Rail Energy Modeling Software

User Manual

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1.0 Introduction

The last decade has seen dramatic changes in the light and heavy duty vehicle powertrain technology marketplace with the emergence of hybrid vehicles, electric vehicles, and other highly advanced powertrains. Significant engineering effort has been expended in those markets to build software design tools to help evaluate early stage fuel savings concepts before the ‘cutting of metal’ prototyping stage. Since the research and development cost to create a prototype of an advanced powertrain can easily reach tens of millions of dollars, the use of early stage conceptual design validation software tools has matured significantly to provide high confidence in the concept’s powertrains potential for fuel saving.

The rail transportation sector can benefit from these major advancements in vehicle design process as well. Migrating automotive-proven tools into this space can provide a valuable economic investment for the rail community since it can dramatically reduce the investment in developing and marketing new technologies by allowing new entrants the ability investigate new technologies in a very low cost way, as well as providing a mechanism for other stakeholders such as policy makers, rail operators, and locomotive OEMs to develop and test new product concepts in an extremely low-cost manner that can have a direct reduction on air pollution.

The purpose of the project is to develop an easy to use software simulation tool that will allow stakeholders to build and test a number of different types of rail powertrain technology. This tool will be released under a freeware license for use by research institutes, rail- equipment manufacturers, technology investors, policy-makers or anyone else who might be interested in the evaluation of powertrain technologies for rail systems. The software will run on Microsoft Windows based PCs.

1.1 Objective

The Rail Energy Modeling Software is a Microsoft Windows program that enables users to investigate fuel savings and emissions reductions in locomotive powertrain technologies. The software allows users to define different train types (*e.g.,* passenger, freight, switch), powertrain types (*e.g.,* engine electric, engine battery hybrid), and drive cycles to compare simulated fuel consumptions and emissions of different train architectures. In this user manual, Section 2 provides the basic steps for getting started with the software, and is meant for users who quickly want to obtain simulation results. Section 3 provides a deeper level of technical explanation of the different components and features of the software for the advanced user. Section 4 provides a tutorial and Section 5 provides model validation information.

1.2 Functionality

The software operates as follows:

1. A wide variety of tunable parameters are available to construct a train model, including:
    a. Fuel type:
        i. Diesel
        ii. Gasoline

    iii. Compressed Natural Gas (CNG)
    iv. Liquefied Natural Gas (LNG)
  b. Powertrain topology:
    i. Engine-Electric
    ii. Electric
    iii. Engine Hybrid (with the following available energy storage systems)
      1. Battery
      2. Flywheel
      3. Ultracapacitor
    iv. Fuel Cell (with the following available energy storage systems)
      1. Battery
      2. Flywheel
      3. Ultracapacitor
    v. Automatic Engine Start-Stop System (Anti-Idling System)
    vi. Auxiliary Engine Systems (Auxiliary Power Unit, Head-End Power)
  c. Train length and payload mass configuration
  d. Aerodynamic performance and rolling resistance
2. The option is available to load a custom or built-in drive cycle that defines the train's speed and grade with time.
3. The software simulates the train on the loaded drive cycle to generate simulated results such as power consumption, fuel consumption and greenhouse gas (GHG) emissions.

1.3 Unit System

This software defaults to the metric system, but the US imperial system is also available from the ***Unit System*** drop-down in the top-left corner of the application.

1.4 Software Layout

The window shown below opens after launching the Rail Energy Modeling Software (Figure 1).

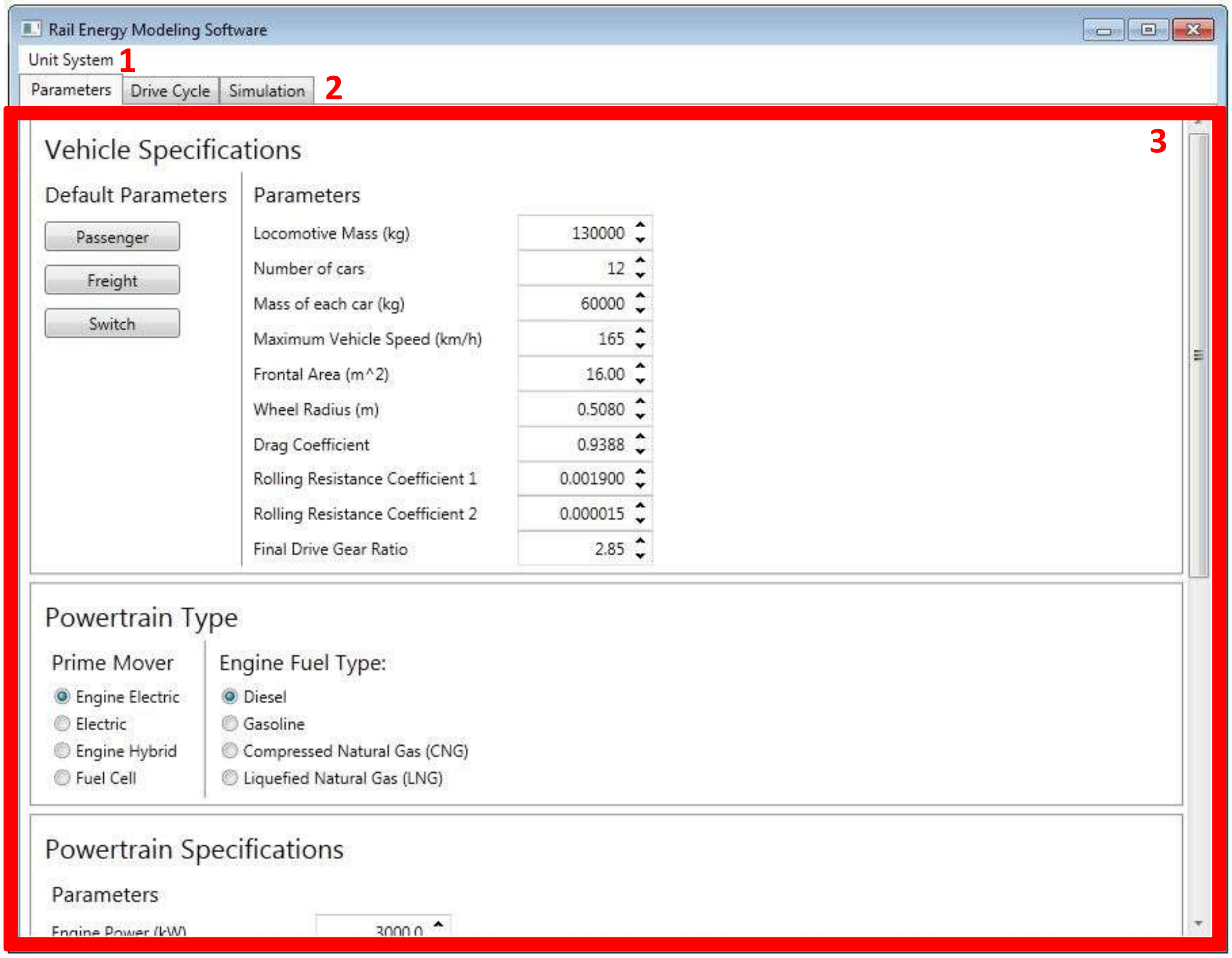


Figure 1. Home screen (Parameters Window) of the Rail Energy Modeling Software

The window aspects identified above are detailed below:

1. Unit System Selector – change between metric and US imperial unit systems
2. Navigation Tabs – navigate through the application to the following windows:
    a. Parameters Window
    b. Drive Cycle Window
    c. Simulation Window
3. Parameters Window – workspace for defining the train model

Once a train model has been defined, the ***Drive Cycle*** navigation tab is selected to open the Drive Cycle Window (Figure 2).

