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Development of Fleet Energy Savings Evaluation Tools for SMART Mobility:
Smart Vehicle Energy Technology (SVET) Model for Passenger Fleets and Freight Fleet Level Energy Estimation Tool (FFLEET) for Freight Fleets

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OAK RIDGE NATIONAL LABORATORY
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Energy & Transportation Science Division

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1.0 Introduction

As part of the U.S. Department of Energy's (DOE) Systems and Modeling for Accelerated Research in Transportation (SMART) Mobility Initiative, the Oak Ridge National Laboratory (ORNL) led a study to develop web-based tools intended to enable vehicle fleet operators, including both passenger and freight fleets, to quantify the energy savings achievable by implementing advanced transportation technologies. By developing a profile of a fleet's existing vehicle inventory and providing data about how and where the vehicles are driven, fuel consumption can be calculated for the entire fleet and users can perform "what if" scenarios to evaluate the energy savings that can be realized when replacing existing vehicles and implementing new technologies. The models use vehicle drive cycles that can include both speed and road grade so that the vehicle energy use is calculated based on driving conditions that are representative of those experienced by the fleet, and novel approaches to defining the vehicle usage are employed to make drive cycle selection easier for users that are not familiar with drive cycles and their importance to vehicle efficiency evaluations. These tools were developed to assist those responsible for fleet procurement and operations to select alternative fuel/energy efficient vehicles and technologies and to quantify the energy savings provided by these vehicle/technology selections, including the implementation of various connected and automated vehicle (CAV) technologies.

Two separate tools were developed to address the different types of vehicles and technologies in passenger and freight fleets, but both tools operate based on the same principles, and the underlying models are very similar. The Smart Vehicle Energy Technology (SVET) model—for passenger vehicle fleets—and the Freight Fleet Level Energy Estimation Tool (FFLEET)—for freight fleets—were developed to calculate energy savings based on the difference in energy consumption between an existing fleet and future scenarios for deployment of advanced vehicle technologies. Virtually any advanced vehicle technology such as new powertrain systems (new engine designs, electric vehicles, and hybrids), alternative fuel options (CNG, ethanol, etc.), and connected and automated vehicle (CAV) applications (signal eco-approach and departure (EAD) and Eco-Cruise), can be evaluated with the tool. The tools were designed so that users without knowledge of vehicle performance analysis can still easily evaluate advanced vehicle technology options and estimate their energy benefits under the use conditions of the user's fleet. Tools that are easy to use can increase the range of users, and the energy benefits of advanced technologies can be better understood by more fleets, leading to increased implementation of technologies that yield the greatest reductions in energy use, as well as cost savings to the fleets.

This project was funded by the DOE Energy Efficient Mobility Systems (EEMS) Program and was part of research conducted under the Multi-Modal Pillar of the DOE SMART Mobility Initiative, a collaborative research effort led by five Department of Energy national laboratories that aims to deliver new EEMS data, analysis, and modeling tools, and create new knowledge to support smarter mobility systems. The project was initially planned as a three-year R&D effort, but a change in priorities in the SMART Mobility research resulted in the activity being stopped after the first year of funding in FY17. The main model development was completed in FY17 and a prototype set of tools was developed. This final report describes the SVET and FFLEET models and their development, and sample results are provided to show the types of outputs generated by the tools. The work plan for the study included a review of current scientific research on energy saving vehicle technologies and models, particularly the research underway or completed by the national laboratories. The literature review is presented in the next section, and the rest of the report documents the SVET and FFLEET model design and development.

2.0 Literature Review

A large number of models and software tools have been developed to evaluate the energy savings, as well as greenhouse gas (GHG) emissions reductions, that can be achieved by employing advanced vehicle technologies. This literature review summarizes a number of the existing models to illustrate the approaches that are normally followed to evaluate energy consumption from modern highway vehicle technologies and to highlight opportunities for further improvement and identify needs for additional capabilities in vehicle energy savings analysis. The models of interest have been developed by universities, national laboratories, government agencies and other foundations or organizations with missions to reduce energy consumption and/or GHG emissions.

A primary focus of the present review is on tools from national laboratories and government agencies in the United States, especially tools that are relevant to energy savings evaluations by passenger and freight fleets, but additional models and tools are reviewed to show the variety of the types of models available, to identify foundational analyses that have served as a basis for later model development, to demonstrate differences in the simplifications used among the models, and to showcase those models that are in very widespread use or are distinct based on a specialized functionality.

A comprehensive literature review of fuel consumption models was conducted by Faris et al [1] that categorized vehicle fuel consumption and emissions models into five classification types and presented models associated with each classification. The classifications considered include the following: (1) modelling based on the time scale of data characterizing vehicle operation; (2) modelling based on a particular formulation approach; (3) modelling based on the type of explanatory variables; (4) modelling based on state variable values and (5) modelling based on the number of dimensions. Some of the same models are reviewed here, but model types that have little relevance to fleet-based energy savings evaluations were not given significant attention, and we do not address highly detailed engine models such as those considering detailed thermodynamics or combustion in each cylinder since such models are more appropriate for engine design than vehicle performance evaluations and the simulation time requirements for this type of model is generally prohibitive for large scale evaluations. We also consider an additional category of energy and emissions analysis, life cycle assessments (LCAs), due to their prominence in fleet-level emissions and fuel evaluations. It is noted that all of the models described, unless otherwise noted, are publicly available.

2.0.1 Model types

The first category of model we consider includes those used to quantify energy consumption and/or emissions of an individual vehicle while driving under a specified usage condition by employing a physics-based or empirical analysis of the complete vehicle and its sub-systems. Models of this type directly calculate the energy required to propel the vehicle and use sub-models or characterization data for the efficiency of the components that comprise the vehicle drivetrain to calculate the total energy consumption provided by the fuel that powers the vehicle. The total fuel energy and/or emissions can be calculated using this type of model by integrating second by second results, with the emissions rates normally being related to the fuel power consumption as well as other variables characterizing the operational state of the vehicle. Many of these models are focused on the vehicle propulsion system and we therefore refer to them in a general sense as powertrain models. A powertrain model can be used to obtain detailed information about how individual vehicles perform, but generalized assessments can also be made that yield important insights into the energy benefits achievable from new technologies in a broader setting. With a detailed powertrain model, it is possible to predict the energy efficiency of a vehicle before it is actually built for design purposes. Additionally, results from more generalized powertrain models can be applied to policy and planning decisions for technology deployment since they can provide reasonable estimates of the energy savings that may be realized with changes to vehicle technology across an entire fleet. Furthermore, traffic simulations that incorporate a powertrain model for individual vehicles can be used to characterize system level impacts on energy consumption resulting from technologies such as vehicle-to-vehicle (V2V) or vehicle-to-infrastructure (V2I) communications and other connected and automated vehicle (CAV) technologies.

Our interest lies mainly in the microscopic models (based on instantaneous data, generally using a specified drive cycle as an input to characterize the vehicle usage). It is noted that various macroscopic models have been used in the U.S. in the past for transportation planning and conformity analysis, in particular the U.S. Environmental Protection Agency's (EPA's) MOBILE model. Macroscopic models use average aggregate network parameters such as average speeds and accelerations to estimate network-wide energy consumption and emission rates. Since very different drive cycles can have similar average speeds, macroscopic models often cannot differentiate between certain driving characteristics, and energy consumption estimates from the macroscopic models can have significant errors as a result. Additionally, they are not able to capture the benefits of some technologies that are frequently employed to minimize traffic-induced energy and emissions, such as coordination of traffic signals along a primary traffic corridor [2]. EPA effectively acknowledged the shortcomings of the macroscopic modeling approach when the Motor Vehicle Emission Simulator (MOVES) model officially replaced MOBILE6 in 2010.

A very different type of model that is frequently employed for transportation energy and emissions evaluations is the life cycle assessment (LCA) approach, which is also referred to as a “cradle-to-grave” analysis. LCA can be used for the evaluation of any product or service, and is used primarily to determine the environmental impacts of a product by quantifying all inputs and outputs of materials over the product’s life span. For transportation system analyses, the focus is normally on assessing the energy use and emissions associated with both the vehicle and all its subcomponents, in addition to the fuel used to propel the vehicle, over the entire life of the vehicle. LCA considers the impacts of all aspects of the vehicle life cycle on energy consumption and emissions, including raw material extraction, manufacturing of all components of the vehicle, fuel use, production and distribution, and disposal of the vehicle at the end of its usable life. This type of model is clearly much more general in the energy/emissions that are evaluated, in that the upstream and downstream energy use and/or emissions are quantified in addition to those consumed or generated during the use phase of the vehicle. The evaluation of fuel use in a LCA considers the complete “well-to-wheel” (WTW) fuel cycle, which includes not only the energy consumed to propel the vehicle (referred to as the “tank-to-wheel” or “pump-to-wheel” (PTW) energy consumption), but also the energy associated with extracting, processing and transporting the fuel. This approach is useful for making “apples to apples” comparisons among vehicles that use different energy sources, even if the user is interested in only evaluating the energy use or emissions associated with the vehicle operation. For example, while driving an EV, electric energy is converted very efficiently to mechanical energy for propulsion and there are no on-vehicle emissions generated. Nevertheless, the impact of driving an EV on total energy consumption and emissions is not limited to those that take place during driving. The electricity must be produced elsewhere, typically at a natural gas, coal or nuclear power plant, and the overall energy consumption associated with the electricity produced is typically a few times greater than the generated electrical energy itself, and emissions are also generated during the electricity production. It is therefore clear that the electricity use on an EV does not accurately reflect the total energy and emissions impacts from the use of the vehicle. This example highlights the importance of considering upstream factors on the overall energy consumption and emissions impacts, and even for a conventional vehicle powered by an internal combustion engine (ICE) the fuel production and distribution are responsible for additional energy use and emissions.

The scope of a LCA is much more general than that of a vehicle powertrain model for energy or emissions evaluations. Generally, however, LCA models require fuel efficiency for the technology under consideration as an input to the model, so a LCA model by itself is not able to predict the direct change in energy or emissions resulting from the technology implementation for a given usage. Once the energy efficiency is known, however, a LCA can be used to quantify the overall impacts associated with selecting the given technology. On the other hand, in a powertrain model, the energy or emissions can be predicted for a specific use when the vehicle configuration is fully specified, but the results are associated only with the use phase of the vehicle and represent only the PTW energy consumption. The purpose of each type of model is very different but they are complementary, and results from a fuel economy model can be used as inputs to a LCA to more fully characterize the impact of a given transportation technology.

2.1 Powertrain Models

Vehicle powertrain modeling has proven to be an invaluable tool in vehicle design and development. Vehicle performance models have been used by automobile manufacturers for many years, and their use has continued to increase over time with increased computer power, more refined modeling capabilities, and the desire to limit design cycle iterations and vehicle testing [3]. The development and use of vehicles using alternative fuels, advanced powertrain systems and other advanced transportation technologies has accelerated in the recent past to meet higher standards for vehicle emissions and fuel economy, and powertrain models have been utilized extensively for developing these advanced vehicles. Computer simulation of performance can be employed at virtually any stage of the development process, from evaluating fuel savings for preliminary powertrain design evaluations, to detailed design and optimization of powertrain gear ratios, to control system performance validation in the final vehicle implementation. This use of powertrain modeling has resulted in large gains in efficiency in the design process [4].

Early efforts in modern powertrain model development employed simplifications to engine map data as well as simplified analytical representations of drivetrain component efficiency data. Sovran and Bohn [5] developed an early model for calculating the tractive energy requirements over a drive cycle using fundamental properties of vehicle energy losses to estimate the tractive power as a function of time. They characterized the energy dissipation associated with aerodynamics, rolling resistance, and net increases to kinetic energy during powered driving, in addition to braking. These are the primary physical factors influencing fuel consumption, and this basic approach using fundamental physical parameters for calculating tractive power serves as the starting point for determining vehicle energy consumption in most modern vehicle powertrain models. The tractive power is calculated as

$$P_{trac} = m(1+\varepsilon)v\frac{dv}{dt} + mgv\sin\theta + P_{aero} + P_{RR}, \tag{1}$$

where *m* is the vehicle mass, ε accounts for additional inertias due to rotating masses, *v* is the vehicle velocity, *g* is the gravitational constant, sin θ is the road grade, and P_{aero} and P_{RR} are the power due to aerodynamic drag and rolling resistance, respectively. The P_{aero} term is calculated from the aerodynamic drag coefficient C_d, vehicle frontal area A_f, air density ρ, and vehicle speed *v* as

$$P_{aero} = F_{aero}\, v = \tfrac{1}{2}\rho\,(C_D A_f)\, v^3, \tag{2}$$

while the rolling resistance is calculated using a linear rolling resistance relation,

$$P_{RR} = F_{RR}\, v = mgv(c_0 + c_1\, v). \tag{3}$$

By identifying the portions of the drive cycle corresponding to four basic driving modes—powered accelerations and cruising, powered decelerations, braking, and stops—Sovran and Bohn showed that the tractive power can be integrated over periods when the engine must provide a positive driving force to determine the driving tractive energy required over the complete drive cycle. This driving tractive energy output is closely related to fuel consumption. The criteria for each driving mode was identified as a function of the vehicle parameters and the drive cycle, and the driving tractive energy was determined as a series of integrals, which can be obtained numerically through direct calculation for a given drive cycle. This approach was applied by Sovran and Bohn for the EPA urban and highway drive cycles. By numerically integrating the tractive power equations for powered driving and applying some simplifications, a linear relationship was developed for the tractive energy as a function of the primary physical parameters characterizing the vehicle as well as the drive cycle characteristics. The equations were used to evaluate the sensitivity of the tractive energy requirement for the two EPA drive cycles to the vehicle mass, aerodynamic drag and rolling resistance. The model was also used to identify limits for regenerative braking based on the vehicle and drive cycle parameters.

2.1.1 The An/Ross Model

The methodology developed for calculating the driving tractive energy was extended to the calculation of vehicle fuel consumption in a model developed by An and Ross [6]. In this approximate analytical model, a generalized engine map developed by the authors based on measurements from a large set of engines [7] was used to estimate the fuel consumption at each powered driving segment of the drive cycle, and accessory power requirements were also considered in the calculation. An engine performance map characterizes the steady state fuel consumption rate over a set of engine operating conditions and is obtained by direct measurement of the engine fuel consumption as a function of torque and engine speed (rpm). For low to moderate levels of engine power output that are typical of most driving conditions (and for almost all periods in regulatory drive cycles, in particular), the rate of fuel consumption for an engine was found to be very well approximated as a linear function of engine rpm, N, and the engine brake power output, P_b, so that

$$P_f = a\,N + b\,P_b, \tag{4}$$

where P_f is the fuel rate expressed in energy terms, i.e. $P_f = \dot{m}_f$ LHV, with LHV representing the lower heating value of the fuel and $\dot{m}_f$ the fuel mass flow rate. For a given model year, the coefficient a was found to be approximately proportional to engine displacement V, so that $a = \alpha V$. On the other hand, b, which is effectively an inverse thermal efficiency, is approximately constant among different engine types and sizes. This relationship reflects a rather impressive fact that, although many manufacturers have designed a range of engine types and models, their performance characteristics tend to be quite consistent [8]. Over time, engine design has become more efficient, and the α coefficient tends to decrease for later model year vehicles. An and Ross employed this simplification using average values of the α and b coefficients to derive a numerical model of fuel consumption for any drive cycle. By using average values of the engine coefficients, the model is representative of a typical engine (for a given model year), but the vehicle mass, aerodynamic drag coefficient, frontal area and rolling resistance coefficient make the model specific to individual vehicles. Cold-start engine operation was approximated by assuming a 15% increase in fuel consumption rate, and the corresponding α coefficient was modified to provide an appropriate adjustment factor in the model. Calculations for nine vehicles were found to be within 10% of the measured fuel economy for any single EPA city or highway cycle, and the average error for EPA combined cycles was within 5%. The authors implemented the model in a spreadsheet calculation to evaluate fuel economy differences among five different drive cycles, including the EPA urban and highway cycles, European cycle, Japan cycle and New York cycle, and they considered several measures of the drive cycle to simplify its characterization. Based on these evaluations, a simplified drive cycle characterization was developed, and An and Ross concluded that the following five primary parameters of the drive cycle could be used to accurately calculate the vehicle fuel economy performance for the drive cycle: the number of stops per mile, average peak speed, fraction of time spent at vehicle stops, fraction of time using brakes, and the average running speed.

Although the fuel consumption of a vehicle could already be predicted for a given drive cycle by using the tractive power approach along with an engine map measured for the vehicle's particular engine [9,10], the An/Ross model was a significant development in fuel economy modeling. The analytical form for the approximate model provided a rather comprehensive description of fuel economy that allowed a generalized understanding of how vehicle characteristics and the usage are related in determining fuel consumption. Furthermore, the application of the simplified engine fuel consumption relation of Eq. (4) in the fuel consumption calculation provided a very reasonable estimate of fuel consumption for a very broad range of vehicles. Models employing a similar approach to that of the An/Ross model have been used for vehicle fuel economy evaluations. While such models have often been used for light duty (LD) vehicles [11,12], the same approach is applicable to buses [13] and heavy duty (HD) vehicle configurations [14,15], although the powertrain, vehicle and drive cycle characteristics are very different for the different vehicle types and HD vehicles tend to encounter more diverse driving conditions, and are therefore more difficult to characterize [16].

2.1.2 ADVISOR

Although vehicle manufacturers have employed proprietary powertrain models for vehicle design for many years [17-19], generic powertrain models available in the public domain that could be used for detailed analysis and design began to emerge in the 1990s and early 2000s. The National Renewable Energy Laboratory (NREL) developed the Advanced Vehicle Simulator (ADVISOR) model in 1994 to support the U.S. Department of Energy (DOE) hybrid propulsion system program in developing and analyzing technical targets for the program and to quantify system requirements of components used in hybrid vehicle designs. It was publicly released in 1998 [20,21]. ADVISOR uses characterization maps of drivetrain component performance to estimate fuel economy and emissions on given drive cycles as well as predicting vehicle acceleration and gradeability capabilities. ADVISOR was implemented in the MATLAB/Simulink environment. Matlab is a popular programming environment that provides easy access to all variables included in the analysis as well as the ability to use high level functions for post processing and visualization of results. Simulink is used to represent complex systems graphically using block diagrams to simplify model building while enabling advanced dynamic analysis tasks.

For model creation in ADVISOR, a graphical user interface (GUI) provides guidance to the user and is used to interact with the data stored in the Matlab workspace. Pull-down menus are used to select a vehicle configuration (conventional, series or parallel hybrid, and electric vehicle configurations are available) and the components that compose the drivetrain. In order to build the vehicle model, component models can be inserted into a vehicle model and then connected to define the flow of torque/speed and power from one component to the next. The component models can be saved in a model library and reused in different vehicle configurations, and the user has access to many component models that are available in a pre-defined model library. Furthermore, different levels of detail can be used in creating a component model to evaluate whether the model is sensitive to such details, and the user can modify virtually any variable characterizing each component. In this manner, the final vehicle model is composed of a collection of component models, which provides a high degree of flexibility in model creation. The drive cycles allow grade data to be included, and over 40 drive cycles are available for user selection, including measured data from various NREL vehicle evaluations.

For the vehicle simulation, ADVISOR uses a hybrid approach that incorporates both backward and forward-facing simulation attributes and is intended to allow calculations to be performed rapidly while enabling performance and control logic evaluations that are not possible with a purely backward simulation methodology. The term "backward simulation" for a vehicle powertrain model refers to an approach in which one assumes that the input vehicle speed at each time step (i.e. the speed given in the drive cycle) can always be achieved by the vehicle, and the torque and power requirements of the drivetrain are determined by calculating what is necessary from each preceding component, i.e. by moving backwards through the drivetrain. A "forward simulation," on the other hand, considers the powertrain response to inputs received from the driver for the throttle and brake control and calculates the power and torque transfers while moving forward through the drivetrain. The forward approach therefore requires a driver model, and it is generally the preferred method employed in detailed hardware or control system design. Determining the driver inputs needed to follow a specified speed trace generally requires an iterative approach, and smaller time steps are often needed in the simulation to have a stable vehicle response. This causes the simulation time to be longer than for a backward simulation. A backward simulation, on the other hand, does not consider limitations of the powertrain performance, so it can result in operating states that cannot be achieved by the vehicle. The hybrid approach used in ADVISOR was developed to allow fast simulation times while still restricting powertrain performance to physically feasible operating states, which allows vehicle acceleration performance to be calculated quite accurately. It should be apparent that the simplified powertrain models described previously use the backward simulation approach.

