

FASTSim: A Model to Estimate Vehicle Efficiency, Cost and Performance

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Abstract

The Future Automotive Systems Technology Simulator (FASTSim) is a high-level advanced vehicle powertrain systems analysis tool supported by the U.S. Department of Energy's Vehicle Technologies Office. FASTSim provides a quick and simple approach to compare powertrains and estimate the impact of technology improvements on light- and heavy-duty vehicle efficiency, performance, cost, and battery life. The input data for most light-duty vehicles can be automatically imported. Those inputs can be modified to represent variations of the vehicle or powertrain. The vehicle and its components are then simulated through speed-versus-time drive cycles. At each time step, FASTSim accounts for drag, acceleration, ascent, rolling resistance, each powertrain component's efficiency and power limits, and regenerative braking. Conventional vehicles, hybrid electric vehicles, plug-in hybrid electric vehicles, all-electric vehicles, compressed natural gas vehicles, and fuel cell vehicles are included. Powertrains with electric-traction drive can optionally be simulated using electric roadway technologies such as dynamic wireless power transfer. FASTSim also has an interface for running large batches of real-world drive cycles. FASTSim's calculation framework and balance among detail, accuracy, and speed enable it to simulate thousands of driven miles in minutes. The key components and vehicle outputs have been validated by comparing the model outputs to test data for many different vehicles to provide confidence in the results. A graphical user interface makes FASTSim easy and efficient to use. FASTSim is freely available for download from the National Renewable Energy Laboratory's website (see www.nrel.gov/fastsim).

Introduction

The Future Automotive Systems Technology Simulator (FASTSim) was created to support high-level powertrain analysis. While more detailed models are able to answer almost any question, they require detailed data and expert knowledge to run correctly [1]. For many types of analysis, however, the details can be simplified and still provide accurate results. FASTSim took this approach, which makes finding inputs, running the model, and interpreting results easier, faster, and less error prone.

Approach Overview

FASTSim was developed to be an accessible, efficient, accurate, and robust tool for comparing vehicle powertrains. The vehicle components are modeled at as high a level as possible while still being accurate. They are simulated through time-versus-speed drive cycles. Running the standard city and highway fuel economy drive cycles takes less than one second for most vehicles. The high-level results include efficiency, performance, and cost. They have been validated for hundreds of different vehicles and most existing powertrain options. FASTSim has a graphical user interface (GUI) that steps through the processes of selecting a vehicle to run, choosing the drive cycles to simulate, and viewing the results. The beta version has proven to be robust with over 1,800 unique downloads and no reports of errors or inaccuracies.

While many simulations do not require it, FASTSim's open source approach allows for customization to capture temperature-dependent characteristics, component speed-related variations, and other detailed aspects.

Powertrain Components

FASTSim captures the key inputs for most high-level vehicle powertrain modeling. They include parameters that define the vehicle, including the fuel storage, fuel converter, motor, traction battery, wheel, and energy management strategy.



Vehicle

The top-level vehicle input parameters include:

- Drag coefficient
- Frontal area
- Glider mass
- Cargo mass
- Center of gravity
- Drive axle weight fraction
- Wheel base.

The first four parameters play a large role in the road load equations that estimate the power required for the vehicle to meet the cycle. The next three contribute to the traction limitations for meeting drive cycles and the acceleration test.

Fuel Storage

The fuel storage model represents the liquid or gaseous fuel and storage. It has four input parameters:

- Power
- Time to full power
- Energy
- Mass scaling.

These parameters estimate the power limitations, range, and mass implications that different types of fuel storage may have. For gasoline and diesel vehicles, the fuel storage power is not a limiting factor and can be set to a very high value. The engine power will limit the amount of fuel in these cases. Fuel storage is a limiting factor, however, for some hydrogen storage systems that can supply limited amounts of hydrogen at a time. The time to full power captures transient limits. The energy parameter represents the amount of usable energy stored. The mass scaling parameter captures mass implications from changing the amount of energy specified.

Fuel Converter

The fuel converter is defined by four parameters and an efficiency curve. The four parameters are:

- Power
- Time to full power
- Base mass
- Specific power.

The power and time to full power limit the fuel converter performance. The base mass and specific power are used to estimate and scale the mass of the fuel converter based on power.

The fuel converter efficiency is modeled as a power vs. efficiency curve as seen in [Figure 1](#). Five efficiency options exist:

- Spark ignition
- Atkinson: Spark ignition that uses an Atkinson cycle commonly found in hybrid electric vehicles (HEVs)
- Compression ignition
- Fuel cell
- Hybrid diesel.

Fuel Converter Efficiency

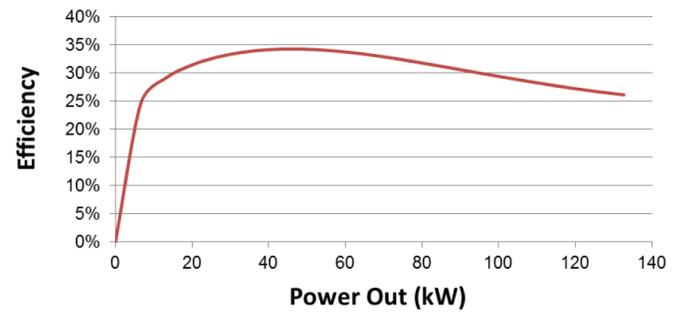


Figure 1. Fuel converter efficiency model

Each option has a different efficiency curve. The list can be expanded or the existing curves modified to represent specific engines or fuel cells.

Approximating fuel converter efficiency as a function of power works well. For fuel cells, FASTSim's model matched well with proprietary test data from a fuel cell vehicle. For conventional engines, the shifting patterns and the alignment of power and efficiency curves allow a more traditional torque/speed/efficiency engine map to be accurately modeled by a two dimensional power/efficiency map, as seen in [Figure 2](#). The torque speed map has contour lines of efficiency. To maximize efficiency, the vehicle operation generally takes place between the two solid black lines that represent shifting. Between these lines, the red efficiency curves align well with the blue constant power curves. When the operating points are plotted on the power map, they approximate the polynomial used in FASTSim.

