Fuel and Emissions Calculator (FEC), Version 3.0, Summary Report

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A National Center for Sustainable Transportation Report

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TABLE OF CONTENTS

List of Tables

List of Figures

List of Acronyms

AE	All-electric
ANL	Argonne National Laboratory
BEV	Battery electric vehicle
BRT	Bus rapid transit
CCSD	Cobb County School District
CO	Carbon monoxide
CBD-SAE1376	Central Business District Cycle
CI	Compression ignition
CNG	Compressed natural gas
CO_2,	Carbon dioxide
CO_2e	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
IM	Inspection and maintenance
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	Megawatt hour
NA	Not applicable
NaviGAtor	The intelligent transportation system operated by GDOT
N_2O	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
WTW	Well-to-wheel (includes WTP and PTW)

Fuel and Emissions Calculator (FEC), Version 3.0, Summary Report

EXECUTIVE SUMMARY

The Fuel and Emissions Calculator (FEC) is an operating-mode-based, life-cycle energy and emissions modeling tool developed by 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 operating 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 FEC Version 2.0 and Version 3.0, the research team also created an online Python version of the model. 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). The first major update of the model was finished in 2016 (FEC Version 2.0). FEC Version 2.0 expanded the initial FEC to include a heavy-duty truck calculator and an online Python version of the transit fleet model (transit bus and shuttle bus). Version 2.0 also significantly improved the model performance by incorporating the latest emission rates, advancing the methodologies, and fixing some errors. The research team completed the next major updates in 2018, releasing FEC Version 3.0. Version 3.0 is the "FEC for all transportation modes", with mode-specific calculators for light-duty passenger vehicles, buses, heavy-duty trucks, and rail. This report first summarizes the FEC Version model's main features in Version 3.0. 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, where case study examples are provided to help users prepare customized analysis of their own fleets. The key considerations for establishing the online FEC are discussed in Chapter 4. Ongoing work to verify model elements and calibrate the FEC is introduced in Chapter 5. Current research achievements and future 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 (ORNL and Georgia Tech, 2014), 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 environmental conditions. The FEC facilitates customized and flexible assessments that account for local on-road operating conditions. The research team has applied the FEC in a number of published applications, assessing 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 and Version 3.0 have also been prepared using 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 (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 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 light-duty vehicles, other buses and trucks 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 and Version 3.0 was decomposed into separate spreadsheets for each mode, so that emission rates can be expanded. Individual Excel spreadsheet calculators for other applicable transportation modes are developed for Version 3.0. Currently, all transportation modes have been supported in separate spreadsheets for emission and energy calculation.

- With FEC Version 2.0 and Version 3.0, the research team has tailored the model to support real-time analyses and direct linkages between the FEC and travel demand and traffic simulation models. An online version of FEC written in Python provides the same functionality as the Excel spreadsheet calculators. All the transit calculator functions scripted in Python are hosted on a Georgia Tech server.

- Finally, previous publications, tool documentations and model tutorials 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 Python version. After describing the methodologies that apply to each mode, the report provides several case studies 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 the user or driving cycle defaults selected by the user. **Figure 1** below illustrates the FEC modeling framework. 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's input processors (rail modules use a separate scenario-creation process).

- The model employs scaled tractive power (STP), or vehicle-specific power (VSP) depending on vehicle type and hybrid powertrain type to estimate energy consumption for the selected vehicle type and powertrain options. Separate methods are used for rail options (rail-cycle modules).

- Tailpipe emissions (pump-to-wheel) are estimated by matching STP/VSP operating mode bins with emissions rates from the U.S. Environmental Protection Agency's (USEPA's) MOVES (MOtor Vehicle Emissions Simulator) model (USEPA, 2014).

- Emissions associated with 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, 2018). 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:
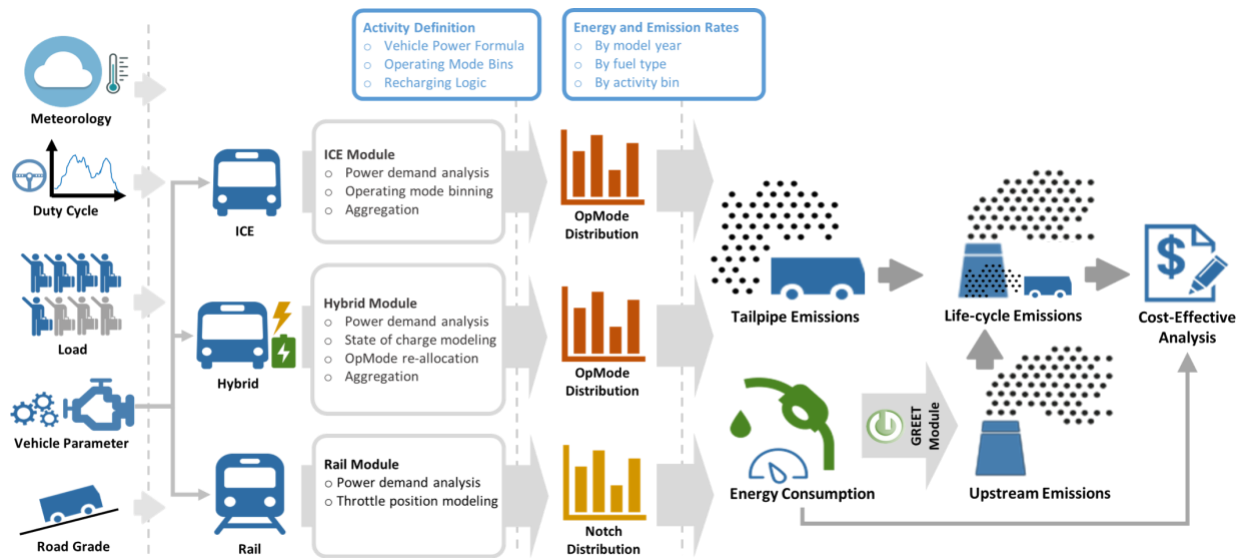
Figure 1. Calculator Structure

2.1. Scenario Setting Module

In the FEC 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 a literature review and previous research efforts 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 are introduced separately in following chapters), the following information must be prepared to run the model:

- **Fleet option:** FEC adopts the vehicle types defined in MOVES to represent fleet options. Users need to choose the fleet before performing calculations. The FEC modeling system has incorporated most widely used vehicle fleet, including passenger cars, passenger trucks, shuttle buses (or light commercial trucks), intercity buses, transit buses, school buses, single-unit short-haul/long-haul trucks, and combination short-haul/long-haul trucks. Each fleet option has mode-specific input sets, default driving cycles and emission rates.

- **Geographic Boundary**: The geographic input is the city and state for the modeling work. The geographic boundary is used to select an appropriate terrain roughness, meteorology, fuel composition, and I/M program characteristics (for applicable energy use and emissions rates). Location also impacts the power generation mix employed in life-cycle emission estimates for electricity production. The MOVES-Matrix model (as described later) has been run for 12 representative counties, or FEC analysis regions, using the fuel composition and inspection and maintenance program data for these

counties (Guensler, et al., 2016). Expanding beyond 12 regions in the FEC was not practical given the spreadsheet format. However, 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 and terrain roughness. Future online versions of the FEC will eventually be able to integrate energy use and emission rates from all 117 unique regional combinations of fuel compositions and inspection and maintenance programs across the country.