The performance of an internal combustion engine in ADVISOR is defined using an engine map for which inputs are entered as a function of the engine speed and torque, and the model includes emissions data inputs in addition to the fuel consumption map. To account for cold engine operation, temperature correction factors can be entered, either as a function of temperature or of temperature, engine load and speed, and a multi-node lumped capacitance thermal model is used to estimate engine temperature. This allows differences in engine fuel consumption and emissions due to cold-start engine operation to be simulated. For battery electric vehicles (BEVs) and hybrid electric vehicles (HEVs), several different energy storage system (battery) models are available, with varying degrees of complexity and input data requirements. Similarly, three types of fuel cell models are available, allowing simulations to be performed for fuel cell vehicles (FCVs).

ADVISOR is used primarily for analysis of fuel consumption and engine out emissions over a specified drive cycle in addition to vehicle acceleration and gradeability performance evaluations.

2.1.3 FASTSim

The National Renewable Energy Laboratory (NREL) released a simple vehicle powertrain simulation tool, referred to as the Future Automotive Systems Technology Simulator (FASTSim), in 2011 that is implemented in an Excel spreadsheet [22]. FASTSim provides a quick and easy approach to compare powertrains and estimate the impact of technology improvements on LD and HD vehicle efficiency, performance, cost, and battery life. Models with typical configurations for conventional vehicles, hybrid electric vehicles, plug-in hybrid electric vehicles, all-electric vehicles, compressed natural gas vehicles, and fuel cell vehicles are included in FASTSim. The vehicle components are modeled at as high a level as possible while still being accurate, and a function is included so that input data for most LD vehicles can be imported using an automated methodology. Vehicles can be simulated using existing speed-versus-time drive cycles, or user-specified cycles can be created.

FastSim uses an efficiency vs. power curve for all fuel converters in the model, i.e. for any engine, energy storage system (battery) or fuel cells included in the model. A single efficiency curve for each engine type, scaled for different engine powers, can represent most internal combustion engine vehicles within 5%, and this approach has been well validated in comparisons of model results with measured fuel economy data. Similarly, for hybrid electric powertrain configurations, the amount of regenerative braking energy that can be captured is defined as a function of vehicle speed, and a standardized approach is used for the energy management strategy as a function of the battery state of charge (SOC). Shifting in the model is done in a manner that optimizes efficiency. This may not be very representative for certain driving styles. For example, fuel economy is likely to be over-estimated in the case of an aggressive driver as a result of the fuel efficient shifting strategy. FASTSim includes a function to simulate electric power transfer from the roadway, to evaluate the impacts of wireless electric charging, and a vehicle cost model is also included. The model has been validated with EPA fuel economy test results for over 100 vehicles and has shown excellent results. FASTSim's efficiency estimates match most EPA test data within 5%, and almost all within 10%, for many different vehicles and powertrains. The figure below shows validation data for a portion of the vehicles evaluated, and the results for other vehicles were very similar. Required inputs to the model include the selection of a vehicle and the drive cycle to evaluate. Any of the vehicle configuration parameters can be entered manually, and all of the parameters described above can be entered/modified by the user, as desired. As in Autonomie and Advisor, the user can select existing models included with the software or build his or her own vehicle using from scratch. Outputs from FASTSim include calculated fuel economy results, acceleration and gradeability performance, present and lifetime cost information, and additional details for energy use in PHEVs.

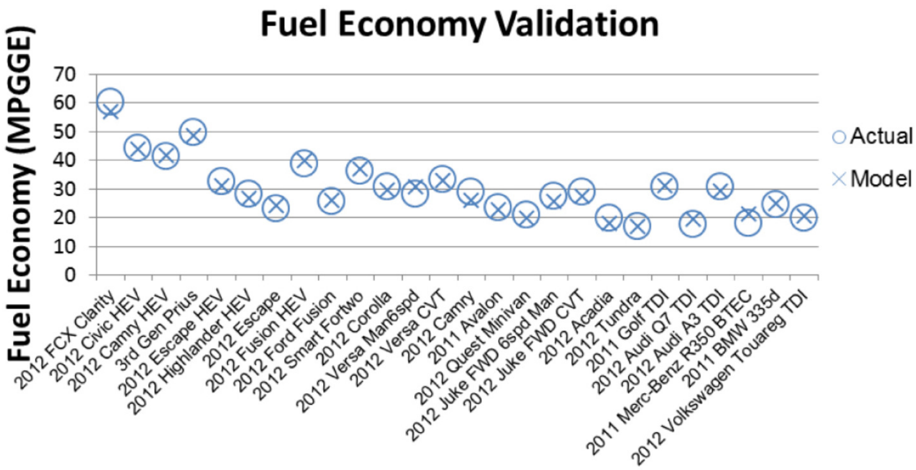


Figure 1. FASTSim Validation results.

2.1.4 Autonomie

Argonne National Laboratory developed and maintains a high precision vehicle simulation software environment and framework for automotive control system design, simulation and analysis. Autonomie [23] is implemented in the Matlab/Simulink environment and includes a graphical user interface to manage all models, which provides a high degree of flexibility and control of the model development. Component models and control strategies can be saved, reused and shared in Autonomie for use in different vehicle models. It includes a broad range of built-in vehicle configurations and templates, and advanced users can create new configurations so that it is possible to model virtually any vehicle using the flexible tool. Additionally, it is possible to access all input and output variables as well as many variables generated during a calculation so that new modeling variables and algorithms can be created if existing functions do not meet the needs of the user. As an example, ORNL has developed a novel approach to evaluate engine out and tailpipe emissions by simulating multi-species chemical reactions while tracking concentrations and temperatures at different locations within the engine and aftertreatment-train. With this flexible configuration, component performance can be evaluated in practically any manner the user wishes, but default models are available that employ commonly used sub-models and analysis methodologies, and a number of default vehicle models are available representing common configurations. Autonomie employs a forward-based simulation approach and multiple numerical algorithms are available to assist in obtaining converged results. Autonomie is also able to be implemented in hardware- or software-in-the-loop simulations, so that real hardware or control software can be integrated into a vehicle model. In this way, actual components or software can tested while some parts of the vehicle are emulated, and testing can be performed in real time while using this virtual testing. The Autonomie framework allows extreme flexibility in simulation and testing of very complex vehicle models, while a basic level of functionality can be accessed without too much difficulty. Much of the functionality is comparable to other commercially available powertrain simulation tools on the market, such as GT-Drive [24] or AVL Cruise [25], but Autonomie's implementation in Matlab provides a higher degree of flexibility for user inputs than is possible with other executable-based software, since the Matlab environment itself enables a high level of user interactivity. Nonetheless, detailed model development requires a large amount of input data to fully specify a vehicle configuration, and obtaining access to all elements of a model for advanced functionality can be a formidable task, particularly for new users. Autonomie provides many post-processing tools and reports that can be run with any model. The user is also able to create customized reports and graphs depending on their particular needs.

2.1.5 CMEM

A model for modal emissions was developed by Barth et al [26,27] that is based on analytical functions describing the physical phenomena associated with vehicle operation and emissions generation. The Comprehensive Modal Emissions Model (CMEM) is able to predict second-by-second tailpipe emissions and fuel consumption for a wide range of vehicle/technology categories. The model employs a parameterized empirical approach that incorporates physical modeling and includes six modules that predict engine power, engine speed, air/fuel ratio, fuel use, engine-out emissions, and catalyst pass fraction. The model was derived from detailed dynamometer measurements from 343 vehicles that included second-by-second pre- and post-catalyst measurements of CO2, CO, HC, and NOx over three separate driving cycles. The model uses three dynamic variables (acceleration, air/fuel equivalence ratio, and fuel rate), along with a drive cycle specification in terms of both speed and road grade as well as accessory use (such as air conditioning) as the input operating variables. These are used to specify an activity file, which can be used to predict second-by-second emissions either for a single vehicle type or for the national fleet.

The model uses a simplified calculation of the tractive energy that uses A,B,C coefficients to characterize the vehicle energy losses (as available from the EPA test car list) instead of using the physical properties of aerodynamic drag, frontal area and rolling resistance coefficient:

$$P_{trac} = mv\frac{dv}{dt} + mgv\sin\theta + Av + Bv^2 + Cv^3, \quad (5)$$

while the engine power is estimated using a vehicle drivetrain efficiency η_{tr} and average accessory power P_{acc}:

$$P_{eng} = \frac{P_{trac}}{\eta_{tr}} + P_{acc}, \quad (6)$$

Engine speed is determined from the vehicle speed using specified gear ratios and a shift schedule to determine up- or downshift, while the air/fuel ratio is calculated based on the typical relations for operation in one of three regions: lean, stoichiometric, and rich. Lean operation is determined due to both aggressive transient and lasting deceleration episodes, while enrichment takes place during a cold start. The fuel rate is evaluated from a relation similar to that described by Eq. (4) above, but modified by the air/fuel ratio, and engine out emissions are calculated for CO, HC and NOx as a function of fuel rate and air/fuel ratio that take into account enrichment/enleanment conditions and rapid load changes. Tailpipe emissions are calculated using a catalyst pass fraction (CPF) determined for each pollutant that is primarily a function of temperature and equivalence ratio and accounts for cold-start and closed loop operation.

2.1.6 MOVES

The MOtor Vehicle Emission Simulator (MOVES) is an emission model and simulator that was developed by the U.S. EPA to estimate emissions and energy consumption from mobile sources, covering a broad range of pollutants, at the national, county, and project level. MOVES is used for State Implementation Plans and Transportation Conformity Analyses in air quality nonattainment areas [28], and has also been used as a research tool to support new emissions modeling needs. MOVES uses a modular structure with the underlying emissions and energy consumption data stored in a relational database, which EPA can update as new data becomes available so that users have access to current data without the need to modify the software itself.

The three options available for MOVES evaluations require different levels of data inputs and also provide different degrees of specificity in the results. National level evaluations, which are used for general types of emissions assessments but are not permissible for conformity analysis, use national defaults for many inputs so that local data is not necessary. The option for county level evaluations requires inputs that are specific to the local area considered, such as vehicle population and vehicle miles travelled (VMT) by vehicle type. This mode is designed to be compliant with regulations for transportation conformity analysis in areas that do not attain the national air quality standards. Project level evaluations are the most detailed and allow emission rates to be derived from second-by-second speed data employing a modal emission rate approach. The primary output is the emission rate of components for NOx, PM, CO, CO2, SO2, and NH3, expressed on a per vehicle specific power (VSP) basis and assigned to operating mode bins that are defined in terms of ranges of speed and VSP. The VSP is equal to the tractive power (as calculated using Eq. (5)) divided by the vehicle mass, and is normally expressed in kW/ton. Outputs are specific to vehicle type, and can be used to calculate emissions at the individual vehicle level or for groups of vehicles of the same type. This capability is complementary to the powertrain model evaluations, allowing emissions to be determined using results from a powertrain model. Grade can also be accounted for in the emissions calculation by including the grade term in Eq. (5) when calculating the VSP.

2.1.7 PERE

The Physical Emission Rate Estimator (PERE) was developed by the U.S. EPA to complement the MOVES GHG emissions model for increasing the level of accuracy in estimating on-road vehicle emissions [8]. Its purpose is to fill data gaps in MOVES and to provide a tool to extrapolate to future projections of energy and emissions outputs. PERE calculates Pump-to-Wheel (PTW) fuel consumption rates for advanced vehicle technologies, and is designed for LD, medium-duty (MD) and HD vehicles with gasoline, diesel, battery, fuel cell, and hybrid electric propulsion systems.

Though the model is based on mathematical and physical principles, it is intended to be aggregate, and is not appropriate for engineering or product design. Thus it is designed to model a “typical” vehicle of technology type, rather than a specific vehicle. The basic mechanism of PERE involves calculating the road load energy required to move the vehicle mass along a driving trace, then distributing that energy demand to the various vehicle components (engine, electric motor, fuel cell, etc). The energy components are modeled using overall systems efficiencies. The PERE model begins with a calculation of the vehicle specific power (VSP), which is simply the tractive power (calculated using either Eq. (1) or Eq. (5)) per unit mass of the vehicle. For a spark-ignition engine, the model of Ross [29] is employed in PERE, which is effectively equivalent to the An and Ross fuel consumption model described previously and represented by Eq. (4). Fuel consumption is described in terms of a mean equivalent pressure (mep) acting on the piston, which is a convenient method to characterize the engine power inputs and outputs, and is defined as

$$\text{mep (kPa)} = \frac{4\pi\tau}{\text{V}_\text{d}}, \tag{7}$$

where τ is the torque (in N-m) and V_d is the engine displacement (in L). An equivalent expression to Eq. (4) but expressed in mep terms is the following,

$$fuel\ mep\ \text{(kPa)} = \text{k} + \text{bmep}/\eta = (\text{fmep} + \text{bmep})/\eta = \text{imep}/\eta. \tag{8}$$

For this relation, k=fmep/η is a value that is related to the engine friction and is very nearly constant, while bmep is the brake mean effective pressure, which corresponds to P_b in Eq. (4). The indicated mep, or imep, is the product of the fuel mep and the engine thermal efficiency η. As described earlier, gasoline engine performance is very consistent even for different manufacturers and engine sizes. It has been found that the indicated efficiency has not changed significantly over the preceding 3 decades [30], as shown in Fig. 2. As a result of this consistency in engine performance, it is possible to develop relatively simple models that represent the engine efficiency quite reasonably, given only its displacement, peak power and model year.

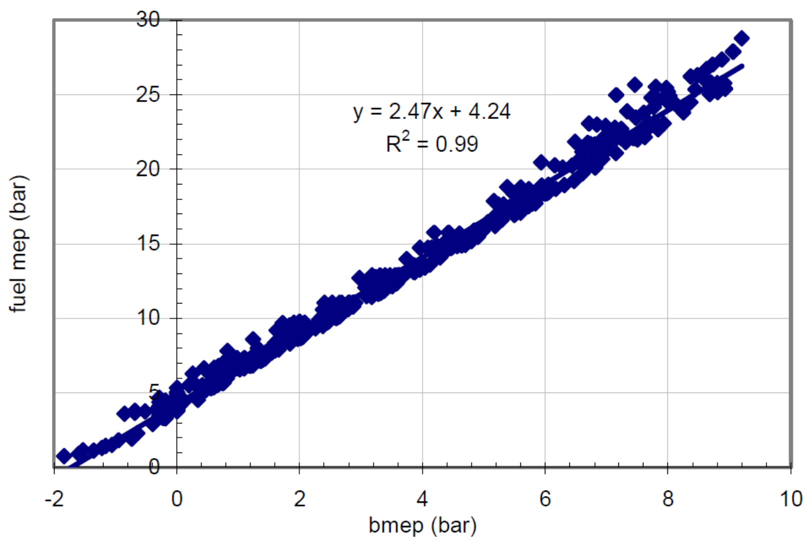


Figure 2. Fuel mean effective pressure as a function of brake mep for 10 engines from 4 different manufacturers, omitting wide-open throttle points [29].

The PERE model uses well established characterizations for other components used in conventional and advanced powertrain types that are also generalized to represent behavior that can be expected to be typical for most vehicles. The result is a model that provides reasonable estimates for the energy consumption that can be expected from a broad range of vehicle technologies. Nam points out, however, that due to the approximations made in some parameters, it is not expected to accurately capture fuel consumption of specific vehicles better than within 10% of measured values. Nonetheless, it was found that the main impacts from different operating conditions on the vehicle fuel economy, as well as differences in performance between vehicles with different vehicle powertrain technologies, are rather well approximated by the modeling approach employed.

User inputs include the selection of the vehicle powertrain type, model year, weight, body type (resistive coefficients and size, which can be approximated), engine displacement, motor power (if applicable), fuel type and the selection of appropriate drive cycle. Outputs include a set of fuel consumption rates as a function of vehicle specific power (VSP), which can be entered into MOVES.

2.1.8 FTA GHG Emissions Calculator

The FTA GHG Emissions Calculator is a tool developed by ORNL and Georgia Tech for transit bus GHG emission evaluations that aims to help public transit agencies choose between alternative transit vehicles [31]. Attention was given to electric drive and hybrid vehicles to enable transit agencies to assess the benefits of these vehicles as fleet candidates. The model was implemented as a spreadsheet calculator, and an approach was employed to integrate calculation resources for the estimation of direct GHG emissions, life cycle GHG emissions, and the costs associated with GHG emission reductions. The GHG Emissions Calculator has the capability to estimate emissions as a function of engine load using a tractive power-based approach. The impact of grade is represented in the model using three levels of "roughness" that are characterized for different regions of the U.S., and different weather scenarios are provided so that users can evaluate vehicle emission rates in varying environmental conditions. Fuel consumption and emissions are determined in the model using data extracted from MOVES, and the GHG emissions are a function of tractive power in addition to the selected vehicle type. The GHG Emissions Calculator provides accurate GHG emissions estimates, using a combination of load-based emissions estimated from MOVES and life-cycle emissions estimated from the GREET model (described below). The calculator contains three embedded modules: 1) an operating mode bin calculator as needed for MOVES evaluations, 2) a MOVES-matrix emissions rates lookup table, and 3) a hybrid bus energy balance model designed to shift energy demand across the operating mode bins. Outputs from the calculator include summary charts and tables for GHG emissions and cost-effectiveness comparisons intended to aid in decision making for transit fleet procurement. The calculator allows emissions comparisons to be performed across vehicle operating modes, allowing users to compare fuel consumption and vehicle emissions across energy technologies based on route characteristics such as road grade, number of stops, average speed, etc.

2.2 Fleet Inventory and Life Cycle Assessment Tools

Many fleets, and public transit agencies in particular, receive guidance, and may even be required, to perform regular GHG assessments and demonstrate reductions in fuel use and GHG emissions as part of the funding requirements to receive federal subsidies or grants. The American Public Transportation Association (APTA) provides specific guidance to transit agencies for quantifying their greenhouse gas emissions, including both emissions generated by transit and the potential reduction of emissions through efficiency and displacement by laying out a standard methodology for transit agencies to report their greenhouse gas emissions in a transparent, consistent and cost-effective manner [32]. As a result, transit agencies are in need of tools and resources that enable effective GHG emissions management. In addition to providing energy and emissions efficiency benefits to society at large, successful carbon management practices can bring some immediate rewards to the transit agency itself by helping to market services to environmentally conscious riders, reducing the costs of purchased energy, making the agency more attractive to federal grant programs [33], and preparing the agency for participation in climate change registries [34] and carbon trading schemes, which offer funding opportunities for GHG emissions reductions. While such evaluations are worthwhile for any fleet or potential consumer of advanced vehicle technologies, there are perhaps additional pressures imposed on transit fleet operators to manage their GHG emissions and energy use and to actively track them using a structured and well justified approach [35].

A framework for evaluating and managing cost-effective public transit GHG emissions reductions must not only help agencies identify economically viable opportunities, it must also be easily implemented by personnel who have limited time and resources available for additional management responsibilities. Measurement of transit agency GHG emissions requires tools for the quantification of GHGs from transit agency activities, and such tools should be appropriate to the unique context and needs of public transit agencies. As such, it is desirable to have tools available that can help agencies identify strategies that will have the greatest GHG reduction impact and are the most cost-effective.

There are a number of tools available for conducting fleet GHG emissions inventories or a LCA, but uncertainties in the energy and emissions reductions can be significant as a result of unknown impacts on the GHG emissions displaced by public transit and a high sensitivity to ridership and vehicle occupancy, among other factors [35].

The inventory calculators that are based on a reporting protocol follow what has become a standard "three-scope" division of emissions:

1. Scope 1: Direct emissions controlled by the agency;

2. Scope 2: Indirect combustion emissions that occur outside of the agency (primarily the emissions produced from the generation of purchased electricity);

3. Scope 3: Indirect "optional" emissions produced upstream or downstream of an organization's activities or control.

The standard approach for calculating public transit agency GHG emissions is defined by the Recommended Practice published by the American Public Transportation Association [32]. While the inventory protocols provide a comprehensive accounting framework for estimating GHG emissions from both mobile and stationary sources, they provide very little technical guidance for estimating upstream fuel-cycle, vehicle-cycle, or infrastructure-cycle emissions (Scope 3). The most common inventory evaluation tools provide a guidance report and, in about 2/3 of the cases, also include either online forms or spreadsheets to provide specific calculation guidance to the user. For the most part, the calculation methodology and formulas for the inventory protocols adequately account for direct combustion emissions, but supplemental calculations are necessary if the user wishes to also estimate GHG emissions in supply chains [35]. There are about 7 of these tools available, for which the tool functions, inputs and outputs are relatively similar.

