own notch specific-emission rates if they are available from their locomotive vendors. The on-road emissions are estimated by multiplying total notch power of the trip by the notch-specific emission rates, with post-processing applied to each pollutant to reflect hoteling load and fuel quality (ORNL and Georgia Tech, 2014).

In FEC Version 1.0, emission rates were prepared for transit bus, shuttle bus and rail from 2010 to 2012. In FEC Version 2.0, emission rates were prepared for same vehicle types from 2015 to 2025. Emission rates were also integrated for heavy-duty trucks. Emission rates will be updated through on-going projects for additional vehicle types, such as school bus, intercity bus and passenger cars.

2.4 Well-to-pump Energy and Emissions Module

In the FEC, WTP emissions were prepared using data from the GREET model (ANL, 2015) and the eGRID database (USEPA, 2015a). GREET was developed by ANL in Excel and provides energy consumption and emission information by vehicle and fuel system. The USEPA developed eGRID to assess the energy and environmental impacts of electricity generation and included a comprehensive resource of almost all U.S. electric power generation.

GREET includes more than 100 presentative fuel production pathways and more than 70 vehicle/fuel systems. For the FEC, it was feasible to pull well-to-pump energy and emissions rates directly from GREET. For all fuel types except electricity, the emission rates on a gram/kWh basis were generated from the GREET 2015 fuel cycle model for calendar year 2015 to 2025, using default feedstocks, crude oil, and transport options. The GREET upstream fuel model (well to pump) operates independently from the downstream model (pump to wheel). That is, the upstream energy and emissions associated with fuel production are the same, no matter what vehicle is consuming the fuel. Upstream emissions depend only on the amount of fuel consumed by the downstream vehicles. Well-to-pump emissions can be derived by multiplying downstream pump-to-wheel fuel consumption by the applicable upstream energy consumption and emission rates for the fuel used.

The GHG emissions intensity of the electric grid varies regionally, across the United States, because the proportion of various types of renewable and fossil fuels that are used to generate the electric power also vary regionally. Each energy input has a different impact on the upstream energy efficiency associated with delivering electricity to the grid. In the FEC, separate emission rates are prepared for different regions to consider the emission impact of fuel sources. The annual emissions generated from MWh of electricity production by states were used as the emission rates in the FEC, and WTP emissions of electricity are calculated by multiplying energy consumption and emission rates per unit energy use for selected states.

The WTP and PTW emissions are summed to calculate the total fuel-cycle emissions per run. The unit emissions per run are projected to annual total emissions by multiplying the fleet size and total annual runs.

2.5 Life-cycle Assessment Module

Numerous studies have evaluated alternative bus technologies through environmental and economic life-cycle assessment (LCA), incorporating various components of the fuel cycle (also known as well-to-wheels analysis, which includes well-to-pump and pump-to-wheels elements), and the vehicle-cycle, which includes vehicle manufacture and scrappage elements (Samaras, 2008; Chester, 2009; Cooney, 2011). In the transportation sector, fuel-cycle energy use and emissions generally account for the biggest contribution to the total LCA results. Furthermore, it is relatively difficult to quantify energy use and emissions reduction potential associated with the vehicle-cycle (LCA data for vehicle components are typically presented in an aggregate average form). The FEC focuses on fuel-cycle energy and emissions, including: 1) upstream well-to-pump (WTP) energy and emissions, related to the production and distribution of the fuel; and 2) on-road pump-to-wheel (PTW) energy and emissions. The cost-effectiveness module considers both the fuel-cycle and vehicle-cycle (vehicle manufacture and scrappage) components.

2.6 Cost-Effectiveness Module

Life-cycle cost analysis (LCCA) is a tool to assess the most cost-effective option for purchase, operation, maintenance, and disposal of a unit or process. In the FEC, LCCA accounts for the procurement cost, facility improvement cost, equipment procurement cost, operation cost, vehicle maintenance cost, and also the surplus value and end-of-life. All of these costs are discounted (applied discount rate) and then totaled to a net value in current dollars, known as net present value (NPV). The initial cost includes the bus procurement and facility costs in the first year of the vehicle life cycle. The operation and maintenance (O&M) cost are considered as constant for each year. The NPV is calculated for the total operation and maintenance cost over the system life cycle. The total cost can be estimated by summing the cost components, with the life-cycle cost represented by NPV. Finally, the cost-effectiveness is assessed in terms of cost per mile of operation, and cost per tonne of CO₂ emissions, for a 12-year life-cycle.

The current cost-effectiveness module includes an analysis module and a vehicle cost profile module. The life-cycle assessment algorithm is embedded in analysis module. In the cost profile

module, empirical data collected from previous research were tabulated for typical transit bus fleets, including diesel buses, diesel hybrid buses, biodiesel buses, battery electric buses, CNG buses, and hydrogen fuel cell buses. However, because the costs of other fleets can also be represented by initial cost and operation and maintenance (O&M) costs, defined in the cost profile module, users can still apply the cost-effectiveness module to other fleet. Users are allowed to enter their own cost data into this sheet, with all the costs represented by net present values for the modeled calendar year.

2.7 Chapter Summary

In this chapter, the generic methodologies for estimating energy consumption, emissions, and cost-effectiveness in the FEC were introduced. The current methodology is embedded in a spreadsheet tool, and free to all the users. Also, the current tool is now in the form of an online Python calculator that can be integrated into other models. The tool specifications for various transportation mode and online calculator information will be given in the following chapters.

3. Transportation Mode Specifications and Case Studies

The online FEC is evolving from an energy and emissions calculator for transit modes, into a calculator that is applicable to all transportation modes, including: walk, bike, motorcycles, light-duty vehicles, buses, rail, and heavy-duty trucks. FEC Version 1.0, finalized in 2014, only include transit bus, shuttle bus and rails, with a limited calendar years available for analysis (ORNL and Georgia Tech, 2014). The latest FEC (Version 2.0) includes dedicated algorithms for transit bus, rail, shuttle bus/van, and long-haul combination trucks. Other similar vehicles can also be analyzed using the current FEC by adjusting data inputs or vehicle configuration parameters. This section of the report is designed to assist users in applying the current FEC model version to their research. Specifications are provided for the individual mode calculators and each calculator description is followed by a case study to illustrate the methodology of deploying the mode-specific application.