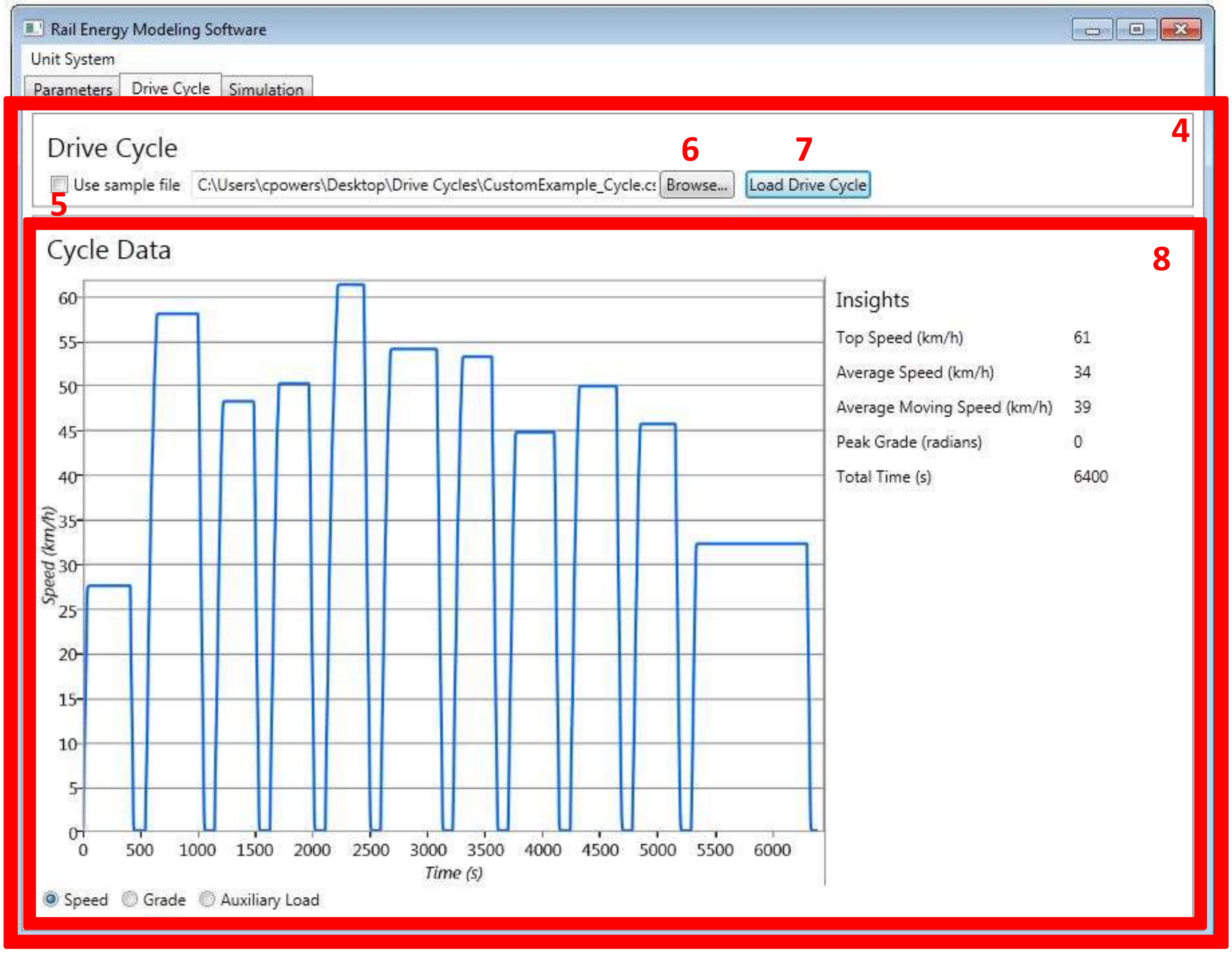


Figure 2. Drive Cycle Window of the Rail Energy Modeling Software

The window aspects identified above are detailed below:

4. Drive Cycle Window – where the drive cycle can be loaded and reviewed
5. Sample Drive Cycle Toggle – where the pre-defined sample drive cycle can be selected
6. Browse Button – where custom drive cycles can be selected
7. Load Button – loads the selected drive cycle into the system
8. Cycle Data Window – where the details of the drive cycle will be displayed after being loaded

Once a train model and drive cycle have been defined, the ***Simulation*** navigation tab is selected to open the Simulation Window (Figure 3).

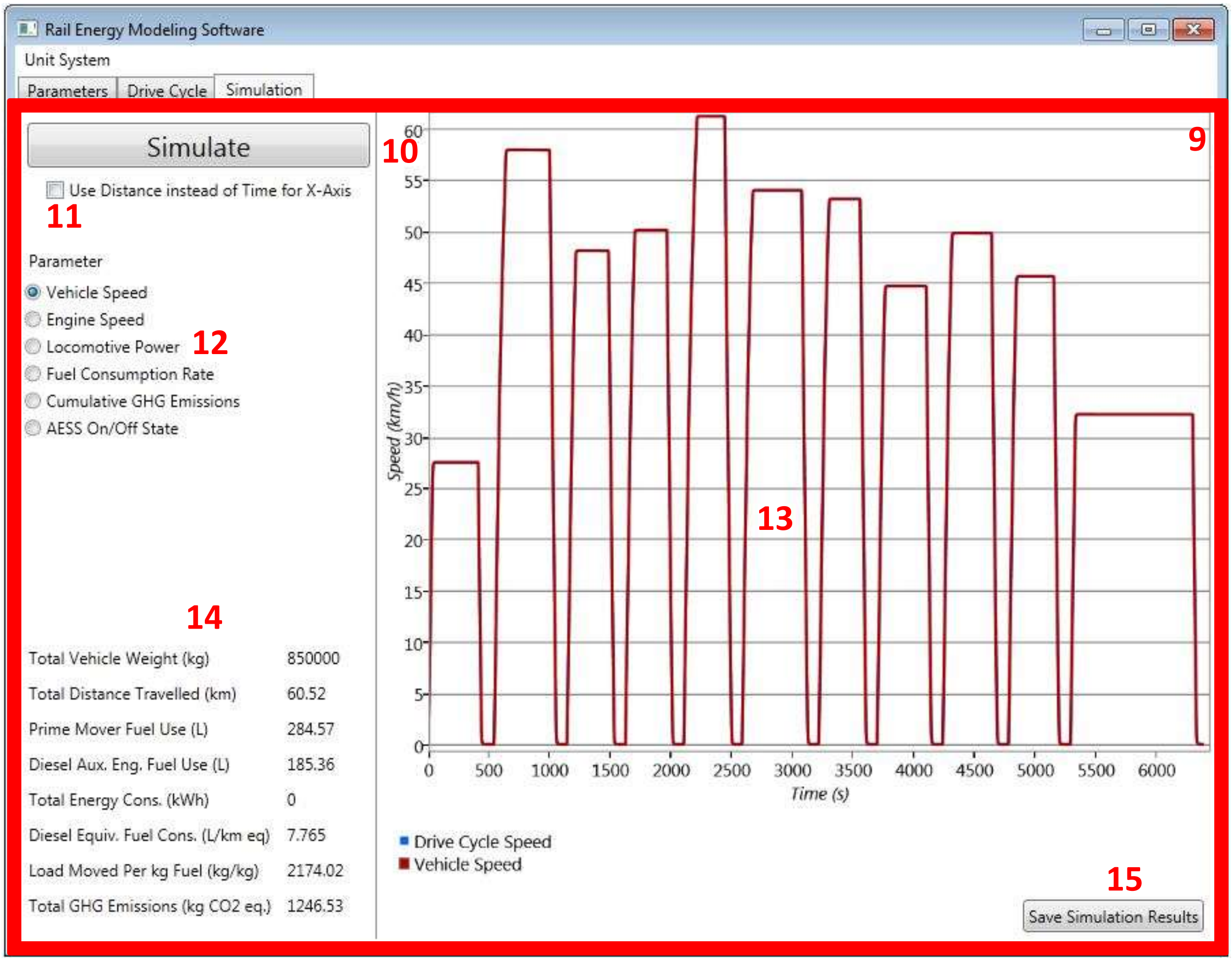


Figure 3. Simulation Window of the Rail Energy Modeling Software

The window aspects identified above are detailed below:

9. Simulation Window – where the train can be simulated and the simulation results can be reviewed and saved
10. Simulate Button – executes the train simulation
11. Distance Instead of Time for X-Axis Toggle – plots the simulation results against distance instead of time if selected
12. Parameter Selection Pane – where the simulation parameter to be plotted can be selected
13. Results Window – where the plotted simulation results are displayed
14. Summary of Results – where a summary of the simulation results is displayed
15. Save Results Button – saves simulation results as either a '.csv' or '.mat' file format

2.0 Getting Started - Basic Simulations

2.1 Defining a Train Model

2.1.1 Defining the Vehicle Specifications

The first step to simulate a train is to define the train itself. To quickly run a simulation, navigate to the Parameters Window and select ***Passenger***, ***Freight***, or ***Switch*** to auto-populate the train parameters with default values for the respective train types (Figure 4). Modifications to these parameters can be made as necessary.