LCA calculators account for a larger array of upstream and downstream processes and emission, and are thus considerably more complex in their calculation methodology. The most commonly used, publicly available resources for calculating life cycle GHG emissions from U.S. on-road transportation modes are the GREET models from the Argonne National Laboratory [36] and GHGenius from Natural Resources Canada [37]. These process-based, spreadsheet calculators enable estimation of fuel-cycle and vehicle cycle energy consumption and GHG emissions associated with various transportation fuels and advanced vehicle technologies. Both tools were originally developed primarily for evaluations of passenger cars and LD vehicles, but GREET was expanded in 2015 to include a variety of conventional (i.e., diesel and/or gasoline) HD vehicle types [38]. Both models utilize national and regional data for default emission factors and consider GHG emission credits of displaced emissions.

The GREET model inputs, outputs, and fuel-cycle model user interface provide functionality for emissions estimation from public transportation modes. The model calculates fuel-cycle emissions of five criteria pollutants (volatile organic compounds, carbon monoxide, nitrogen oxides, particulate matter with diameters of 10 micrometers or less, and sulfur oxides) and three greenhouse gases (carbon dioxide, methane, and nitrous oxide). The model also calculates total energy consumption, fossil fuel consumption, and petroleum consumption when various transportation fuels are used.

A new module was added to GREET in 2016 that is referred to as the Alternative Fuel Life-Cycle Environmental and Economic Transportation (AFLEET) Tool [39]. This allows an estimate of life-cycle petroleum use, life-cycle greenhouse gas emissions, vehicle operation air pollutant emissions, and costs of ownership for both LD vehicles and HD vehicles. The AFLEET Tool provides three calculation methods depending on the user’s goals. The first option is the Simple Payback Calculator that examines acquisition and annual operating costs to calculate a simple payback for purchasing a new AFV as compared to its conventional counterpart, as well as average annual petroleum use, GHGs, and air pollutant emissions. The second option is the Total Cost of Ownership (TCO) Calculator that evaluates the net present value of operating and fixed costs over the years of planned ownership of a new vehicle, as well as lifetime petroleum use, GHGs, and air pollutant emissions. Finally, the Fleet Energy and Emissions Footprint Calculator estimates the annual petroleum use, GHGs, and air pollutant emissions of existing and new vehicles, taking into consideration that older vehicles typically have higher air pollutant emission rates than newer ones. The HD vehicle types included in the model are school and transit buses, refuse trucks, single unit short- and long-haul trucks, and combination short- and long-haul trucks. A broad range of conventional and alternative fuel powertrain options are also available, including gasoline, diesel, gasoline hybrid electric vehicle (HEV), gasoline plug-in hybrid electric vehicle (PHEV), gasoline extended range electric vehicle (EREV), all-electric vehicle (EV), gaseous hydrogen (G.H2) fuel cell vehicle (FCV), biodiesel 20% blend (B20), biodiesel 100% blend (B100), ethanol flex-fuel 85% blend (E85), propane / liquefied petroleum gas (LPG), and compressed natural gas (CNG). This new module to GREET fills a void that was previously present for HD vehicles and AFVs, and allows comprehensive assessments of the total cost of ownership and payback assessments using the LCA methodology. The petroleum use and GHG calculations are both well-to-wheels (WTW, i.e. life-cycle) estimates and are similar to those in the GREET Fleet tool (calculations/data are largely based on GREET).

2.3 Other National Laboratory Tools related to vehicle energy performance evaluations

2.3.1 Argonne National Laboratory Tools

2.3.1.1 POLARIS

POLARIS is an agent-based modeling framework designed for simulating large-scale transportation systems that is intended for evaluations of network operation improvements and ITS implementations from a planning perspective [40]. It includes a mesoscopic traffic flow simulator, activity based demand simulation, model building and GIS analysis tools, and tools for analysis of results. A key feature of the framework is that it allows integrated models to be created in which all of the aspects of travel decisions (departure time, destination choice, planning and rescheduling as well as route choices) can be modeled simultaneously.

Applications include: Evaluation of the energy impact of vehicle and transportation technologies in a multi-agent context (small neighborhoods to entire metropolitan areas), energy impact of connected and automated vehicles at the regional level, and evaluating benefits of Intelligent Transportation Systems.

2.3.1.2 VISION

The VISION model provides estimates of the potential energy use, oil use and carbon emission impacts of advanced LD and HD vehicle technologies and alternative fuels through the year 2100 [41]. It uses vehicle survival and age-dependent usage characteristics to project total LD and HD vehicle stock, total vehicle miles of travel (VMT), and total energy use by technology and fuel type by year, given market penetration and vehicle energy efficiency assumptions developed exogenously. The model consists of two Excel workbooks: a Base Case of US highway fuel use and carbon emissions to 2050 (to 2100 in 2008 and newer versions) and a copy (of the Base Case) that can be modified to reflect alternative assumptions about advanced vehicle and alternative fuel market penetration. The tool is similar in scope to the US Energy Information Administration's (EIA's) National Energy Modeling System (NEMS), but extends the projection timeframe.

2.3.1.3 TRUCK and HTEMS

The TRUCK Heavy Vehicle Market Penetration Model estimates future market penetration of advanced or alternative vehicle technologies based on fuel savings and vehicle cost; emphasizing the incremental cost of the energy efficiency technology [42]. The TRUCK model is one component of the Heavy Truck Energy Modeling System (HTEMS), which consists of a set of linked Excel workbooks that are used to calculate the annual energy consumption of heavy trucks in weight classes 3 through 8 with projections from the current year up through the year 2050. The primary purpose of the modeling system is to estimate energy, environmental, and economic benefits of U.S. DOE Vehicle Technologies Program heavy vehicle program elements using a market-based approach.

2.3.1.4 HTEBdyn

The Heavy Truck Energy Balance Dynamic (HTEBdyn) model estimates the impact of technology improvements and innovations on heavy truck fuel consumption for a variety of duty cycles [43]. The model was developed to support analysis of the benefits of U.S. Department of Energy Vehicle Technologies Office programs in terms of fleet level reductions in energy and petroleum consumption and associated emissions and it is designed to interface with the analytical tools used for that assessment. The model is capable of analyzing waste heat recovery systems and hybrid drivetrains. HTEBdyn is not a full vehicle simulation model, but rather, a tool that provides quick analysis and rough estimation of fuel consumption benefits based on user input engine, drivetrain, and vehicle system characteristics.

> Inputs: 1) Engine – size, efficiency, friction Losses; 2) Vehicle – operating weight, frontal area, aerodynamic drag coefficient, tire rolling resistance coefficients, driveline losses, accessory and auxiliary loads; 3) Duty Cycle – drive schedule, annual VMT, non-cycle idling hours
>
> Outputs: 1) Power flows, 2) Duty cycle average fuel consumption

2.3.1.5 NEAT

Non-Light Duty Energy and Greenhouse Gas (GHG) Emissions and Accounting Tool (NEAT) provides estimates of the potential end-use energy consumption, upstream energy consumption, and GHG emissions impacts through 2050 of a Base Case and user defined alternative case(s) relating to five domestic freight carrying modes and their use of alternative fuels [44]. The five modes are: (1) Intercity freight-carrying Trucks, (2) Freight Rail, (3 Domestic Freight Marine, (4) Domestic Freight Aviation, and (5) Pipeline. NEAT is an Excel-based tool that reflects data from Federal Highway Administration's Freight Analysis Framework (FAF) projections and Energy Information Administration's (EIA's) Annual Energy Outlook (AEO) projections. To generate estimates of full fuel cycle GHG emissions and upstream energy consumption for freight modes, NEAT uses feedstock, fuel production, and exhaust GHG emissions and upstream energy use rates from Argonne National Laboratory's GREET model.

2.3.2 NREL Tools

2.3.2.1 ADOPT

The Automotive Deployment Options Projection Tool (ADOPT) estimates the petroleum use impacts of alternative technologies and policies [45]. The tool predicts consumer demand for different vehicle types based on key vehicle attributes including vehicle price, fuel cost, performance, range and size, as well as income distribution and fuel prices in a given region. (This tool is not presently available from the NREL website.)

2.3.2.2 Drive Cycle Analysis Tools: DriveCAT and DRIVE

DriveCAT (Drive Cycle Analysis Tool) is used to find and select drive cycle data for modeling, simulating, and testing vehicle systems and components, or to understand the real-world benefits of drive cycles for specific vehicle applications [46]. The tool currently contains 19 drive cycles.

DRIVE produces representative, testable drive cycles at record speed from large amounts of vehicle data gathered via onboard logging devices [47]. DRIVE uses GPS and controller area network data to characterize vehicle operation and produce custom vehicle drive cycles based on real-world activity, analyzing thousands of hours of data in a matter of minutes.

2.3.2.3 Fleet DNA

Although not a tool for estimating energy consumption, Fleet DNA is an important “tool supplement” that contains detailed fleet vehicle driving data measurements. It is a clearinghouse of commercial fleet vehicle operating data intended to help vehicle manufacturers and developers optimize vehicle designs and help fleet managers choose advanced technologies for their fleets. The online tool provides data summaries and visualizations for MD and HD commercial fleet vehicles operating in a variety of vocations.

2.4 Tools Summary

Table 1 presents a summary of the tools described above that are relevant to the intended use of fleet evaluations using the SVET and FFLEET tools, and several factors are compared.

Table 1. Model Comparison Summary

	An/Ross model	ADVISOR	FASTSim	Autonomie
General description	Early, analytical model that provides insights into basic dependencies of fuel economy on drive cycle and vehicle parameters	Advanced Vehicle Simulator. uses characterization maps of drivetrain component performance to estimate fuel economy and emissions on given drive cycles as well as predicting vehicle acceleration and gradeability capabilities.	Future Automotive Systems Technology Simulator. High-level vehicle powertrain analysis tool to compare different vehicle designs and estimate the impact of technology improvements on light- and heavy-duty vehicle efficiency, performance, cost, and battery life.	Detailed vehicle performance model development framework: used for detailed vehicle design and performance assessments of advanced vehicle technologies
Primary model assumptions	Fuel consumption rate linear in terms of engine speed and brake power output	Requires full engine map. Calculator uses a hybrid forward/backward approach to ensure performance not exceeded, but model runs very quickly.	Efficiency for engine, battery or fuel cell is modeled as a function of the power.	Comprehensive vehicle and powertrain models can be developed that account for practically any aspect of powertrain system design and control. High degree of flexibility in model development.
Currently available?	No, but relatively easy to program in spreadsheet	Yes	Yes	Yes
Inputs	engine displacement, model year, vehicle mass, rolling resistance coefficient, aerodynamic drag coefficient and frontal area, average accessory power, any drive cycle	Vehicle type, and basic configuration data. All component map efficiencies must be entered via drop-down menus.	To fully specify the vehicle, there is a set of data inputs for the vehicle chassis, fuel storage, fuel converter, motor, traction battery, wheel, energy management.	All factors of the vehicle design must be specified. Submodel inputs
Outputs	fuel consumption and distribution of energy consumption among the loss factors: rolling resistance, air resistance, braking, accessories	fuel consumption, emissions, acceleration/gradeability performance. Several standard graphs, can be customized in Matlab.	Primary results for fuel economy, price, lifetime cost, acceleration and gradeability performance and details of the PHEV configuration.	Fuel consumption and powertrain results for every instant of the simulation are available for output
Passenger or Freight	Both	Both	Both	Both
Software platform	spreadsheet	Matlab/Simulink	Excel spreadsheet	Matlab/Simulink
Drive cycle with grade permitted?	Not in model but easily added	Yes	Yes	Yes
Technologies evaluated	vehicle configuration only (mass, rolling resistance, aerodynamic parameters, engine displacement)	Primarily developed for hybrid powertrain evaluations.	Compares conventional, HEV, PHEV and EV powertrains, and parametric studies can be configured to evaluate a single variable.	Any advanced vehicle powertrain technology could be evaluated with Autonomie.
Specialized functionality, other notes	analytical model for any drive cycle. Fuel economy result is expressed in terms of integrals over segments of the drive cycle, based on acceleration, powered deceleration, braking, and stopped conditions.	Includes function to size engine, motor, and batteries to meet user-defined minimum performance requirements for acceleration and gradability.	There is a process to automatically import the input data for most light-duty vehicles.	User has access to almost all variables in the simulation for both input and output and is able to create custom reports in addition to custom models for any component. The high degree of flexibility, however, also results in increased complexity.
Designed for full-fleet evaluations?	No	No	No	No
Model developed by	University of Michigan	NREL	NREL	Argonne

	CMEM	MOVES	PERE	POLARIS	GREET
General description	Predicts second-by-second tailpipe emissions and fuel consumption for a wide range of vehicle/technology categories.	A MOVES project level emission rates run produces a table of emission rates. Total emissions are obtained by multiplying the emissions rates by the corresponding vehicle specific power (VSP) and summing the result	Designed to complement the MOVES GHG emissions model for increasing the level of accuracy in estimating on-road vehicle emissions. Its purpose is to fill data gaps in MOVES and to provide a tool to extrapolate to future projections of energy and emissions outputs.	High-performance, open-source agent-based modeling framework designed to simulate large-scale transportation systems. It features an integrated network-demand model, in which all the aspects of travel decisions (departure time, destination choice, route choice, planning and rescheduling) can be modeled simultaneously.	Greenhouse gas, Regulated Emissions, and Energy use in Transportation. LCA tool for GHG evaluations. Several GREET-based calculators are available for different purposes and vehicle types, including light duty vehicles, transit vehicles, medium duty trucks and freight truck
Primary model assumptions	Empirically based model; emissions are derived from dynamometer measurements of pre- and post-catalyst emissions from over 340 vehicles. Reduced tractive power calculation using A,B,C coefficients for vehicle energy losses. Uses average powertrain efficiency and accessory power.	MOVES will provide emissions rate data as a function of operating mode (speed and VSP). The total emissions or fuel rate is obtained by taking the product of the emissions rate and the VSP, then summing over all times.	Uses well established characterizations for other components used in conventional and advanced powertrain types that are also generalized to represent behavior that can be expected to be typical for most vehicles. Engine efficiency based on Ross model (fuel mean equivalent pressure [mep])	Mesoscopic traffic simulation is integrated with the agent-based modeling approach to calculate energy use of all vehicles operating on the modeled traffic network	Life cycle assessment uses upstream and downstream factors to account for emissions associated with manufacture, fuel production and distribution, and recycling/disposition of the product at end of life, in addition to the total fuel use over the life of the product
Currently available?	Yes	Yes	No	Yes	Yes
Inputs	Each sub-model uses three dynamic operating variables as input, including second-by-second speed, grade and accessory use data. Additional parameter inputs are used for each vehicle/technology category.	Emissions and fuel consumption can be calculated from a project level MOVES run based on vehicle speed data and vehicle specific power (VSP)	model year, weight, coefficient of drag, frontal area, rolling resistance coefficient, mass, engine displacement, motor power (if present), and fuel type	The assumptions employed in the agent-based model and the traffic network are effectively inputs for the analysis.	Fuel economy is a primary input, so this is not a predictive tool with respect to the fuel consumption on the vehicle itself, i.e. for the PTW phase of use.
Outputs	Second-by-second Fuel rate and emissions for HC, CO, NOx and CO2.	Fuel consumption and emissions, including NOx, PM, CO, CO2, SO2 and NH3.	PERE outputs Pump-to-Wheel (PTW) fuel consumption rates. It is intended to fill data gaps in MOVES.	Energy use on the selected transportation system	Total energy use during the life of the vehicle
Passenger or Freight	Passenger car/light truck only	Both	Both	Both	Both
Software platform	Executable run from command line	Java code integrated with MySQL database	Excel Spreadsheet	Dedicated model	Excel Spreadsheet
Drive cycle with grade permitted?	Yes	Yes, can be included in VSP calculation	Yes	Yes, this can be modeled in the traffic network	N/A
Technologies evaluated	N/A. Only defined vehicle/technology categories can be evaluated.	MOVES by itself will generate different emissions data only if the vehicle type changes according to MOVES' definition. PERE used with MOVES can be used to obtain modified emissions rate data.	gasoline, diesel, battery, fuel cell, and hybrid electric propulsion systems.	This approach can be used to evaluate CAV technologies, among others.	N/A
Specialized functionality, other notes	Emissions can be determined for a wide variety of LDVs in various states of condition (e.g., properly functioning, deteriorated, malfunctioning).	The methodology of the MOVES calculation is very different than with most other models described here.	To determine the impact on emissions, the user should follow guidance provided in (Nam and Giannelli, 2005).	Implements all the major components of a transportation modeling suite by including traffic flow simulator, activity based demand model, network/demand integration, event engine and visualization. Agent-based model structure, Integrated with Autonomie, flexible programming.	Very complete LCA GHG and fuel evaluations, including upstream and downstream emissions factors. The GREET model is considered the standard for LCA analysis, many other tools use GREET emissions factors. If GREET is integrated with a powertrain tool to estimate the fuel savings for the PTW stage, this would yield a complete LCA based on a particular powertrain change
Designed for full-fleet evaluations?	Yes, entire U.S. passenger car fleet	Yes	Yes, by integrating with MOVES	Yes	No
Model developed by	UC-Riverside	U.S. EPA	U.S. EPA	Argonne	Argonne

3.0 Details of the SVET and FLEET Models

3.0.1 Rationale for Development of SVET and FFLEET

The tools developed for this project were aimed at a very specific use—quantifying the energy savings in individual passenger or freight transport fleets that can be achieved as a result of vehicle replacements with advanced technology vehicles and/or the implementation of other energy efficiency technologies such as CAVs deployments. A number of models are available that address fleet energy consumption or the energy efficiency of advanced vehicle technologies. However, existing tools tend to either be oriented toward single vehicle evaluations for which a large number of inputs and knowledge of the technologies involved are generally required, or they are geared towards quantifying the energy and/or GHG emissions associated with a fleet of existing vehicles for which the fuel efficiency of the vehicles is known, i.e. the efficiency is a required input. The first type of model includes predictive evaluations that employ vehicle powertrain and use characterizations and calculate vehicle fuel economy and/or emissions based on detailed evaluations of the physics of vehicle operation. Examples of such tools include comprehensive vehicle/powertrain models developed with tools such as Autonomie [23],GT-SUITE [24]or AVL Cruise [25] (GT-Suite and AVL Cruise are commercially available products) as well as simulators that use reduced vehicle parameter sets in a simplified vehicle model but are designed for individual vehicle evaluations and require user-specified drive cycles to characterize vehicle usage. Tools that fall under this category include FASTSim (Future Automotive Systems Technology Simulator) [22],PAMVEC (Parametric Analytical Model of Vehicle Energy Consumption) [48],and VT-CPFM (Virginia Tech Comprehensive Power-Based Fuel Consumption Model) [49]. While such models can be used in principle to determine the fuel savings from a set of vehicles employing different vehicle technologies, the tools are not configured to do this systematically, and to do so requires that the user develop a separate model in the tool for each vehicle. The detail required for each is generally rather significant, and this approach requires the user to manage all results and combine the individual vehicle energy consumptions to determine the total energy use in the fleet. In general, the data requirements for this type of model are at a level that is beyond the knowledge or expertise of many fleet users. While some models (for example, FASTSim) have been designed to select entries that correspond to existing vehicles and thus require fewer user inputs, the structure of the tool is not designed to perform energy savings estimates for a full fleet evaluation. The strength of this type of model is the ability to predict the energy consumption for individual vehicles of any design under specific driving conditions, but the flexibility of this approach results in increased complexity which can quickly make a tool untenable for performing broad fleet evaluations, particularly for users that are not expert in vehicle modeling.

The second type of tool described above, referred to as a life cycle assessment (LCA) calculator, is frequently used for GHG emissions evaluations but also include results for energy use. LCA tools are designed to quantify environmental impacts and assess costs of new technologies over their lifetime, often including energy/emissions associated with manufacturing and disposal of the vehicle as well as numerous other upstream and downstream energy uses associated with vehicle and fleet operations. Examples include the GREET (Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation) and AFLEET (Alternative Fuel Life-Cycle Environmental and Economic Transportation) tools from Argonne National Laboratory [36,39], and GHGenius from Natural Resources Canada [37].

These tools can be used by transit agencies or other entities for GHG emissions reporting or for research assessments of the benefits of one vs. another technology for reducing holistic GHG emissions/energy consumption, and are appropriate for documentation of regulatory compliance or for self-reporting of sustainability goals. Although such tools can be used for quantifying the overall impact of vehicle technology choices for a fleet, this class of model requires pre-knowledge of the fuel economy of the vehicles considered, and existing tools cannot be used to predict energy savings based on specific usage conditions. As such, they are largely irrelevant to the goals of the current project, although the results from the energy evaluations generated from the SVET and FFLEET tools could be used as inputs to the LCA tools to evaluate the broader implications of the technologies for GHG emissions.