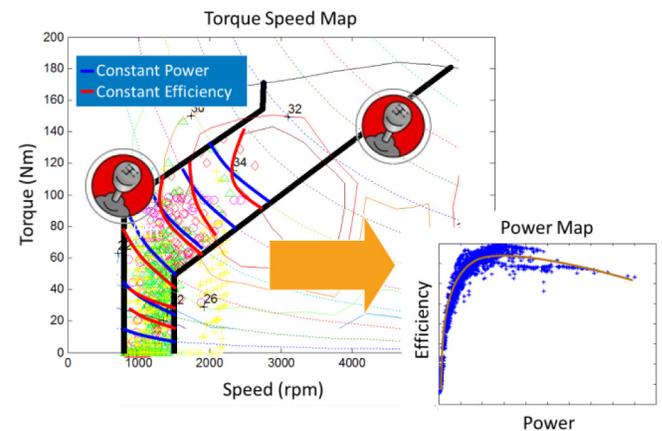


Figure 2. Efficiency and power align well for conventional engines

A single efficiency curve for each engine type, scaled for different engine powers, can represent most internal combustion engine vehicles within 5%. This is illustrated in the Validation section where FASTSim closely estimates the fuel economy of many different vehicles by scaling the power of the same efficiency curve.

While a single efficiency curve for each engine type works well for most vehicles, it may not work as well for some performance vehicles. In a few cases, FASTSim overestimated fuel economy and underestimated how quickly the vehicle can accelerate. This may be due to a shifting schedule aimed more at performance than efficiency.

The fuel converter rate of increase in power is limited by a specified “time to full power” parameter. This time is set to account for both changing gears and ramping up the engine power.

Motor/Controller

The motor controller model is similar to the fuel converter. It is defined by the same four parameters: power, time to full power, base mass, and specific power, and an efficiency curve. The shape of the efficiency curve, shown in Figure 3, is based on sampling simulated operating points on a Nissan Leaf efficiency map [2]. The shape of the curve changes with power level to capture the higher efficiency typical of higher power motors. It can be modified on the “Motor” worksheet.

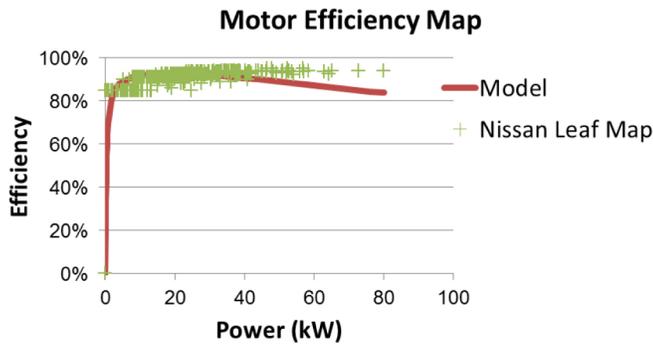


Figure 3. Motor efficiency

Battery

Like the motor, a high-level representation of the battery is used. The battery parameters include:

- Power
- Energy
- Base mass
- Specific energy
- Round trip efficiency
- Two battery life coefficients.

A constant efficiency assumption works well for new batteries that do not have a significant drop in voltage over their usable or typically used state of charge (SOC). FASTSim’s energy management input parameters control how it is used and the SOC bounds. The simplicity makes it easy to populate with input data for different vehicles and easy to scale.

Battery life estimates are based on cycling depth and frequency [3]. The VARTA GmbH, later Johnson Controls, battery data [4] illustrates the number of cycles possible at different depths of discharge, as seen in Figure 4. This curve is defined by the two battery life coefficient inputs.

The city and highway drive cycles are simulated to determine the magnitude and frequency of battery cycling from acceleration and regenerative braking events. Each battery cycle is recorded and applied to the life chart equation to estimate the wear per mile.

Plug-in electric vehicle cycle life has additional wear applied. The daily recharging events are estimated based on the distribution of driving distances from the 2001 National Household Travel Survey data set [5], as illustrated in Figure 5, and the electric efficiency of the vehicles estimated by FASTSim. The recharging wear rate is added to the acceleration and braking cycling wear rate to estimate total battery life.

Battery Cycle Life

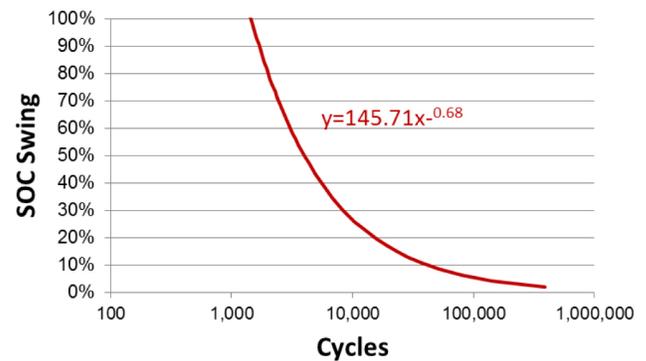


Figure 4. Battery cycle life

Driving Distribution

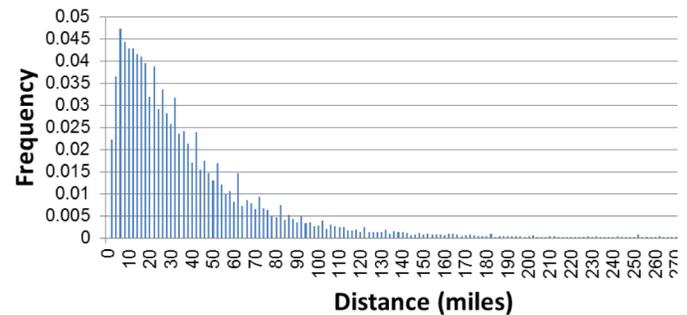


Figure 5. Distribution of driving distances

The life estimates are used to help optimize the battery size and energy management. FASTSim has two options. One option, “Optimize battery depth of discharge for life,” increases or reduces the SOC range that the battery can use until it meets the life goal. The other option, “Optimize battery for electric range & life,” resizes the battery energy and SOC range until both the vehicle range goal and life goal are met.

Wheel

The wheel is defined by five parameters:

- Inertia
- Number
- Rolling resistance coefficient
- Radius
- Coefficient of friction.

They are used by the road load and traction limit equations.

Energy Management

The energy management strategy controls how the battery and fuel converter operate. The inputs include:

- Battery minimum SOC
- Battery maximum SOC
- Level of discharge aimed at improving the fuel converter efficiency
- Level of charge aimed at improving the fuel converter efficiency
- Speed at which the battery energy reserved to assist acceleration is zero

- Percent of usable battery energy reserved to assist acceleration
- Speed at which the fuel converter is turned on
- Power at which the fuel converter is turned on.