3.1 FEC Version 2.0 Improvements

FEC Version 2.0 covers all of the major functions in Version 1.0. Updated energy consumption and emission rates have been included from MOVES and GREET. Methodologies were updated with latest research findings, and more scenario options available in the scenario setting module. First, the major features of Version 1.0 are listed below:

- The tool was built in a single spreadsheet.
- **Scenario Setting module:** Version 1.0 facilitated emission analysis for transit buses, shuttle buses/vans and rails (include all-electric and diesel-electric rail systems) for calendar year 2010 to 2012.
- **Energy consumption module:** The VSP/STP equations and parameters came from MOVES 2010. There were several scripting errors related to hybrid calculators.
- **On-road emission rate module:** The on-road emission rates came from MOVES 2010.
- **Life-cycle analysis module:** The upstream emission rates were prepared for all applicable fuel types, but uniform for all calendar years. A cost-effectiveness module was produced using Life-cycle analysis framework. The cost profiles were provided to sample transit buses, while cost profiles for other vehicle types are under developing. The costs in cost-effectiveness module were not represented by NPV values. And the O/M costs were incomplete in the cost-profiles.

Some of the tool limitations in Version 1.0 have been addressed in Version 2.0. The major updates in Version 2.0 were listed below:

- Individual calculators for transit bus and heavy-duty trucks were developed.
- **Scenario Setting module:** Version 2.0 facilitated emission analysis for transit buses, shuttle buses/vans, heavy-duty trucks and rails (include all-electric and diesel-electric rail systems) for calendar year 2015 to 2025.
- **Energy consumption module:** The VSP/STP equations and parameters came from MOVES 2014. The scripting errors related to hybrid calculators were fixed.
- **On-road emission rate module:** The on-road emission rates came from MOVES 2014.

- **Life-cycle analysis module:** The upstream emission rates were prepared for all applicable fuel types, differentiated by calendar years. The cost profiles were provided to sample transit buses, while cost profiles for other vehicle types are under developing. The costs in cost-effectiveness module were represented by NPV values. And the O/M costs were completed in cost modules.
- An online version is developed with the exactly the same functions as the transit bus calculator.

Users are recommended to use Version 2.0 for their analysis, unless they need to use some old scenarios or conduct a comparison between old version and new version. The detailed updates made to the FEC Version 2.0 algorithms are provided in Appendix A. The team is working on adding more transportation modes, including school bus, intercity bus, single-unit trucks, passenger cars and non-motorized modes for Version 3.0. The online version will also be updated to incorporate more functionalities listed above. Suggestions for users to customize the FEC for their own fleet are introduced in the following sections.

3.2 Transit Bus Calculator

In the FEC, the transit bus calculator was developed based upon the features of a typical transit bus fleet. However, users are still able to analyze similar vehicles and fleets, such as express buses or school buses, by adjusting model inputs or vehicle settings. In this section, the specifications of transit bus will be introduced by functional modules, as well as potential adjustments for similar fleets.

3.2.1 Input Module Specifications

The bus-specific inputs include the range of the service, route specification, and fleet information. The transit bus-specific inputs, the range, and potential data source are listed in the table below.

Table 1. Transit Bus Specific Inputs

Variable	Location in Excel	Range	Data Source
Route Length	InputOutput_Bus	Positive values in miles	Bus schedule or GPS data
Number of Buses	InputOutput_Bus	Positive integer	Fleet information
Passenger Loading/Bus/Run	InputOutput_Bus	Positive integer	Ridership record or appointment record
Number of Runs/Bus/Year	InputOutput_Bus	Positive integer	Bus schedule
Idling Speed Range from GPS Data	BinProcessor	Positive values in miles/hour (no more than 5 mph)	Accounts for GPS wander at low speeds, consult GPS device user manual

The transit bus calculator module employs embedded vehicle data for traditional transit buses by bus size. However, users can customize the transit module to evaluate other “similar” bus fleets. As discussed earlier, one of the main advantages of the FEC is that the users can specify

the duty cycle, which varies significantly across other bus modes. As such, users can model the energy and emissions impacts for buses operating primarily on freeways (e.g., express buses) and for buses that operate under heavy urban stop-and-go conditions (e.g., school buses). Until such time as the FEC includes embedded data for non-traditional buses (e.g., school buses and bus rapid transit), users can modify the traditional transit vehicle specifications in the model and apply observed (or default) duty cycles to these fleets. Similarly, until the FEC includes different emission rates for these non-traditional fleets, the MOVES emission rates for traditional transit buses by model year are applied.

To model a non-traditional fleet, users choose the “Transit Bus” vehicle classification. The number of buses is taken from the fleet size provided by users, and the number of passengers entered can either be assumed or derived from transit ridership records. Users enter or select a duty cycle (this is the most important element) and can modify vehicle parameters for the alternative fleets, as discussed below:

- **Traditional Transit Bus:** The FEC currently models traditional city and county buses. These buses are typically used in shorter-distance public transport bus services. Transit bus models include low-floor buses, double-decker buses, articulated buses, and midi-buses. For operation, the city bus usually has low average speeds and makes frequent stops. But, these buses can also be modeled on other facilities under other duty cycles. For bus operation, users can either input an observed duty-cycle from GPS-monitored city bus operations (Yoon, et al., 2005), or choose from a list of representative cycles in the FEC (OCTA, Manhattan, NYBC, NYCC, WMATA, and CBD). Finally, if users analyze larger vehicles, such as articulated buses, they should edit the vehicle load by either adding equivalent passenger load, or modifying the source type physics data (especially the vehicle mass weight parameter) in the “formula” sheet when better vehicle data are available.
- **School Bus:** School bus is a type of bus used to carry students between school and home, or to and from school events. In the U.S., yellow school buses can readily be distinguished from other bus types. Similar to the transit bus, the school bus is usually operated on a stable schedule and a fixed route for student pick-up and drop-off. The operating speeds of school buses are typically low. Currently, users can select “transit bus” as a surrogate for school bus in energy consumption modeling. School buses are a distinct source type in MOVES. Energy consumption and emission rates are currently available from MOVES, but have not yet been incorporated into the FEC. These rates will be added in the next FEC model version. Several school bus duty-cycles have been prepared, so that users can either input the duty-cycles from in-field data collection, or choose from some representative school bus cycles embedded in the FEC.
- **Express Bus/Commuter Bus/Premium Bus:** Commuter bus systems typically provide express services for long-distance commutes between suburban areas and the downtown. Similar to intercity buses, express buses serve passengers on a relatively

long journey, so the buses are designed for comfort. Express buses typically run less frequently than transit buses, during the peak period, and serve fewer bus stops than transit buses. Express buses usually operate on highways, at significantly higher average speeds than city transit bus. Several intercity bus duty-cycles have been prepared, so users can either input the duty-cycles from field data collection, or choose from express bus cycles embedded in the FEC. Currently, users can select “transit bus” as a surrogate for express bus. The research team is currently in the process of generating diesel intercity bus energy consumption and emission rate in the next version of the FEC from MOVES to better represent express bus energy and emission rates.