In contrast to the types of models described above, the SVET and FFLEET tools were designed to predict vehicle energy consumption for sets of vehicles comprising an entire fleet (or for a smaller group of vehicles of interest within a fleet) and for a range of advanced vehicle technologies. Most of the technologies considered are currently available in the market although some technologies that are under development but anticipated to provide significant efficiency benefits are also included in the SVET and FFLEET models. These include several advanced engine types and a range of propulsion systems, aerodynamic options, transmissions, and some CAV technologies aimed at fuel efficient operation. Some of the engine technologies evaluated in SVET and FFLEET are not included in other tools as simply selectable options, and in many cases modeling them in other tools would require obtaining detailed engine map data that is typically not available to fleets. The methodology used to characterize engine efficiencies in SVET and FFLEET can be used to simulate many different engine technologies, permitting vehicle energy consumption to be evaluated and compared for vehicles with different engine types and sizes, without obtaining the specific engine maps. In addition to this simpler methodology for engine technology evaluations, a novel approach was developed to quantify the magnitude of benefits from technologies that impact the fuel economy by modifying the speed profile of the vehicle, as in the case of some CAV technologies as well as the speed governors/limiters that are frequently used in long-haul trucks.

Table 2 shows a summary of several models that are currently in use for vehicle or fleet energy and GHG emissions evaluations. Although this list includes only a limited set of existing models, they are quite typical of the two general categories of model described above. While some vehicle performance software tools could be employed to conduct a brute force calculation of all vehicles in a fleet and make comparisons between vehicle technologies deployed at different points in time to estimate potential energy savings, the models are not intended for this purpose and the time required to do so would likely be cost-prohibitive.

Table 2. Examples of several currently available vehicle and fleet energy or emissions tools/models

Tool / Model	Primary Use	Strengths	Deficiencies for the purpose of predicting full fleet energy savings
Autonomie (Argonne National Laboratory) [23]	Detailed vehicle performance model development framework: used for vehicle design and performance assessments of advanced vehicle technologies	Very detailed vehicle models can be developed that account for any aspect of powertrain design factors and control	Model development requires extensive knowledge of powertrain characteristics, time to develop each vehicle model can be considerable.
FASTSim (National Renewable Energy Laboratory) [22]	High-level vehicle powertrain analysis tool to compare different vehicle designs and estimate the impact of technology improvements on LD and HD vehicle efficiency, performance, cost, and battery life.	Relatively simple interface, includes some automation for LD vehicle selections. Tool is at an appropriate level for comparisons between different vehicle technologies. Existing models with different powertrain options	No options for simplified drive cycle entry (standardized cycle or measured cycle inputs only); not intended for full fleet evaluations.
Virginia Tech Comprehensive Power-Based Fuel Consumption Model [49]	Fuel consumption model with powertrain control strategy to enable relevant control for fuel economy optimizations	Simplified powertrain model, with parameters that can be calibrated using publicly available data	Each vehicle specification still requires many inputs. No simplification for drive cycle inputs.
GREET (Argonne National Laboratory) [36]	LCA tool for GHG evaluations. Several GREET-based calculators are available for different purposes and vehicle types, including LD vehicles, transit vehicles, MD trucks and HD freight trucks	Very complete LCA GHG and fuel evaluations, including upstream and downstream emissions factors. The GREET model is considered the standard for LCA analysis, many other tools use GREET emissions factors	Not intended for predicting energy use/GHG emissions for alternative advanced vehicle technologies. Fuel economy data must be supplied as input
MOVES (Motor Vehicle Emission Simulator), U.S. Environmental Protection Agency (EPA) [28]	LCA tool for GHG evaluations, including emissions factors associated with a broad range of vehicle technologies.	Considered the primary source for mobile source emission factors for vehicle tailpipe GHG and criteria pollutant emissions; used extensively by agencies for GHG reporting	Not predictive for fuel consumption with alternative vehicles and technologies. Speed distribution data is required as an input to the MOVES model (or MOVES defaults can be used).
Environmental Defense Fund (EDF) / NAFA Fleet Management Association Fleet Greenhouse Gas Emissions Calculator [50]	Calculation of direct (scope 1) GHG emissions using total fuel use data and based on EPA GHG emissions factors	Ease of use, allows fleets to quantify GHG footprint and track progress over time. Employs EPA data for vehicle emission factors.	Requires fuel use data for each vehicle type or aggregate fuel data. Not predictive for fuel consumption with alternative vehicles and technologies.

The SVET and FFLEET tools are aimed specifically at predicting the energy use reductions achievable in a fleet with alternative fuel and other advanced fuel efficient vehicle technologies based on the particular usage conditions of the fleet. As such, ease of use and calculation speed are critical for the intended use. To address these needs, a mid-level modeling approach was taken that reduces the complexity of the inputs while still permitting a detailed inventory of the fleet's vehicles and accounting for driving conditions representative of those experienced by the fleet for the energy consumption evaluations.

3.0.2 Objectives and Design of the SVET and FFLEET Models

The project goals were oriented specifically at conducting energy savings evaluations for vehicle fleets, and the tools allow evaluations of a broad spectrum of highway vehicles ranging from passenger cars and light trucks to freight trucks of different weight classes and usages. The development was divided into the creation of two separate tools, the Smart Vehicle Energy Technology (SVET) model for passenger vehicle fleets and the Freight Fleet Level Energy Estimation Tool (FFLEET) for freight transport fleets. Expected users of the tool include managers responsible for fleet operations or procurement from Metropolitan Planning Organizations (MPOs), transit agencies, corporations or other organizations operating passenger fleets, as well as fleet managers or owner/operators of freight transport companies. The tools are intended to quickly guide users through the process of creating their fleet profile of vehicles, including defining the vehicle usage, with varying levels of detail to be provided within the model, depending on the intended purpose of the evaluation and availability of data. Drive cycle/vehicle usage specification is an important part of the vehicle model evaluation, and a novel approach was employed to make the usage specification more intuitive and straightforward for users that are not very familiar with this aspect of vehicle modeling. In addition to allowing selection among a range of standardized drive cycles, users can select several distinct usage cases and define their usages in terms of fractional weighting among these usages. For example, most drivers are able to estimate what portion of their driving is comprised of highway, rural, extra-urban/arterial, and congested city driving and what their average speeds are. The weighted cycle option allows usage to be defined in terms of combinations of very specific driving situations. For users that have data of their fleet's actual drive cycles, measured drive cycle data can be loaded, and the same weighting options are available so that specific routes can be weighted and combined in the manner described above. These options for specifying the vehicle usage were designed to enable users to generate appropriate inputs at a level consistent with their organization's availability of information and needs.

The vehicle models developed employ a tractive energy/vehicle efficiency analysis that incorporates technical parameters characterizing each selected vehicle and appropriate drive cycles, and the analysis is scenario based: Evaluations are run for both the current fleet profile and alternate scenarios representing the future implementation of efficient vehicles/ technologies to estimate the energy savings that can be achieved in each future technology deployment scenario. Vehicle model parameters are automatically selected based on the vehicle selections in each scenario to the greatest extent possible, while users are able to modify any parameter inputs to account for vehicle customizations or alternative configurations desired. A detailed functional specification for both the front end tools and the powertrain simulator calculation engine was written at the outset of the project that detailed the data needs from the user and how the web-based front end tool should interact with the calculation engine to complete the fleet level energy savings evaluations. These specifications were then used to develop the two elements that comprise the SVET and FFLEET tools in parallel. The front end tools were designed so that all data is entered through a user friendly web-based interface that stores inputs in a database structure so users can save their fleet profiles and future use scenarios, and the models can be updated and tracked as the fleet changes over time or future planning evolves. The web interface manages all user inputs and interactions and creates an input file for each vehicle analysis. These input files are then passed by the front end to the calculation engine, which runs each vehicle model and returns the results back to the user interface. The primary results from the simulations are the energy consumption data for the scenarios evaluated and the corresponding energy savings between them, but detailed results for individual vehicles are also available in the form of various graphs showing the second-by-second vehicle operation data.

The SVET and FFLEET vehicle models were designed to calculate the current fleet energy expenditures and allow alternative futures to be modeled and selected based on the most up to date science. These tools are intended to help accelerate the deployment of alternative fuel vehicles and fuel efficient technologies in fleet operations and enable fleets to simply and accurately predict the energy savings that can be realized through deployment of these technologies. The goal for the tools is to estimate energy savings within approximately 10%, although uncertainties with some upcoming technologies (CAV technologies, in particular) limit the accuracy possible in those cases.

The SVET tool was designed to allow evaluations of the following advanced vehicle technologies:

Vehicle types:
Current and past production LD vehicles (cars and light trucks)
Variations of existing vehicles to include any of the technologies below
Propulsion systems:
Conventional internal combustion engine (gasoline, diesel, natural gas or hydrogen)
Gasoline direct injection engines
Naturally aspirated or turbocharged engines (including down-sized turbo engines)
HEV powertrains, including series and parallel configurations
PHEVs
Battery electric vehicles
CAV technologies:
Traffic signal eco approach and departure
Connected eco-driving (traffic smoothing)
Other fuel efficiency technologies:
Advanced aerodynamics (active grill shutters, under body drag reduction devices, etc.)
Advanced transmissions: 7- to 11-speed
Vehicle Lightweighting (carbon fiber body panels, low mass glider, compacted graphite iron (CGI) block)

The FFLEET tool was designed to allow evaluations of the following technologies:

Vehicle types:
Class 7-8 tractor-trailers (day cabs and sleeper cabs)
Box/straight trucks
Delivery/step vans
Car carriers
Flatbed trucks
Propulsion systems:
Conventional internal combustion engine (gas, diesel, or natural gas)

HEVs (series and parallel configurations)
PHEVs
Battery electric vehicles
CAV technologies:
Traffic signal eco approach and departure
Connected Eco-Driving
Platooning
Other fuel efficiency technologies:
Aerodynamic drag reduction devices (advanced cabin fairings, trailer skirts, boat tails, trailer gap reduction, under body drag reduction, wheel covers)
Low rolling resistance tires
Speed limiters/governors
Advanced transmissions: 6-18 speed
Vehicle Lightweighting options (carbon fiber body panels, low mass glider, compacted graphite iron (CGI) block)

The vehicle powertrain models determine the energy consumption of each vehicle based on a series of inputs and calculation steps that account for many factors to characterize both the vehicle and the driving situation/usage. The energy consumption evaluations require a detailed specification of each vehicle as well as a corresponding usage scenario. The process for performing the vehicle-usage specification and the energy consumption evaluation using the vehicle powertrain model includes the following four key elements:

1. Drive cycle: the drive cycle characterizes the usage of the vehicle and plays an important role in the fuel consumption. The drive cycle is a result of the type of roads traveled, traffic conditions (stop and go, etc.), elevation, driving style/aggressiveness, and speed controls.
2. Vehicle design specification: the vehicle design parameters clearly have a direct impact on energy consumption
3. Tractive power calculation: the tractive power depends directly on the drive cycle as an input but also on fundamental vehicle characteristics (mass, rolling resistance and aerodynamic drag) that determine energy losses and kinetic / potential energy changes. It serves as a direct, physics-based link between the speeds and elevations that the vehicle experiences (i.e. the drive cycle) and several primary vehicle characteristics that are a direct result of the vehicle's size and shape (mass, frontal area, aerodynamic drag). This indicates that there are very direct interactions between the vehicle design and the drive cycle in determining the energy consumed by the vehicle.
4. Powertrain efficiency evaluation at each instant in time: the powertrain configuration and the efficiency of all powertrain components have a strong impact on the overall vehicle's energy consumption. Since it is the powertrain that provides the power to propel the vehicle, the tractive power and the powertrain component efficiencies have a combined impact on the vehicle energy consumption.

Figure 3 shows the important interactions between the drive cycle, vehicle specifications, and the powertrain configuration.

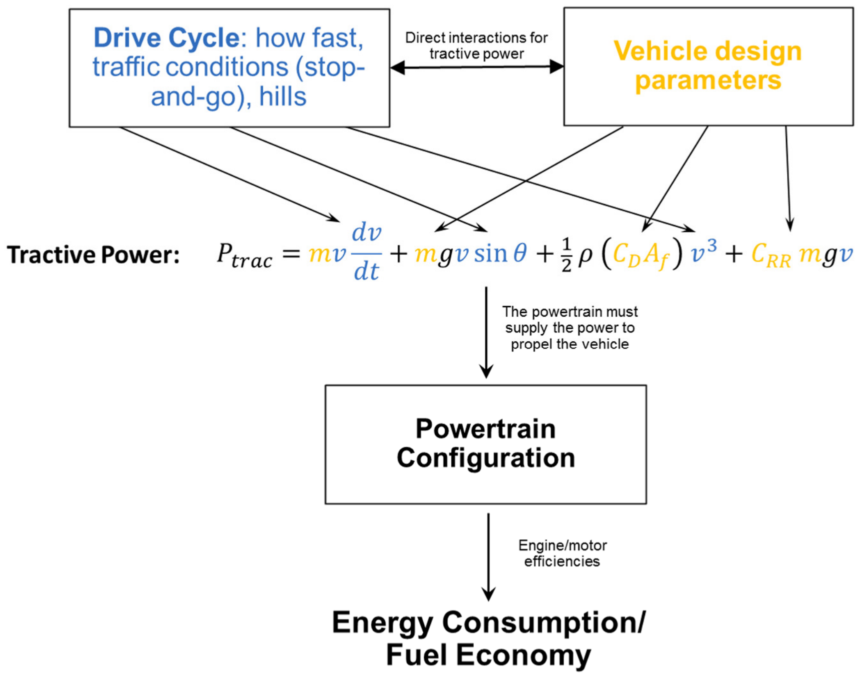


Figure 3. Interactions between the drive cycle, vehicle design parameters and the powertrain configuration, and their role on the total energy consumption.

All of the technologies evaluated in SVET and FFLEET impact one or more of the model elements described above: (1) the road load / energy loss parameters are affected by the selected vehicle types/makes/models, the tire rolling resistance, aerodynamics devices and platooning, and mass changes; (2) the engine efficiency is impacted by the engine type and propulsion system, as well as the engine operating state due to modified gear shifts for advanced transmissions; (3) the drive cycles can be affected by several CAVs technologies, which impact fuel economy through changes to vehicle speeds. To quantify the effects of the technologies, the relevant elements for each technology are therefore modified in the model and the resulting energy consumption is calculated.

3.1 Vehicle model development

The vehicle model was developed based on a tractive power approach similar to that described in the literature review. This methodology allows a physics-based evaluation of the forces acting on the vehicle, and the total load is a combination of the tractive power and other auxiliary loads. The fuel energy consumption is then determined based on the efficiency of all components that make up the selected powertrain configuration. Determining the fuel consumption is therefore a multi-step process, and a separate initial step is included for filtering of the speed and/or elevation data when it is based on measurements and/or lookup data.

All powertrain components for each vehicle are specified as inputs to the model from the “front end” user interface for both the SVET and FFLEET tools, and appropriate vehicle and engine characteristics are selected for the simulation based on these inputs. The same fundamental modeling approach, however, is used in all cases in the powertrain model, just with different vehicle parameters and sub-models. Therefore, the same powertrain calculation is applied for both SVET and FFLEET, and a single calculation engine is used in the analysis for both tools.

The vehicle models and all associated software for the calculation engine for SVET and FFLEET were programmed in the Python programming language. Initial plans were to develop the tool using Matlab, but Python was selected instead due to the easier portability for a web-based tool, the lack of licensing requirements for Python and the ability to compile all functions the need to purchasing specialized toolboxes or other software.

3.1.1 Filtering of speed and elevation data

The drive cycle is a critical data input for any vehicle model. As such, it is important that the data is clean and as representative as possible to the actual driving performed. A common issue with measured vehicle speed data and elevation data obtained by lookup from GPS coordinates is significant noise in the signals, which can lead to unrealistic powertrain behavior in vehicle simulations [51]. To minimize this effect, filtering functions are available in the SVET and FFLEET tools to smooth raw speed and/or elevation data that are derived from on-vehicle measurements and GPS signals. The filtering methodologies employed were developed in a previous study [15]. A visual comparison of the raw and filtered speed data generally shows nearly identical results, as shown in Fig. 4, but the filtered signal nevertheless causes the acceleration to be smoothed, which will minimize spikes in the calculated tractive power that are unrealistic.

Elevation filtering, on the other hand, can generate noticeable differences between raw and filtered data in hilly terrains. Elevations are often obtained from a lookup of ground elevations from GPS latitude and longitude coordinates (the U.S. Geologic Survey elevation data is a readily available source [52] that can be obtained using online tools [53]). The elevations in USGS data and most other sources are not restricted to road elevation data, and the surrounding terrain can have significant grade variations that would not be acceptable on roads. The lookup data, which are generally interpolated, will therefore not be very representative of the road elevation even if the GPS coordinates are completely accurate. Roadway elevations, however, are controlled by engineering standards for road design [54], which provide guidelines for how rapidly the grade should change, and the maximum grade is also limited based on the type of road traveled. This smoothness of road grade allows the GPS elevation signal to be effectively filtered as a function of distance traveled. The filtering methods used for the analysis take advantage of the standardization of road grades to approximate elevation changes that are typical in highway designs. Figure 5 shows the elevation filtering result for a route in the Knoxville, Tennessee area.

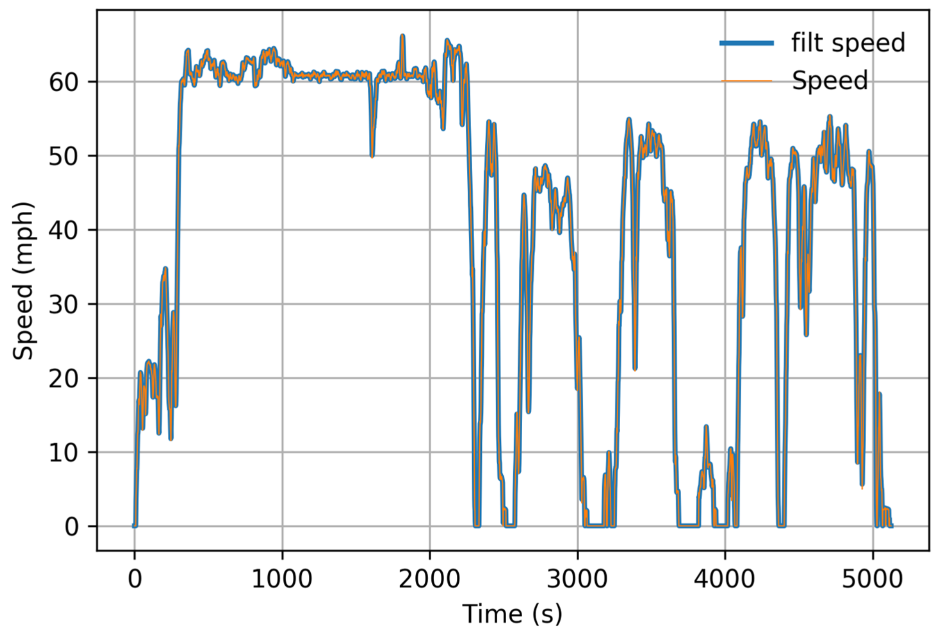


Figure 4. Comparison of raw and filtered speed data.

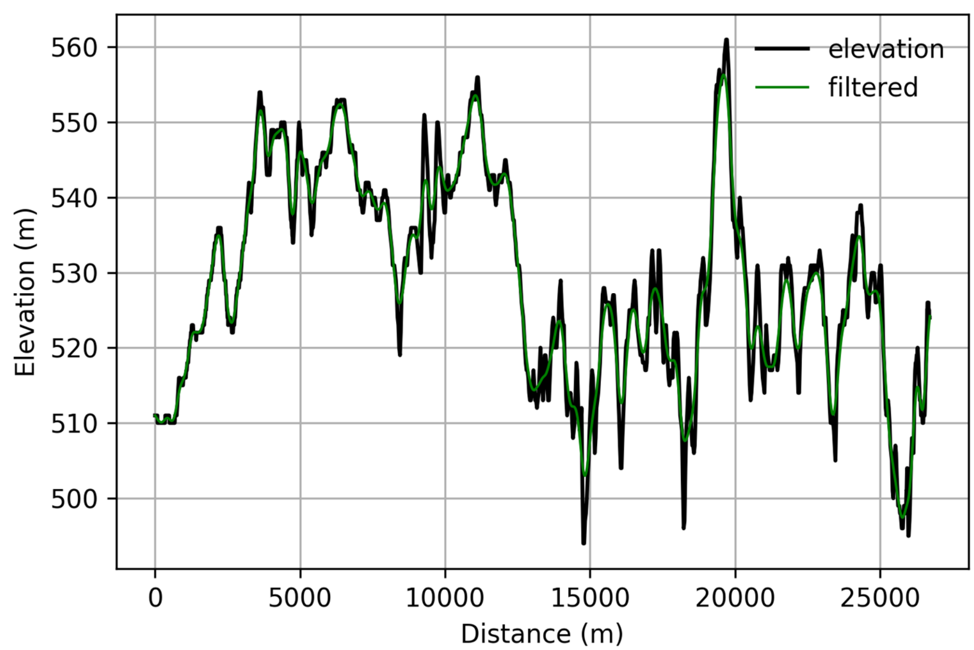


Figure 5. Raw and filtered elevation.