Other Components

Several other additional inputs define the remainder of the vehicle. They include:

- Alternator efficiency
- Charger efficiency
- Auxiliary loads
- Transmission mass
- Transmission efficiency
- Component mass multiplier
- Maximum braking regeneration.

Powertrain Model

The powertrain model links vehicle components to simulate them over the drive cycles. The powertrain calculations are broken into four key groups of columns in the spreadsheet:

- Drive cycle
- Component limits
- Drivetrain power required
- Drivetrain power achieved.

The first group contains drive cycle data. It includes the time, speed, grade, and road type.

The next group of columns calculates the component limits, as seen in Figure 6. These limits are used later to simplify the drivetrain calculations. The component limits start by calculating the maximum power out of the fuel storage. The next component is the fuel converter, which estimates its maximum power based on the fuel storage power out, the fuel converter maximum power, and a transient limit. Similarly, limits are calculated for the remaining powertrain components, including the battery, electric roadway, electric motor, and transmission.

Component limits							
Current max fuel storage power out (kW)	Current max fuel converter power out (kW)	Current max ESS power out (kW)	Current max ESS charge power (kW)	Current max charger power (kW)	Current max motor power out (kW)	Current max mech. motor power in (kW)	Current max Trans/wheel power out (kW)
curMaxFsKwOut	curMaxFcKwOut	curMaxEssKwOut	curMaxEssChgKw	curMaxRoadwayChgKw	curMaxMotorKwOut	curMaxMechMcKwIn	curMaxTransKwOut
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
1000.0	11.6	20.0	20.0	0.0	3.4	17.0	14.2
1000.0	11.6	20.0	20.0	0.0	3.4	17.0	14.2

Figure 6. FASTSim component limits calculations

The next group of columns calculates the drivetrain component power required at the transmission to meet the cycle, as seen in Figure 7. It starts with the road load equations, including drag,

acceleration, ascent, and rolling resistance. The power required is then adjusted by the transmission efficiency and compared to the maximum transmission power out calculated from the component limit group. If the required power is less than the maximum, the cycle can be met. If not, the current transmission component power limit is used to estimate the achieved speed.

Cycle drag power (kW)	Cycle acceleration power (kW)	Cycle ascent power (kW)	Cycle power required to road (kW)	Cycle spare traction (kW)	Cycle power required to wheel (kW)	Regen braking power (kW)	Friction braking power (kW)	Cycle transmission power out required (kW)
cycDragKw	cycAccelKw	cycAscentKw	cycTrackwReq	spareTracKw	cycWheelKwReq	cycRegenBrakeKw	cycFricBrakeKw	cycTransKwOutReq
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.00
0.0	0.0	0.0	0.0	17.9	0.0	0.0	0.0	0.00

Figure 7. Drivetrain power requirement calculations

The “transmission power out achieved” data are fed through the powertrain to estimate the power and energy loss of each component as seen in Figure 8. The transmission estimates the power it needs from the motor and fuel converter. The motor estimates the electric power it needs from the battery and roadway to achieve the mechanical power out. The fuel converter supplies the remaining power needed by the transmission. Finally, the fuel required to the fuel converter is calculated.

Transmission power out achieved (kW)	Transmission power in achieved (kW)	Motor mechanical power out achieved (kW)	Motor elect. power in achieved (kW)	Auxiliary loads (kW)	Charger power out achieved (kW)	Battery power out achieved (kW)	Fuel converter power out achieved (kW)	Fuel converter power in achieved (kW)	Fuel storage power out achieved (kW)
transKwOutAch	transKwInAch	mcMechKwOutAch	mcElecKwInAch	auxInKw	roadwayChgKwOutAch	essKwOutAch	fcKwOutAch	fcKwInAch	fsKwOutAch
0.0	0.0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.0	0.0	0.00	0.00	0.30	0.00	0.00	0.00	0.00	0.00
0.0	0.0	0.00	0.00	0.30	0.00	0.30	0.00	0.00	0.00

Figure 8. Drivetrain power achieved calculations

Several Excel columns are hidden in a group before the motor columns that make up the energy management strategy. The energy management strategy determines the power contribution from each of the components. The strategy is primarily based on the battery SOC. The operating range of the battery is limited by a specified maximum and minimum SOC. The strategy consists of three SOC zones within that range, as seen in Figure 9. The first zone is between the maximum SOC and the regenerative braking buffer (Regen Buffer). This area is calculated based on the mass and speed of the vehicle. It is the amount of battery energy reserved to capture a regenerative braking event. Similarly, the zone between the acceleration buffer SOC (Accel Buffer) and the minimum SOC is the amount of battery energy reserved to assist with accelerating the vehicle. Between the Regen Buffer and Accel Buffer, the strategy focuses on maximizing the fuel converter efficiency.

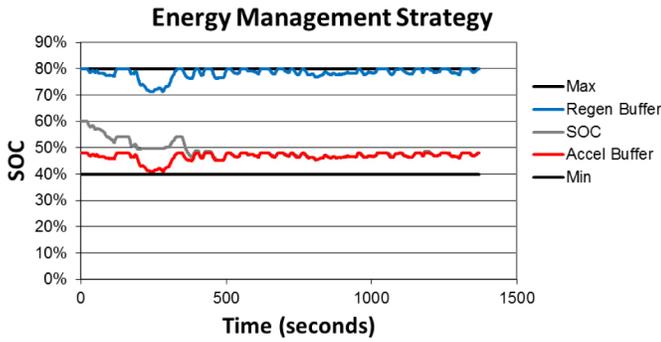


Figure 9. Energy management strategy

The amount of regenerative braking energy achievable is limited by the components and the speed of the vehicle. The battery power, usable SOC range, and motor provide the ultimate regenerative braking power limits. Within those, the amount of regenerative braking that can be captured is defined as a function of vehicle speed, as seen in Figure 10. At lower speeds, more friction brakes are used. While friction brakes are generally employed for strong emergency braking at high speed, FASTSim assumes that the frequency of these events is small enough to neglect.

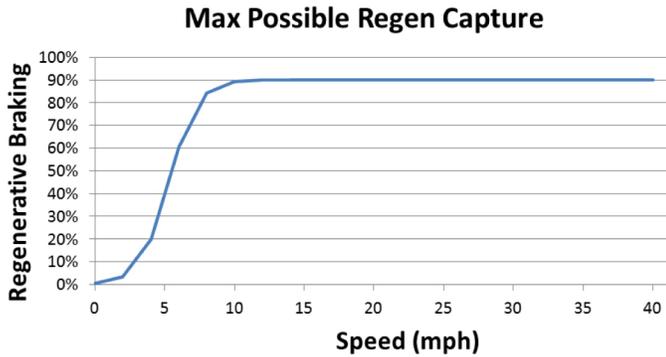


Figure 10. Regenerative braking as a function of vehicle speed

Simulation

FASTSim has several different powertrain simulation options. By default it runs a light-duty fuel economy test. It can also run a specific drive cycle or a batch of drive cycles. These cycles are defined by speed, grade, and optionally electric power transfer during the cycle.