- **Bus Rapid Transit:** Bus rapid transit (BRT) is a mass transit system that meets certain configuration conditions designed to ensure that the buses can provide efficient and high-quality service. A BRT system is usually provided dedicated lanes and are provided with signal priority at intersections. High-capacity vehicles like bi-articulated buses or double-decker buses are usually used to improve efficiency. Compared to regular transit buses, BRT is operated at higher speed with few interruptions. In the FEC, users can select the “Transit Bus” under “vehicle classification” as a surrogate for BRT. The research team will integrate vehicle weight and other parameters that are suitable for representing a BRT fleet (larger than regular buses), and will implemented the parameters in the next version of FEC. Users can either inputs the duty-cycles from in-field data collection, or choose an embedded BRT cycle in the FEC. Alternative fuel options will also be integrated into the next FEC version, as BRT systems are expected to use new technology vehicles.
- **Private City-to-city (Intercity) Bus:** Private city-to-city bus operations provide intercity trips for private purposes. These buses may belong to a community, a club, a travel agency, or a company for their events or business use. Intercity buses are designed for comfort and usually carry passengers on relatively long journeys (with luggage); hence, the buses are heavier than typical transit buses. Intercity buses typically operate on highways, with a significantly higher average speeds than city transit buses. Because intercity buses are private, the fleet is varied, with no standardized design. In the FEC, users can select “transit bus” as a surrogate for intercity buses. The research team recently collected data from a few Megabus intercity bus routes to develop future duty-cycles. The research team plans to integrate energy consumption and emission rate from MOVES into a new intercity bus module in the next version of the FEC. Users can either input duty-cycles from in-field private bus data collection, or choose a representative express bus cycles embedded in the FEC. intercity buses are a distinct source type in MOVES. Energy consumption and emission rates for intercity buses are currently available from MOVES, but have not yet been incorporated into the FEC. These rates will be added in the next FEC model version.

3.2.2 Energy Consumption Module Specifications

One of the primary advantages of the FEC is that it allows users to estimate energy consumption and emissions as a function of the vehicle duty-cycle (second-by-second speed profiles). The Tractive Power Calculator is designed to process high-resolution vehicle operations data to utilize the mode-based emission rates from MOVES. The MOVES equation for VSP and STP employed in the FEC is shown below (Xu, et al., 2013). The equation is the same for VSP (light-duty vehicles) and STP (heavy-duty vehicles), but the coefficients are different. The second-by-second speed and acceleration come from selected duty cycle. The road grade currently comes from a roughness index (but grade can be specifically integrated into the model for each route such that the spatial location when collected speed/acceleration data point can be associated with the grade at that same position). The mass is the individual vehicle mass plus the mass of passengers. All other modeling coefficients come directly from MOVES2014 default database (USEPA, 2016).

$$VSP(STP) = (A/M) \cdot v + (B/M) \cdot v^2 + (C/M) \cdot v^3 + (m/M) \cdot (a + g \cdot \sin \theta) \cdot v \quad (1)$$

Where:

- A = the rolling resistance coefficient (kW•s/m)
- B = the rotational resistance coefficient (kW•s²/m²)
- C = the aerodynamic drag coefficient (kW•s³/m³)
- m = mass of individual test vehicle (metric tonnes)
- M = fixed mass factor (metric tonnes)
- v = instantaneous vehicle velocity at time t (m/s)
- a = instantaneous vehicle acceleration (m/s²)
- g = gravitational acceleration with the value 9.8 m/s²
- θ = the fractional road grade (percent grade)

Passenger loading is also accounted for in the load calculation process, by adding the mass of passengers to the mass of the vehicle (Xu, et al., 2013), such that:

$$m = n \times w + m_c \quad (2)$$

Where:

- n = number of passengers
- w = average passenger mass, default to 68 kg (0.068 metric tonnes) per person
- m_c = standard vehicle mass (curb weight) in metric tonnes

After calculating VSP and STP, the FEC deploys several processors to estimate energy consumption for different powertrain options. The processors, by powertrain, are introduced below:

- **ICE:** In the Bin_Processor module, calculated second-by-second STP/VSP results are processed into STP/VSP operating mode bins (opMode bin) as defined in MOVES (USEPA, 2012). The operating mode bins are presented in Appendix B.

- **HEV (Parallel and Series):** The parallel and series hybrid processors re-assign the opMode bin distributions of the engine load by simulating the interactions between the internal combustion engine (ICE) and the electric drive. This interaction is modeled separately for parallel and series hybrid buses using a simplified algorithm (ORNL and Georgia Tech, 2014). Also, heating, ventilation, and air conditioning (HVAC) power for hybrid-electric transit bus is also modeled to estimate the additional engine power demand. In general, the algorithm performs best when considering a range of routes and a large number of buses.
- **BEV and FCEV:** The electric motor is the sole component that turns wheels in the final axle for series-hybrids, BEVs, and FCEVs. In this case, the energy consumption of electric buses, including BEVs and FCEVs, are modeled based on energy requirements for series hybrid buses (ORNL and Georgia Tech, 2014). Other parameters, including battery/fuel cell efficiency, motor efficiency and inverter efficiency, are used to post-process the total tractive power of series hybrid vehicle into energy consumption of BEVs and FCEVs.
- **PHEV:** The energy consumptions of plug-in hybrid vehicles are estimated based on the electric units and hybrid units deployed by vehicle. For plug-in fuel cell vehicles (PFCVs), it is assumed the powertrain is composed of an electric motor and a fuel cell, and the energy consumption is estimated with energy consumed by BEVs and FCEVs (ORNL and Georgia Tech, 2014). For plug-in hybrid electric vehicles (LHEVs), the energy consumption is calculated by combining the energy consumption of BEVs, and one of the HEV powertrain architectures (parallel or series).

3.2.3 On-road Emission Rate Module Specifications

The emission rates embedded in transit bus calculator were prepared by running MOVES 2014 for Source Type 42, across all possible combinations of model input scenarios. Emission rates are provided for all major fuel sources deployed by transit fleets, including diesel, CNG, biodiesel, and gasoline. However, since the gasoline is rarely applied for transit fleet, the calculator shows warning message when a fuel type is not recommended for a selected bus.

3.2.4 Life-cycle Assessment Module Specifications

The WTP emission rates in GREET are provided for feedstock and fuel combinations. WTP energy and emissions are independent of the specific vehicle types that use the fuel. Hence, there is no contribution from end use vehicles to the upstream emissions.