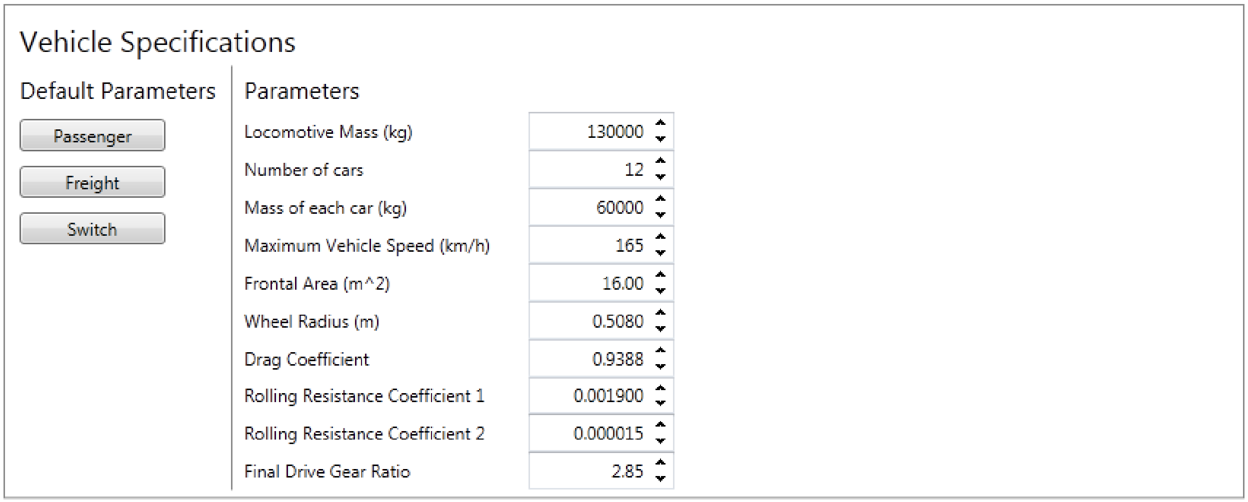


Figure 4. Defining the vehicle specifications

For more information on tuning train parameters, see 3.1 Tuning Train Parameters in 3.0 Advanced Simulations.

2.1.2 Defining a Powertrain

The software allows eight different powertrain topologies to be selected for simulation (Figure 5). If ***Electric*** is selected, there is no further selection needed. If ***Engine Electric*** or ***Engine Hybrid*** is selected, a fuel type must be selected. To change the prime mover's fuel type, select the desired fuel with its corresponding radio button. If ***Engine Hybrid*** or ***Fuel Cell*** is selected, another menu will appear to select the energy storage system (ESS), which can be a ***Battery***, ***Flywheel*** or ***Ultracapacitor***. The electric powertrain is restricted to consuming grid power and the fuel cell powertrain is restricted to consuming hydrogen gas.

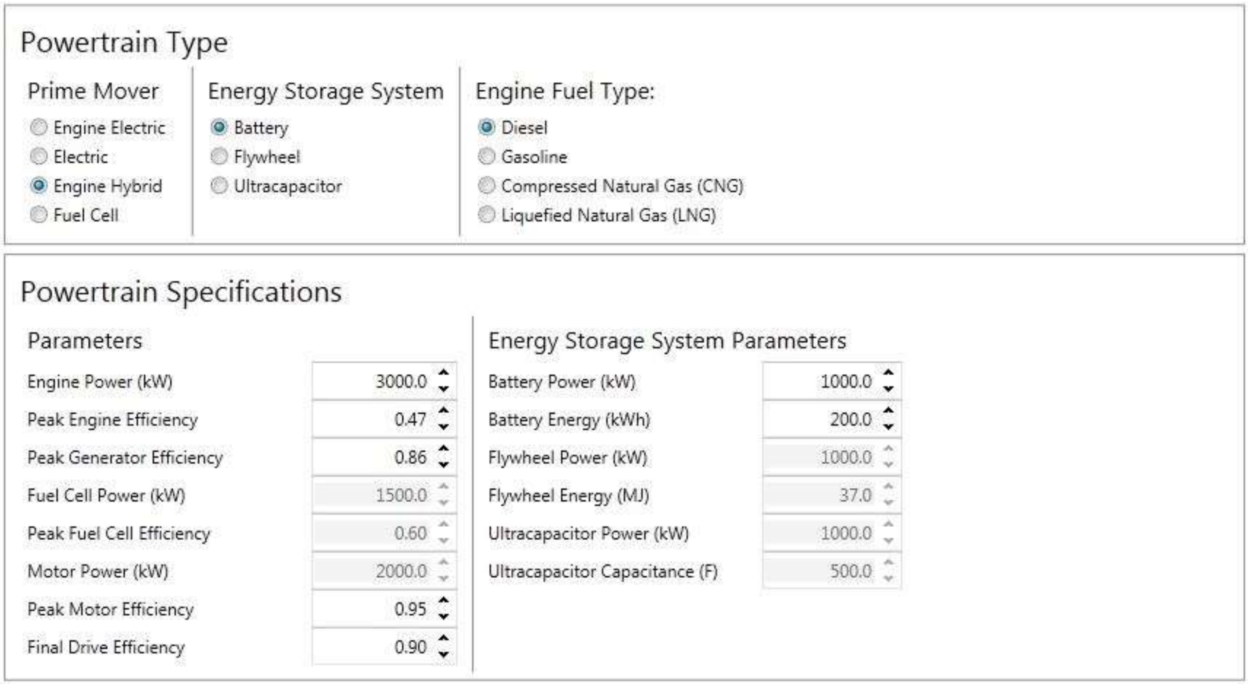


Figure 5. Defining a powertrain topology

For more information on the available powertrain topologies or fuel types, see 3.2 Powertrain Topologies or 3.3 Fuel Types, respectively, in 3.0 Advanced Simulations.

2.1.3 Defining an Auxiliary System

By default, a ***Head-End Power (HEP)*** system is selected as an auxiliary system. Selecting an ***HEP*** or an ***Auxiliary Power Unit (APU)*** allow the option of an ***Automatic Engine Start Stop (AESS)*** system; however if no auxiliary system is selected the ***AESS*** option is no longer available (Figure 6).

Figure 6. Defining the auxiliary systems

Note: If the auxiliary system is changed, the drive cycle must be reloaded before simulating.

For more information on defining the auxiliary system, see 3.4 Auxiliary Systems in 3.0 Advanced Simulations.

2.2 Loading a Drive Cycle

To load a drive cycle into the system, first select the ***Drive Cycle*** navigation tab (Figure 7).

Then select ***Use sample file*** or click ***Browse…*** to search for a custom drive cycle. Once a drive cycle has been chosen, select ***Load Drive Cycle***. The desired drive cycle will be plotted in the Cycle Data Window. The speed, grade and auxiliary load can be viewed using the radio buttons beneath the plot.