Drive Cycle Options

By default, the U.S. Environmental Protection Agency's (EPA's) standard city and highway cycles, also known as the Urban Dynamometer Driving Schedule (UDDS) and the Highway Fuel Economy Driving Schedule (HWFET), are run to estimate light-duty fuel economy using EPA's two-cycle approximation of the five-cycle test [6]. These are shown in Figure 11 and Figure 12, respectively [7].

Several other cycles from EPA's website are also included. The US06 is an aggressive, high speed, high acceleration cycle. The New York City Cycle (NYCC) has stop-and-go conditions. The Heavy Duty Urban Dynamometer Driving Schedule (HD UDDS) is used for heavy-duty vehicles. The California Air Resources Board LA92 and LA92 Short cycles, which feature higher speeds, accelerations, and fewer stops, are also included. An interface aids in adding other drive cycles.

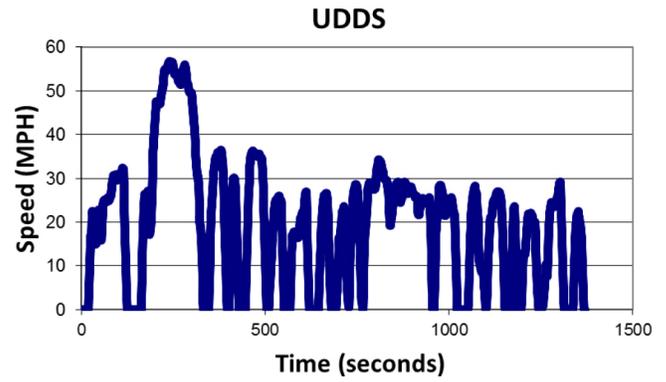


Figure 11. EPA's Urban Dynamometer Driving Schedule

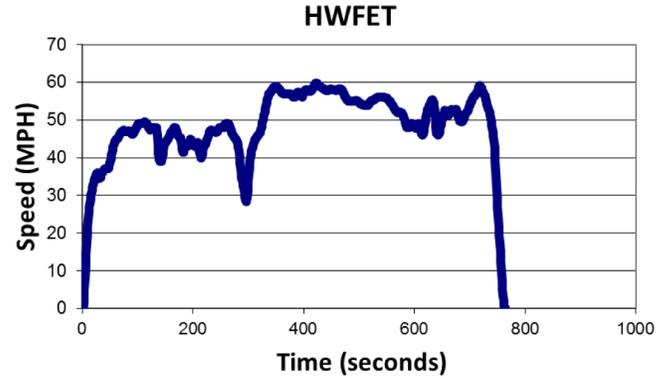


Figure 12. EPA's Highway Fuel Economy Driving Schedule

Batch Runs

FASTSim is also capable of running a large number of drive cycles at once. It has been used to estimate the benefits of changing a fleet of vehicles to an advanced powertrain or to capture a more realistic representation of light-duty vehicle real-world driving by using datasets from the National Renewable Energy Laboratory's Transportation Secure Data Center [8, 9].

Electric Power from the Road

Electric power transfer from the roadway can be simulated for any of the drive cycles. The concept involves transferring electric power from along the roadway to the vehicle. The concept is being developed by many organizations [10, 11, 12, 13, 14, 15] as an enabler for electric-powered travel [16]. It is aimed at eliminating electric vehicle (EV) range anxiety, displacing more petroleum, and reducing cost [17].

Cost Model

After the components are specified and simulated, the cost model estimates the present price of the vehicle, fuel, and battery replacements. The present price adds the price of the vehicle with tax to the discounted fuel and discounted battery replacement costs. Discounting is used to capture the time value of money. When comparing two powertrains, the present value effectively shows if the additional price paid upfront for an advanced fuel saving technology is more beneficial, or if the money would have been better invested by purchasing the other powertrain and investing the balance elsewhere at a real interest rate equivalent to the discount rate specified.

The price of the vehicle is estimated from component-level cost inputs that are defined and saved with the vehicle inputs. The default values are based on [18]. The costs are scaled with the components to capture the effects of resizing. The component costs are multiplied by a specified markup factor, which is set to 1.5 by default [19]. This markup translates the cost to make the component to an estimated price impact on the vehicle.

The fuel cost estimates are based on several inputs and the vehicle efficiency results. The inputs include average vehicle miles traveled (VMT) per year, reduction of vehicle travel per year, a discount rate, and fuel/electricity prices. Two parameters are needed for VMT to capture the change in VMT with vehicle age. Trends suggest that new vehicles travel twice as many miles per year as old vehicles [20]. This significantly reduces the impact of the discount rate on fuel cost because more of the fuel is used early when the discount rate has the least effect. Capturing the lower impact from the discount rate improves the relative benefit of fuel saving technologies.

Validation

Validation is integrated into FASTSim to ensure accurate results in key dimensions. FASTSim provides the option to save known validation data for 15 different metrics. Some validation data link to the results section for immediate comparison. All of them are used by the Validation worksheet. The Validation worksheet has a "Run Validation" button on the top left. When clicked, all the saved vehicles are automatically run, and the results are recorded and compared for the saved validation inputs.

FASTSim matches well with the EPA's fuel economy test for light-duty vehicles. It simulates the city and highway drive cycles to estimate the two-cycle dynamometer test results. It then adjusts them to approximate real-world driving using the EPA's two-cycle approximation of the five-cycle procedure. HEV simulations are repeated with different starting SOC until the change in battery energy to fuel use ratio is below a specified fraction [21]. For plug-in hybrid electric vehicles (PHEVs), the city and highway cycles are repeated until the battery stops having a net discharge, and one full charge sustaining cycle is complete. The EPA adjustment equations are applied to each repetition. The repetitions are combined by a weighted average based on the amount of travel at each distance interval determined by the distribution of driving distances shown in Figure 5. As seen in Figure 13 and Figure 14, FASTSim's efficiency estimates match most EPA test data within 5%, and almost all within 10%, for many different vehicles and powertrains. While only the first fraction of vehicles that were validated is shown, hundreds of existing vehicles were tested with similar results.