3.1.2 Tractive power calculation

The first calculation needed in the model for any powertrain configuration is the vehicle tractive power requirement, which is based on application of Newton's 2nd law of motion to a vehicle in motion and is used to determine the power required at the wheels to propel the vehicle. The tractive power calculation uses vehicle model parameters that characterize the road load in addition to the drive cycle speed and grade data. The tractive power can be calculated using either fundamental parameters for rolling resistance and aerodynamic drag or empirically measured coefficients that characterize the forces acting on the vehicle while driving. The equation in terms of the aerodynamic and tire rolling resistance forces is

$$P_{trac} = mv\frac{dv}{dt} + mgv\sin\theta + (F_{aero} + F_{RR})v. \tag{9}$$

This equation includes the mass *m* of the vehicle, its speed *v*, the gravitational acceleration *g*, the road grade sin θ, and the aero and drag forces, F_{aero} and F_{RR}. The aerodynamic drag force F_{aero} is determined by the aerodynamic drag coefficient C_D, the vehicle frontal area A_f, the air density ρ, and the vehicle speed *v* as

$$F_{aero} = \left(C_D A_f\right)\tfrac{1}{2}\rho v^2. \tag{10}$$

The rolling resistance force is given by

$$F_{RR} = C_{RR}\, mg, \tag{11}$$

where C_{RR} is the coefficient of tire rolling resistance (which may be speed dependent). For testing of vehicles on a dynamometer, it is convenient to determine a set of "road load" coefficients that characterize the forces acting on the vehicle in terms a 2nd order polynomial of the vehicle speed. The aerodynamic and rolling resistance forces are combined and are evaluated empirically using a vehicle coastdown procedure. The road load forces are fit to the following equation:

$$F_{road} = a + bv + cv^2. \tag{12}$$

In this case, the tractive power is given by

$$P_{trac} = mv\frac{dv}{dt} + mgv\sin\theta + (a + bv + c^2)\, v. \tag{13}$$

<u>Parameter specification in SVET and FFLEET</u>:

The so-called "a,b,c coefficients" are measured for most passenger vehicles as part of fuel economy certification testing in the U.S. and their values are published annually by the U.S. EPA in its "test car list." For this reason, use of the a,b,c coefficients is the preferred method to characterize production LD vehicles in the SVET tool. For MD and HD vehicles, however, a,b,c coefficients are not generally publicly available, and estimates for the rolling resistance coefficient, aerodynamic drag coefficient and frontal area are needed instead. In FFLEET, when the user selects a truck type, the tool will load default values for the vehicle parameters characterizing the aerodynamic forces that act on the vehicle, and typical rolling resistance coefficients are provided when the user makes a selection among low, medium, or high rolling resistance tires. These default parameter values can be modified by the user after selection if specific information is available. In the SVET tool, the user may select any vehicles that are included in the EPA test car list using the user interface, as shown in Fig. 6, to automatically populate the a,b,c coefficients for the model. The rolling resistance coefficient and aerodynamic drag parameters may be specified as an alternative, and any of the parameters can be manually changed as desired by the user.

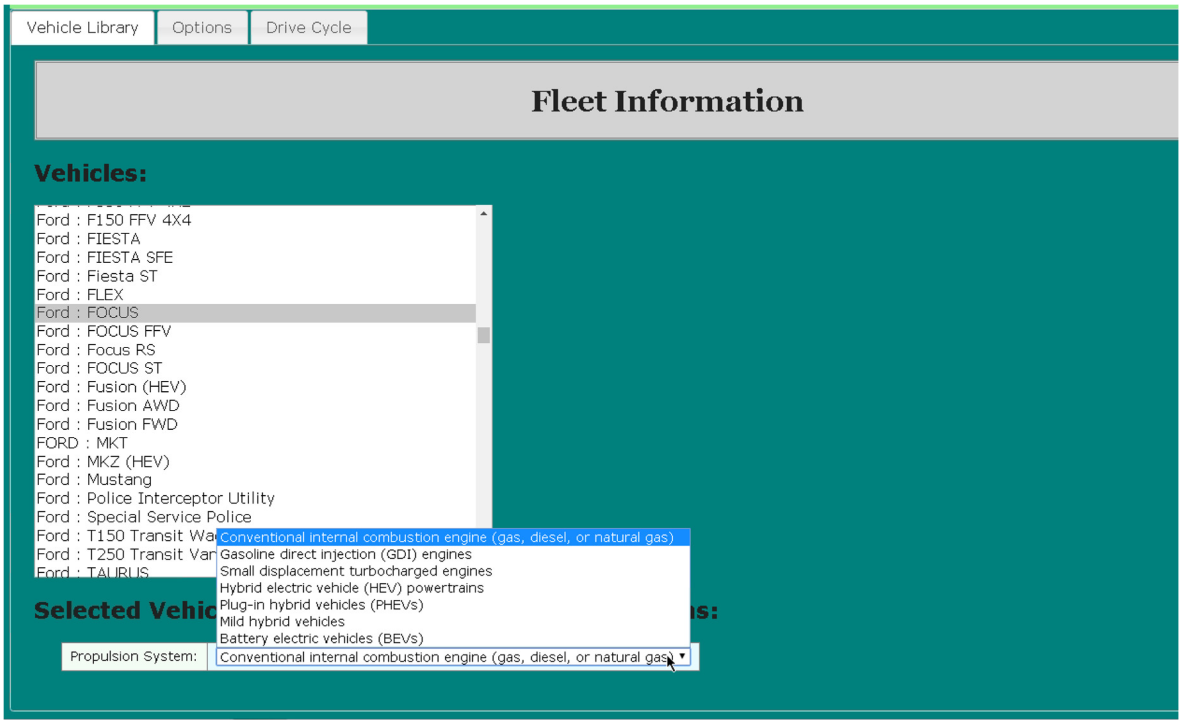


Figure 6. The selection of LD vehicles in SVET can be done based on year, make and model, which links to the a,b,c coefficients from the EPA test car list to populate the vehicle model.

3.1.3 Specific powertrain models

After the tractive power is calculated in the model, the next step in the evaluation is to determine the power that must be produced by the engine and/or motor, as appropriate. This calculation obviously depends on the specific powertrain configuration selected, and different powertrain modules are run to determine the power from the engine and/or motor for the different powertrain configurations that are available. There are four separate powertrain modules for the following powertrain configurations: (1) conventional vehicles powered only by an engine, (2) electric vehicles (EVs), which are powered only by an electric motor, (3) hybrid electric vehicles (HEVs) that include both an engine and motor, and (4) plug-in HEVs (PHEVs), which are powered by a motor and engine but additional energy is stored in the vehicle's battery by plugging in the vehicle when it is not being driven. The PHEV is a special case of the HEV powertrain, but its operation is rather different so a separate module was created for its evaluation.

3.1.3.1 Engine efficiency evaluations

Different types of engines could be used for the same powertrain configuration so the engine type is an independent selection in the model (for those configurations that include an engine). The engine efficiencies at different operating conditions will change for the different engine types, and this is handled using separate sub-models characterizing each engine type within the powertrain configuration modules. The engine types that are modeled include conventional naturally aspirated spark ignition (SI) engines, gasoline direct injection (GDI), turbocharged SI (with and without GDI), and turbo-diesel designs. For modeling these engine technologies, a general approach was desired that can provide estimates of the efficiencies under different operating conditions without the need for measured engine map data. As shown by Ross and An [7], fuel consumption for an engine is approximately proportional to the work output per cycle, and this proportionality holds over a range of engine speeds that covers most normal driving. As a result, a simple linear engine model can be used to represent the efficiency at different loads and speeds. This behavior is characterized by the relationship between the engine power output per cycle normalized by the engine displacement—the brake mean equivalent pressure (bmep)—and the fuel mean equivalent pressure (fumep), which is the rate of fuel energy per cycle normalized by the displacement. The bmep is given as

$$bmep = \frac{P_{eng}}{V_d\, N/2} = \frac{4\pi\,\tau}{V_d}, \tag{14}$$

where P_{eng} is the engine power output, V_d is engine displacement, N is the engine speed (RPM), and τ is the engine torque. The fumep is given by

$$fumep = \frac{P_{fuel}}{V_d\, N/2} = \frac{\dot{m}_f \cdot LHV}{V_d\, N/2}, \tag{15}$$

where $\dot{m}_f$ is the fuel flow rate and LHV is the lower heating value of the fuel. The linear relationship is therefore described by

$$bmep = \mu\, fumep - k. \tag{16}$$

For engines using similar technology, the constants μ and k have been found to be quite similar [55], so this relation provides an excellent approach to obtain a first order estimation of fuel consumption for a given engine as well as quantifying differences in behavior among different engine technologies under similar load conditions (refer to Fig. 2). The fact that these equations are normalized by the engine displacement allows engines of any size to be determined using the same methodology. Both LD and HD engines can be evaluated using the same approach, although a different set of coefficients was used for HD diesel engines in the FFLEET model than for LD diesel in SVET.

Although using these linear bmep vs. fumep relationships is not as accurate as fuel map data measured for specific engines, it allows simple evaluations that are appropriate for the intent of the SVET and FFLEET tools without obtaining engine map data for each vehicle. It is noted that the linear relationship does not hold at higher loads for naturally aspirated SI engines, particularly near wide open throttle (WOT) operating conditions. However, with modern automatic transmissions (and normal shifting patterns for manual transmissions), most driving conditions result in low to mid loads and quite moderate engine speeds that fall within the range where the linear model is quite accurate. Phlips evaluated the distribution of engine operating points for a vehicle with a naturally aspirated engine and an eight-speed automatic transmission over the EPA city and highway drive cycles, as shown in Fig. 7. It was found that less than 1% of the operating points were above bmep=8 bar, which is a level where the accuracy of the linear model begins to break down [55]. The effect of operation outside the linear region on the fuel consumption over the entire drive cycle is therefore expected to be quite small, although more aggressive driving conditions may lead to some operating conditions that lie outside the linear region of the fumep vs. bmep relationship.

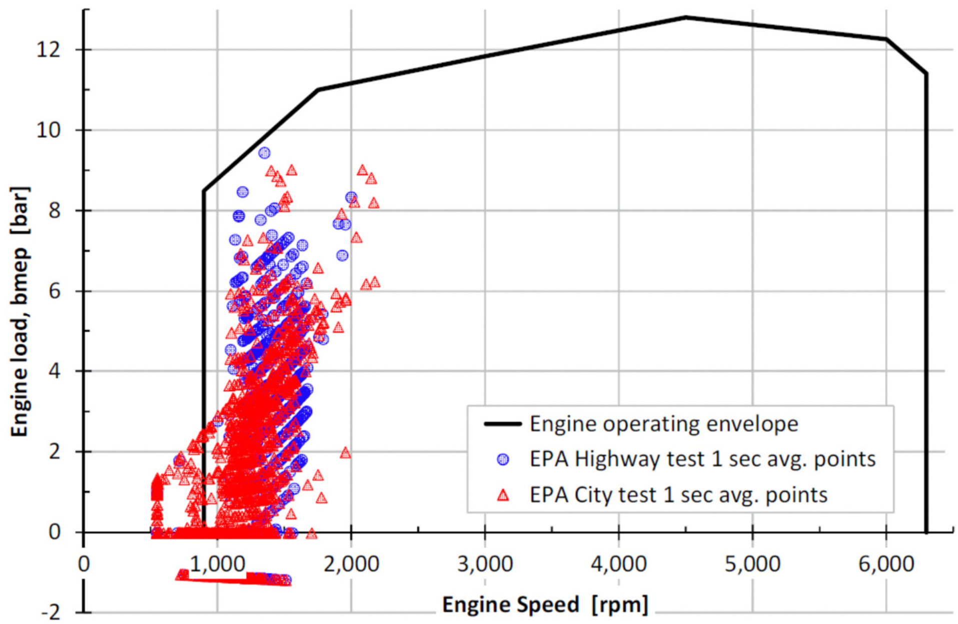


Figure 7. Distribution of operating conditions during EPA city and highway tests (from [55]).

For turbocharged engines, higher load ranges are possible (increased peak torque). The relationship given by Eq. (16) was found to hold for bmep levels up to about 10 bars in turbocharged SI engines, while beyond this level, there is a smooth transition to a constant brake efficiency mode of operation up to about 16 bars. The higher load efficiency line is given by

$$bmep = \eta_m \, fumep, \tag{17}$$

where η_m is the engine maximum brake efficiency, which can be estimated from the efficiency ($\eta_{m,lin}$ = bmep/fumep) determined at a load of bmep=10 bars using Eq. (16).

For LD diesel engines, the linear behavior of Eq. (16) is found to work well up to the full load bmep of about 19 bars.

For implementation in the SVET and FFLEET models, a single set of coefficients corresponding to each engine type was selected for the bmep vs. fumep calculation. Since there are differences in engine technologies among different manufacturers and vehicles, this approach cannot yield perfect fuel consumption results for all engines. Nonetheless, this approach provides a means to consistently estimate the engine efficiency for different engine types and sizes and will provide appropriate trends between technologies. Data obtained from Phlips [55] was used for the SI engine selections and the LD diesel engine, while the HD diesel engine model used in FFLEET was obtained from Nam and Giannelli [8]. Formulas for maximum torque curves, which are used to evaluate maximum accelerations and gear shifting, were also obtained from reference [8]. The maximum torque curves are calculated based on a polynomial for the bmep at peak torque as a function of engine speed. When both engine torque and power specifications are provided for an engine, in many cases it was found that the maximum power determined from the polynomial function did not match the maximum power specification very well. Engine manufacturers can adjust calibrations or otherwise change the torque and power curves, and the the decrease in torque after peak torque is reached is often reduced. The torque range in the model was therefore extended linearly so that if the power is also specified, the model can match this. The polynomial peak torque and power curves for a 1.8L engine are shown in Fig. 8, along with the curves from a Toyota engine map. The dashed lines are the extended torque and power curves using the modified method to demonstrate the fit using this approach.

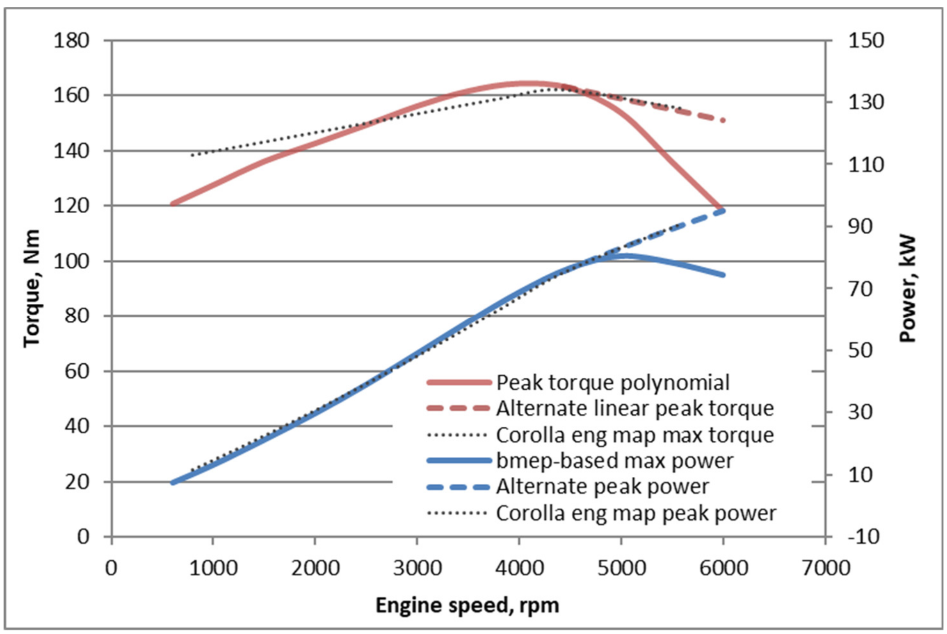


Figure 8. Maximum torque and power curves based on bmep polynomial. A linear extension to the torque curve was used to better match specified engine power

3.1.3.2 Calculation Methodology for a Conventional Engine Configuration

In the case of a conventional engine evaluation, the fuel consumption calculation consists of several steps that use the engine bmep and fumep relationship described previously to determine the quantity of fuel required at each time during the drive cycle. The starting point of the calculation is the tractive power, which is determined using Eq. (9) or (13), depending on whether the tire rolling resistance and aerodynamic drag data or a,b,c coefficients were provided for the road load specification. A constant value for the transmission efficiency η_{trans} is used, along with the accessory power consumption P_{acc}, to determine the power required by the engine, which is given as

$$P_{eng} = \frac{P_{trac}}{\eta_{trans}} + P_{acc}. \tag{18}$$

For each time step, the selected gear and resultant engine speed are determined based on the vehicle speed and targeted up- and downshift engine speeds, using the transmission specification data from user inputs (gear ratios for all gears, including the final drive or N/v ratio). A simple shifting strategy is employed in most cases, with constant upshift and downshift speeds used to determine the target gear selection.

From the gear selection, engine speed is calculated using the vehicle speed and the gear ratios. The torque is then determined from the engine power and engine speed as

$$\tau_{eng} = \frac{P_{eng}}{\omega_{eng}} = \frac{P_{eng}}{N/60*2\pi}, \tag{19}$$

Where ω_{eng} is the engine speed in radians/second. Using the torque and engine speed, the rate of fuel consumption is calculated using the bmep vs. fumep method. These calculations are completed for all time steps, and the calculated fuel rate is integrated as a function of time to determine the total fuel consumption for the drive cycle.

In most cases the shifting occurs as described above using fixed upshift and downshift points, but additional downshifting may be needed if the calculated torque for the targeted gear exceeds the maximum torque available for the engine speed determined for that gear. If the required engine torque/power can be met by shifting to a lower gear, the calculation continues with the modified gear selection for that time step. However, if the torque necessary to satisfy the instantaneous power requirement exceeds the peak torque that the engine can provide in any gear, then the maximum available power is selected and the acceleration is modified for that time segment based on the corresponding torque level available. In this case, the vehicle will be unable to follow the speed specified in the drive cycle, and the maximum speed attainable is calculated based on the available power. The maximum acceleration is maintained at each time step until the vehicle "catches up" to the speed trace of the given drive cycle, after which the normal operation continues while following the specified speeds.

Figure 9 shows the result for the fuel rate and cumulative fuel consumption from a simulation of a LD vehicle with a conventional, naturally aspirated SI engine, and the drive cycle is included in the stacked plot for comparison. At the end of each calculation, the results are returned to the "front end" tool that manages the individual runs (either for SVET or FFLEET) so the data from all runs can be processed together for the fleet evaluation. Standard output graphs showing the results from each vehicle run are returned to the front end along with the numerical data for the fuel consumption so that the user can review results in detail if desired.