3.2.5 A Transit Bus Case Study

A transit bus case study is conducted to demonstrate that activity-based approach is significantly superior than many generic methods (e.g. deploying fuel economy). To depict impact of driving cycles on the estimation, carbon dioxide equivalent (CO₂e) emissions estimated by the Calculator with five drive cycles, including HD-UDDS, NYBC, NYCC, San Francisco (SF) Bus Cycle, and CBD-SAE1376 (ORNL and Georgia Tech, 2014). Other inputs are listed in the table below:

Table 2. Transit Bus Calculator Sample Inputs

Variable	Values
City and state	Knoxville, TN
Season Scenario	Summer
Severity Index	4
Inventory Year	2015
Duty Cycle (average speed)	HD-UDDS (18.86 mph) NYBC (3.57 mph) NYCC (8.76 mph) SF (8.82 mph) CBD (12.73 mph)
Vehicle Classification	Combination Long Haul Truck
Route Length (mile)	22
Average Freight Loading per Truck per Run	10

The figure below includes the CO₂e emissions per mile. Results from different cycles are marked with different markers. The case study demonstrated that deploying different driving cycles yield significantly different emissions. The energy and emissions for the NYBC are higher than those of other cycles.

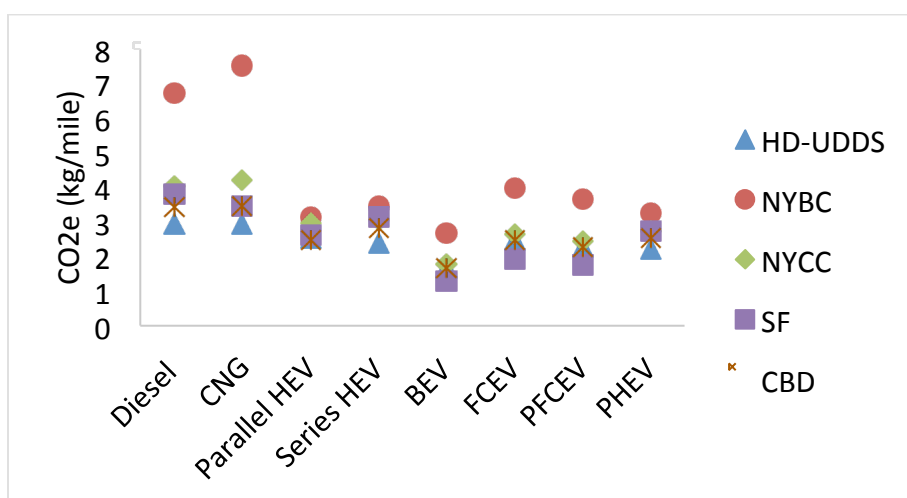


Figure 2. Comparison of Five Driving Cycles with the CO₂e Emissions

3.3 Shuttle Bus Calculator

The shuttle bus calculator applies the same algorithm used for transit buses. The only change is that the shuttle bus calculator employs different on-road emission rates. The tailpipe emission rates have been updated with emission rates of light commercial truck (MOVES Source Type 32) from MOVES2014 for year 2015 to 2025. The FEC Version 1.0 included emission rates for CNG shuttle buses. However, since MOVES2014 (updated version) assumes that there are no light-

duty fleets using CNG fuels, the emission rates of CNG for light commercial trucks (shuttle bus in FEC) are no longer included in FEC Version 2.0.

The shuttle bus calculator can also be customized to evaluate similar shuttles. Users should choose “Paratransit van/shuttle bus” under “vehicle classification” for their fleet (more detailed vehicles may be developed in the future). Similar to the transit bus option, the number of buses can be estimated by fleet size, and the number of passengers can be entered based upon observed ridership data or an estimate of ridership based upon the number of paratransit appointments. Other vehicle specifications for different shuttle buses are introduced below:

- **Private Shuttle:** Private shuttle are often dedicated for private uses and profit-oriented. Sample private shuttle systems include UberXL and BRIDJ. Depending on the specific purpose of the service, the frequency and distance may vary significantly by service provider. In the FEC, users can select the “Shuttle Bus/Van” under “vehicle classification” as a surrogate for private shuttle, and the emissions rates of light commercial trucks will be applied for modeling. Representative traces should be collected as the duty-cycle input to account for the potentially higher average speed than the currently embedded duty cycle traces. And, because shuttle bus operations may fluctuate in route length and number of passengers, users are encouraged to input average base data, or run the tool multiple times for different routes and time periods.
- **Public Transit Shuttle:** Public transit shuttles are often operated by public transit agencies. Also, many universities provide campus transit service using shuttle bus, such as the Stingerette Shuttle at Georgia Tech. Public transit shuttles often serve local areas, and may operate on fixed routes or deviate from a route within a dedicated corridor and direction. In the FEC, users can select the “Shuttle Bus/Van” under “vehicle classification” as a surrogate for transit shuttle, and the emissions rates of light commercial trucks will be applied for modeling. Users can set the inputs based on the bus schedule if it serves as fixed routes. Or, users can input observed operating mode conditions if the shuttle serves as on-demand service.
- **Airport Connection Shuttle:** Airport shuttles often provide door-to-door pick-up service between airports and various passenger trip origins. Airport shuttle services often deploy vans or shuttle buses for their fleet. The number of stops is limited by vehicle capacity. The shuttle may also operate at relatively high speeds between airport and destination. In the FEC, users can select the “Shuttle Bus/Van” under “vehicle classification” as a surrogate for airport shuttle, and the emissions rates of light commercial trucks will be applied for modeling. It is recommended that users collect their own GPS operating traces to serve as duty-cycle inputs (especially highway traces) because all of the embedded cycles have average speeds less than 25 mph. For route length, users can use estimated average home-to-airport distances from a travel demand model, or run the model multiple times for different scenarios. Users should

not use the shuttle bus calculator if services are provided by passenger cars or heavy-duty buses.

- **Dial-a-ride/Paratransit:** Paratransit is recognized as special transit services for people with disabilities, often provided by public transit agencies as a supplement to fixed-route bus and rail systems. In the FEC, users can select the “Shuttle Bus/Van” under “vehicle classification” as a surrogate for paratransit, and the emissions rates of light commercial trucks will be applied for modeling. Users can customize the paratransit service in the FEC using the similar method deployed for on-demand service introduced above. Most paratransit vehicles are equipped with wheelchair lifts or ramps; hence, users are recommended to add the equipment into vehicle load by convert the mass of equipment into equivalent passenger load. The cost associated with any ADA equipment should also be incorporated in the vehicle cost profile.
- **Other On-demand Transit:** The research team is working on developing cost profiles for shuttle buses. Users should develop their own vehicle profiles with their own practice whenever practicable.

3.3.1 Shuttle Bus Case Study

A case study is conducted to investigate the impact of passenger load of shuttles on total CO₂e emission. We assume there is a shuttle bus which operating on a fixed route with fluctuating demand. The average passenger loads during peak hour, mid of day and late night are 10, 5, and 2 passengers respectively. Other inputs are listed in the table below.