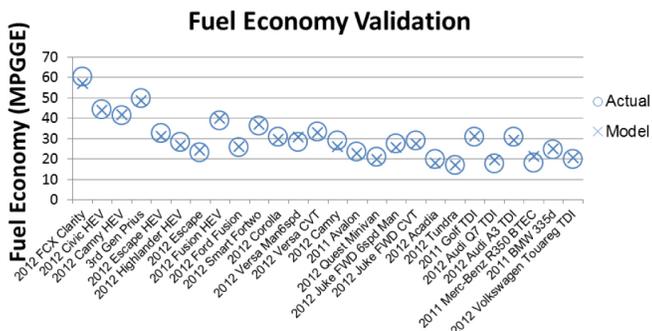


Figure 13. Fuel economy validation

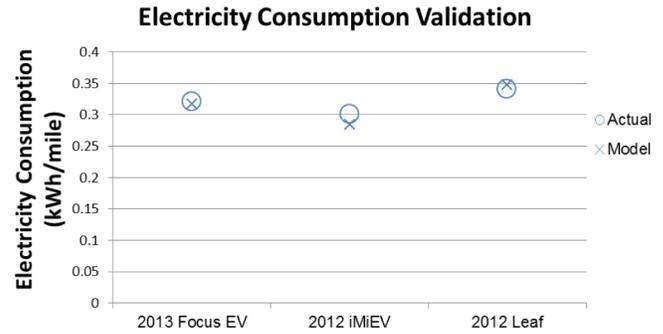


Figure 14. Electric efficiency validation

FASTSim also matches acceleration test data [22, 23] well as seen in Figure 15. FASTSim simulates a drive cycle that has a large step change in speed to determine the acceleration. It primarily depends on the vehicle's power, transient limits, mass, and tire coefficient of friction.

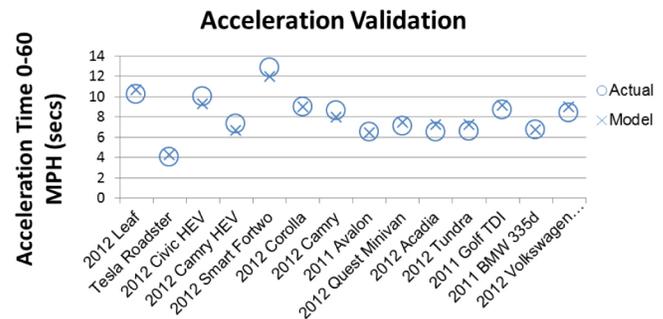


Figure 15. Acceleration validation

FASTSim's cost model matches general trends, as seen in Figure 16. The prices of the advanced vehicles are estimated by adjusting the price of a comparable conventional vehicle based on component size and type differences. For example, FASTSim's estimate of the 2012 Civic HEV is based on taking a similarly equipped conventional Civic price, reducing it for the smaller engine size, and increasing the price for the additional battery and motor. FASTSim's estimate is then compared to the actual vehicle price.

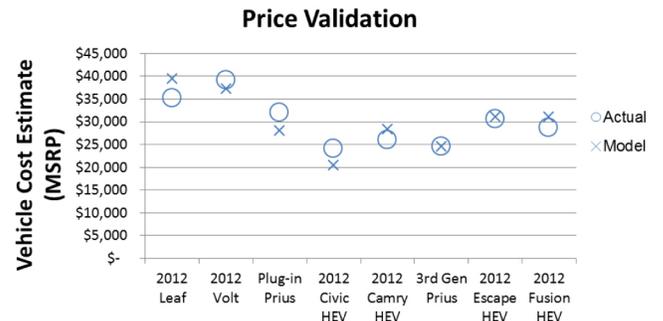


Figure 16. Cost validation

Component mass scaling in FASTSim also validates well as seen in Figure 17. Similar to cost, the mass scaling is done based on component size and type. The mass of a conventional version of an advanced powertrain is modified by the difference in components. A factor for mass compounding is also used. This captures the additional structure mass that is needed to support heavier components. The calculated advanced vehicle mass is then compared to the actual mass [24, 25].

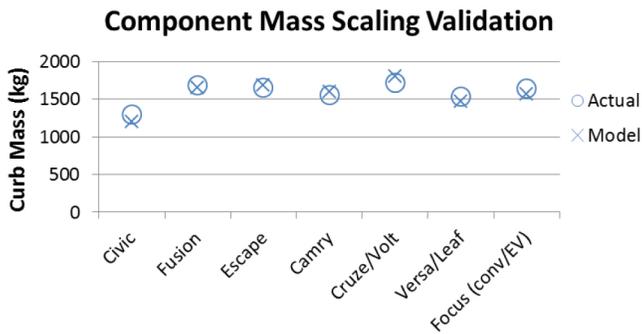


Figure 17. Compounding mass validation

While estimating and validating battery life are challenging, FASTSim's cycle depth and frequency-based estimates are fairly close to actual estimates, as seen in Figure 18. The actual data are estimates based on warranty information or public statements made by manufacturers as specified in FASTSim. While the temperature, voltage level, and calendar effects are not explicitly modeled in FASTSim, the general trends still match well with the rough estimates found.

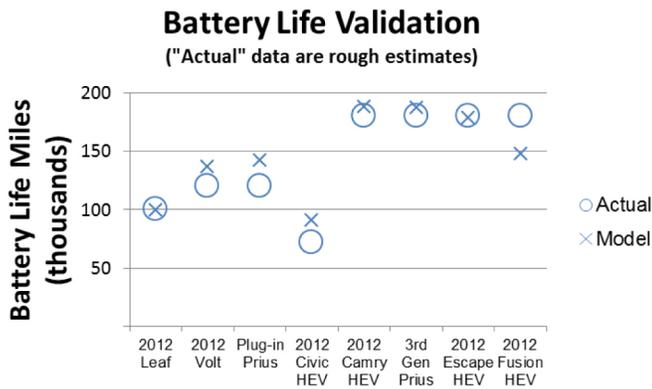


Figure 18. Battery life validation

Model Implementation

FASTSim was developed in Excel. The model calculations reside in the various worksheets. Visual Basic for Applications, which is embedded in Excel, is used to run and manage the models.

The key user worksheets have highlighted tabs and include:

- Documentation
- VehicleIO (Vehicle Input/Output)
- Powertrain comparison
- Parametric study
- DOE (Design of Experiments)
- Batch interface.