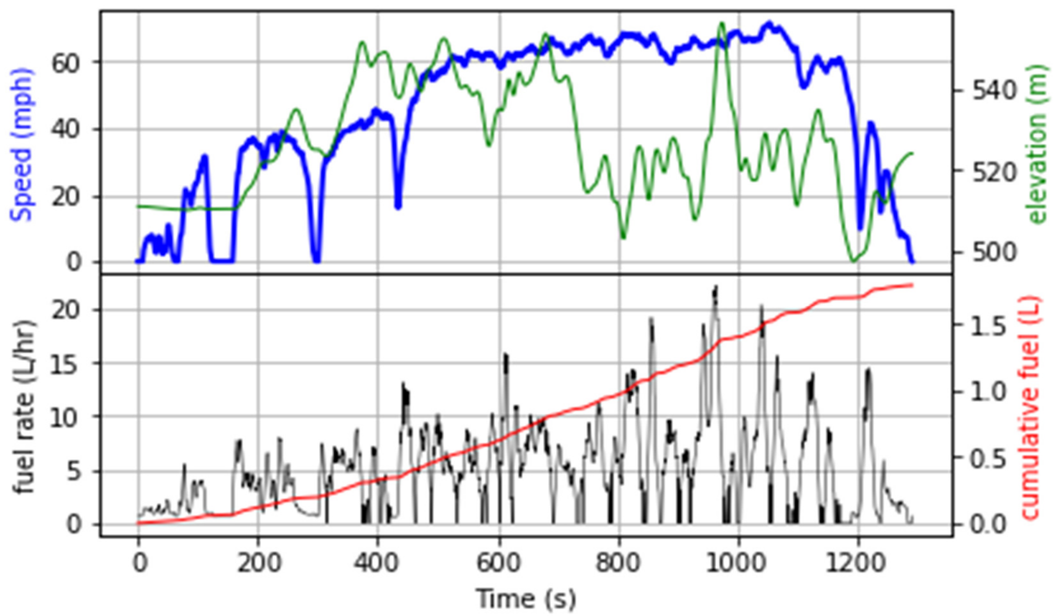


Figure 9. Fuel consumption results for a car with a conventional gasoline engine

3.1.3.3 Calculation Methodology for EVs

For EVs, determining the electrical energy consumption over a given drive cycle requires the addition of regenerative braking, and the motor efficiency is determined in a different manner than engine efficiency. The calculation begins once again with the tractive power calculation as described in section 3.1.2. For EVs, there is no mechanical accessory load (only electric accessories). Due to the large speed range that electric motors operate over, a multi-geared transmission is not required and only a final drive gear is typically used, so determining the motor power from the tractive power must only account for the efficiency of the final drive:

$$P_{mot} = \frac{P_{trac}}{\eta_{FD}}. \tag{20}$$

Since the single gear power transfer is very efficient, a constant final drive efficiency of 0.98 is assumed in the model, consistent with the final drive efficiency employed in Autonomie and other vehicle models [23]. With the single gear, the motor speed N_{mot} is directly proportional to the vehicle speed, as quantified either by the N/v ratio or the final drive ratio r_{fd} and tire diameter D_{tire}:

$$N_{mot} = N\_v * v(mph) = \frac{60\, r_{fd}}{(\pi D_{tire})} v(m/s). \tag{21}$$

Where N_v is the N/v ratio, given in RPM/mph, specified by the user or extracted from the EPA test car list. As in the case of the engine calculation, the motor torque is calculated from the power and motor speed:

$$\tau_{mot} = \frac{P_{mot}}{\omega_{mot}} = \frac{P_{mot}}{2\pi(N_{mot}/60)}. \tag{22}$$

High efficiency motors are invariably used in EVs to achieve optimal performance, and similar peak efficiency values can be expected. For the purposes of the model, it is desirable to use a single model or map for the motor. The motor torque and speed characterize its operating state, and the combined efficiency of the motor and inverter is determined in the model using a measured motor efficiency map from the 2010 Toyota Prius [56]. The efficiency map employed is shown in Fig. 10. The map efficiency data is entered in tabular form within the software as a function of the motor speed and torque, and the efficiency is interpolated for any operating condition. The peak torque curve is also stored as a function of the motor speed. Scaling of the base map is accomplished by adjusting all torque values by the ratio of the user-specified maximum motor power to that of the original motor.

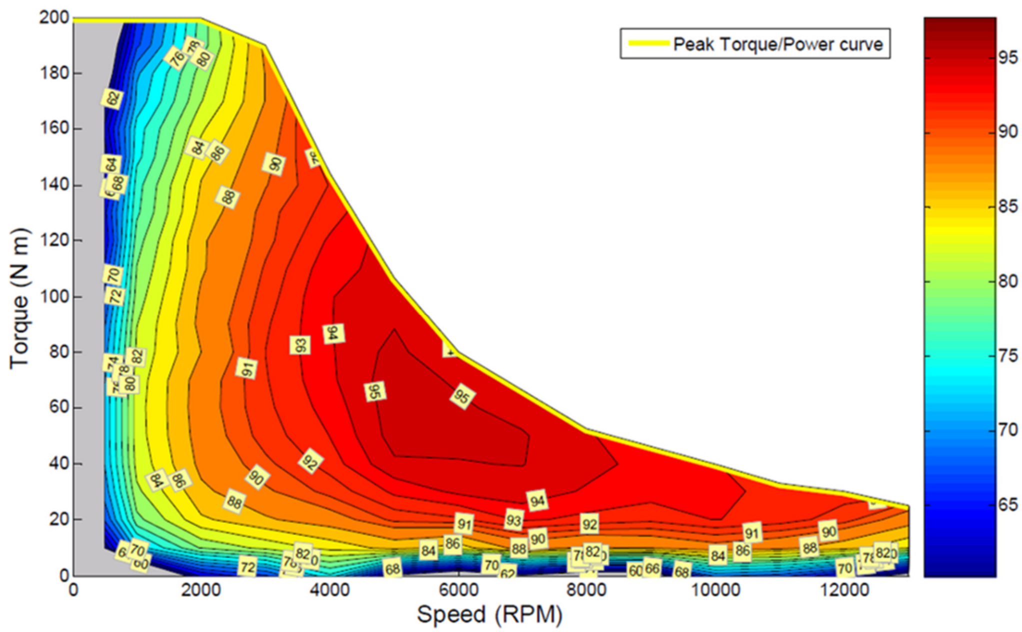


Figure 10. Motor-inverter efficiency contours for the 2010 Prius motor (from [56]).

Similar to the engine propulsion model, the maximum torque available from the motor must be considered to determine whether the calculated tractive power can be satisfied at each time step of the simulation. If the demanded torque exceeds the maximum torque available, then the maximum acceleration is calculated using an approach analogous to that described previously and the speeds are adjusted accordingly.

The EV consumes energy from the battery any time that power is transferred from the motor to the wheels, providing propulsion, but regeneration is possible when power is transferred from the wheels back to the motor (this corresponds to a negative motor power in Eq. (20) and the motor acts as a generator). When the motor power is positive, the battery energy that must be supplied to deliver the demanded mechanical power is given by

$$P_{batt,out} = \frac{P_{mot}^{+}}{\eta_{mot-inv}} + P_{acc,elec}, \tag{23a}$$

where $\eta_{mot\text{-}inv}$ is the combined efficiency of the motor and inverter. The term $P_{acc,elec}$ is the electrical accessory power, which is assumed to be constant. Since the conversion from electrical to mechanical energy in the motor requires a greater electrical input power than the output mechanical power, the motor power must be divided by the efficiency. When the motor power is negative, however, the mechanical power is the input to the motor (acting as a generator) for the energy conversion and the output electrical power must be *reduced* by the efficiency. Therefore, the efficiency multiplies the motor power during regen and the power transferred to the battery is calculated as

$$P_{batt,regen} = P_{mot}^{-}\,\eta_{mot-inv} + P_{acc,elec}. \tag{23b}$$

The term $\eta_{mot\text{-}inv}$ is determined in the same way for both positive and negative motor powers since the efficiency of the motor while acting as a generator has the same functional dependence on the motor speed and torque. Eq. (23b) represents the maximum power that could be regenerated if all braking power (determined from the drive cycle data) can be absorbed by the motor/generator. The magnitude of the motor braking torque, however, cannot exceed the maximum torque of the motor, so the battery regeneration is limited by the peak torque/power curve. When the calculated value of $|P_{mot}^{-}| > P_{mot,peak}$, the frictional brakes must provide the braking power that exceeds $P_{mot,peak}$. We modify Eq. (23b) to account for this limiting behavior. The regen power supplied to the battery is therefore given as

$$P_{batt,regen} = \max(-P_{mot,peak}, P_{mot}^{-})\,\eta_{mot-inv} + P_{acc,elec}. \tag{23c}$$

As the battery discharges and charges during EV operation, a portion of the energy transferred is lost through internal resistance of the battery, and the efficiency of the charge/discharge process depends on the battery chemistry used. The net charge and discharge efficiency also depends on the rates of charge and discharge [57]. In the model, a single average value of $\eta_{charge} = \eta_{discharge} = 0.94$ is used, which results in a roundtrip charge-discharge efficiency of about 88%, which is typical of batteries commonly used in current EVs.

The cumulative stored battery energy stored is given by

$$E_{batt,st}(t) = -\int_{t_0=0}^{t} P_{batt}\,\mathrm{d}t_0. \tag{24}$$

If the initial state of charge is given by SOC_0, then SOC(t) is calculated as

$$SOC(t) = SOC_0 - \frac{E_{batt,cum}(t)}{E_{cap}}. \tag{25}$$

Figure 11 shows the result for the battery output power and SOC from a simulation of a LD EV. The drive cycle is included in the stacked plot for comparison.

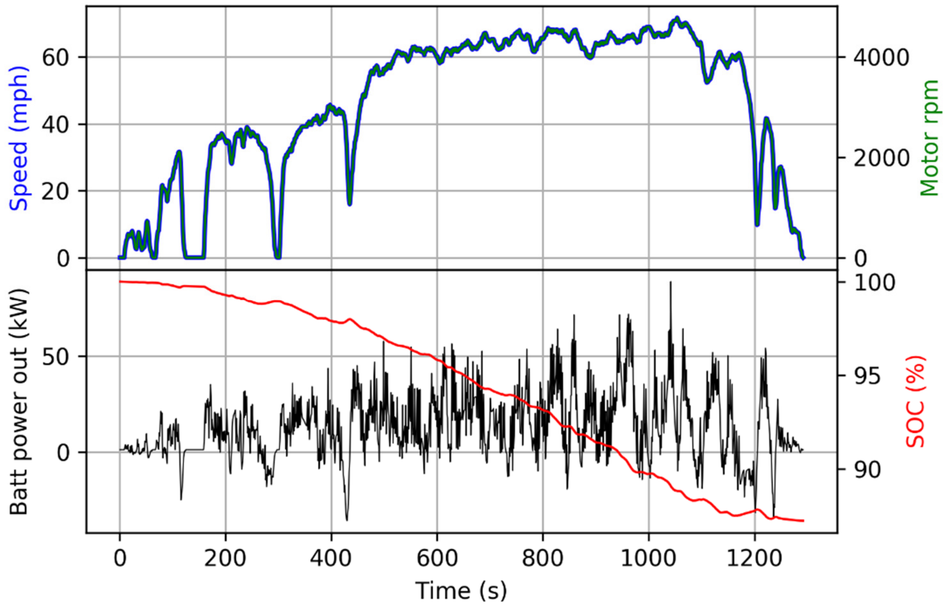


Figure 11. Battery output power and SOC result from a LD electric vehicle simulation.

3.1.3.4 Calculation Methodology for a Parallel HEV, including Plug-In HEV (PHEV)

Hybrid electric vehicles combine the use of an internal combustion engine with an electric motor for propulsion of the vehicle. This enables more efficient operation in a vehicle that maintains the range and fueling convenience offered by the internal combustion engine but provides regenerative braking energy recovery and storage, which allows kinetic energy that would otherwise be dissipated by the friction brakes to be recovered and reused. Since the motor efficiency characteristics are quite different than the engine, it can be run at times when the engine efficiency is poor, enabling the engine to operate in a higher efficiency regime than is possible without a motor.

The model developed for the HEV powertrain selection uses the same engine and motor efficiency calculations as described in the preceding sections, but additional data is employed for peak engine efficiency vs. engine speed during charge sustaining operation. How the power demand is divided between the motor and engine plays an important role on the fuel efficiency of a HEV and different vehicle designs have used different HEV powertrain control strategies. For the SVET and FFLEET tools, it was not feasible to create a general model capable of representing any hybrid vehicle with an arbitrary control strategy. To best meet the intent of the tools, it was decided that the model employed for parallel HEVs should be based on a powertrain configuration that is in common use for current hybrid vehicle designs and that yields a significant energy efficiency benefit relative to conventional vehicle designs with similar power. The power-split hybrid configuration was selected for the model, in which a planetary gearset and two electric motors are used to enable control of the engine speed independently of the vehicle speed to optimize its efficiency. This serves as a continuously variable transmission (CVT) for the engine and enables the engine and motor to run independently or in combination over a wide range of power levels. The primary motor used for propulsion is connected directly to the driveshaft in the power-split HEV configuration, so its speed is proportional to the vehicle speed. This configuration allows significant flexibility in the powertrain operation and large improvements in efficiency are possible. The configuration is also used in some of the most popular hybrid vehicles on the market today. Details of the power-split design and operation of the CVT are not required to describe the model and are not provided here. However, many very good descriptions of this powertrain configuration are available in the literature, as well as online [58-61]. Although the physical system for the power-split hybrid configuration includes two motors, the model description below is simplified and only addresses the fundamental energy implications for combined engine and motor operation and treats the system as if it consists of a single motor, an engine and a CVT, without consideration of how power is transmitted between the physical powertrain elements.

Since the HEV is propelled by both engine and motor, the proportion of the total power demand provided by each element over the drive cycle must be determined in the model. The control strategy therefore consists of determining the motor and engine powers as a function of time in response to the drive cycle power requirements. The battery SOC must be tracked and maintained within an appropriate operating range, and the model keeps an account of the fuel/energy consumption from the engine and battery. For a HEV, energy is stored in the traction battery during regenerative braking events or when the engine provides additional charging, and the battery energy is consumed when the motor provides all or part of the propulsion for the vehicle. Since non-plug-in HEVs do not include an option for charging from an external source, all of the energy used to propel the vehicle ultimately comes from the engine in HEVs, and energy used from the battery must be periodically replenished to prevent the battery SOC from falling below acceptable levels. This same *charge sustaining* mode of operation is also followed in PHEVs after an initial period of *charge depleting* operation when it is propelled only by the battery. The only difference between the model for the PHEV and HEV, therefore, is that at the beginning of the drive cycle, the PHEV begins using only the battery (identical to the EV model described in the previous section) in charge depletion mode. When the battery SOC reaches its lower threshold, the PHEV switches to operate in charge sustaining mode, which the HEV model always follows. The control strategy in charge sustaining mode, which is described in the rest of this section, aims to optimize the engine efficiency so that any consumption of fuel results in the greatest energy output possible, whether that energy is immediately used for propulsion or is stored in the battery for later use by the motor.

There are several different phases of operation that the HEV/PHEV experiences during charge sustaining operation, and separate control algorithms for the engine and motor control are used for each phase. These phases include (1) regenerative braking, (2) low powered propulsion using only the motor, (3) high tractive power periods requiring operation of both the motor and engine to satisfy the power requirement, and (4) cruising, which corresponds to moderate power levels that allow the motor and engine powers to be adjusted over relatively broad ranges with the engine running under high efficiency operating conditions while the motor's power output can be either positive, negative or zero.

3.1.3.4.1 Regenerative braking

Whenever a net braking torque is required at the wheels, the tractive power is negative and there is an opportunity for *regenerative braking*. In the model, the motor will generate electrical power and charge the battery any time the power conversion from the motor can provide battery charging power. Regen will continue until the tractive power becomes positive again for the drive cycle, the vehicle slows below a threshold speed at which regen is not enabled in the model, or the battery charge reaches its maximum capacity. As described in the previous section for EVs, during regen the model assumes that the maximum power the motor and battery can produce and accept will be used to charge the battery, and the frictional brakes will supply any additional braking power needed to decelerate the vehicle at the rate prescribed in the drive cycle. The model operation for regenerative braking for HEVs is identical to that described previously for EVs. At stops or other periods when no tractive power is required, both the motor and engine are turned off in the model (although the battery will still provide electric accessory power, which is assumed constant).

3.1.3.4.2 Low power phase

At low levels of power demand, it is preferable to only use the motor for propulsion since engine efficiency is lowest at low load conditions. In the model, the low power phase is active and the engine is always off when the tractive power requirement is below 10% of the engine's maximum rated power, unless the battery SOC is below its normal lower threshold limit. When the tractive power requirement rises above this level, the engine is turned on in the model based on the criteria for the cruise or acceleration phases of operation.

3.1.3.4.3 Periods of high tractive power demand

In a power-split HEV configuration, when the engine and motor provide power simultaneously the motor can rapidly adjust its applied torque, while longer reaction times are required for the engine [59]. The simulated behavior is similar in that the model uses smoothed engine speed transitions while providing power at the engine's peak efficiency for each engine speed selected, and the motor will adjust its torque/power output to account for faster transients in the power demand, allowing the engine to maintain more steady speeds. The engine speed selection is therefore associated with a targeted engine power output. The motor operation then "buffers" the power inputs to satisfy the instantaneous variations in the required power. The model uses a 3-second moving average of the total mechanical power demand P_{dem} to characterize the power needs. This is given as P_{MA3}, where

$$P_{MA3}(t) = \frac{1}{3}\int_{t_0=0}^{3} P_{dem}(t-t_0)dt_0. \tag{26}$$

For periods of rapid acceleration that require power from both the engine and the motor to meet the tractive power demand, a target motor power $P_{mot,0}(t)$, defined as 50% of the peak motor power corresponding to the vehicle's current speed, is used as a baseline to determine the engine power target. The target engine power is calculated as the difference between the smoothed power demand and the motor target power:

$$P_{eng,0}(t) = P_{MA3}(t) - P_{mot,0}(t). \tag{27}$$

Finally, the instantaneous motor power is determined as the difference between the instantaneous power demand and the engine target power, so that the instantaneous power demand is precisely met by the combined power output from the motor and engine:

$$P_{mot}(t) = P_{dem}(t) - P_{eng,0}(t). \tag{28}$$

If the motor power calculated from Eq. (28) exceeds the available (peak) motor power for the current speed, then the peak motor power must be used instead, $P_{mot}(t) = P_{mot,max}(N_{mot})$. In this case, the engine power must also be adjusted to attempt to match the high power demand. As in the previous models, if the maximum power available from the powertrain (combined engine and motor) for the current operating condition is insufficient to meet the power required to follow the drive cycle, then a maximum acceleration is determined and the speed is modified according to the maximum acceleration until a time when the modeled vehicle speed once again reaches the speed specified in the original drive cycle and the normal evaluation is continued.

This methodology for selecting the motor and engine power in the model was designed to provide a relatively efficient operation of both motor and engine for the high acceleration phase of operation. Using the CVT, the engine speed can be selected to provide the optimum efficiency for the targeted engine power. The peak efficiency curve used in the model, shown in Fig. 12, is defined at each speed in terms of a ratio of the peak torque, which allows the scaling approach used for the engine model described previously to be extended to the hybrid model.

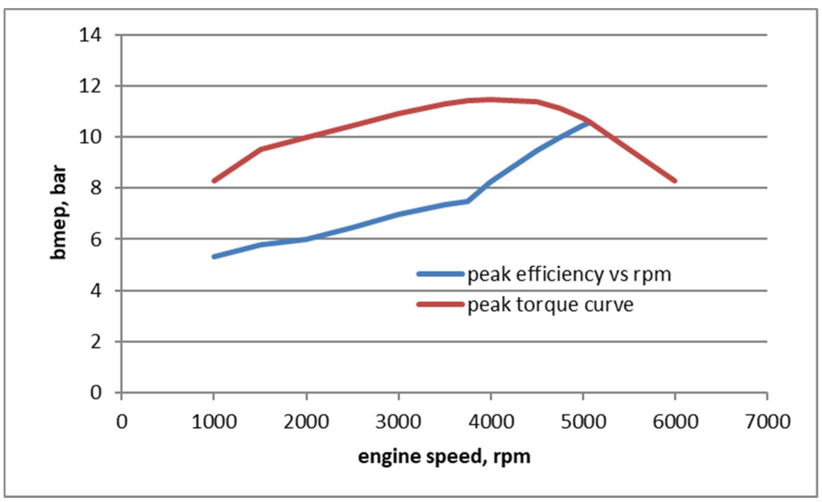


Figure 12. The peak torque and peak efficiency curves used in the HEV model. The torque at peak efficiency is determined as a fraction of the peak torque up to the maximum power of the engine.

If the battery SOC reaches its minimum threshold at any time in the model, the motor power will be discontinued until additional energy is stored in the battery (through regenerative braking or engine powered recharging). The default battery capacity selection in the vehicle specifications will allow a maximum acceleration from zero speed to 75 mph on flat ground with additional energy reserve, so the battery should not be fully depleted in normal use of the tool. However, if the vehicle specification includes a lower battery capacity or an unusual condition is modeled (for example, extended accelerations requiring maximum power up a long incline), it is possible that the energy available in the battery could limit the vehicle's ability to follow the specified speed. Similarly, if the energy stored in the battery reaches its full capacity (100% SOC) during regeneration, then regenerative braking is discontinued in the model. In an actual HEV, compression braking from the engine may be activated to supplement braking provided by the frictional brakes if the battery reaches full charge during regen.