Table 3. Transit Bus Calculator Sample Inputs

Variable	Values
City and state	Atlanta, GA
Season Scenario	Winter
Severity Index	4
Inventory Year	2015
Duty Cycle (average speed)	OCTA (12.33 mph)
Vehicle Classification	Combination Long Haul Truck
Route Length (mile)	10
Average Freight Loading per Truck per Run	10/5/2

The figure below includes the CO₂e emissions per mile. Results from passenger loads are marked with different markers. The case study demonstrated that passenger load can affect energy consumption and CO₂e emissions. Vehicles with higher passenger load yield slightly higher emissions.

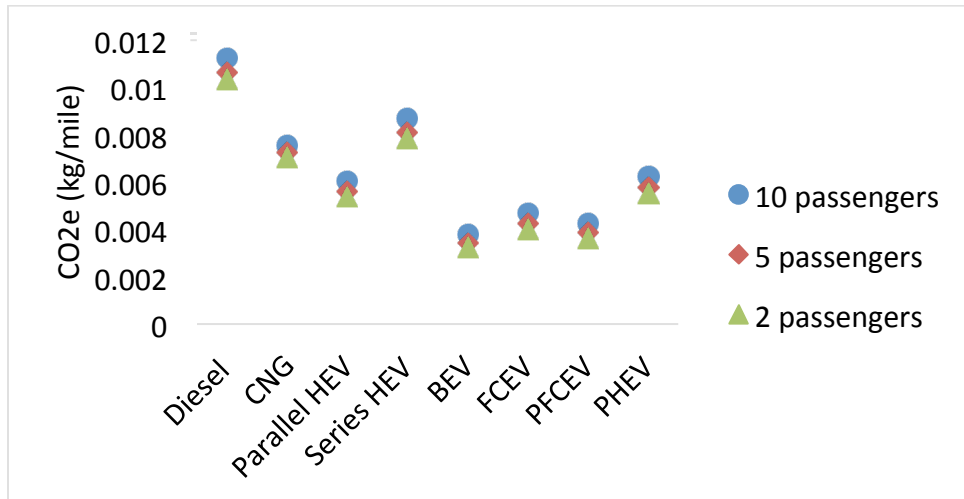


Figure 3. Comparison of Three Passenger Loads with the CO₂e Emissions

3.4 Heavy-Duty Truck Calculator

The heavy-duty truck calculator uses a similar modeling approach to the bus calculator. Few modifications were required to customize the FEC for truck fleet analysis. The first modification is the input settings. The specific input settings for trucks are listed below:

- **Vehicle Type:** Use combination long-haul truck (MOVES Source Type 62).
- **Duty Cycle:** Besides keeping the HD-UDDS cycle, new cycles from MOVES2014 database were added into the calculator to represent various heavy-duty truck operation conditions.
- **Weight:** The average freight load per run, which should be filled with a non-negative number in pounds.
- **Fuel Type:** Because the USEPA does not provide energy consumption and emission rates for CNG, ethanol, and gasoline for combination trucks, the fuel type is limited to conventional diesel and biodiesel.
- **Idling Hours:** A variable called “idling hours per run” is added with hour as the unit.

The truck calculator employs MOVES heavy-duty truck emission rates. The tailpipe emission rates have been updated with emission rates for long-haul combination trucks (MOVES source type 62) from MOVES2014 for year 2015 to 2025. The hourly idling emission rate is prepared by running MOVES 2014 for extended idle operations (opMode bin number 200).

An idling algorithm was added to the truck calculator to assess energy consumption and emissions during extended engine idle, which is common for heavy-duty trucks. The idling energy consumption for traditional combustion engine can be directly estimated as the product of idling hours and the hourly energy consumption rate for the selected meteorology, source type, calendar year, and fuel. The hybrid bin calculator was modified to adjust bin distribution

during idling for hybrid trucks. The output indicates the fraction of time that engine needs to provide power for hoteling, and used to calculate the energy consumption during engine operation.

The team is currently working on developing cost profiles for trucks. The team recommends that users develop vehicle profiles for their own fleets using local data whenever practicable.

3.4.1 A Truck Case Study

A truck case study is conducted to analyze the fraction of idling energy consumption in total energy use. A truck route with half-an-hour idling during each truck run is assessed with the FEC truck calculator. The inputs of a diesel combination truck are shown in table below.

Table 4. Heavy-duty Truck Calculator Sample Inputs

Variable	Values
City	Minneapolis - St. Paul, MN
State	MN
Season Scenario	Summer
Severity Index	2
Inventory Year	2015
Duty Cycle	25mph_Non-Freeway
Vehicle Classification	Combination Long Haul Truck
Idling hours per Run	0.5
Route Length (miles)	10
Average Freight Loading per Truck per Run	0

The energy consumption for different powertrain option is shown in Table 2 below. The idling energy consumption accounts for about 17% of total energy consumption. Electric vehicles have significantly lower idling energy consumption.

Table 5. Heavy-duty Truck Calculator Sample Energy Consumption Output

Vehicle Technology	SI/CI	Parallel	Series	Battery Electric (BE)	Fuel Cell Electric (FCE)
Fuel Type	Diesel	Diesel	Diesel	Diesel	Hydrogen
Operation Energy Consumption per Run (kWh)	83.24	68.80	58.60	29.44	51.41
Extended Idle Energy Consumption per Run (kWh)	16.98	1.58	0.00	0.00	0.00
Energy Consumption per Run (kWh)	100.2	70.38	58.60	29.44	51.41

3.5 Rail Calculator

The transit rail energy and emissions calculator is composed of two sub-models; one for all-electric (AE) rail operations (street-cars, light-rail, and sometimes heavy-rail) and one for diesel-electric (DE) rail operations, which use diesel locomotive engines as the source of power and electric motors to turn the wheels. Each sub-model includes data entry modules, an analysis module, and an output module.

3.5.1 Rail Data Entry Module

Each sub-model includes a data entry for inputting information about the train and another for inputting information about the route. For each data entry module, following input information are needed to running the model:

- **Route Information Module:** Users input basic route information, including the name of route, the names of stations or way points on the route, station or way point mileposts, and the elevation (feet) for each station or waypoint.
- **Train Information Module:** Include passenger load and air conditioning level.
- **Railcar Information:** Include typical features of railcars, such as average weight of unloaded car, number of axles per coach car and train drag coefficient.
- **Diesel Electric (DE) Specifications:** Includes DE configurations such as rated engine power of the locomotive, source of hotel load power supply and number of traction locomotives.
- **Starting Tractive Load (STL):** The specific information used for STL include temperature, track type, weather condition, and track condition.
- **Energy Recovery:** Users can provide information on regenerative braking capability used for energy recovery during braking.
- **Fuel Properties:** The module contains information about the properties of the diesel fuel, including: sulfur content, sulfur content converted to SO₂, fuel density, and carbon content.
- **Notch Power Output Set:** For DE trains the model requires the minimum and maximum throttle power outputs expressed as a percentage of rated engine power.
- **Analysis Options:** Users must select their preferred analysis options for DE trains, including: the applicable locomotive standard, the notch power output set, and maximum percent of rated engine power allowed for hotel load.