- **Calendar Year:** Emission rates are affected by calendar year of analysis due to fleet turnover, as new vehicles and advanced engine technologies that meet more stringent emissions standards replace older vehicles dropped from the fleet (fleet emissions decline and fuel economy increases with fleet turnover). The FEC currently includes single calendar year options between 2015 and 2025. For projects that need to assess the impacts of older transit vehicles, users can integrate applicable emission rates from MOVES-Matrix for these model years directly into the FEC worksheet.

- **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 in the FEC, the user can 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 for 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 per vehicle 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. The sets of driving cycles vary by vehicle categories, and separate cycles are prepared for light-duty passenger vehicles, buses, trucks and rails. Moreover, 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 vehicle can be significantly affected by vehicle occupancy and cargo load, which impacts engine load. Users can set default vehicle loading or enter loading data from other sources.

- **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, 85% ethanol (E85), 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 (or E85 vehicles), and compression ignition (CI), diesel vehicles (or CNG 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 model 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 and 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 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 use 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 (i.e., pump-to-wheel, or PTW) by matching the calculated operating mode bin (based upon VSP/STP 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. Vehicle model years are currently set to be the same as calendar year for emission rates because the FEC was designed to assess the impacts of new fleets. The current emission estimation includes three steps:

1) Second-by-second operating mode (opMode) bins are aggregated to obtain the opMode distribution for ICE, parallel-hybrid, and series-hybrid vehicles respectively.

2) 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.

3) 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 CO_2, methane (CH_4), nitrous oxide (N_2O), elemental carbon, CO_2 equivalent, carbon monoxide (CO), volatile organic compounds (VOCs), oxides of nitrogen (NO_x), total primary exhaust $PM_{2.5}$, total primary exhaust PM_{10}, and sulfur dioxide (SO_2).

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 rates are used 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 and 3.0, emission rates were prepared from 2015 to 2025 for all vehicle types, which will be introduced in following chapters.

2.4. Well-to-pump Energy and Emissions Module

In the FEC, well-to-pump (WTP) emissions were prepared using data from the GREET model (ANL, 2015) and the eGRID database (USEPA, 2018). 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 representative 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 well-to-pump (WTP) fuel model operates independently from the downstream pump-to-wheel (PTW) model. 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 used to generate electricity vary across regions. 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 producing total megawatt hours (MWh) of electricity by state were used as the emission rates in the FEC. WTP emissions for electricity are calculated by multiplying energy consumption by emission rates per unit energy use for selected states.

Finally, 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-wheel analysis, which includes well-to-pump and pump-to-wheel 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 consumption 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) WTP energy and emissions, related to the production and distribution of the fuel; and 2) 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, equipment surplus value, and end-of-life disposal costs. All of these costs are discounted (a discount rate is applied) and then totaled to a net value in current dollars, known as net present value (NPV). The initial cost includes 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 CO_2 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 O&M costs, defined in the cost profile module, users can still apply the cost-effectiveness module to other fleets. Users are allowed to enter their own cost data into this sheet, with all the costs represented by NPVs 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 open source, all calculations are embedded in a spreadsheet tool, and the tool is provided free to all the users. The current tool is also now available 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 FEC has evolved from a transit mode energy and emissions calculator into a calculator that is applicable to all transportation modes. FEC Version 1.0 only included transit bus, shuttle bus and rails, with limited calendar years available for analysis (ORNL and Georgia Tech, 2014). The interim version of FEC (Version 2.0) includes dedicated algorithms for transit bus, rail, shuttle bus/van, and long-haul combination trucks. The latest version of FEC (Version 3.0) incorporates all widely used fleets, including passenger cars, passenger trucks, shuttle buses, intercity buses, transit buses, school buses, rails and trucks. Other similar vehicles can also be analyzed using the current FEC by customizing data inputs or vehicle configuration parameters. This section of the report is designed to assist users in applying the current FEC model in 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 and Version 3.0 Improvements

So far, FEC has experienced two major updates since the release of the first version. The major updates in FEC Version 2.0 and Version 3.0 have listed in **Table 1** below.

Table 1. Major Updates in FEC Version 2.0 and Version 3.0

Fleet Option	Version 1.0	Version 2.0	Version 3.0
Bus	Transit bus only; Obsolete emission rates.	Transit bus only; Updated emission rates.	Separate tools for transit bus, school bus and intercity bus; Updated emission rates.
Light-duty passenger vehicle	Shuttle bus only; Obsolete emission rates.	Shuttle bus only; Updated emission rates.	Separate tools for shuttle bus, passenger car and passenger truck; Updated emission rates.
Truck	No truck module available.	Combination long-haul truck only; Updated emission rates.	Separate tools for single-unit short-haul truck, single-unit long-haul truck, combination short-haul truck and combination long-haul truck; Updated emission rates.
Rail	All-electric (AE) rail and diesel – electric (DE) rail.	No updates.	Python version of AE rail calculator; An Atlanta case study.

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. The O/M costs in the cost-profiles were incomplete.

FEC Version 2.0 included all of the major functions in Version 1.0. Updated energy consumption and emission rates have been included from MOVES and GREET. In each new version, methodologies are updated using the latest research findings, and more scenario options are made available in the scenario setting module. The major updates in Version 2.0 are 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 remained under development. The costs in cost-effectiveness module were represented by NPV values. The O/M costs in the cost-profiles were incomplete.

- An online version is developed with the exactly the same functions as the transit bus calculator.

FEC Version 3.0 includes all of the major functions previously included in Version 2.0. FEC Version 3.0 now incorporates all common vehicle fleets in the MOVES modeling system (small fleet elements, such as trash collection trucks and recreational vehicles, are not yet included). The major updates in Version 3.0 are listed below:

- Individual calculators were developed for common vehicle fleets, including light-duty passenger vehicle types, buses, trucks, and rails.

- **Scenario setting module:** Version 3.0 facilitated emission analysis for all transportation modes for calendar year 2015 to 2025. The input settings have been customized for each fleet and will be introduced in following sections.

- **On-road emission rate module:** The on-road emission rates came from MOVES 2014 have been added for all transportation modes.

- **Life-cycle analysis module:** The upstream electricity emission rates have been updated using latest eGRID database.

- A Python version of all-electric rail calculator has been developed and applied for the Atlanta heavy-rail system energy calculation/

The Georgia Tech research team recommends using Version 3.0 for all current and future analysis (unless there is some need to re-run older scenarios or compare previous work with new work). The detailed updates made to previous modeling algorithms are provided in Appendix A of this report. The team will continually update the online version, incorporating new features and functionalities. The sections of this report that follow provide suggestions for user-customization of the FEC for their own fleets.

3.2. Bus Calculator

In the FEC, the 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, bus specifications will be introduced by functional module, as will 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 **Table 2** below:

Table 2. 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 (≤ 5 mph)	Accounts for GPS wander at low speeds, consult GPS device user manual

The 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). So far, separate spreadsheet tools have been developed for other typical bus fleet, such as intercity buses and school buses. The users are able to apply vehicle specific parameters for energy calculations and vehicle specific emission rates for emission calculations. It is preferred that users customize some settings for alternative fuel and powertrain vehicles, such as battery size and electric motor power, in the hybrid processor module to properly estimate the energy consumption and emissions from such vehicles.