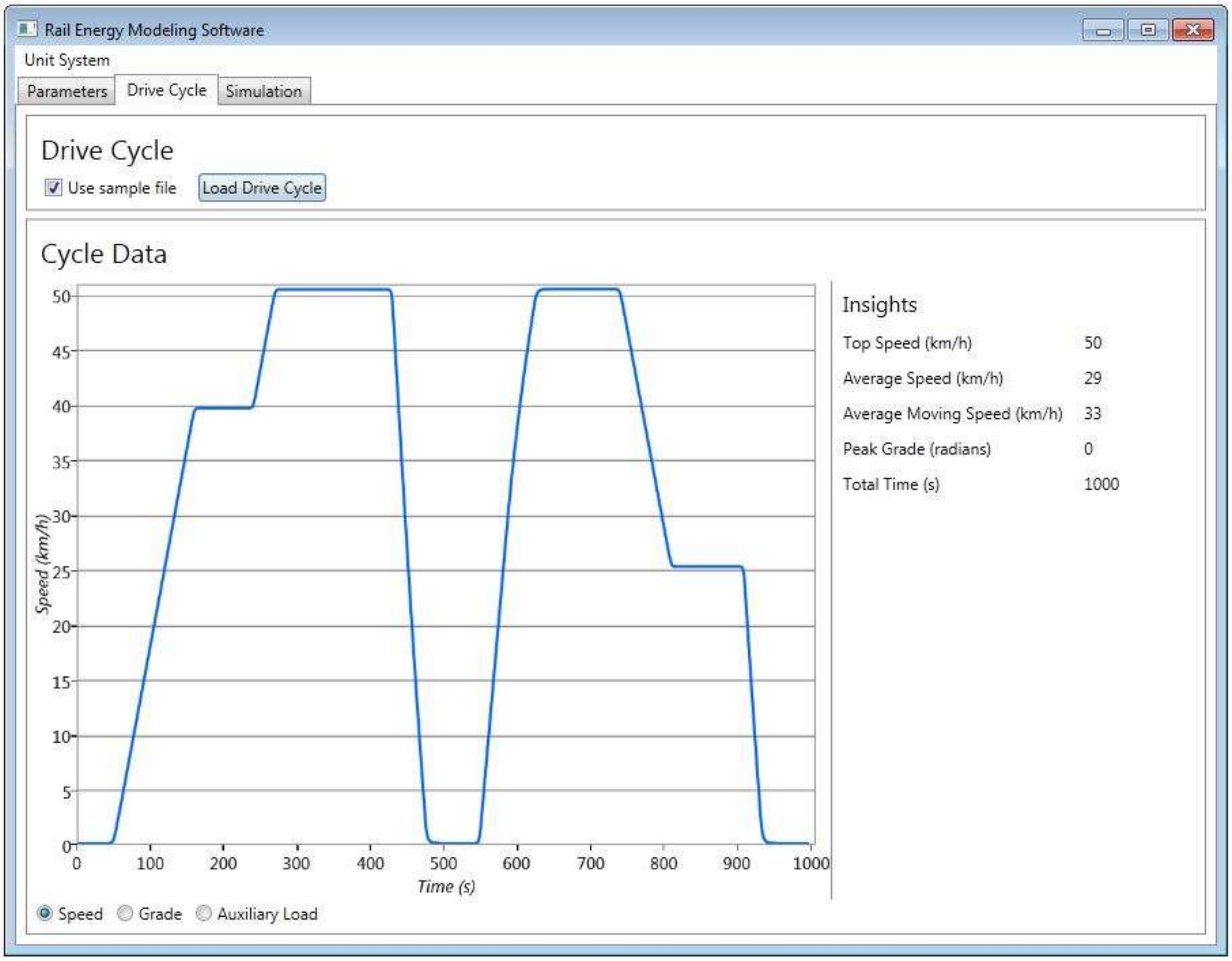


Figure 7. Loading a drive cycle

The ***Auxiliary Load*** radio button will display the operation of the Auxiliary System as defined in the Diesel Auxiliary Systems section in the ***Parameters*** tab.

For more information on building custom drive cycles, see 3.5 Custom Drive Cycles in 3.0 Advanced Simulations.

2.3 Running a Simulation

Once a train model has been defined and a drive cycle has been loaded, the system is ready to simulate the train. To do so, simply select the ***Simulation*** navigation tab followed by the ***Simulate*** button (Figure 8). The simulation may take a few moments, but a progress bar will appear to show the simulation is running. Once the simulation completes, the results are presented for the user to review.

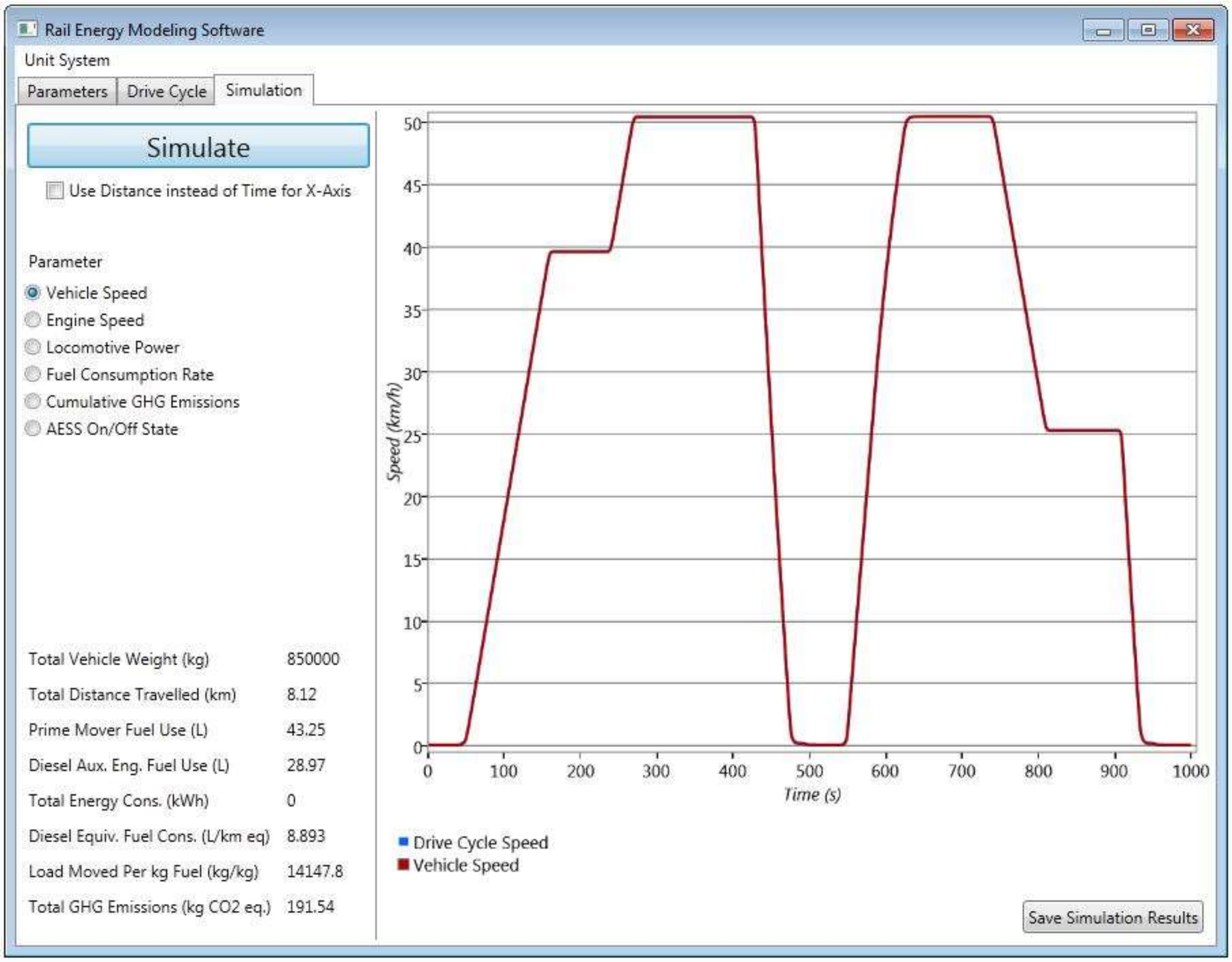


Figure 8. Viewing simulation results

2.3.1 Interpreting and Saving Results

There are six plots available as radio buttons to showcase how the train model performed on the selected drive cycle. There is also a summary of results of the train's performance in the bottom left corner of the Simulation Window.

The summary of results contains useful statistics from the simulation that give an overview of the locomotive's performance (Table 1).

Table 1. Descriptions of summary results statistics

Summary Result	Description
Total Vehicle Weight	Total weight of the locomotive

Total Distance Travelled	Total distance travelled by the locomotive
Prime Mover Fuel Use	Total fuel consumed by the locomotive, units vary with fuel type
Diesel Aux. Eng. Fuel Use	Total fuel consumed by the auxiliary engine
Total Energy Consumption	Total energy consumed by the electrical grid or the energy storage system
Diesel Equiv. Fuel Cons.	Total fuel consumption and electrical energy consumption as a single diesel equivalent fuel consumption value
Load Moved Per kg Fuel	Total weight of the locomotive divided by the total weight of fuel consumed (not a fuel equivalent)
Total GHG Emissions	Total mass of greenhouse gas emissions

The ***Diesel Equiv. Fuel Cons.*** statistic is particularly useful for comparing various powertrain topologies and fuels as it converts all fuel types and electrical energy consumption into a diesel fuel equivalent. This value factors in prime mover fuel or energy consumption, auxiliary engine fuel consumption, and ESS energy consumption.