Different settings should be applied for the different types of rail systems listed below:

- **Streetcar and Light-rail:** Light-rail is an urban transit mode using rolling stock similar to a tramway, but operating at a higher capacity, and often on an exclusive right-of-way. Light-rail systems are usually powered by electricity. Because there is no strict definition for streetcar and light-rail, some railcars can be almost as heavy as commuter rail, and some may be closer to bus rapid transit (BRT). Hence, it is fairly important to customize

the railcar configurations for light-rail systems. Some critical factors for railcar features are listed below:

- Typical or average weight of unloaded car (tons)
- Number of axles per coach car
- Train drag coefficient (this value can be obtained from railcar vendor)
- Number of cars in the train
- Maximum seating per car
- Average load capacity per car; this is a percent value that represents the average car loading for the time period the user is interested in analyzing emissions
- Average weight per passenger (pounds); the default value is 150 pounds
- Maximum hotel load per coach (kW); the default value used in the module is 25kW
- Car HVAC operating level (normal, high, and maximum)

Also, because different rail cars serve different regional demands, the operating conditions of light-rail trains can vary greatly. Whenever possible, users should use second-by-second speed data collected from the field as input to the rail power estimators.

- **Heavy-rail Transit:** Heavy-rail trains are usually larger and longer than light-rail trains, and operate on fully-grade-separated rights-of-way. A heavy-rail train can normally hold up to 1,500 passengers. Heavy-rail often receives power from an electrified rail below the train, which should be processed using the AE calculator in the FEC. The same list of vehicle configuration data used in the light-rail calculator above should be provided for heavy-rail systems, including the average weight of unloaded car, number of axles per car, train drag coefficient, number of cars and seats, passenger load, hoteling load and weight of passengers. Furthermore, there are several additional inputs should be specified for a heavy-rail system. First, the elevation of stations should be provided in the route information module to assess the impact of grade separation. Second, the mass components of the railcar, including the mass of unloaded car and the mass of passengers, should be customized to reflect the influence of this weight. Finally, the train demand may vary greatly by time periods, and representative operating data should be prepared by users to analyze one or more time periods.
- **Commuter Rail:** Commuter rail passenger train service often utilizes DE propulsion trains. Commuter rail only appears in large metropolitan areas within the U.S., normally serving longest-distance trips made during weekday peak periods. Commuter rail often operates at speeds between 30 and 50 mph, with relatively few station stops. In the FEC, the DE calculator should be used for commuter rail, and additional information should be provided to configure the train, which are listed below:
 - Rated engine power of the locomotive (hp)
 - Source of hotel load power supply for DE trains
 - Number of traction locomotives or locomotive units in the train assembly (currently the model is only supporting one traction locomotive; future versions will incorporate the functionality to analyze multiple traction locomotives per train)

- Average weight of locomotive (tons)
- Typical weight of locomotive (tons)

The diesel fuel properties should also be provided by users. Finally, the research team recommends that users provide representative second-by-second speed profiles as inputs.

3.5.2 Rail Analysis Module

The rail calculator employs six major steps for analyzing the energy consumption of different rail options:

- The module uses the second-by-second speed values to estimate instantaneous distance traveled (miles) each second.
- The unit resistance to the moving train is estimated from the modified Davis Equation, grade resistance, and resistance due to acceleration and deceleration.
- The second-by-second speed data are used to assess whether the train is starting from idle at any instance. The total estimated starting tractive effort is compared to the maximum rated starting tractive effort for the locomotive. If the estimate is higher than the rated starting tractive effort, the module defaults to the rated value.
- The hoteling load is estimated for each train option.
- Energy recovery from regenerative braking is estimated for trains with in-built regenerative braking systems.
- The total tractive power and total hotel load are estimated separately. Instantaneous tractive power is also expressed as a percentage of the rated engine power.

3.5.3 Rail Output Module

The AE rail output module estimates energy consumption and emissions in four steps, starting with a throttle/notch based analysis for tractive power generation. The second step yields related emissions for hotel load supply. The third step estimates equivalent emissions for SO₂ and CO₂. The fourth step produces the related N₂O and CH₄ emissions.

The AE rail output module estimates energy consumption and emissions based on the estimated total electrical power consumed for propulsion and the WTP emission rates from GREET. The estimated emissions from these modules are converted into per seat-mile equivalents by dividing the outputs by: the length of the trip, the number of railcars in the train, and the seating capacity per railcar.

The research team is currently working on developing cost profiles for rail systems. Until such cost estimates are available in the model, users can input their own profiles into the model.

3.5.4 Rail Case Study

The MAX Blue Line light-rail route in Portland, OR is assessed using the FEC AE sub-model. The general settings of this train are provided in Table 3 below. The station mile post, station

elevations, and second-by-second speed profile are also provided as model inputs (data are entered into the spreadsheet tool).

Table 6. MAX Blue Line Input Settings

Coach Information	
Typical weight of unloaded car (tons)	54.5
Number of axles per car	6
Train drag coefficient	0.07
Number of cars in train	2
Maximum seating per car	64
Average load capacity per car (%)	43
Average weight per passenger (pounds)	150
Maximum Hotel load (kW) per car	25
Car HVAC Operating Level	Normal
Starting Tractive Load (STE)	
Ambient Temp. (°F)	74
Track Type	115 lb. track
Weather	Dry
Track Condition	Good rail and crossties
Maximum STE (pounds)	80,000
Energy Recovery	
Is Regenerative Braking Available?	No
Efficiency (%)	0
Application in All-Electric Trains	Back into Grid

The light-rail train traveled 32.4 miles during 1.67 hours, with an average speed of 19.35 mph. The emissions estimated for the selected rail routes are shown in table below. With 55 passengers on board (based on average load percentage), the CO₂e emission per passenger mile is about 0.158 kg/passenger/mile.