To model a bus fleet, users choose the corresponding vehicle classification as discussed below. 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 field-collected on-road speed-time data 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 for short-distance public transport bus services. Transit bus models include low-floor buses, double-decker buses, articulated buses, and midi-buses. For on-road operation, city buses usually experience low average speeds and makes frequent stops. However, the performance of 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 parameter) in the "formula" sheet when better vehicle data are available.

- **School Bus:** School buses carry students between school and home, or to and from school events. In the U.S., standard yellow school buses are readily distinguishable 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 use the school bus calculator with specific MOVES emission rates and STP parameters. Several 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 cycles embedded in the FEC.

- **Private City-to-City (Intercity) Bus:** Private city-to-city bus operations provide intercity trips for private purposes. These buses may belong to travel agencies, private companies (for event or business use), local communities, churches, clubs, etc. Intercity buses are designed for passenger comfort and usually carry passengers with their luggage on relatively long journeys; hence, these buses are heavier than typical transit buses. Intercity buses typically operate on highways, with 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 use the intercity bus calculator with specific MOVES emission rates and STP parameters. Users can either input duty-cycles from in-field private bus data collection, or choose a representative 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. Commuter buses are designed for comfort and business productivity, often providing internet connectivity, reading lights, and drop-down writing tables. Express buses typically run less frequently than transit buses, during the peak period, and serve fewer stops than transit buses. Express buses usually operate on highways, at significantly higher average speeds than urban transit bus. Users can either input the duty-cycles from field data collection or choose from default bus cycles embedded in the FEC. Currently, users can select "intercity bus" as a surrogate for express bus and apply an express bus duty cycle. The diesel intercity bus energy consumption and emission rate in the FEC reasonably represent express bus energy and emission rates, as they are similar in vehicle characteristics.

- **Bus Rapid Transit:** Bus rapid transit (BRT) is a mass transit system designed to provide efficient, limited-stop, high-quality service. High-capacity vehicles, such as articulated or double-decker buses, are often used to improve efficiency. BRT systems often operate on dedicated lanes and receive signal priority at intersections. Compared to regular transit buses, BRT operate at higher speed with fewer station stop interruptions. In the current version of the FEC, users can select "Transit Bus" under the "vehicle classification" option as a surrogate for BRT, and then apply the GRTA express bus driving cycle or a user-collected driving cycle from the bus route. In Version 4.0, the research team plans to integrate vehicle weight and other parameters to better-reflect BRT bus options (which are larger and heavier than regular buses). Alternative fuel options will also be integrated into the next FEC version, as BRT systems are expected to use new technology vehicles.

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. 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 and in emission rate generation is shown below (Guensler, et al., 2016; 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. 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•s^2/m^2)

C = the aerodynamic drag coefficient (kW•s^3/m^3)

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/s^2)

g = gravitational acceleration with the value 9.8 m/s^2

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, defaults to 68 kg (150 lbs) 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 use 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. The research team is currently developing a more advanced HEV module for integration into FEC Version 4.0.

- **BEV and FCEV:** The electric motor is the sole component that turns the wheels at the final axle for series-hybrids, BEVs, and FCEVs. The energy consumption modeling of electric buses, including BEVs and FCEVs, employs the calculated 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 electric vehicles (PFCEVs), 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 (PHEVs), 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 ID 41 (intercity bus), 42 (transit bus), and 43 (school bus), across all possible combinations of model input scenarios. Emission rates are provided for all major fuel sources deployed by bus fleets, including diesel, CNG, biodiesel, and gasoline. Because gasoline is rarely used in these transit fleets, 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 demonstrates that the activity-based approach is preferable to applying generic methods that employ average fuel economy. To depict the impact of driving cycles on the estimation, carbon dioxide equivalent (CO_2e) emissions are estimated by the FEC for 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 **Table 3** below:

Table 3. 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	Transit bus
Route Length (mile)	22
Average Passenger Loading per Bus per Run	10

Figure 2 below includes the CO_2e 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 use and emissions under the NYBC are much higher than under other cycles.
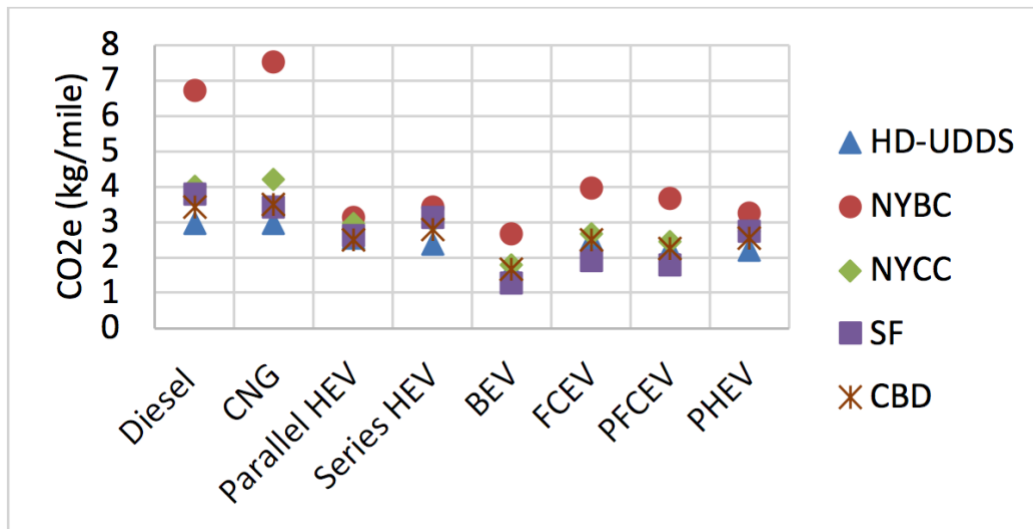
Figure 2. Comparison of Five Driving Cycles with the CO_2e Emissions

3.3. Light-duty Passenger Vehicle Calculator

The light-duty vehicle calculators apply the same basic algorithms used for larger transit buses. However, the light-duty vehicle calculators employ different vehicle parameters (for each selected vehicle type), on-road emission rates, and driving cycles. On the emission rate side, the tailpipe emission rates have been updated with emission rates of light-duty cars and trucks

(MOVES Source Type 21, 31 and 32) from MOVES2014 for year 2015 to 2025. 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 and Version 3.0. On duty cycle side, the typical local and highway light-duty vehicle driving cycles have been integrated into FEC for users to choose from. The cycle information is listed in **Table 4** below.