There is also an option to display the results of the simulation against the distance driven by the train rather than the elapsed time of the drive cycle. To use this feature select the ***Use Distance instead of Time for X-Axis*** toggle and reload the plots by selecting the ***Reload*** button.

The simulation results can be saved to '.mat' or '.csv' format by selecting the ***Save Simulation Results*** button, entering the file name, and choosing the desired format. The output signals saved to the file are defined below (Table 2).

Table 2. Definitions of output signals saved to file

Signal Name	Description	Units
sim_AESS_on_bool	AESS Functionality (TRUE = Engine Off)	Boolean
sim_apu_fuel_cumulative_kg	Cumulative APU Fuel Consumption	kg
sim_apu_fuel_rate_kgps	APU Fuel Consumption Rate	kg/s
sim_apu_GHG_emissions_rate_kgps	APU GHG Emissions Rate	kg/s
sim_apu_power_W	APU Power	W
sim_electrical_accessories_power_W	Electrical Accessories Power	W
sim_engine_fuel_cumulative_kg	Cumulative Engine Fuel Consumption	kg
sim_engine_fuel_rate_kgps	Engine Fuel Consumption Rate	kg/s
sim_engine_GHG_emissions_rate_kgps	Engine GHG Emissions Rate	kg/s
sim_engine_on_bool	Engine On\Off State	Boolean
sim_engine_power_W	Engine Mechanical Power	W
sim_engine_speed_radps	Engine Speed	rad/s
sim_engine_torque_N	Engine Torque	Nm
sim_ess_power_W	ESS Power	W
sim_ess_state_of_charge_percent	ESS State of Charge	%
sim_fuelcell_GHG_emissions_rate_kgps	Fuel Cell GHG Emissions Rate	kg/s
sim_fuelcell_h2_cumulative_kg	Cumulative Fuel Cell H_2 Consumption	kg
sim_fuelcell_h2_rate_kgps	Fuel Cell H_2 Consumption Rate	kg/s
sim_fuelcell_on_bool	Fuel Cell On\Off State	Boolean
sim_fuelcell_power_W	Fuel Cell Power	W
sim_generator_electrical_power_W	Generator Electrical Power	W
sim_generator_mechanical_power_W	Generator Mechanical Power	W
sim_grid_energy_Wh	Cumulative Grid Energy	Wh
sim_grid_power_W	Grid Power	W
sim_locomotive_GHG_emissions_cumulative_kg	Cumulative Locomotive GHG Emissions	kg
sim_locomotive_GHG_emissions_rate_kgps	Locomotive GHG Emissions Rate	kg/s
sim_mechanical_accessories_power_W	Mechanical Accessories Power	W
sim_motor_electrical_power_W	Motor Electrical Power	W
sim_motor_mechanical_power_W	Motor Mechanical Power	W
sim_time_s	Time	s
sim_tractive_power_W	Tractive Power (Wheel Output Power)	W

2.4 Rapid Simulations

The Rail Energy Modeling Software allows the quick modification of simulation parameters by retaining the parameters entered into the previous simulation; provided the software is not closed. This allows users to quickly modify the simulation parameters and simulate the new locomotive without having to reload the drive cycle unless the auxiliary system has been modified.

3.0 Advanced Simulations

3.1 Tuning Train Parameters

The software allows tuning of various parameters within reasonable limits. To tune the parameters, modify the number in the box that corresponds to the parameter being tuned. Alternatively, the arrows can be used to increase or decrease the parameter value in consistent intervals. For example, to modify the ***Number of Cars*** in the train, the value in the corresponding box can be changed directly or by using the arrows next to the value (Figure 9).

Figure 9. Tuning of train parameters

Various performance aspects of the train can be modified by tuning specific parameters. Some performance aspects include:

- payload mass, tuned through
  - locomotive mass
  - car mass
  - number of cars
- performance specifications, tuned through
  - maximum train speed
  - wheel radius
  - final drive gear ratio
- vehicle losses, tuned through
  - frontal area
  - drag coefficient
  - rolling resistance coefficients

Once these parameters are set, the software scales the locomotive components to match the tunable parameters entered by the user. Realistic values have been set as default values for every tunable parameter for ease of use, however in order to model specific trains the user may need to change these parameters to match those of the specific train in question.

The two rolling resistance coefficients are used to tune the rolling resistance of the locomotive which contributes to the vehicle losses. They represent the coefficient of rolling resistance between the locomotive wheels and rail tracks. These parameters are related to rolling resistance based on the following relationship (Equation 1):

Equation 1. Rolling resistance calculation

$$F_r = (R_1 + \mathrm{v}R_2)W$$

Where ‘F_r’ is the rolling resistance in N, ‘W’ is locomotive weight in N, ‘v’ is vehicle speed in m/s, and ‘R_1’ and ‘R_2’ are the rolling resistance coefficients (which are dimensionless).

Conflicting parameters are disabled when necessary to ensure there is no way the train can be over-constrained or improperly sized. For example, for an engine electric powertrain topology the ***Engine Power*** can be set, but the ***Motor Power*** is disabled because it is automatically scaled to be compatible with the engine power (Figure 10). The ***Fuel Cell Power*** and ***Peak Fuel Cell Efficiency*** parameters are also disabled since there is no fuel cell stack present in an engine electric powertrain.

Figure 10. Conflicting parameters are disabled to prevent over-constrained train models

3.2 Powertrain Topologies

The software allows the user to define eight unique powertrains. All powertrains contain only one motor, final drive gear, and wheel (Figure 11). Since tractive motors in a locomotive are installed in a parallel configuration, their tractive power is cumulative. Therefore, the motor in this software represents the sum of all tractive motors on-board the locomotive. The final drive gear represents the final gearing ratio per axle of the train because every motor is subject to the same final drive ratio. The same concept is used for the wheel (axle) in the powertrain. The components preceding the motor are defined by the user and are what make the powertrains unique.

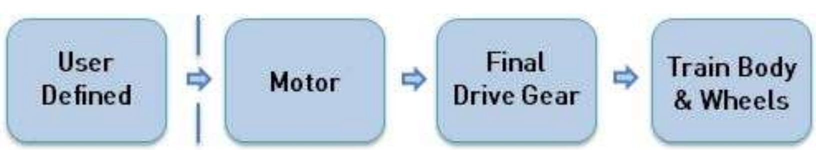


Figure 11. Generic powertrain topology

3.2.1 Engine Electric

The engine electric powertrain topology contains an engine and generator to power the locomotive (Figure 12). The configuration is the most basic of the available engine topologies. There is no ESS available in this configuration, which means that the system is powered only by the engine. This topology resembles that of a standard locomotive found in most fleets.

Figure 12. Engine electric powertrain topology

3.2.2 Electric

The electric powertrain topology is the simplest of all available topologies. This model uses electrical energy from the grid to power the locomotive. There is no engine or generator in this architecture, as it is pure electric (Figure 13).

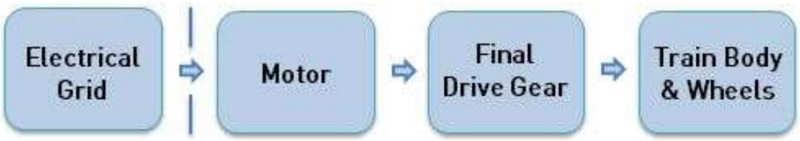


Figure 13. Electric powertrain topology

3.2.3 Engine Hybrid

The engine hybrid powertrain topology allows the use of three different ESSs: a battery, flywheel, or ultracapacitor. The architecture contains an engine and generator in series with an ESS to provide power to the locomotive (Figure 14). This configuration allows the user to specify which ESS is to be used for the model.