Table 7. MAX Blue Line Emission Outputs

TOTAL EMISSIONS									
CO ₂ (kg)	CH ₄ (g)	N ₂ O (g)	CO ₂ e (metric tonnes)	CO (g)	VOCs (g)	NO _x (g)	PM _{2.5} (g)	PM ₁₀ (g)	SO ₂ (g)
278.6	9.7	5.3	0.28	245.3	5.19	336.2	13.89	25.41	422.2
EMISSIONS PER VEHICLE MILE									
CO ₂ (kg)	CH ₄ (g)	N ₂ O (g)	CO ₂ e (metric tonnes)	CO (g)	VOCs (g)	NO _x (g)	PM _{2.5} (g)	PM ₁₀ (g)	SO ₂ (g)
8.6	0.3	0.16	8.7E-3	7.57	0.16	10.38	0.43	0.78	13.03
EMISSIONS PER SEAT MILE									
CO ₂ (kg)	CH ₄ (g)	N ₂ O (g)	CO ₂ e (metric tonnes)	CO (g)	VOCs (g)	NO _x (g)	PM _{2.5} (g)	PM ₁₀ (g)	SO ₂ (g)

0.067	2.3E-3	1.3E-3	6.8E-5	0.059	1.3E-3	0.081	0.0033	0.0061	0.102
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3.6 Chapter Summary

In this chapter, the FEC specifications by transportation mode were provided for FEC Version 2,0 calculators. The description of each mode-specific modeling approach in the FEC was followed by a case study to illustrate how the model can be employed for specific research purposes. Notes describing ongoing development efforts were also provided for some of the specific modules and modes.

4. FEC Online Version 2.0

As discussed in the introduction, the researcher team concluded that an online calculator written in Python code was needed to support the implementation of more complex analyses and to improve modeling convenience and speed. To preserve the transparency of the model, it was imperative that the online model contain all of the same functions and algorithms and perform exactly the same as the Excel model with respect to inputs and outputs.

The development of the online calculator development included two major steps. First, all of the FEC algorithms were replicated using Python Script. Second, the look-up tables used in the FEC spreadsheet tool, such as MOVES emission rate table, were stored as CSV files accessible to the Python program. The restructured FEC approach to algorithm implementation is shown in the following diagram. The yellow box indicates the model input, the green boxes indicate the individual Python scripts, the red boxes refer to data tables, and blue boxes represent model outputs.

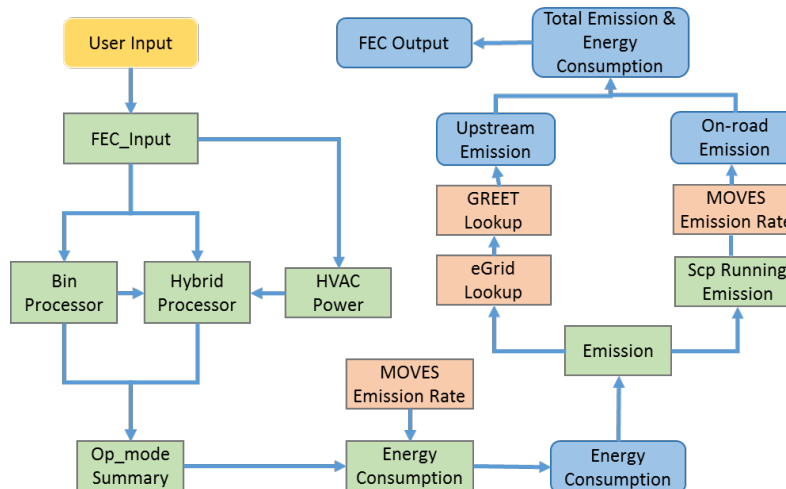


Figure 4 FEC Python Version Work Flow

The correlation between Python version and spreadsheet version are tabulated in the following tables. Table 8 includes the reference between python script and spreadsheet tool. Table 9 provides the relationship between data files used in Python code and the spreadsheet tables.

The FEC Python version can be run on an individual computer or a server or executed on a server, allowing the model to be integrated into more complex modeling work. Also, the Python version allows users to employ a duty cycle of any length, improving flexibility and estimation accuracy.

Table 8. Summary Table of FEC Online Version 2.0 Python Code

Python File	Tables in Spreadsheet Tool	Function Description
Fec_input	InputOutput_bus	<ul style="list-style-type: none"> • Take user input with the same format as spread sheet tool • Call energy consumption and emission calculation modules • Return emission outputs in the same format as the spreadsheet tool
HVAC_power_cons	HVAC Pwr Cons.	<ul style="list-style-type: none"> • Estimate hoteling power
Bin_Processor	Bin_Processor New Bin Generator P New Bin Generator S	<ul style="list-style-type: none"> • Allocate bin distributions to selected duty cycle • Receive processed STP as input
Hybrid_processor	HybridProcessor	<ul style="list-style-type: none"> • Adjust bin distribution for hybrid vehicles
op_mode_summary	OpModesummary	<ul style="list-style-type: none"> • Summarize bin distributions for combustion engine and hybrid engine
Energy_consumption	OpModesummary; Energy consumption part within InputOutput_bus	<ul style="list-style-type: none"> • Calculate energy consumption for all powertrain options
scp_running_emission_calculation	Scp1RunningEmissionsCalculation	<ul style="list-style-type: none"> • Calculate tailpipe emissions
Emissions	Emission calculation part within InputOutput_bus	<ul style="list-style-type: none"> • Calculate emissions for all powertrain options
Constant	-	<ul style="list-style-type: none"> • Provide necessary reference tables, path to data files and vocabularies

Table 9. Summary Table of FEC Online Version 2.0 Data Files

Csv file	Tables in Spreadsheet Tool	Content	Editable?
sourceusertypephysics.csv	sourceTypePhysics	Parameters used for VSP/STP formula	No
MeteoLookup.csv	MeteoLookup	Meteorology scenario lookup	No
CycleLookup.csv	Cycle_Lookup	Sample cycle from FEC excel	No
CustomInput.csv	Cycle_Lookup	Duty cycle provided by user	Yes
GreetLookup.csv	Em_Fact_Upstream	GREET data for upstream emission	No
eGridLookup.csv	eGRID	Emission rate for EV	No
FuelTypeIDNameMap.csv	Fuel_Type_Lookup	MOVES standard fuel ID	No
MovesER.csv	MOVES emission rates	MOVES emission rate	No
CityLookup.csv	CityLookup	City terrain roughness lookup file	No

With the algorithm scripted in Python, the online calculator has been established at the URL <http://fec.ce.gatech.edu/bus/>. The web interface is scripted with HTML and JavaScript, and

hosted on the same server as FEC official website. The online version currently incorporates only the transit bus calculator. The calculators for other transportation modes and cost-effectiveness modules are still being translated to Python code. The final goal of the online calculator is to incorporate complete functionalities for all modes, all source types within each mode, and all cost modules.