Table 4. Light-duty Vehicle Driving Cycles

Cycles	Cycle Names	Avg. Speed (mph)
LD Low Speed 2	LD Low Speed 1	2.50
FC14LOSF	Final FC14LOSF Cycle (C15R05-00424)	8.72
FC19LOSAC	Final FC19LOSAC Cycle (C15R08-00267)	15.73
FC11LOSF	Final FC11LOSF Cycle (C15R01-00876)	20.60
FC14LOSC	Final FC14LOSC Cycle (C10R04-00104)	25.38
LOSE Freeway	LD LOS E Freeway	30.50
FC12LOSE	Final FC12LOSE Cycle (C15R10-00782)	43.27
FC11LOSE	Final FC11LOSE Cycle (C15R11-00851)	46.13
FC12LOSD	Final FC12LOSD Cycle (C15R09-00037)	52.83
FC11LOSD	Final FC11LOSD Cycle (C15R10-00068)	58.79
FC11LOSC	Final FC11LOSC Cycle (C15R09-00849)	64.40
FC11LOSB	Final FC11LOSB Cycle (C10R02-00546)	66.36
FC01LOSAF	Final FC01LOSAF Cycle (C10R04-00854)	73.80
High Speed Freeway	LD High Speed Freeway 3	76.00

The major challenge of using FEC light-duty passenger vehicle calculator is to properly-select the vehicle source types for the fleet, which affects the VSP parameters applied. It is difficult to distinguish between passenger cars (STID 21) and light-duty trucks, which include passenger trucks (MOVES source type 31) and light commercial trucks (MOVES source type 32), as discussed in Liu, et al. (2015). Users can use the vehicle makes and models as references and search the EPA registration database to determine the appropriate vehicle types or fleet mix.

After selecting the vehicle source type, the user can choose to use the passenger car calculator, passenger truck calculator, or shuttle bus calculator for their fleet. 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 Shuttles:** Private shuttle are often dedicated for private uses and profit-oriented. Sample private shuttle systems include UberXL and Metropolitan Shuttle. Depending on the specific purpose of the service, the frequency and distance may vary significantly by service provider. In the FEC, as introduced above, the users need to select the proper calculator(s) for their fleet, based on the fleet makes and models.

Users should consider collecting more representative drive traces from the vehicle fleet to provide fleet duty-cycle input to account for potentially higher average speeds than are represented in current FEC-embedded duty cycles. 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 Shuttles:** Public transit shuttles are often operated by public transit agencies. Many universities also provide campus transit service using shuttle buses, 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 calculator for transit shuttle, and the emissions rates of light commercial trucks will be applied for modeling. Alternatively, users can select other light-duty passenger vehicle calculators if different types of vehicles are applied. Users can set the inputs based on the bus schedule if it serves as fixed routes, or input observed operating mode conditions if the shuttle serves as on-demand service.

- **Airport Connection Shuttles:** Airport shuttles often provide door-to-door service between airports and passenger origins/destinations. Airport shuttle services often deploy vans or shuttle buses for their fleet. Vehicle capacity limits the number of stops served. The shuttle may also operate at relatively high speeds between airport and destination. In the FEC, users can select the shuttle bus calculator for airport shuttles, and the emissions rates of light commercial trucks are applied. Users can select other light-duty passenger vehicle calculators if different vehicle types are used. The research team recommends that users collect their own GPS operating traces to serve as duty-cycle inputs (especially highway traces) to represent local condition. For route length, users can use estimated average to and from airport distances from a travel demand model under different scenarios.

- **Dial-a-ride/Paratransit**: Paratransit is specialized transit service for individuals 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 calculator for transit shuttles, and the emissions rates of light commercial trucks are applied. Users can select other light-duty passenger vehicle calculators if different vehicle types are used. 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 should consider adding the equipment into vehicle load by converting the mass of equipment into equivalent passenger load. Users should also integrate the cost associated with any ADA equipment into the vehicle cost profile.

- **Other On-demand Transit**: The research team plans to continue working on enhanced cost profiles for shuttle buses. Users are encouraged to develop their own vehicle profiles based upon their own local data whenever practicable and share this information with the research team.

3.3.1. Light-duty Passenger Vehicle Case Study

The case study below demonstrates the impact of passenger load of shuttles on total CO_2e emissions for a shuttle bus 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 **Table 5** below.

Table 5. Sample Inputs for the Transit Bus Calculator

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	Shuttle bus
Route Length (mile)	10
Average Freight Loading per Truck per Run	10/5/2

The figure below includes the CO_2e emissions per mile. Results from passenger loads are marked with different markers. The case study demonstrated that passenger load can affect energy consumption and CO_2e emissions. Vehicles with higher passenger load yield slightly higher emissions.
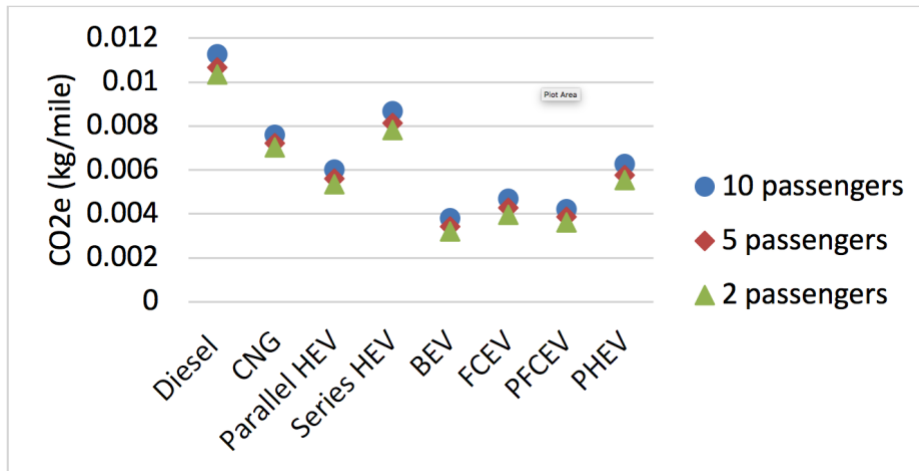

Figure 3. Comparison of Three Passenger Loads with the CO_2e Emissions

3.4. Heavy-Duty Truck Calculator

The heavy-duty truck calculator uses the same basic modeling approach as the bus calculator. Few modifications were required to customize the FEC for truck fleet analysis. The current FEC includes a single-unit short-haul truck calculator (MOVES source type 52), a single-unit long-haul truck calculator (MOVES source type 53), a combination short-haul truck calculator (MOVES source type 61), and a combination long-haul truck calculator (MOVES source type 62). Specific input settings for heavy-duty trucks are provided below:

- **Duty Cycle:** Besides keeping the HD-UDDS cycle, new cycles from MOVES2014 database were added into the calculator to represent a wide variety of heavy-duty truck operating conditions.

- **Weight:** The model provides a user-prompt to enter average freight load per run, which should use 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 types are limited to conventional diesel and biodiesel.

- **Idling Hours (for combination long-haul truck):** 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 MOVES2014 for extended idle operations (opMode bin number 200).

The major challenge in using the FEC heavy-duty truck calculator is properly selecting the vehicle source types for the fleet. It is relatively easy to distinguish single-unit truck and combination truck by counting axles and observing vehicle powertrain structures (Liu, et al. 2015). However, it is hard to separate short-haul and long-haul trucks. Users are encouraged to use the vehicle registration data for identification, the regional truck distribution, or MOVES default fraction as a surrogate.

An idling algorithm was added to the combination long-haul calculator to assess energy consumption and emissions during extended engine idle, which is common for heavy-duty trucks. Idle energy consumption for traditional engines 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 and share the information with the research team and other interested parties.

3.4.1. A Truck Case Study

The truck case study below analyzes 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 6** below.