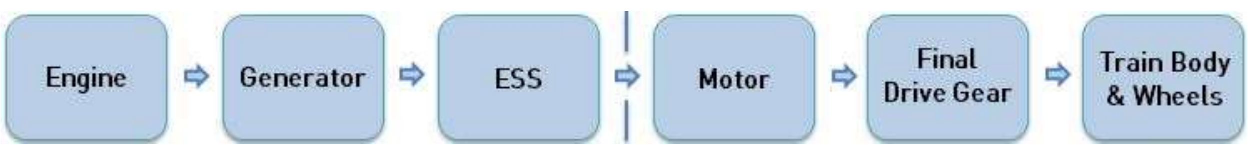


Figure 14. Engine hybrid powertrain topology

The battery option for the ESS is the most common of the three in terms of hybrid architectures today. The battery has a relatively long runtime but also has a longer recharge time than the other two available ESSs. Furthermore, the battery has a higher energy and lower power than the other options, making it more suited for drive cycles with little stop and go. The flywheel option for the ESS has a short runtime and a short recharge time compared to the battery. The low energy but high power nature of the flywheel makes it better suited for drive cycles with more stop and go. The ultracapacitor option for the ESS also has a fast recharge time and a short runtime. Like the flywheel, the ultracapacitor has low energy and high power, and is better suited for more stop and go drive cycles.

Each of the three storage systems available has different advantages and disadvantages, none are necessarily better than the other and their performance largely depends on the requirements of the individual train to be simulated.

3.2.4 Fuel Cell

The fuel cell powertrain topology also allows the use of a battery, flywheel, or ultracapacitor ESS in series with a hydrogen fuel cell stack to provide power to the locomotive (Figure

15).

Figure 15. Fuel cell powertrain topology

3.3 Fuel Types

The software allows the user to choose between six fuel types, although there are some restrictions as to which fuel type can be used for each powertrain topology. The table below summarizes which powertrain topologies are capable of using which fuels (Table 3).

Table 3. Fuel type and powertrain compatibility

Fuel Type	Available Powertrain Topologies
Electrical Grid	Electric
Diesel	Engine Electric, Engine Hybrids
Gasoline	Engine Electric, Engine Hybrids
Compressed Natural Gas (CNG)	Engine Electric, Engine Hybrids
Liquefied Natural Gas (LNG)	Engine Electric, Engine Hybrids
Hydrogen Gas	Fuel Cells

3.4 Auxiliary Systems

This software allows the customization of accessory loads and auxiliary engines, as well as the option of an AESS system (Figure 16).

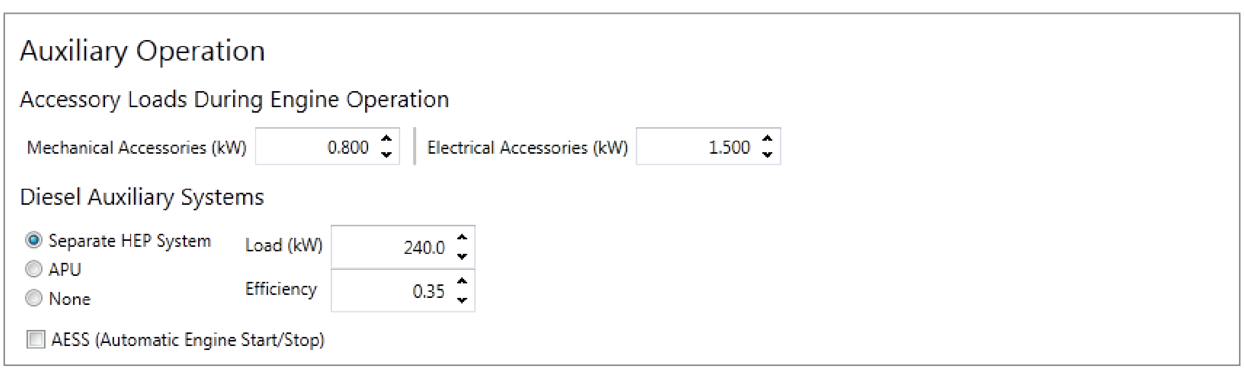


Figure 16. Defining the auxiliary operation of the locomotive

3.4.1 Accessory Loads

Accessory loads are the loads required to keep the train functioning at an optimal state. These can be broken down into mechanical and electrical loads. For example ***Electrical Accessories*** include any electronics or gauges that the operator would see in the cab and ***Mechanical Accessories*** would include any pumps, compressors, or fans required to keep the engine in operational condition. If the prime mover is turned off (*e.g.*, by the AESS), the accessory loads turn off as well since they are tied to the locomotive's primary systems.

3.4.2 HEP

HEPs are auxiliary diesel engines which are used on passenger trains to provide lighting, heating and other hoteling needs for the passenger cars. These systems are active throughout the duration of the simulation.

3.4.3 APU

APUs are auxiliary diesel engines used on a locomotive to provide energy for functions other than propulsion such as maintaining engine fluid temperatures and cab hoteling. These units are only activated when the prime mover is turned off.

3.4.4 AESS

AESS systems are idle-reduction systems that automatically shut down the prime mover of a locomotive when idling occurs for an extended period of time. The system also starts the prime mover when it is required again in the drive cycle. Typically, and in this software, the AESS system waits 20 s before shutting down the prime mover. When the AESS system is connected with an APU the AESS activates the APU when shutting down the prime mover. To use an AESS in a simulation, either an HEP or an APU must be selected (this also means that the electric powertrain topology cannot be selected).

3.5 Custom Drive Cycles

3.5.1 Defining a Custom Drive Cycle

The software allows the construction of custom drive cycles. To create a custom drive cycle:

1. Enter the drive cycle information into a matrix in the following format, excluding column headers (Table 4):

   Table 4. Formatting of custom drive cycle

A	B	C	D	E
Time (s)	Vehicle Speed (m/s)	Grade (rad)	Ones	Zeros

   Notes:
   - Every row of column D should be set to 1 (placeholder for engine key-on)
   - Every row of column E should be set to 0 (placeholder for APU/HEP power)
   - These columns will be modified by this software according to the auxiliary and AESS systems selected in the Auxiliary Operation section of the Parameters Window.
2. Save the matrix as a comma separated value ('.csv') file

A screenshot of the beginning of a custom built drive cycle is presented below (Figure 17).

	A	B	C	D	E
1	0	0	0	1	0
2	0.1	0.1	0	1	0
3	0.2	0.3	0	1	0
4	0.3	0.5	0	1	0
5	0.4	0.7	0	1	0
6	0.5	0.9	0	1	0

Figure 17. Beginning of a custom drive cycle made in Microsoft Excel

When defining a custom drive cycle, it is important to be aware of some notes. First, the time interval in the drive cycle can affect the simulation. The simulations are run at 0.1 s time intervals, so if a drive cycle is constructed at 1 s time intervals there may be some noise in the output signals as the proportional-integral controller is sampling more frequently than there is data from the drive cycle. To minimize noise in signals caused by this issue, drive cycles should be smoothed and constructed at a smaller time interval.

Furthermore, the drive cycle acceleration should be a realistic acceleration since the maximum motor torque in the models is designed according to the eighth notch of a locomotive. While the model can handle a high acceleration, a conductor would not typically accelerate from a stop in notch eight.

Finally, if building the drive cycle in MATLAB, it is recommended to use the ‘dlmwrite’ function instead of the ‘csvwrite’ function to save the cycle to a ‘.csv’ as ‘csvwrite’ introduces round off errors in the drive cycle which may lead to transients or unexpected results.

3.5.2 Loading a Custom Drive Cycle

To load a custom built drive cycle follow the steps below:

1. Navigate to the Drive Cycle Window (Figure 18)
2. Ensure ***Use sample file*** is not checked
3. Select the ***Browse…*** button, navigate to the drive cycle, and select the ***Open*** button
4. Select the ***Load Drive Cycle*** button

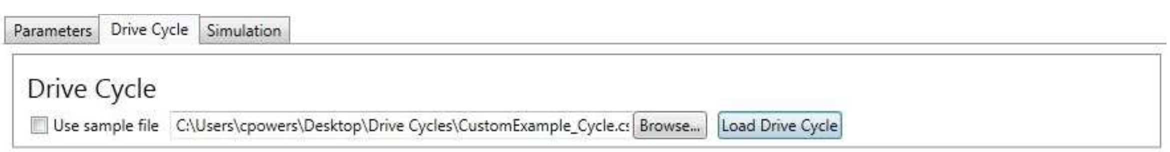


Figure 18. Drive cycle loading section in the Drive Cycle Window

The desired drive cycle will be plotted in the ***Cycle Data*** section. The speed, grade and auxiliary load can be viewed using the radio buttons beneath the plot. The ***Auxiliary Load*** radio button will display the operation of the ***Diesel Auxiliary Systems*** section in the ***Parameters*** tab.