3.1.3.4.4 Cruising

The control methodology during cruising (with power demands lying between the low power and high power phases of operation) is somewhat similar to that used during the high power phase, except that the SOC maintenance is included as a control objective. For optimal battery performance and durability for a HEV, the SOC of the battery is normally maintained within a relatively narrow range of preferred operation. In the model, a target SOC value of 60% (SOC_{target}=0.60) is used and normal variations of +/- 12% (δSOC_{prop}=0.12) are permitted. This results in a normal SOC range of 48-72%. Additional shifts of 10% are accepted during the acceleration and regenerative braking phases before the battery charging or discharging are discontinued in the model.

In the cruising phase, the control algorithm aims to correct any offset in SOC that occurred previously, and the motor and engine power levels are modified so that the SOC is adjusted toward its target value. The default target engine power during this phase of operation is set to follow the smoothed power demand profile:

$$P_{eng,0}(t) = P_{MA3}(t). \tag{29}$$

The motor power is normally determined so that the instantaneous power demand is satisfied using Eq. (28), but to correct the SOC when it is not at the target value, a proportional control strategy is used to generate an offset value to the actual engine power setpoint by adding a term δP_{bias} to the motor power term, which will tend to either charge or discharge the battery depending on whether the current SOC is below or above SOC_{target}, respectively. An increase in the motor power will tend to cause the battery to discharge over time (decreasing the SOC), while decreasing the motor power will cause the SOC to increase over time. The motor power is therefore given as

$$P_{mot}(t) = P_{dem}(t) - P_{eng,0}(t) + \delta P_{bias}(SOC). \tag{30}$$

Over the range of normal SOC, the offset/bias power used is proportional to the offset in SOC:

$$\delta P_{bias}(SOC) = \alpha\left(SOC - SOC_{target}\right). \tag{31}$$

The value of α depends on the battery capacity in the model, so that the rate of change of the SOC will be approximately constant. For a battery capacity $E_{cap,batt}$ given in kWh, the model uses the value

$$\alpha = 20\, E_{cap,batt}, \tag{32}$$

where α is given in kW. For every 1 kWh of battery capacity, this corresponds to 0.2 kW offset in the motor power for each percent that the SOC differs from SOC_{target}. Since the engine and motor powers must provide the power demand, it is clear that the engine power is also offset by -δP_{bias}. The final result is

$$P_{eng}(t) = P_{eng,0}(t) - \delta P_{bias} = P_{MA3}(t) - \delta P_{bias}. \quad (33)$$

As before, the engine speed is selected based on the peak efficiency curve.

Figure 13 shows results for the engine power and fuel consumption, in addition to the motor power and SOC, from a HEV model run for a MD delivery truck. The drive cycle is included in both stacked plots.

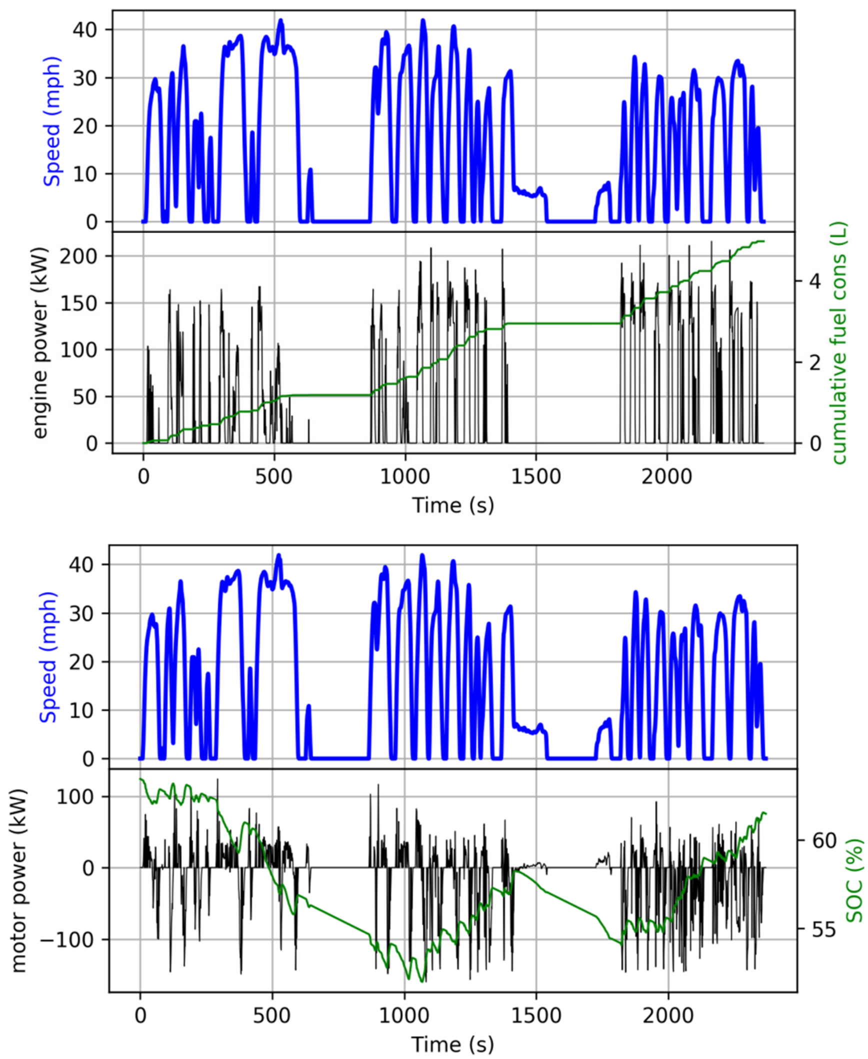


Figure 13. Sample results from a HEV simulation for a MD truck.

3.2 Drive cycle modifications for CAVs evaluations that function through optimal speed control

There are several advanced Connected and Automated Vehicle (CAV) technologies that are expected to provide efficiency improvements by modifying the speed of vehicles in a way that smooths traffic, reduces braking, improves powertrain efficiency and/or eliminates stops. The eco-Cruise application (also referred to as speed harmonization), for example, uses vehicle-to-vehicle (V2V) communications to help smooth vehicle speeds and reduce braking between vehicles during highway driving. Traffic signal eco-Approach and Departure (EAD) uses vehicle-to-infrastructure (V2I) communications and signal phase and timing (SPaT) data to provide speed control signals as vehicles approach intersections that will allow vehicles to decelerate in advance of red lights and arrive at the signal location only after the light has turned green. Comprehensive speed optimizations using the EAD can reduce or eliminate braking, which is expected to yield significant efficiency improvements in addition to benefits in traffic throughput.

In principle, a specified drive cycle can be modified to eliminate much or all braking from the original drive cycle, using coasting in advance of the periods when the braking was initially required. By developing an optimized drive cycle in this manner and performing a powertrain evaluation using the original and modified drive cycles, it is possible to estimate the effect on the driving efficiency that these CAV applications can provide.

Braking is required whenever the tractive force or power becomes negative, and the times when this occurs in the drive cycle can be easily identified following a tractive power evaluation. To develop an optimized drive cycle that eliminates braking, it is necessary to determine the coasting deceleration rate, which is given by

$$a_{coast} = \frac{dv}{dt} = -g \sin\theta(x) - \frac{1}{m}(a + b\,v + c\,v^2). \tag{34}$$

Note that we have used the a,b,c coefficients in the formulation, but this is done without loss of generality since the rolling resistance and aerodynamic drag formulation can be converted to the same format. The grade, sin θ(x), is shown explicitly as a function of position to highlight the fact that the elevation and grade are inherently distance-dependent, so a distance-based evaluation of the grade is necessary. Otherwise, modifying the acceleration and speed will cause a change in the position as a function of time, and the grade with respect to time will also change if it is not a constant function. It is noted that a distance-based formulation for the acceleration and speed can eliminate the need to use an iterative solution for determining the coasting speed profile that starts or ends at a specified location. Multiplying Eq. (34) by (dx = v dt) and integrating, we can obtain an integral equation for the distance-based speed profile, and the speed can be determined as a function of position by (numerically) obtaining the root of the resulting equation. The result can also be converted back to the time domain using the appropriate relationship. It should be noted that a coasting solution can be calculated from any starting location and speed, but different end points and times will of course be obtained for different starting locations. Figure 14 shows several coasting results starting at different starting times/locations along the same drive cycle. In Fig. 14(a) the speed vs. time is shown, while in Fig. 14(b), the distance vs. time is shown for the same set of coasting solutions.

(a)

(b)

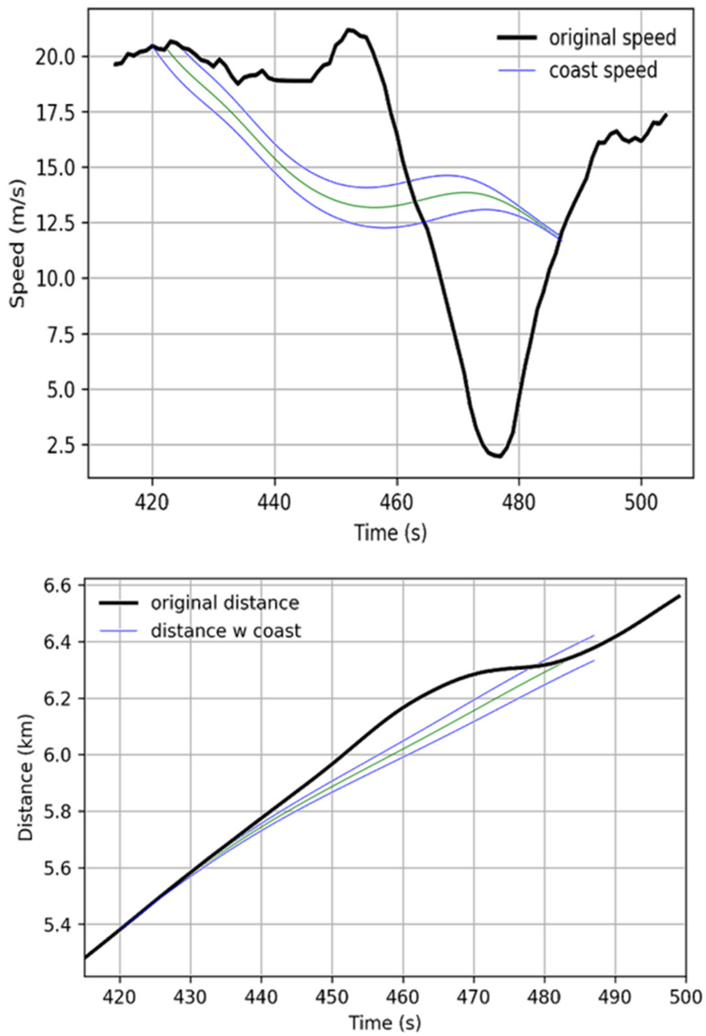


Figure 14. Distance vs. time for several coasting solutions starting at different locations/times in the original drive cycle.

The curve shown in green corresponds to a case where the end point of the coasting intersects the original drive cycle at both the same time and location. Considering the distance traveled, it is apparent that starting at a later time and location results in overtaking the original drive cycle, while starting at an earlier time/position results in the distance of the coast always trailing the original drive cycle. The case with equal time and distance is the ideal case for the optimization, and the speed vs. time data provides an insight into how this is achieved. Since the distance traveled is the integral of the speed vs. time plot, we must have the areas between the original drive cycle and the coasting segment equal for the regions above and below the coast segment. That is, in Fig. 14(a), the area between the black and green curves where they intersect from about 425s to 465s must equal the area between the curves from 465s to 485s (all times are only approximate).

This methodology can be automated to obtain optimized coasting solutions for different positions where braking was present in the original drive cycle to develop a highly optimized drive cycle. Note that when down hill grades are present, the coasting solution can result in accelerations, so there may be periods of increasing speeds during the result. In some situations with these negative grades, however, it may not be possible to obtain an optimized solution with pure coasting that results in a coasting end point at the same time and location as the original cycle.

Figure 15 shows a complete eco-optimized drive cycle with most segments of braking replaced by coasting (except for the final decelerations before extended stops, which would require an extended time to coast to a full stop after the original drive cycle already completed).

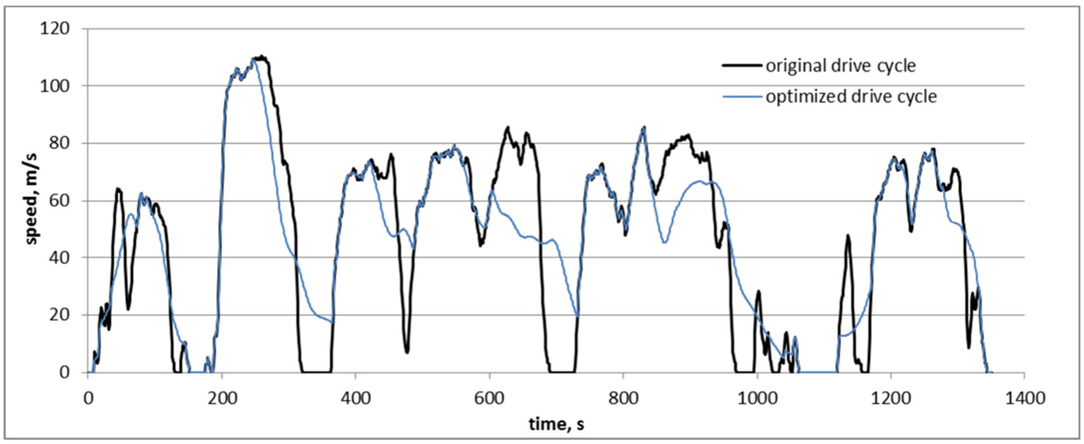


Figure 15. Optimized drive cycle with most periods of braking eliminated by using coasting.

The fuel consumption for the optimized drive cycle, compared with the same LD vehicle driving the original drive cycle, resulted in a fuel savings of approximately 27%. Although it may be difficult to achieve a speed optimization with the CAVs applications in real traffic conditions that eliminates all of the braking in this manner, this result shows that there is a very significant potential benefit using this methodology.

4. Development of the User Interface for the SVET and FFLEET Web-Based Tools

4.1 Overview

In order to create a usable tool for fleet managers to evaluate various alternatives to improve fuel efficiency for passenger vehicles and freight trucks, a user interface needed to be developed. The idea behind the structure of the user interface was to create a simple and basic layout, incorporating the use of dropdown menus, checkboxes, and lists. Originally, the layout consisted of a separate Webpage for each grouping of user-selected choices, but the plan later evolved to being one page with tabbed additional forms for the user to make selections. Development of the user interface for both SVET and FFLEET required similar procedures and scripts but required different database structures to accommodate the varying amount of data required for vehicle selection. The SVET and FFLEET interfaces look quite similar, with the same color schemes, but with obvious variations in context.

The basic architecture of the user interface is such that each component relies on input, processing, and/or output from another component. The basic components include the browser, web services, database management, the database itself, and calls to the SVET and FFLEET vehicle models (see Fig. 17). The structure for developing the user interface for SVET and FFLEET is a basic design that is commonly used in many web development applications. All scripts used to develop the user interface are housed on a server at the Oak Ridge National Laboratory. The server-side scripting contains the databases, data handling and processing, the main model calculations, and the necessary functions created to handle user input. The client-side of the user interface contains the Webpage and the prompts created to obtain necessary information from the user to perform the calculations and produce useable output.

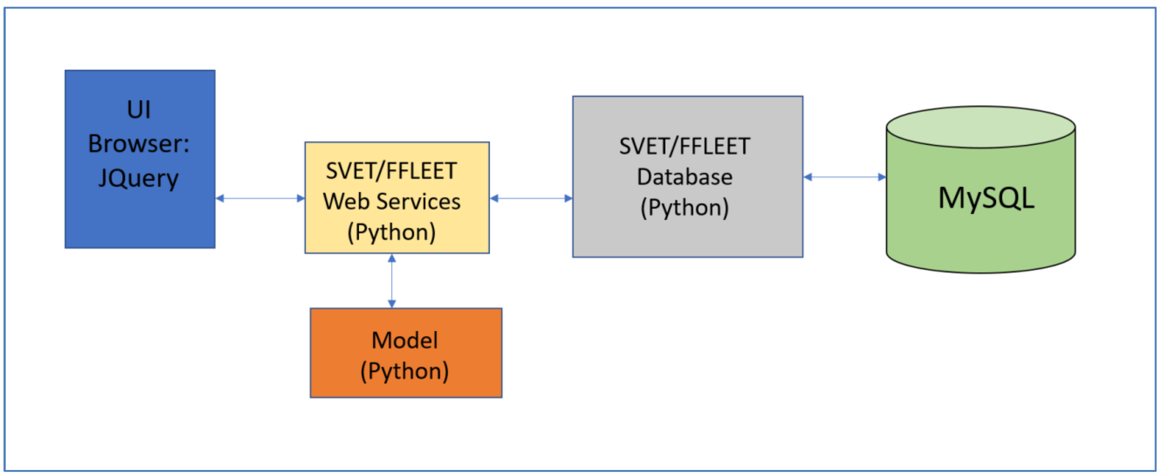


Figure 17. User Architecture

4.2 Server-Side Design Structure

The basic components for the server-side of the user interface for both SVET and FFLEET consisted of a series of Python scripts which performed the majority of functions, such as processing user-selected inputs and transferring of information to the main model's Python scripts that performed the calculations. All of the scripts were housed on a central server at ORNL. The server also housed the scripts which developed, maintained, and populated the database. These scripts defined the table structures (refer to Fig. 18) and defined the data to populate the tables. These tables contained user-specified inputs, as well as default values, and were joined based on common keys. Structured Query Language (MySQL) was used to define these table structures, as well as specify when these tables were accessed within the Python scripts. For SVET, the vehicle selection list contained a large dataset, obtained from EPA's Test Car vehicle list, so that the user was provided with many options for passenger vehicles (refer to Fig. 20). A comma separated values (CSV) file was incorporated into the database and was displayed in list format on the Webpage. For FFLEET, a list of truck types was manually created in the database because there weren't as many options for vehicle types necessary to display within the Webpage.

```sql
-- Run this as user 'root'
--
drop table if exists users;
create table users
  (
  id            int not null auto_increment,
  name          varchar( 64 ) not null,
  password      varchar( 128 ) not null,
  primary key( id )
  );


--------------------------------------------------------------------------
--  Projects
--------------------------------------------------------------------------
drop table if exists projects;
create table projects
  (
  id            int not null auto_increment,
  name          varchar( 128 ) not null,
  descr         text,
  notes         text,
  primary key( id )
  );


drop table if exists user_projects;
create table user_projects
  (
  user_id       int not null,
  project_id        int not null
  );


--------------------------------------------------------------------------
--  Vehicle Library
--------------------------------------------------------------------------

drop table if exists vehicle_options;
create table vehicle_options
  (
  id            int not null auto_increment,
  name          varchar( 128 ) not null,
  primary key( id )
  );
insert into vehicle_options ( name )
    values ( 'Traffic signal eco approach and departure' );
insert into vehicle_options ( name )
    values ( 'Connected Eco-Driving' );
insert into vehicle_options ( name )
    values ( 'Advanced cruise control' );
insert into vehicle_options ( name )
    values ( 'Grade/traffic-based powertrain control and optimization' );
insert into vehicle_options ( name ) values ( 'Platooning' );
insert into vehicle_options ( name )
    values ( 'Aerodynamic drag reduction' );
insert into vehicle_options ( name )
    values ( 'Low rolling resistance tires' );
insert into vehicle_options ( name )
    values ( 'Speed limiters' );
insert into vehicle_options ( name )
    values ( 'Auxiliary power units' );
insert into vehicle_options ( name )
    values ( 'Advanced transmission' );
insert into vehicle_options ( name )
    values ( 'Vehicle lightweigting options' );
```