Table 6. **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 options is shown in **Table 7** below. The idling energy consumption for this case accounts for about 17% of total energy consumption. Electric vehicles have significantly lower idling energy consumption.

Table 7. **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
Combined Energy Consumption per Run (kWh)	100.22	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 run 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 locomotive rated engine power, hotel load power supply source, and number of traction locomotives.

- **Starting Tractive Load (STL):** The specific information used for STL includes 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 SO_2, 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 operated 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:

    o Typical or average weight of unloaded car (tons)
    o Number of axles per coach car
    o Train drag coefficient (this value can be obtained from railcar vendor)
    o Number of cars in the train
    o Maximum seating per car
    o 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
    o Average weight per passenger (pounds); the default value is 150 pounds per passenger
    o Maximum hotel load per coach (kW); the default value used in the module is 25kW
    o 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 for 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 typically carry up to 1,500 passengers. Heavy-rail often receives power from an electrified rail below the train, which should be processed using the all-electric (AE) calculator in the FEC. The same list of vehicle configuration data used in the light-rail calculator above serve as input to the heavy-rail system, 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, users should specify several additional inputs 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, passenger demand may vary greatly during the day or by day of week, and users should consider developing representative operating data for one or more time-periods.

- **Commuter Rail:** Commuter rail passenger train services often utilize DE propulsion locomotives. Commuter rail only appears in large metropolitan areas within the U.S., normally serving longest-distance trips made during weekday peak periods. Commuter rail typically 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 all-electric (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 SO_2 and CO_2. The fourth step produces the related N_2O and CH_4 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 eGRID. The direct DE emission rates by notch come from the average emission rates generated from EPA's locomotive standards, while the upstream emission rates come from GREET. The estimated emissions from these modules are converted into per seat-mile equivalent 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. The team recommends that users develop cost profiles for their own systems, using local data whenever practicable, and share the information with the research team and other interested parties.

3.5.4. Python Version of the All-electric Rail Calculator

To enable rapid assessment of rail system energy and emissions in Metropolitan Atlanta, the AE rail calculator in FEC was coded using Python Script. The major benefits of the Python version of the AE calculator include fast execution speed, more flexibility in model inputs and highly detailed energy, and provision of emission profiles for each route and each station. The Python version of the rail calculator is composed of one input processing module and one emission processing module. For input processing module, the rail calculator needs two parts of input information as introduced above, including the route information and the railcar information. The route information includes general route information (location, route name, cycle name, etc.), route profile (mileposts and elevation) and speed profile (second-by-second speed profile). The railcar information includes the railcar characteristics (weight, drag coefficient, number of axles, etc.), passenger load information (number of passengers, average passenger weight, etc.), hoteling load and so on. In emission analysis module, the energy consumptions of rail operation are firstly estimated by calculate the tractive load, hoteling load and energy from recovery respectively. Each portion of energy consumption is calculated from second-by-second speed profile and user-specified gradient settings. Next, the total energy consumption is calculated by summing up the tractive load and hoteling load, then subtract the recovered energy consumption from regenerative braking. Finally, the emission results are estimated by multiplying energy consumptions and emission rates per unit energy consumed, where the electricity emission rates come from the eGRID database (USEPA, 2015). In FEC Version 4.0, the

research team will update the DE rail calculator parameters (via literature review) and a Python version will support online calculations.

3.5.5. Rail Case Study

In previous study, the model was applied to several rail systems in Portland, Oregon and Chicago, Illinois (Gbologah, et al. 2014). The results showed a predicted 1% to 8% difference in expected power consumption relative to estimates derived from the national transit database. Recently, the research team applied the Python Version AE rail calculator for the Metropolitan Atlanta Rapid Transit Authority's (MARTA's) heavy rail system, which is the 8th largest heavy-rail system within U.S. ranked by unlinked passenger trips in 2014 (2016 APTA Fact book, 2017). MARTA currently operates four rail routes, maintains 338 railcars, 38 stations and 48 miles of double track (MARTA, 2016). Here, this study is an example illustrating how to adopt the Python version AE calculator for any scale of all-electric rail service, like the MARTA rail system.

The critical part of energy and emission analysis is to prepare the route and railcar information which should be representative for the rail system operation. For the route information, the team adopted the route and trip information from General Transit Feed Specification (GTFS) data, which contains the route attributes such as route name, station location, schedules and mile post. In addition, the real-world GPS traces were used to generate speed profiles for each route. The vehicle occupancy come from real-world station-level entry and exit card reading data, which have been post-processed to remove duplicates, add transfer points and match with routes. The sample speed profile and route profile are provided in **Figure 4** and **Table 8** below.
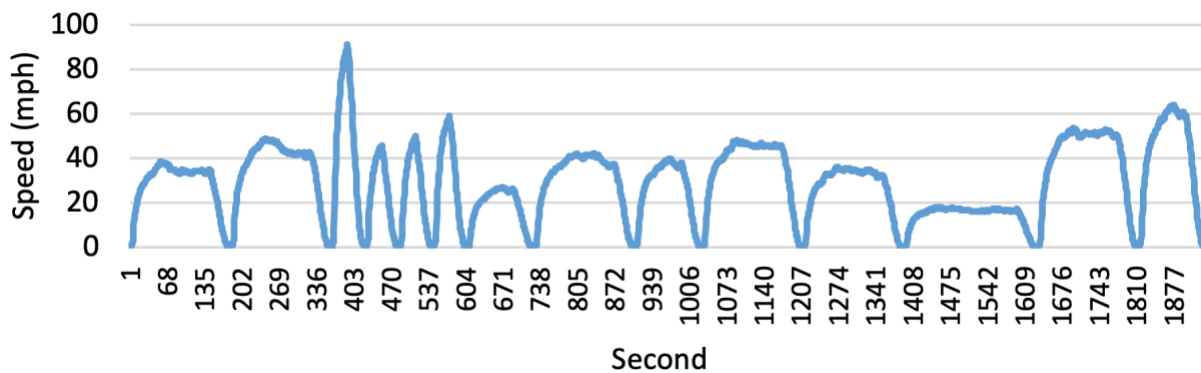

Figure 4. **Sample MARTA Speed Profile for Blue route**

Table 8. Sample MARTA Route Settings

	ID	Station Name	Occupancy (seating)	Occupancy (seating + standing)	Mile Post	Elevation
0	27	HAMILTON E HOLMES STATION	0.08	0.032	0.00	200
1	28	WEST LAKE STATION	0.10	0.04	1.40	200
2	485	ASHBY STATION	0.11	0.044	3.17	200
3	470	VINE CITY STATION	0.11	0.044	3.93	200
4	796	DOME-GWCC-PHILIPS ARENA-CNN STATION	0.11	0.044	4.32	200
5	797	FIVE POINTS STATION	0.06	0.024	4.74	200

For railcar information, railcar size, weight, and capacity come from the MARTA procurement plan, while other key parameters come from FEC default values. The railcar attributes are listed in **Table 9** below.