The primary worksheet is the "VehicleIO" tab, as seen in Figure 19. It consists of three sections: inputs, simulation, and results. The vehicle is defined in the inputs section at the top. The drive cycle simulation is selected in the middle section. The results are displayed in the lower section

The screenshot shows the FASTSim primary interface, which is organized into three main sections: Inputs, Simulation, and Results.

- Inputs:** This section allows users to define the vehicle and its components. It includes a dropdown menu for the vehicle (currently set to "2012 Camry HEV"), buttons for "Delete", "Save As", "Reload", and "Save", and a "Load A New Vehicle" button. Below this, there are icons and labels for various components: Fuel storage, Fuel converter, Motor, Traction battery, Wheel, Energy management, Misc., and Validation data (marked with a red checkmark).
- Simulation:** This section is used to configure the simulation. It includes a "Charging by Road Type/Location/Level" section with a checkbox for "Roadway Charging On" (set to FALSE). Below this is the "Current conditions" section. The "Additional drive cycles" section features a list of options (OrgOnly, Japan15Mode, singleCycTest, HHDDT, NYCC, LA92_Unified, HD_UDDS) and a "Selections" list. There are "Add" and "Delete" buttons for these cycles. Below the list are two optimization options: "Optimize battery for electric range & life" and "Optimize battery depth of discharge for life". A large "Run" button is present, along with a checkbox for "PHEV shortcut" and a "Results need run update:" indicator (set to TRUE). The "Run time (second):" is displayed as 1.42.
- Results:** This section displays the simulation results. It includes "Error checking parameters" (marked with a red checkmark), "Laboratory fuel economy", "Adjusted fuel economy", "Performance", "Cost (to consumer pre tax)", "Additional cycle results", "Misc.", and "PHEV details" (with FALSE and TRUE indicators).

Figure 19. FASTSim's primary interface

Other visible worksheets contain more detail that is frequently of interest. Each drive cycle being run has a dedicated worksheet. Also, key components, such as the fuel converter (engine, fuel cell), motor, and battery, have supporting worksheets shown.

Additional worksheets that are not generally needed are hidden. For example, some hold data for GUI operations and others support model scaling trends. They can be unhidden by right clicking on a visible tab and selecting “Unhide.”

Inputs

A vehicle's data can be chosen, added, or redefined in the “Inputs” section of the “VehicleIO” worksheet seen in [Figure 19](#). The vehicle data are loaded by choosing a vehicle from the pull-down menu. If the desired vehicle is not on the pull-down menu, two options are available. One, if it is not a light-duty model that currently exists, a similar vehicle can be loaded, modified, and saved to the menu using the “Save As” button. If it is an existing light-duty vehicle, it can be loaded from an extended vehicle database containing almost 4,000 vehicles by clicking the “Load a New Vehicle” button located just below the pull-down menu. This triggers the GUI in [Figure 20](#).

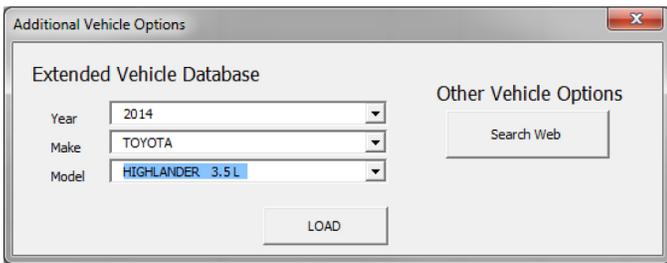


Figure 20. Extended vehicle database

Each saved vehicle has component data. It can be viewed by expanding the grouped rows, as seen in [Figure 21](#). For each parameter, a data value and a reference for that value can be saved.

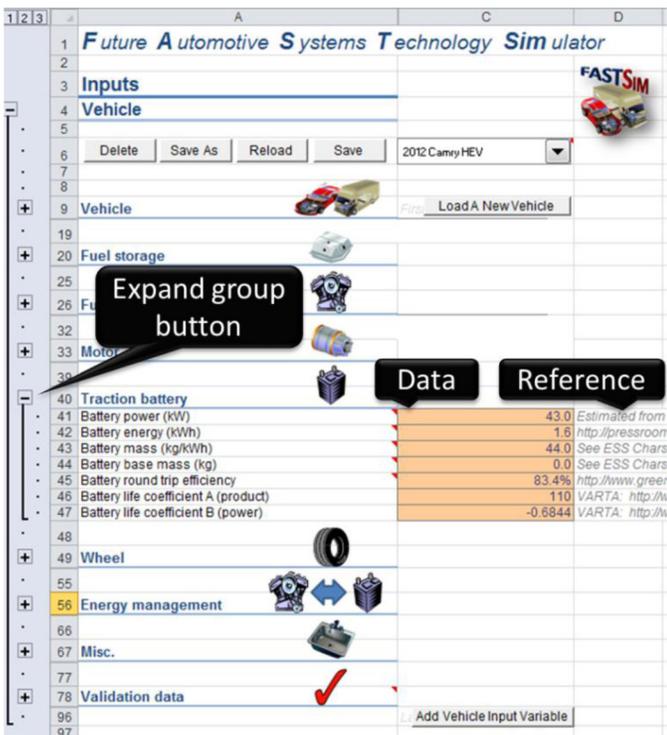


Figure 21. Vehicle inputs

Buttons next to several of the inputs assist with calculating the input, loading default data, or showing related information. For example, in the “Vehicle” grouping, one button helps with calculating the frontal area. The frontal area needs to be entered in meters squared, but vehicle height and width are often listed in inches. The calculator button opens a GUI where the height and width can be entered as inches, converts the units, multiplies them, and then inserts the results into the appropriate cell. Similar buttons assist with calculating glider mass, displaying fuel converter or motor efficiency curves, determining tire radius, loading HEV or PHEV energy management settings, and viewing how the energy management is impacting vehicle operation.

A complete list of vehicle inputs can be found by downloading FASTSim at www.nrel.gov/fastsim. New inputs can be added using the “Add Vehicle Input Variable” button. This ensures that the variable can be saved and loaded using the interface and that it is accessible in the powertrain calculations described later in this paper.