4.0 Tutorial

This tutorial will go through step-by-step instructions for rapid simulation of two basic trains on a custom drive cycle in order to do a comparison of the fuel consumption.

1. Define the parameters for the train. This tutorial uses the default passenger train parameters. To use these parameters, select the ***Passenger*** button (Figure 19).
2. Define the powertrain type. The first simulation is going to use an engine electric architecture that runs on diesel fuel. Since those represent the default powertrain, no action is required for this step.

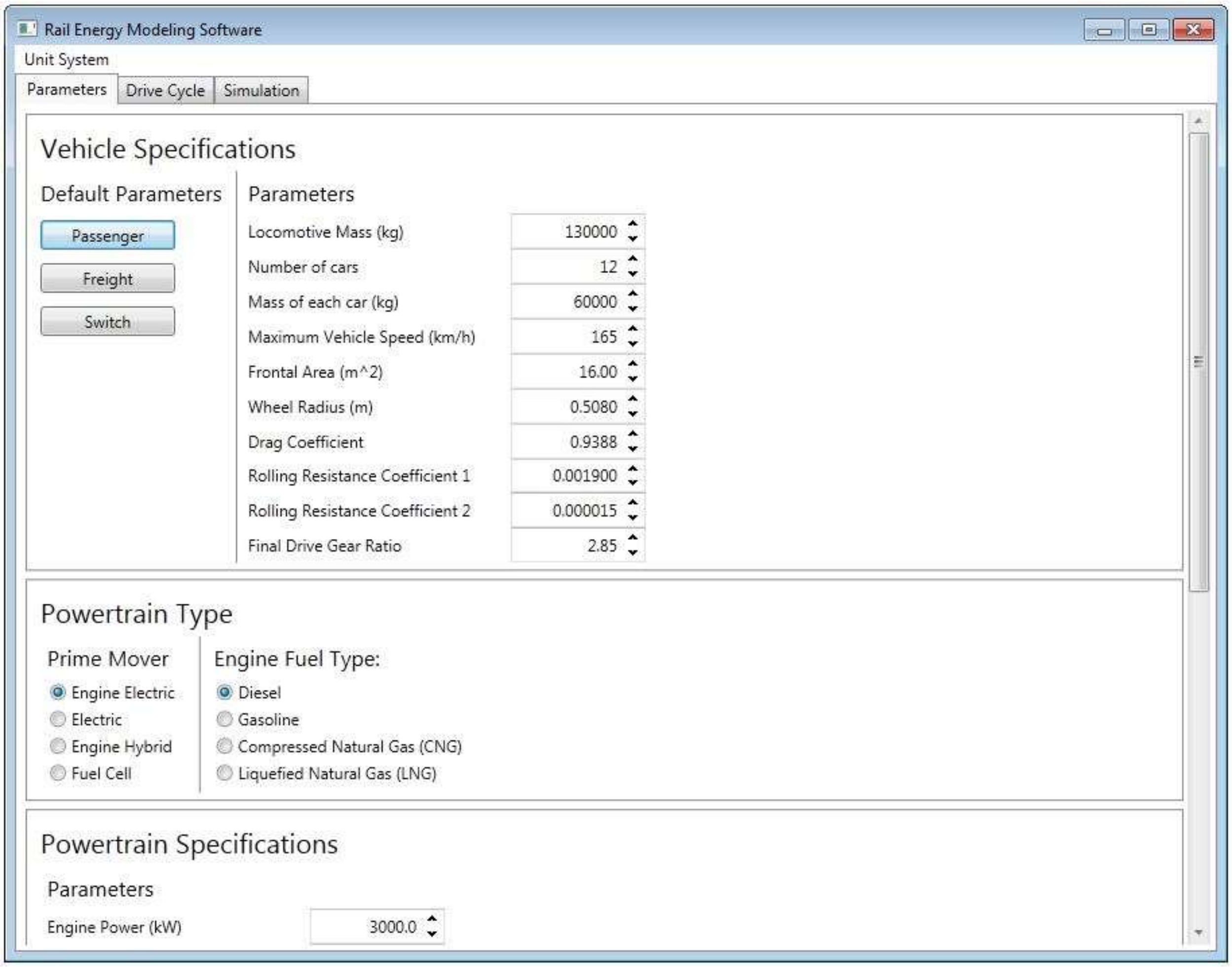


Figure 19. Defining vehicle specifications and powertrain type

3. Leave the powertrain specifications at their default values, though these could be changed using any data available to the user (*e.g.,* known motor efficiency) (Figure 20).
4. Define the auxiliary system. This tutorial will use the default auxiliary system; no action is required for this step (Figure 20).

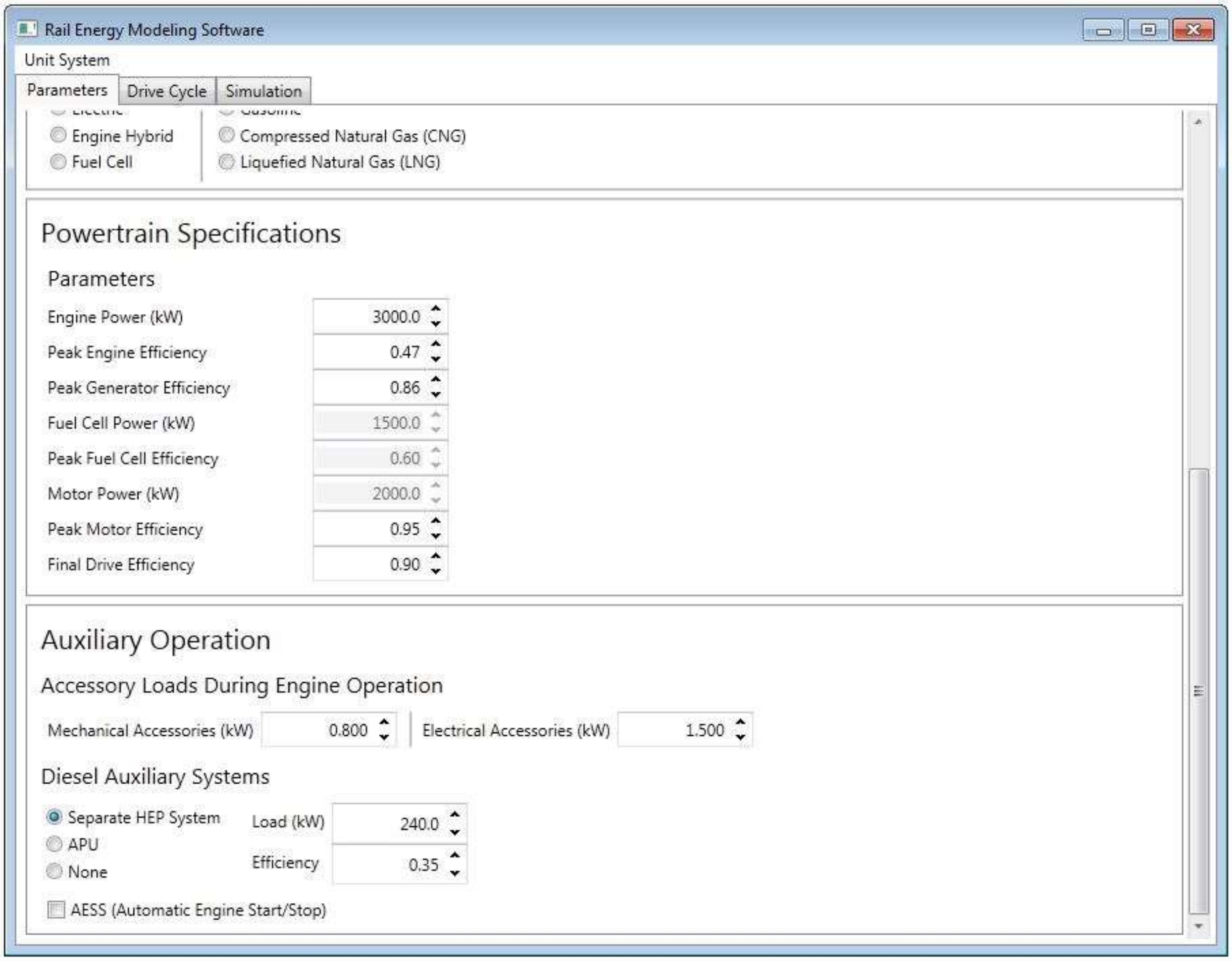


Figure 20. Defining powertrain specifications and auxiliary operation

5. Load a drive cycle. This tutorial will use a custom built drive cycle. To load the custom cycle, select the ***Browse…*** button and open the desired file (Figure 21).