Table 9. MARTA Railcar Settings

Item	Value
Typical weight of unloaded car (ton)	40.5
Number of axles per car	6
Train drag coefficient	0.07
Number of cars in train	8 (blue), 2 (green), 6 (gold and red)
Maximum seating per car	64
Average weight per passenger (lbs.)	150
Max Hotel load per car (kw)	25
Car HVAC Operating Level	Normal
Ambient Temp	74
Track Type	115 lb track
Weather	Dry
Track Condition	Good rail and crossties
Maximum STE (lbs.)	80000
Is Regenerative Braking Available	Yes
Efficiency (%)	10
Application in All Electric Trains	Against Total Load

With those inputs, the AE calculator was executed for each route and each trip. The outputs include the route-level and station-level energy consumption and emissions. The average route level emissions and the one sample station-level energy consumption were provided in **Table 10** and **Figure 5** respectively:

Table 10. Average Emissions by Route

	TOTAL EMISSIONS									
Route	CO_2 (kg)	CH4 (g)	N_2O (g)	CO_2e (tonnes)	CO (g)	VOC (g)	NO_x (g)	$PM_{2.5}$ (g)	PM_{10} (g)	SO_2 (g)
MARTA Red Line	946.64	14.09	15.12	0.95	833.57	17.62	701.76	47.21	86.35	3166.87
MARTA Gold Line	878.50	13.08	14.03	0.88	773.57	16.35	651.25	43.81	80.14	2938.93
MARTA Blue Line	679.95	10.12	10.86	0.68	598.74	12.66	504.06	33.91	62.03	2274.71
MARTA Green Line	343.72	5.12	5.49	0.34	302.66	6.40	254.80	17.14	31.35	1149.87
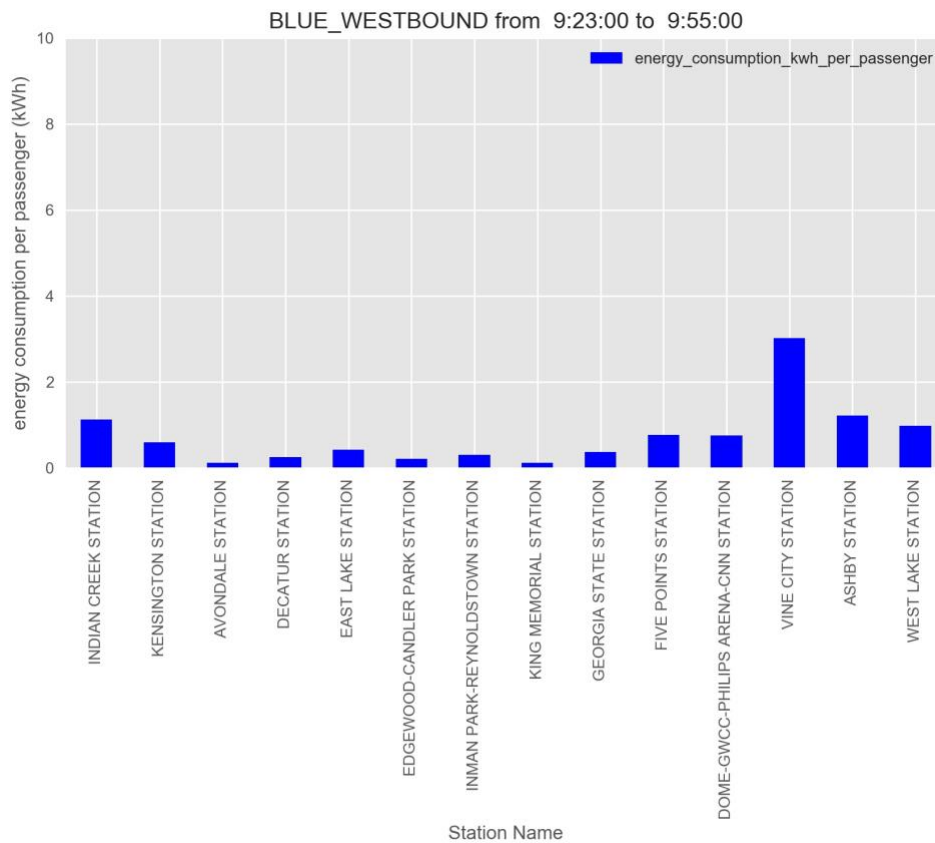
Figure 5. Sample Station-level Energy Consumption per Capita for MARTA Blue Route

3.6. Chapter Summary

In this chapter, the FEC specifications by transportation mode were provided for FEC Version 3.0 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

As discussed in the introduction, the research 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 employ the same functions and algorithms, perform exactly the same calculations as the Excel model, and use the same 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 rates, were stored as CSV files accessible to the Python program. The restructured FEC algorithm is shown in **Figure 6** below. The yellow box indicates the model input, the green boxes indicate the individual functional modules, the red boxes refer to data tables, and blue boxes represent model outputs.
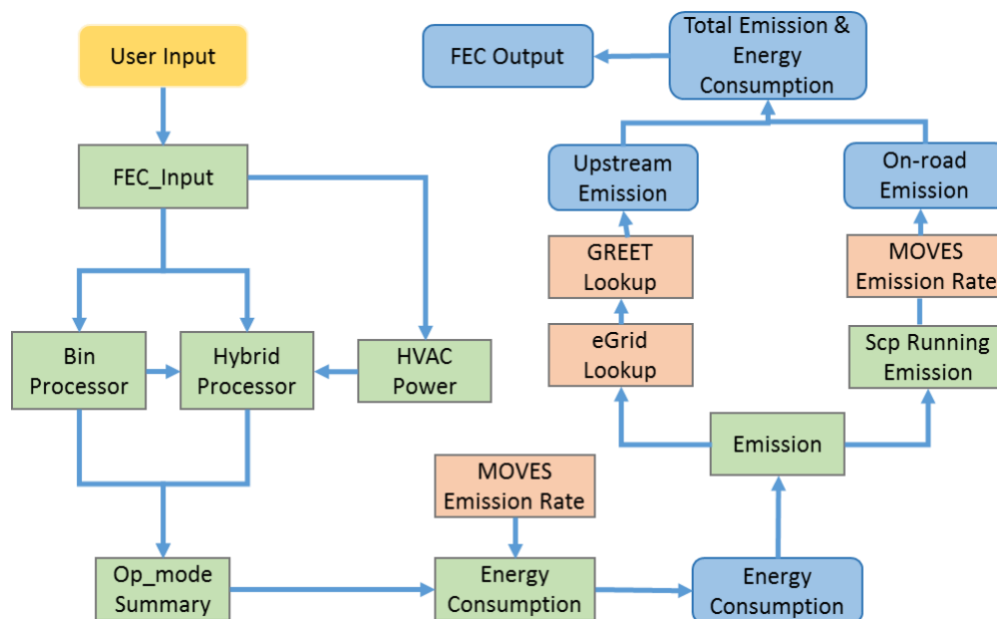
Figure 6. FEC Python Version Work Flow

The correlation between Python version and spreadsheet version are tabulated in the following tables. **Table 11** includes the reference between python script and spreadsheet tool. **Table 12** 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 11. Summary Table of FEC Online Python Code

Python File	Tables in Spreadsheet Tool	Function Description
Fec_input	InputOutput_bus	• 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.	• Estimate hoteling power
Bin_Processor	Bin_Processor New Bin Generator P New Bin Generator S	• Allocate bin distributions to selected duty cycle • Receive processed STP as input
Hybrid_processor	HybridProcessor	• Adjust bin distribution for hybrid vehicles
op_mode_summary	OpModesummary	• Summarize bin distributions for combustion engine and hybrid engine
Energy_consumption	OpModesummary; Energy consumption part within InputOutput_bus	• Calculate energy consumption for all powertrain options
scp_runnning_emission_calculation	Scp1RunningEmissionsCalculation	• Calculate tailpipe emissions
Emissions	Emission calculation part within InputOutput_bus	• Calculate emissions for all powertrain options
Constant	-	• Provide necessary reference tables, path to data files and vocabularies

Table 12. Summary Table of FEC Online Data Files

Csv file	Tables in Spreadsheet Tool	Content	Editable?
sourceusetypephysics.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 is hosted on the same server as the official FEC website identified above. The online version currently incorporates all transit buses and shuttle buses. The research team is currently translating the other transportation modes and cost-effectiveness modules into Python code and will be updating the entire Python model using an object-oriented structure for Version FEC 4.0. The research team's goal is to incorporate complete functionalities for all modes, all source types within each mode, and all cost modules into the online calculator.