Powertrain

The vehicle powertrain calculations that link and manage the components are on the simulation worksheet “Veh Model.” The worksheet is copied and the equations filled down for each drive cycle added or loaded. The columns and input variables are named so that the equations are readable. For example, the equation used to calculate the power to overcome drag in the formula bar reads:

$$=0.5*airDensityKgPerM3*dragCoef*frontalAreaM2*(AVERAGE(+prevMpsAch,+cycMps)^3)/1000$$

Where:

- “airDensityKgPerM3” is the air density in units of kilograms per meter cubed.
- “dragCoef” is the vehicle drag coefficient.
- “frontalAreaM2” is the vehicle frontal area in units of meters squared.
- “prevMpsAch” is the previous vehicle speed achieved in meters per second.
- “cycMps” is the input drive cycle's current speed in meters per second.

The plus sign must be used before array names such as “prevMpsAch” and “cycMps” so that only the value in the corresponding row is used and not the entire array.

FASTSim is structured to maintain and propagate a consistent set of powertrain calculations. They can be updated by making changes on the “Veh Model” worksheet and clicking the “Update Model” button at the top left of that worksheet. This deletes all the drive cycle worksheets and rebuilds them using the updated equations from the “Veh Model” worksheet.

Simulations

By default, the light-duty city and highway drive cycles are always simulated. Additional options can be selected from the “Additional drive cycles” section on the “VehicleIO” worksheet, as seen in [Figure 22](#).

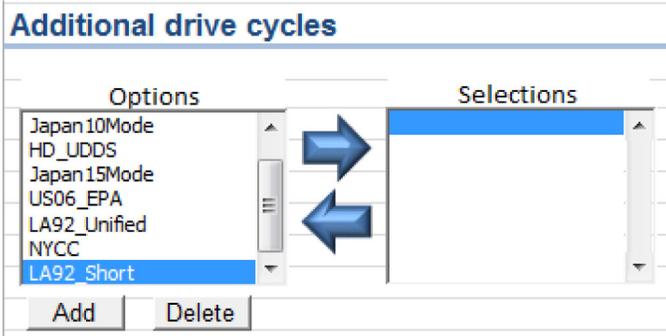


Figure 22. Additional drive cycle options

While the preloaded drive cycles characterize many forms of driving, a GUI was added to help import custom cycles, as seen in Figure 23. The GUI opens with a window describing the four columns of data needed for a custom cycle, including time, speed, grade, and road type. The Time column is typically specified in one-second increments. FASTSim's reverse engineered calculation method described earlier eliminates the need for smaller and slower time steps required by forward facing methods. Speed can be specified in meters per second, miles per hour (MPH), or kilometers per hour (KPH). The units used are specified on the GUI. Grade is entered as a fraction. Road Type is used for specifying when the vehicle is not running by using "Key-off" or to label a section of roadway that has a specified level of static or dynamic charging power.

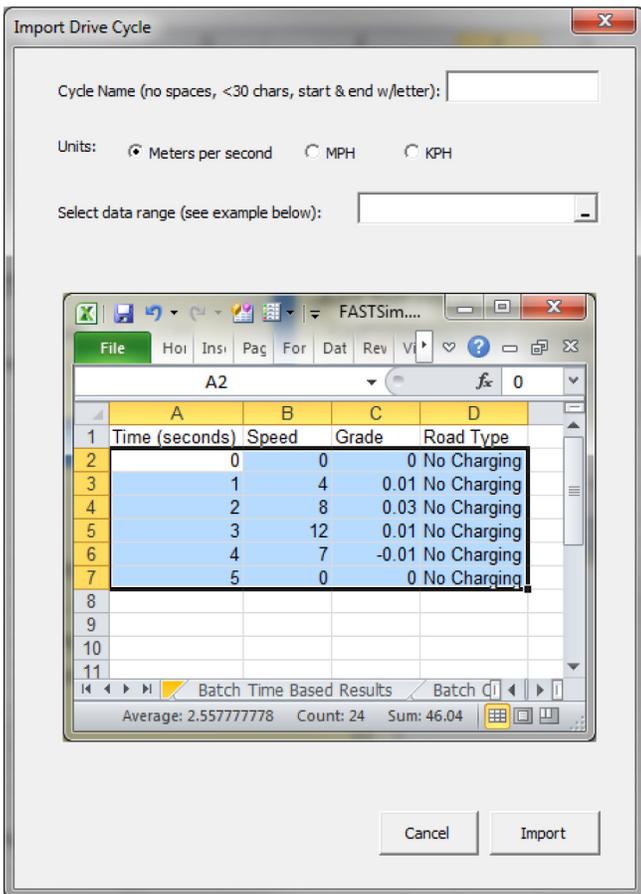


Figure 23. Drive cycle import GUI

Electric Power from the Road

Drive cycles can also be simulated with electric power transfer from the roadway. The charge can occur during stops or while the vehicle is moving. The power level is specified on the "VehicleIO" worksheet in the "Charging by Road Type/Location/Level" grouping. The grouping has two columns. The first is an input list of roadway types. The electric power for each roadway type is specified in the corresponding row of the second column. The roadway type must match those specified for the drive cycles.

Batch Interface

FASTSim has a GUI on the worksheet "Batch Interface" for running large batches of drive cycles, as seen in Figure 24. The vehicle loaded on the "VehicleIO" worksheet is used during batch runs. There are four steps for running a batch of cycles. First, a worksheet containing the drive cycle data must be specified. If the data are in the correct format in a .csv file, it can be loaded using the "Load csv" button. The format is similar to the custom drive cycle import format and can be found on the "Batch Cycles Example" worksheet. Next, if real world conditions are desired, the auxiliary loads must be modified for the loaded vehicle on the "VehicleIO" worksheet. Third, the "Run Batch" button is clicked. This creates a simulation worksheet based on the "Veh Model" template worksheet. It then runs all the drive cycles and saves high-level summary results on the "Batch Interface" worksheet in two sections. The first section includes cycle-specific results such as fuel economy, distance, and battery life. The second results section, "Batch Results," summarizes the averages of all of the cycles. If time-based results for each cycle are desired, they can be chosen in the "Save Time-based Results" section, also seen in the lower portion of Figure 24. They are saved on the "BatchCycRuns" worksheet. The final step is to click the "Clean Up" button. This deletes the drive cycle simulation sheet that was created, which keeps the file size down.