5. Conclusions and Future Work

The Fuel and Emissions Calculator (FEC), Version 2.0, was originally developed for transit vehicles in the form of an Excel spreadsheet, to support analyses by individuals so that all data and calculations are in plain view. Version 2.0 is available in Excel format as well as a Python code, to support connectivity between the FEC algorithms and other models (such as travel demand or simulation models).

Four major functional modules in the FEC were introduced in Chapter 2, including the scenario setting module, energy consumption module, on-road emission rate module, life-cycle assessment module, and cost-effectiveness module. For each transportation mode, separate FEC algorithms have been developed that apply the generalized GREET and MOVES-Matrix methodology, coupled with mode-specific settings. FEC Version 2.0 currently supports four calculators, including the: transit bus calculator, shuttle bus calculator, heavy-duty truck calculator, and rail transit calculator. To support analyses of different vehicle types within each calculator (e.g. school buses and express buses), analysis can be customized through user-specified inputs and modification of vehicle configuration parameters in the model as outlined in this report.

The research team will continue to maintain and update the current FEC and make the spreadsheet model and documentation available online. The team will also continue to publish articles and conduct outreach activities so as to serve more potential users.

The potential future works for FEC are listed below:

- **Hybrid Calculator:** The hybrid module in the FEC will be updated based on most recent research findings, and customized for different vehicle types.
- **Truck Calculator:** The vehicle model specifications of heavy-duty truck calculator will be updated to allow for more MOVES heavy-duty truck classifications. Currently, we only considered some features of heavy-duty truck, including weight, extended idling, duty cycles and source type physics parameters. Additional variables, such as detailed vehicle component (trailers, tanks, refrigeration units, etc.) which affect the engine load, will be included. The features of battery for trucks will also be adjusted, including capacity, efficiency, and cost.
- **FEC for other transportation modes:** the FEC will be updated to include following transportation mode:
 - Express bus (currently modeled as transit city buses)
 - School bus (currently modeled as transit city buses)
 - Passenger car
 - Bike and walk
 - Single-unit heavy-duty truck
- **Online version:** The FEC official website will be further improved to incorporate the latest information as new versions of the model are released (with release notes). The

online tool will be modified to enhance model output visualization, increase functionalities, and provide updated modeling guidance and user instructions.

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Appendix A: Major Updates in the FEC Version 2.0

Table 10. Major Updates in FEC Version 2.0

No.	Module	Version 1.0	New Version 2.0	Affect Output?
1	InputOutput_bus	No warning message	Add warning message for not available or not recommended fuel type	No
2	InputOutput_bus	No biodiesel 100	Add biodiesel 100 (pure biodiesel)	No
3	MOVES emission rate	Use MOVES emission rates from 2010 to 2012	Use MOVES 2014 emission rates from 2015 to 2025	Yes
4	MOVES emission rate	Use road type in lookup function; Use number to format opMode bins	Delete road type; Use text to format opMode bins	No
5	Bin processor Hybrid processor New bin generator p New bin generator s	Apply braking/deceleration bin allocation method based on MOVES2010 documentation	Apply the new braking/deceleration bin allocation method based on MOVES2014 documentation	Yes
6	Hybrid processor New bin generator p New bin generator s	Use 17.1 for all fixed mass factor parameter	Use different fixed mass factors according to source type	Yes
7	EM fact upstream	Using old version of GREET Model from 2010 to 2012	Using new version of GREET Model from 2015 to 2025	Yes
8	EM fact upstream	Use liquid hydrogen	Use gaseous hydrogen	Yes
9	Cost-effectiveness module	Only 2 example cost profiles Cost calculations do not consider time value of money	Update cost profiles for each alternative fuel and powertrain type Reflect time value of money in cost calculations	Yes

Appendix B: VSP and STP Operating Mode Bin Definitions

Operating Mode ID	Operating Mode	Vehicle-Specific Power (or Scaled Tractive Power)	Vehicle Speed	Vehicle Acceleration
	Description	VSP _t (or STP _t), kW/metric ton	v _t , mph	a, mph/sec
0	Deceleration/Braking			a _t ≤ -2.0 OR (a _t < -1.0 AND a _{t-1} < -1.0 AND a _{t-2} < -1.0)
1	Idle		-1.0 ≤ v _t < 1.0	
11	Coast	VSP _t (or STP _t) < 0	1 ≤ v _t < 25	
12	Cruise/Acceleration	0 ≤ VSP _t (or STP _t) < 3	1 ≤ v _t < 25	
13	Cruise/Acceleration	3 ≤ VSP _t (or STP _t) < 6	1 ≤ v _t < 25	
14	Cruise/Acceleration	6 ≤ VSP _t (or STP _t) < 9	1 ≤ v _t < 25	
15	Cruise/Acceleration	9 ≤ VSP _t (or STP _t) < 12	1 ≤ v _t < 25	
16	Cruise/Acceleration	12 ≤ VSP _t (or STP _t)	1 ≤ v _t < 25	
21	Coast	VSP _t (or STP _t) < 0	25 ≤ v _t < 50	
22	Cruise/Acceleration	0 ≤ VSP _t (or STP _t) < 3	25 ≤ v _t < 50	
23	Cruise/Acceleration	3 ≤ VSP _t (or STP _t) < 6	25 ≤ v _t < 50	
24	Cruise/Acceleration	6 ≤ VSP _t (or STP _t) < 9	25 ≤ v _t < 50	
25	Cruise/Acceleration	9 ≤ VSP _t (or STP _t) < 12	25 ≤ v _t < 50	
27	Cruise/Acceleration	12 ≤ VSP _t (or STP _t) < 18	25 ≤ v _t < 50	
28	Cruise/Acceleration	18 ≤ VSP _t (or STP _t) < 24	25 ≤ v _t < 50	
29	Cruise/Acceleration	24 ≤ VSP _t (or STP _t) < 30	25 ≤ v _t < 50	
30	Cruise/Acceleration	30 ≤ VSP _t (or STP _t)	25 ≤ v _t < 50	
33	Cruise/Acceleration	VSP _t (or STP _t) < 6	50 ≤ v _t	
35	Cruise/Acceleration	6 ≤ VSP _t (or STP _t) < 12	50 ≤ v _t	
37	Cruise/Acceleration	12 ≤ VSP _t (or STP _t) < 18	50 ≤ v _t	
38	Cruise/Acceleration	18 ≤ VSP _t (or STP _t) < 24	50 ≤ v _t	
39	Cruise/Acceleration	24 ≤ VSP _t (or STP _t) < 30	50 ≤ v _t	
40	Cruise/Acceleration	30 ≤ VSP _t (or STP _t)	50 ≤ v _t	