5. On-going FEC Calibration and Verification

Vehicle technologies continue to advance rapidly, and vehicle prices continue to decrease over time; hence, the vehicle characteristics and cost profiles in FEC needs to be updated regularly for the latest available vehicle makes and models entering the market. To achieve this goal, the team has three major activities planned:

- **Updating vehicle characteristics**, including engine/motor power, battery size, vehicle efficiency, etc. Those vehicle parameters are essential in accurately estimating vehicle energy consumption under various driving conditions, and affecting the emissions from both upstream and on-road resources.

- **Updating vehicle cost calculation algorithms,** with the goal to build a simple streamline algorithm for all vehicle fleets. The FEC cost calculator has focused primarily on the development of refined transit fleet cost profiles. The team is currently consolidating the initial cost profiles, which contains about 60 cost items, into no more than 10 cost categories. For each cost item, the time stamp along the life-cycle and scaling factors (e.g., interest rate, subsidies, discount rate) is defined to distribute the cost by year. The final life-cycle cost per mile is a weighted average of different parts of cost, divided by actual miles input by users based on operation conditions. Researchers need to continue to collect cost data for all alternative fleet options, and refine the embedded models for the other vehicle classes.

- **Updating vehicle cost profiles,** with prices found for the latest vehicle makes and models. Vehicle cost profiles are embedded in the FEC. With rapid development of new vehicle technologies and federal/state-level incentives for alternative fuel and powertrain vehicles, the cost of purchasing and maintaining fleet changes significantly over time. Also, implementing new technologies may require new facilities to be built, such as fast charging stations and gas storage facilities. Cost profiles need to be updated via ongoing research efforts to ensure that cost-effectiveness comparisons across future fleets remain reliable.

In the summer of 2018, a cadre of undergraduate students registered for summer research units and worked with the graduate student team to review available research and gather data to assist in the update of transit and school bus performance and cost elements. With support from Cobb County School District (CCSD) staff, the research team obtained detailed cost information and updated model elements for school buses. The major findings for intercity bus systems and school bus systems from the summer research efforts are summarized below.

5.1. Intercity Bus Updates

The two most popular intercity bus services in the U.S. right now are Greyhound and Megabus, which primarily adopts the conventional combustion engine vehicles. Alternative fuel intercity buses are not yet widespread, which may be because the benefits of alternative fuel sources diminish with the increased distances and speeds that intercity buses travel. The Yutong ICE12

was the only real example of a battery electric intercity bus found in a recent literature review; currently used on one transit route in France (Manthey, 2018). That development was fairly recent, but alternative fuel intercity buses may become more widespread soon. For hybrid and fuel cell electric vehicles, NREL has performed several studies on hybrid buses for city transportation purposes (Chandler, 2006; Barnitt, 2008; Lammert, 2008; Eudy, 2017). These studies were reviewed to find information about both parallel and series hybrids. The vehicle configurations for battery-electric, fuel-cell electric and hybrid intercity buses are summarized in **Table 13** below.

Table 13. Vehicle Profiles for Intercity Vehicles

Battery Electric				
Manufacturer and Model	Proterra	Yutong ICE 12 Intercity	New Flyer XE40	BYD C10
Length/Width/Height	35ft/102in/129in	39ft/100in/132in	41ft/102in/ 130in	45ft/102in/137in
Hybrid System Model	Permanent Magnet UQM PP220	Electric Motor YTM280-CV4-H	Siemens ELFA2	NA
Power (hp)	295	295	NA	240
Max Torque (ft-lb)	NA	1770	NA	1100
Energy Storage Type	Lithium-Titanite	Lithium Ion	XALT Energy	Iron Phosphate
Purchase Cost	$904,490	NA	NA	NA
Hybrid-Electric Vehicles				
Powertrain	Parallel	Series		Series
Manufacturer and Model	New Flyer D60LF	Orion VII		New Flyer GE40LF
Length/Width/Height	61ft/102in/132in	40ft/102in/132in		41ft/102in/136in
Hybrid System Model	GM Allison Electric Drives EP 50	BAE Systems HybriDrive		ISE Corp Thundervolt Hybrid Drive
Power (hp)	100	250		114
Max Torque (ft-lb)	1050	2700		430-600
Energy Storage Type	Nickel Metal Hydride Batteries	Sealed Lead Acid		Ultra-Capacitor
Purchase Cost	$445,000 - 645,000	$385,000		$462,379
Fuel Cell Electric Vehicles				
Manufacturer and Model	Van Hool A300L		ENC Axcess	
Fuel Cell Manufacturer and Model	UTC Power Puremotion 120		Ballard Fcvelocity HD6	
Power (kW)	120		150	
Energy Storage Manufacturer	EnerDel		A123	
Energy Storage Type	Lithium-Ion		Lithium Ion	
Hydrogen Cylinders	8		8	
Hydrogen Capacity (kg)	40		50	

5.2. School Bus Updates

School bus cost and vehicle profile data was gathered during summer 2018 using latest research findings, release from manufacturers and from shared information contributed by CCSD. There are generally two types of school bus, including longer buses as types C and D school buses, and medium size buses as type A school buses. The cost profiles for each type of school buses were summarized in **Table 14** and **Table 15** below (USDOE, 2009; Johnson, 2010; Alternative Fuels Data Center, 2014; Alleghany County Public Schools, 2015; ANL 2016; Department of the Interior, 2016; Bureau of Labor Statistics, 2017; Thomas, 2018; Warner, 2018). So far, the information is mostly available for conventional types of school buses, as well as for some hybrid and electric school buses. It was difficult to gather vehicle profile data for hydrogen fuel cell and hybrid buses due to the lack of existing technology for these bus types.