Batch Run Directions

1. Specify batch cycles worksheet (or load new csv file) (<400 cycles,
2. Increase auxiliary load on VehicleIO worksheet for real world heat/AC
3. Run batch cycles (optional: repeat for different VehicleIO setups)
4. Delete cycle data and model worksheets (keeps file size down)

Save Time-based Results (optional) - Saved in "Batch Time Based

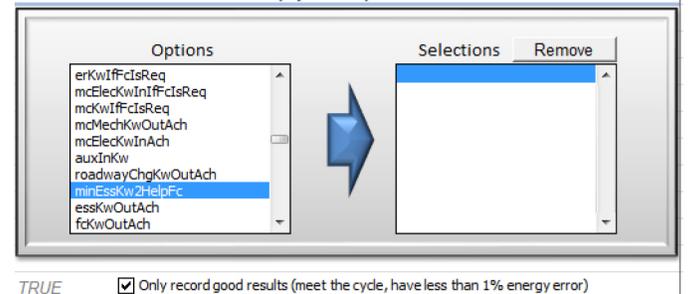


Figure 24. Interface for running large numbers of custom drive cycles

Analysis Tools

FASTSim has several worksheets that assist with common analysis tasks:

- Powertrain comparison
- Parametric study
- DOE.

They each use the data from the “VehicleIO” worksheet unless otherwise specified.

Powertrain Comparison

The “Powertrain Comparison” worksheet compares the impact of using four different powertrains in a selected vehicle:

- Conventional vehicle
- HEV
- PHEV
- EV.

It swaps out the powertrain of the selected base vehicle with each of the alternative powertrains based on the characteristics specified. Then it optimizes the control and sizing of the battery and compares the cost and petroleum use as seen in [Figure 25](#).

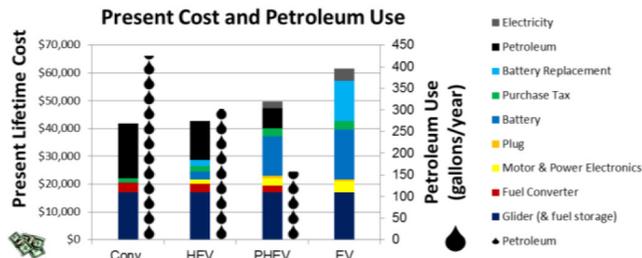


Figure 25. Powertrain comparison example results

Parametric Study

The “Parametric Study” worksheet expands on the use of the powertrain comparison algorithm. It sweeps a chosen design variable, such as mass or auxiliary load, through a range of values. At each value, the powertrain comparison algorithm is run, and the results are recorded. The final trends are output as seen in [Figure 26](#).

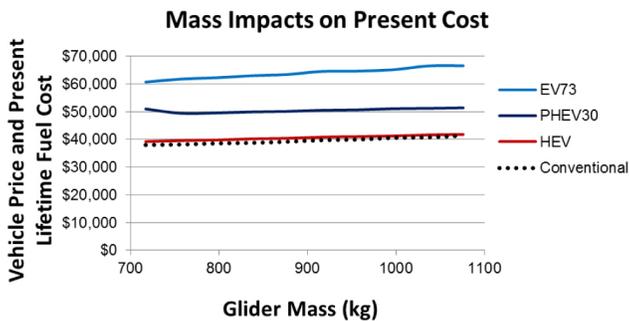


Figure 26. Parametric study example results

Design of Experiments

The “DOE” worksheet assists with running a DOE. A “Run DOE” button on the top initializes a GUI that allows the selection of the design variables, their ranges, and the number of increments for each, as seen in [Figure 27](#). A “Help” tab on the GUI shows an example, as seen in [Figure 28](#). When the DOE is used with FASTSim, the macro “Run.Run” must be added to the “Macros to run” text input to ensure proper simulation of the vehicle.

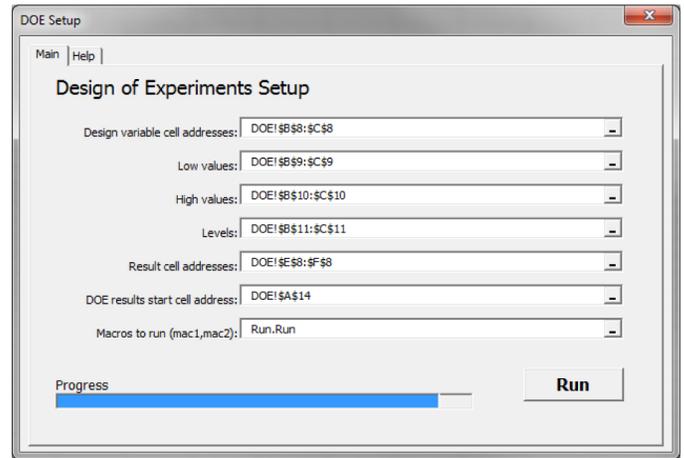


Figure 27. Design of experiments GUI

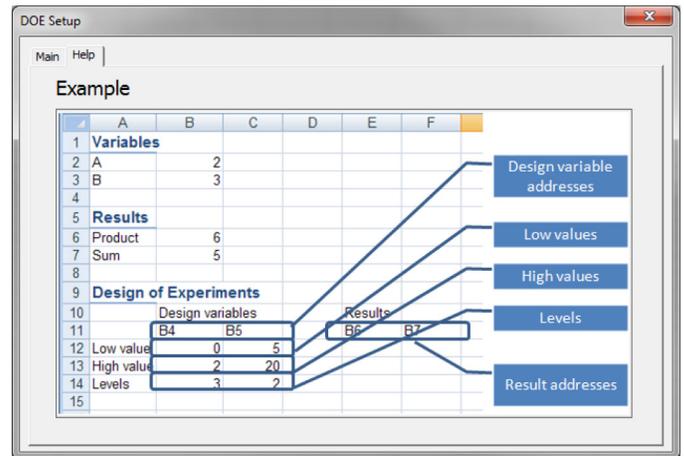


Figure 28. Design of experiments help tab

Because FASTSim is an Excel-based open source model, other modifications and customizations are possible.

Summary

FASTSim is a high-level advanced vehicle powertrain systems analysis tool. It provides a quick and easy way to compare powertrains or estimate the impact of technology improvements on light- or heavy-duty vehicle efficiency, performance, cost, and battery life. Its power-based approach makes it easy to populate with vehicle data, fast, and intuitive while still being accurate.

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Definitions/Abbreviations

DOE - design of experiments
EPA - U.S. Environmental Protection Agency
EV - battery electric vehicle
FASTSim - Future Automotive Systems Technology Simulator
GUI - graphical user interface
HD UDDS - Heavy Duty Urban Dynamometer Driving Schedule
HEV - hybrid electric vehicle
HWFET - Highway Fuel Economy Driving Schedule
PHEV - plug-in hybrid electric vehicle
SOC - state of charge
UDDS - Urban Dynamometer Driving Schedule
VMT - vehicle miles traveled

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