Figure 18. Sample Script to Create Tables in Database

```sql
drop table if exists powertrain_types;
create table powertrain_types
  (
  id              int not null auto_increment,
  name            varchar( 64 ) not null,
  primary key( id )
  );
insert into powertrain_types ( name ) values ( 'BEV' );
insert into powertrain_types ( name ) values ( 'Conventional Diesel' );
insert into powertrain_types ( name ) values ( 'Conventional Gas' );
insert into powertrain_types ( name ) values ( 'Conventional Natural Gas' );
insert into powertrain_types ( name ) values ( 'HEV' );
insert into powertrain_types ( name ) values ( 'HPDI' );
insert into powertrain_types ( name ) values ( 'Other Electric' );
insert into powertrain_types ( name ) values ( 'PHEV' );


drop table if exists vehicle_library;
create table vehicle_library
  (
  id              int not null auto_increment,
  name            varchar( 128 ) not null,
  vehicle_type_id     int not null,  -- just one
  powertrain_type_id     int not null,  -- just one
  engine_displacement     float not null,
  engine_power      float not null,
  curb_weight       float not null  default 10000.0,
  gvwr            float not null  default 22000.0,
  frontal_area      float not null  default 8.0,
  rear_area       float not null  default 8.0,
  aero_drag_coeff     float not null  default 0.59,
  roll_resist_coeff float not null  default 0.009,
  primary key( id )
  );


drop table if exists vehicle_library_options;
create table vehicle_library_options
  (
  vehicle_id        int not null,
  option_id       int not null
  );


drop table if exists vehicle_types;
create table vehicle_types
  (
  id              int not null auto_increment,
  name            varchar( 64 ) not null,
  primary key( id )
  );
insert into vehicle_types ( name ) values ( 'Tractor Trailer' );
insert into vehicle_types ( name ) values ( 'Box Truck' );
insert into vehicle_types ( name ) values ( 'Delivery Van' );
insert into vehicle_types ( name ) values ( 'Car Carrier' );
insert into vehicle_types ( name ) values ( 'Flatbed Truck' );
insert into vehicle_types ( name ) values ( 'Freight Train' );
insert into vehicle_types ( name ) values ( 'Refrigerated Truck' );
```

Figure 19: Sample Script Used to Populate Lists

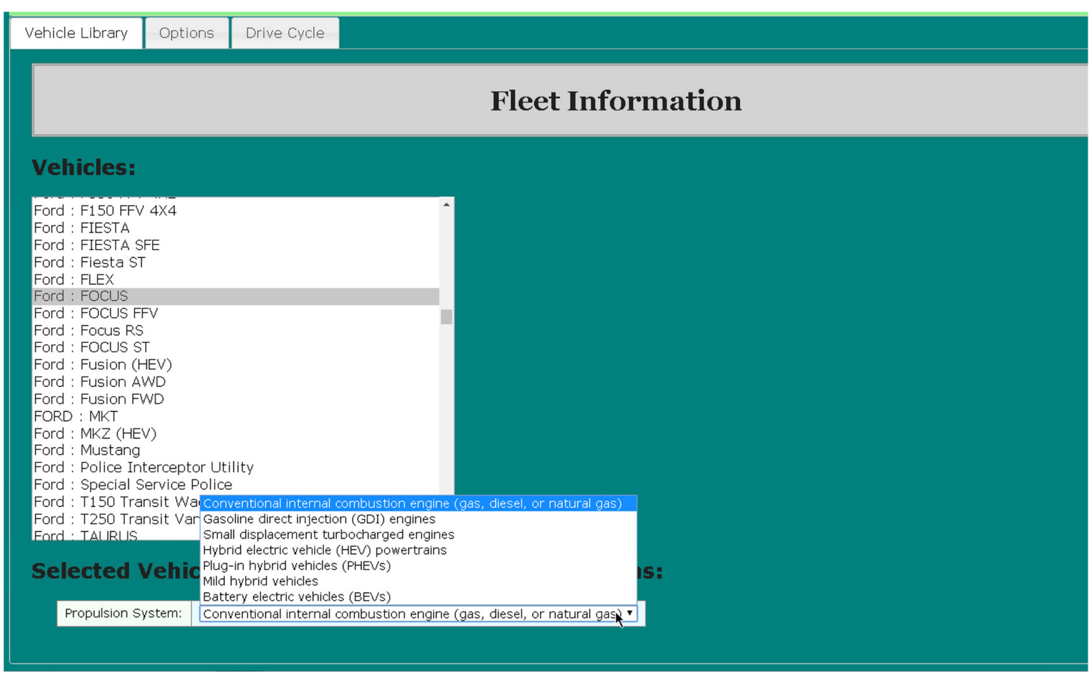


Figure 20: Fleet Vehicle List in SVET (list obtained from EPA Test Car list)

4.3 Client-Side Design Structure

The components for managing the client-side of the interface consisted of Webpages designed using Hyper-Text Markup Language (HTML) and Javascript languages. Within the Python scripts, additional Javascript functions were used to handle the user selection process. Jquery language was used to update the Webpage after changes had been made by the user. Using Jquery avoided the need to constantly refresh the page after the user made changes. Cascading style sheets (CSS) were used for aesthetic purposes and to create a unified theme for the Webpage design. The CSS files were directly referenced in the HTML files to apply a unified color scheme and other details. The overall design and color scheme were chosen for its simplicity and ease of use. The majority of the selection tools were lists, although the parameter specifications (refer to Fig. 22) contained default values which could be changed manually by the user. The values were imported directly into the main model's Python scripts. Checkboxes and dropdown menus were also incorporated for ease of use, and these values were also imported directly into the model.

In order to keep the Webpage structure simple, three tabbed pages were incorporated. The steps for the user were such that the "Vehicle Library" tab contained the list of vehicle makes and models and fuel or battery type and configuration. For SVET, the user can scroll down the list of vehicle makes and models from the EPA Test Car List. After the user selects a vehicle make and model, the propulsion system can then be chosen from the list. For FFLEET, the user can select a truck and trailer configuration from the list. A table is then populated based on the user's selection. This table includes details about the particular truck type and parameter specifications that will be used in the model calculations. The user's options are saved, and the user can then tab over to the "Options" tab.

The following tab, "Options" contained checkboxes and dropdown menus to select various technology types (refer to Fig. 23). The user can select various technology types by checking boxes, choosing from a selection in short dropdown lists, and manually entering values. The values chosen correspond with specific calculations within the main model's Python scripts. The scripts processing the user input receive a Boolean value (such as when the user selects a checkbox) and a particular function from the main model's Python script is used to perform the calculation. The results will be used for the final output.

The third tab, "Drive Cycle" refers to a default drive cycle (for the example run), but the user can also potentially upload a CSV file for a specified drive cycle. Once the user enters or selects all of the necessary information, the "Run Model" button is selected and a table is then displayed with the results from the selections (refer to Fig. 24). The output table is a simple way to display the results from the model, so that the fleet manager (SVET and FFLEET) can potentially make decisions based on energy consumption for the various fleets chosen.

```
<html>
<head>
    <title>Freight Fleet Energy Estimation Tool (FFLEET)</title>
    <link rel="stylesheet" type="text/css" href="css/style.css">
  <link rel="stylesheet" href="css/jquery-ui-themes-1.12.1/themes/smoothness/jquery-ui.css">
  <script src="scripts/jquery-1.12.4.min.js"></script>
  <script src="scripts/jquery-ui-1.12.1.custom/jquery-ui.min.js"></script>
    <script type="text/javascript" src="scripts/VehicleLibraryPage.js"></script>
<title>FFLEET Vehicle Library</title>
<script>
var VPpage_;

$( document ).ready(
    function()
    {
    //var urls = Utils.parselocationURI( window.location.href );

    //VPpage_ = new VehicleLibraryPage ( urls[ 0 ], 'http://localhost:9080' );
    VPpage_ = new VehicleLibraryPage ( '/fleet2', '/fleet-server2' );
    VPpage_.init();
    }
    );
</script>
</head>


<body style="background-color:teal">
<div class="container">
  Menu: <a href="Link Here"  style="color:blue">FFLEET Info</a></p>
</div>
<div id="header">
  <h1><center>Freight Fleet Energy Estimation Tool (FFLEET)</center></h1>
</div>

<div id="tabs" style="background-color:teal">
  <ul>
    <li><a href="#tab-vehicle-library"><span>Vehicle Library</span></a></li>
    <li><a href="#tab-options"><span>Options</span></a></li>
    <li><a href="#tab-drive-cycle"><span>Drive Cycle</span></a></li>
  </ul>

  <div id="tab-vehicle-library">
    <div class="container">
    <h1><center>Fleet Information</center></h1>
    </div>

    <h2>Vehicles:</h2>
    <select name="vehicles_list" id="vehicles_list" size="5">
    </select>

```

Figure 21: Sample Script to Develop Webpages (HTML and Javascript)

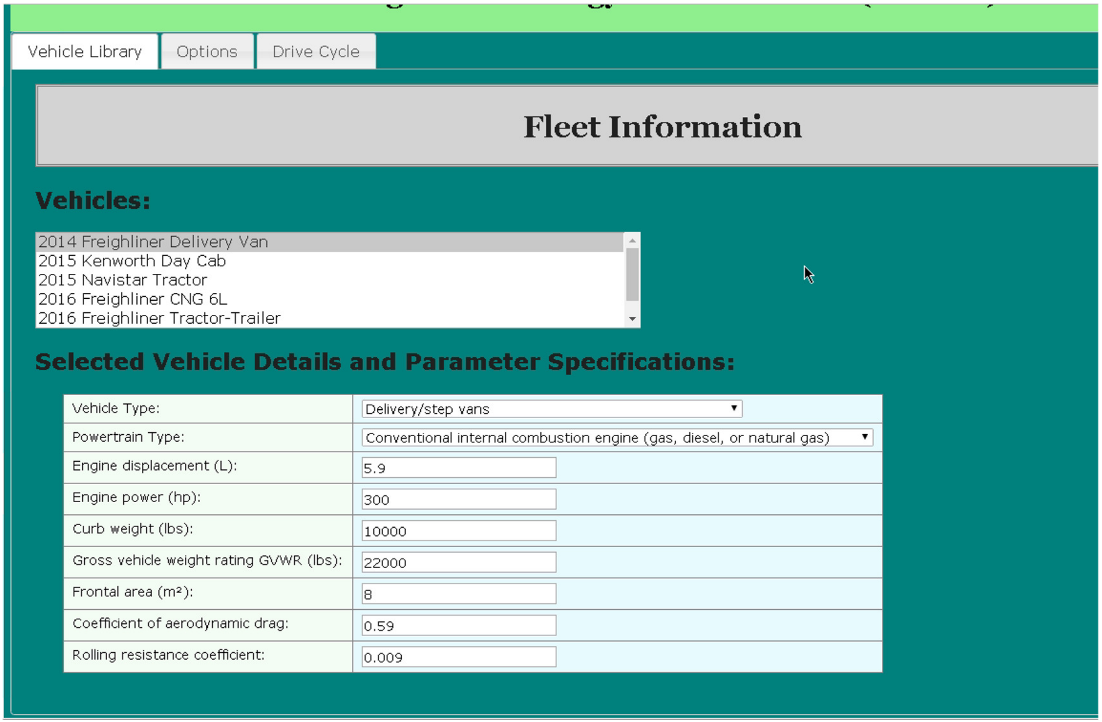


Figure 22: FFLEET Main Page with Vehicle Selection List

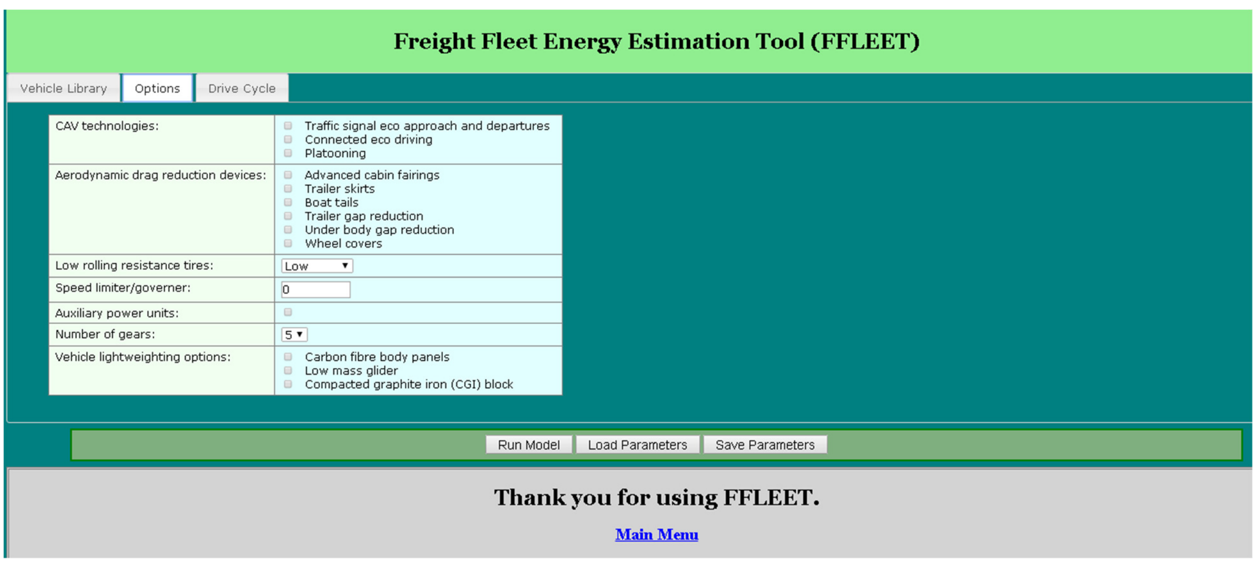
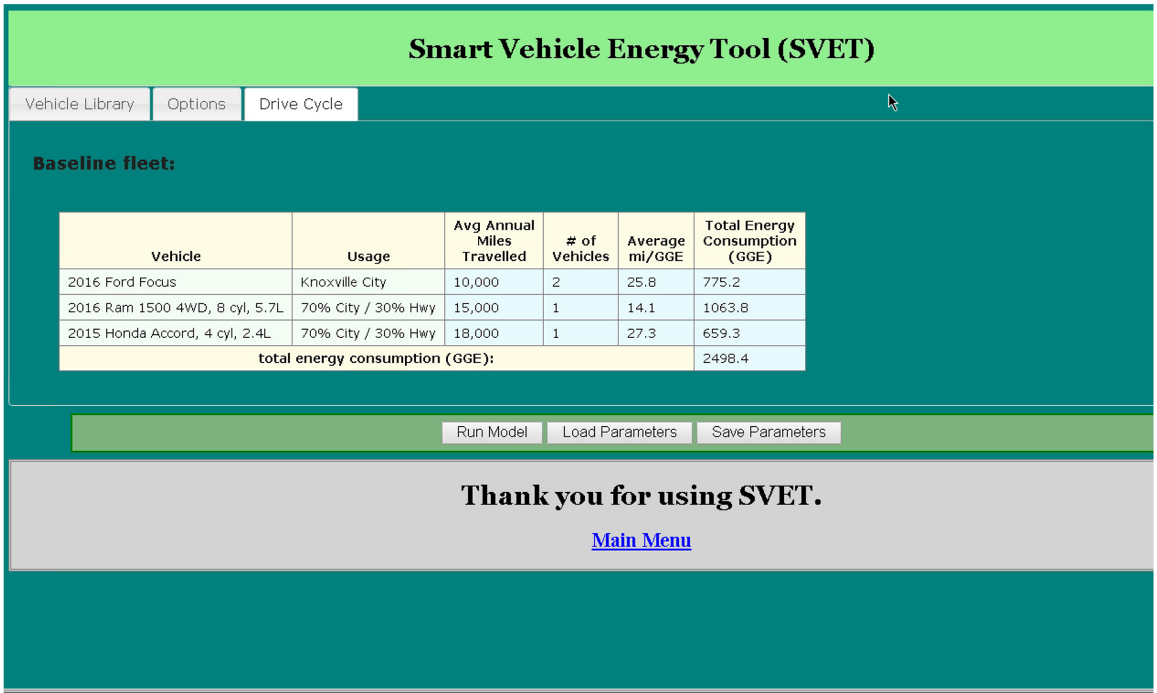


Figure 23: Options Page with Prompts for User to Make Selections from Checkboxes and Dropdown Lists



Vehicle	Usage	Avg Annual Miles Travelled	# of Vehicles	Average mi/GGE	Total Energy Consumption (GGE)
2016 Ford Focus	Knoxville City	10,000	2	25.8	775.2
2016 Ram 1500 4WD, 8 cyl, 5.7L	70% City / 30% Hwy	15,000	1	14.1	1063.8
2015 Honda Accord, 4 cyl, 2.4L	70% City / 30% Hwy	18,000	1	27.3	659.3
total energy consumption (GGE):					2498.4

Figure 24: Drive Cycle Page Displaying Results after Drive Cycle is Entered and Model is Run

5. Key Accomplishments

The goals of the project included developing new software tools that enable fleet level evaluations of the energy savings that can be expected from advanced vehicle technologies in both passenger vehicle fleets and freight hauling trucking fleets. Although many vehicle models of varying degrees of complexity exist to perform powertrain fuel consumption calculations, no previously existing tools were identified that were developed specifically for fleet-wide assessments. SVET and FFLEET were designed for this purpose and the prototype tools can be used to make comparisons between different user scenarios to evaluate replacements of existing vehicles and implementation of new technologies in a fleet. These tools were developed with ease of use in mind to assist those responsible for fleet procurement and operations to select alternative fuel/energy efficient vehicles and technologies and to quantify the energy savings provided by various vehicle/technology selections.

The vehicle powertrain models developed for the tool were designed to allow a high degree of flexibility in simulating vehicles of very different configurations, including LD, MD and HD vehicles with powertrain configurations including a range of conventional and advanced engines, EVs, HEVs and PHEVs. Other vehicle technologies including advanced aerodynamic devices, low rolling resistance tires, several CAVs technologies and advanced transmissions can also be evaluated using the FFLEET and SVET tools. The calculation engine, developed in the Python programming language, receives parameter data from the front end to define each simulation based on detailed vehicle configuration and usage data, and the models are launched using generalized sub-models and motor maps that include scalable efficiency data for different engine types, motors and a range of powertrain configurations. This framework enables very diverse vehicles and efficiency technologies to be evaluated using the same set of tools, which provides a powerful basis for the diverse types of fleet evaluations the tools were designed to address.

The SVET and FFLEET tools are intended to help accelerate the deployment of alternative fuel vehicles and fuel efficient technologies in fleet operations and enable fleets to simply and accurately predict the energy savings that can be realized through deployment of these technologies. Several novel modeling approaches and alternative user selection options were incorporated in the tools to improve the modeling process and enable assessments that have not been possible in the past, including the following:

1. Drive cycle selection: the drive cycle characterizes the usage of the vehicle and plays an important role in the fuel consumption. Innovations in specifying the vehicle usage were implemented by allowing users to define their vehicle usage in terms of weighted combinations of any drive cycles, which allows usage to be defined in terms of percentage combinations of very specific driving situations, such as weighting of interstate vs. secondary highways (including average speeds), to specify a regional trucking operation. Most drivers can explain their usage at a high level with reasonable accuracy by estimating what percentage of their driving is comprised of highway, rural, arterial, and congested city driving and what their average speeds are in different situations. Such options for describing usage are expected to be easier and more intuitive for new users to understand and use than a selection of standardized drive cycles.
2. Vehicle design specification: the vehicle design parameters have a very direct impact on energy consumption. The user interface provides a broad array of vehicle design options, and default input values obtained from the literature are provided to characterize each technology's performance in terms of fundamental physical parameters for the selections offered. However, the user has the ability to modify any of the input parameter values when specific information is available.
3. Generalized powertrain models: Recently developed powertrain characterizations for both conventional gasoline and diesel engines and advanced engine types including turbocharged engines and gasoline direct injection were used in the powertrain models. This enables interesting powertrain comparisons between recent engine advancements. These powertrain technologies are expected to provide significant energy savings in new vehicle deployments in coming years. The ability to scale engine models for different levels of engine power and displacement in a way that provides meaningful comparisons across technologies is a valuable addition to generalized powertrain modeling.
4. Idealized drive cycle modifications to represent technologies that function by smoothing traffic or optimizing speed under specific conditions: Modification of speed data can be used to evaluate the potential impact of new technologies that aim to smooth traffic flow and reduce speed variations during congested traffic conditions. The eco-Cruise and signalized intersection eco-Approach and Departure (EAD) CAV applications, for example, are intended to reduce or eliminate braking due to vehicle following and when vehicles pass through an intersection by using vehicle-to-vehicle communications and signal phase and timing (SPaT) data to adjust

vehicle speeds in traffic and in advance of an intersection to always allow traffic to pass through when the light is green. An algorithm was developed as part of this project to create optimized drive cycles using coasting to reduce or eliminate braking, and the modified speed drive cycles were used to estimate the magnitude of energy savings that could be expected from such CAVs technologies. A simplified and fully automated approach to evaluate the effect of speed governors for trucks was also developed. Such approaches for CAVs applications will not likely provide highly accurate fuel benefits, but they can assess the magnitude of savings potential or provide upper bounds for the benefits of these developing technologies.

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