Table 14. Various cost parameters for class C and D school buses

	ICEV Diesel	ICEV Gas	ICEV Bio-diesel	Parallel HEV Diesel	Series HEV Diesel	BEV	FCEV	PFCEV	PHEV Diesel
Bus/Equipment Lifetime (yr)	16.2								
Bus/Equipment Age (yr)	9								
Telematics Equipment ($/vehicle)	$1,800 for CalAmp box plus monthly fee								
Bus Purchase Cost ($)	96,795.29	N/A	96,795.29	161,325.48	161,325.48	311,895.93	N/A	N/A	N/A
Bus Depreciation rate ($/yr)	6,374.49								
Bus Operator (Labor) ($/mi)	2.24								
Bus Maintenance (Labor) ($/mi)	Estimated: 0.21, Minimum: 0.10								
Bus Maintenance (Parts) ($/mi)	0.935	0.935	0.935	0.892	0.892	0.873	0.873	0.873	0.892
Battery Replacement for Hybrid ($)	N/A	N/A	N/A	26,097.78		N/A	N/A	N/A	N/A
Fuel ($/kWh)	0.11	0.11	0.11	0.11	0.11	Varies by state	0.11	0.11	0.11
Fueling Station Construction Cost ($)	Dependent on location, but a Cobb County replacement was $1,200,000					9,245.81 per charger	1,389,112.97	1,389,112.97 + 9,245.81 per charger	diesel station + 9,245.81 per charger
Fueling Station Private O&M ($/yr)	An average of 5% to 8% of upfront costs					765.17 per charger	About 6.1% of total cost	About 6.1% of total cost + 765.17 per charger	Average of 5% - 8% of upfront costs + 765.17 per charger

Table 15. Cost parameters for class A school buses

	ICEV Diesel	ICEV Gas	ICEV Bio-diesel	Parallel HEV Diesel	Series HEV Diesel	BEV	FCEV	PFCEV	PHEV Diesel
Bus/Equipment Lifetime (yr)	14.6								
Bus/Equipment Age (yr)	9								
Telematics Equipment ($/vehicle)	$1,800 for CalAmp box plus monthly fee								
Bus Purchase Cost ($)	104,000	N/A	104,000	N/A	N/A	N/A	N/A	N/A	N/A
Bus Depreciation rate ($/yr)	6,375								
Bus Operator (Labor) ($/mi)	2.24								
Bus Maintenance (Labor) ($/mi)	Estimated: 0.21, Minimum: 0.10								
Bus Maintenance (Parts) ($/mi)	0.935	0.935	0.935	0.892	0.892	0.873	0.873	0.873	0.892
Battery Replacement for Hybrid ($)	N/A	N/A	N/A	26,098		N/A	N/A	N/A	N/A
Fuel ($/kWh)	0.11	0.11	0.11	0.11	0.11	Varies per state	0.11	0.11	0.11
Fueling Station Construction Cost ($)	Dependent on location, but a Cobb County replacement was $1,200,000					9,246 per charger	1,389,000	1,389,000 + 9,246 per charger	diesel station + 9,246 per charger
Fueling Station Private O&M ($/yr)	An average of 5% to 8% of upfront costs					765.17 per charger	About 6.1% of total cost	About 6.1% of total cost + 765.17 per charger	Average of 5% - 8% of upfront costs + 765.17 per charger

5.3. Chapter Summary

In this chapter, ongoing FEC development work was introduced, including: calibrating vehicle configurations, updating cost profiles, and improving current cost-effectiveness algorithms. Initial research findings for intercity buses and school buses were summarized. These improvements are currently being incorporated into the next FEC update (once QA/QC is completed). Current efforts expanded the model and data to include light-duty passenger vehicles and heavy-duty trucks and support more reliable analysis of refined fleets. The team continues to seek additional real-world activity, fuel use, emissions, and cost data to enhance the model, verify the accuracy of model algorithms, and improve the overall performance of FEC for various subfleets.

6. Conclusions and Future Work

The Fuel and Emissions Calculator (FEC) 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 and 3.0 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 3.0 is now capable of estimating energy and emissions for all commonly used on-road fleets, including light-duty passenger vehicles, buses, heavy-duty trucks, and rail. To support analyses of different vehicle types within each calculator, 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 planned future works for FEC are listed below:

- **Updating vehicle characteristics for all transportation modes:** The vehicle parameters will be updated based on latest fleet information, including engine/motor power, battery size, vehicle efficiency, etc.

- **Improving vehicle cost calculation algorithms:** The new cost calculator consolidates the highly detailed cost items in the old version of FEC to simplify the modeling process and allow rapid assessment of cost-effectiveness of users. The new cost calculator will be applied for all transportation modes.

- **Updating vehicle cost profile:** For each transportation mode, the cost profiles will be updated with data for the most commonly used vehicle makes and models. The vehicle cost profiles will be applied as a reference to support the cost calculator development and essentially embedded in FEC as default cost values. When cost profiles use the latest available information, FEC cost-effectiveness outputs will be more reliable for fleet alternatives.

- **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 16. 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			$a_t \leq -2.0$ OR ($a_t < -1.0$ AND $a_{t-1} < -1.0$ AND $a_{t-2} < -1.0$)
1	Idle		$-1.0 \leq v_t < 1.0$	
11	Coast	VSP_t (or STP_t) < 0	$1 \leq v_t < 25$	
12	Cruise/Acceleration	$0 \leq VSP_t$ (or STP_t) < 3	$1 \leq v_t < 25$	
13	Cruise/Acceleration	$3 \leq VSP_t$ (or STP_t) < 6	$1 \leq v_t < 25$	
14	Cruise/Acceleration	$6 \leq VSP_t$ (or STP_t) < 9	$1 \leq v_t < 25$	
15	Cruise/Acceleration	$9 \leq VSP_t$ (or STP_t) < 12	$1 \leq v_t < 25$	
16	Cruise/Acceleration	$12 \leq VSP_t$ (or STP_t)	$1 \leq v_t < 25$	
21	Coast	VSP_t (or STP_t) < 0	$25 \leq v_t < 50$	
22	Cruise/Acceleration	$0 \leq VSP_t$ (or STP_t) < 3	$25 \leq v_t < 50$	
23	Cruise/Acceleration	$3 \leq VSP_t$ (or STP_t) < 6	$25 \leq v_t < 50$	
24	Cruise/Acceleration	$6 \leq VSP_t$ (or STP_t) < 9	$25 \leq v_t < 50$	
25	Cruise/Acceleration	$9 \leq VSP_t$ (or STP_t) < 12	$25 \leq v_t < 50$	
27	Cruise/Acceleration	$12 \leq VSP_t$ (or STP_t) < 18	$25 \leq v_t < 50$	
28	Cruise/Acceleration	$18 \leq VSP_t$ (or STP_t) < 24	$25 \leq v_t < 50$	
29	Cruise/Acceleration	$24 \leq VSP_t$ (or STP_t) < 30	$25 \leq v_t < 50$	
30	Cruise/Acceleration	$30 \leq VSP_t$ (or STP_t)	$25 \leq v_t < 50$	
33	Cruise/Acceleration	VSP_t (or STP_t) < 6	$50 \leq v_t$	
35	Cruise/Acceleration	$6 \leq VSP_t$ (or STP_t) < 12	$50 \leq v_t$	
37	Cruise/Acceleration	$12 \leq VSP_t$ (or STP_t) < 18	$50 \leq v_t$	
38	Cruise/Acceleration	$18 \leq VSP_t$ (or STP_t) < 24	$50 \leq v_t$	
39	Cruise/Acceleration	$24 \leq VSP_t$ (or STP_t) < 30	$50 \leq v_t$	
40	Cruise/Acceleration	$30 \leq VSP_t$ (or STP_t)	$50 \leq v_t$	