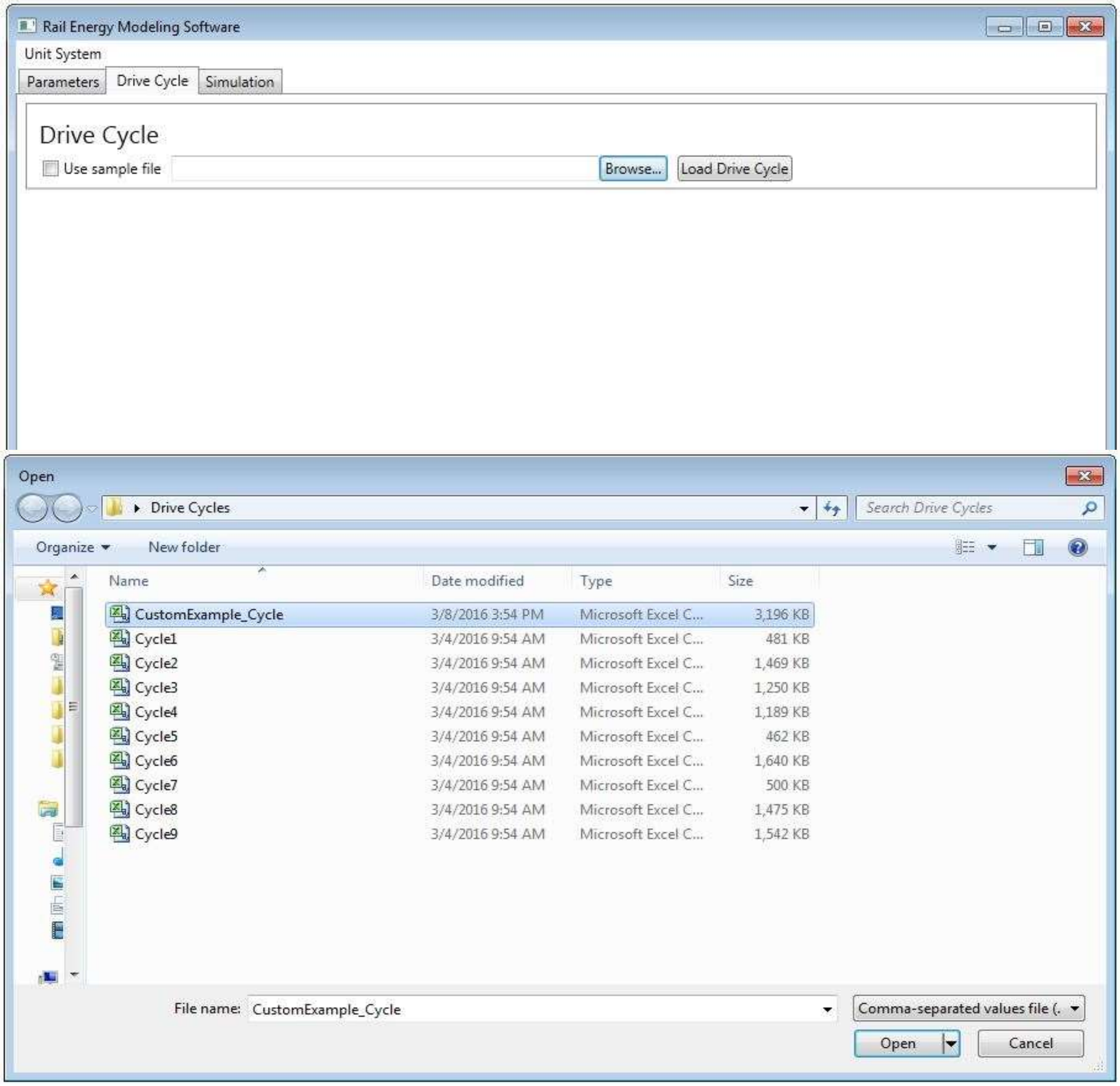


Figure 21. Browsing for a custom drive cycle

6. Once the file location appears in the text box, select the ***Load Drive Cycle*** button and the drive cycle will appear in the Cycle Data Window (Figure 22).

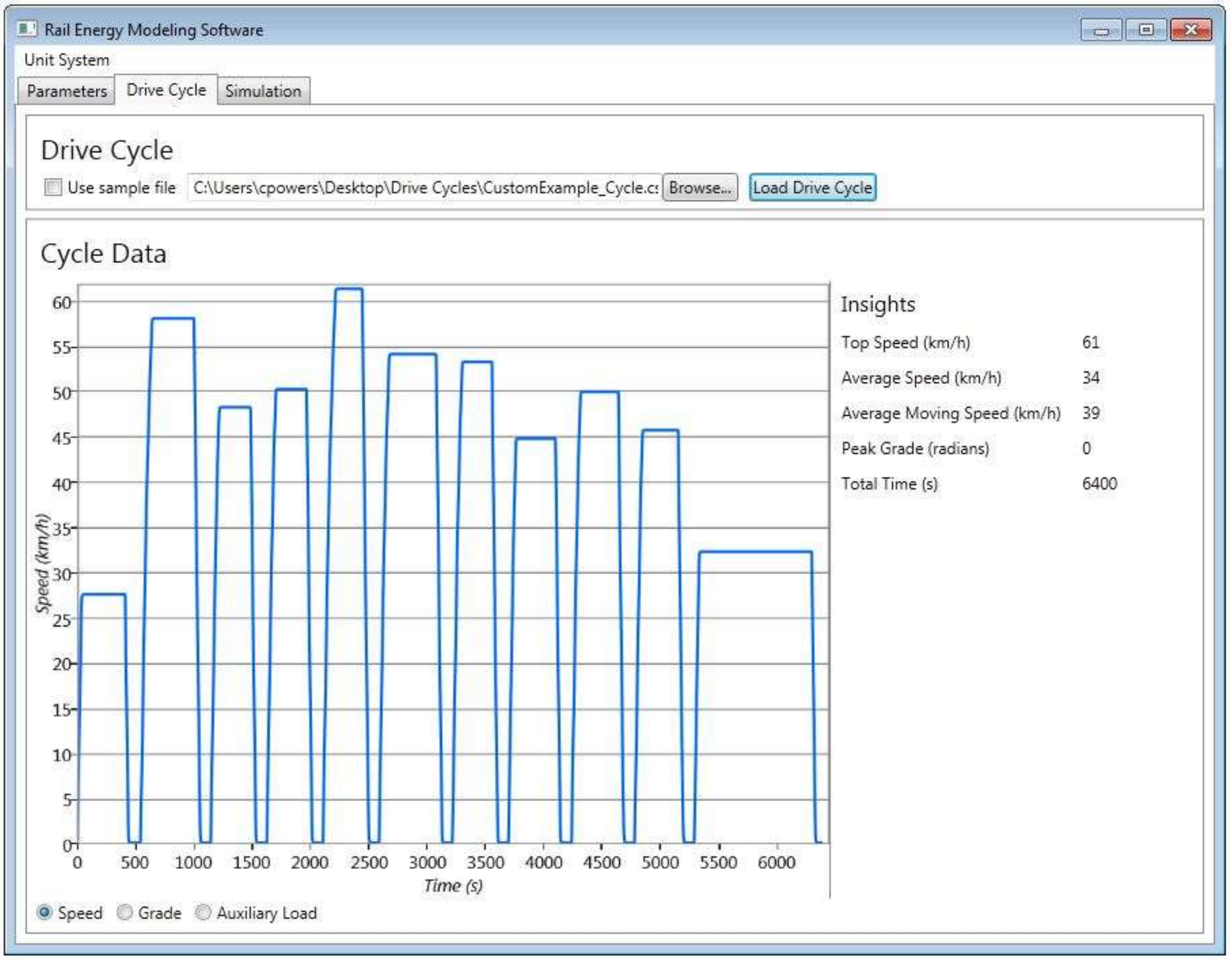


Figure 22. Loading a custom drive cycle

7. View the auxiliary load profile by selecting the ***Auxiliary Load*** radio button in order to validate that the auxiliary system is behaving as expected (Figure 23).

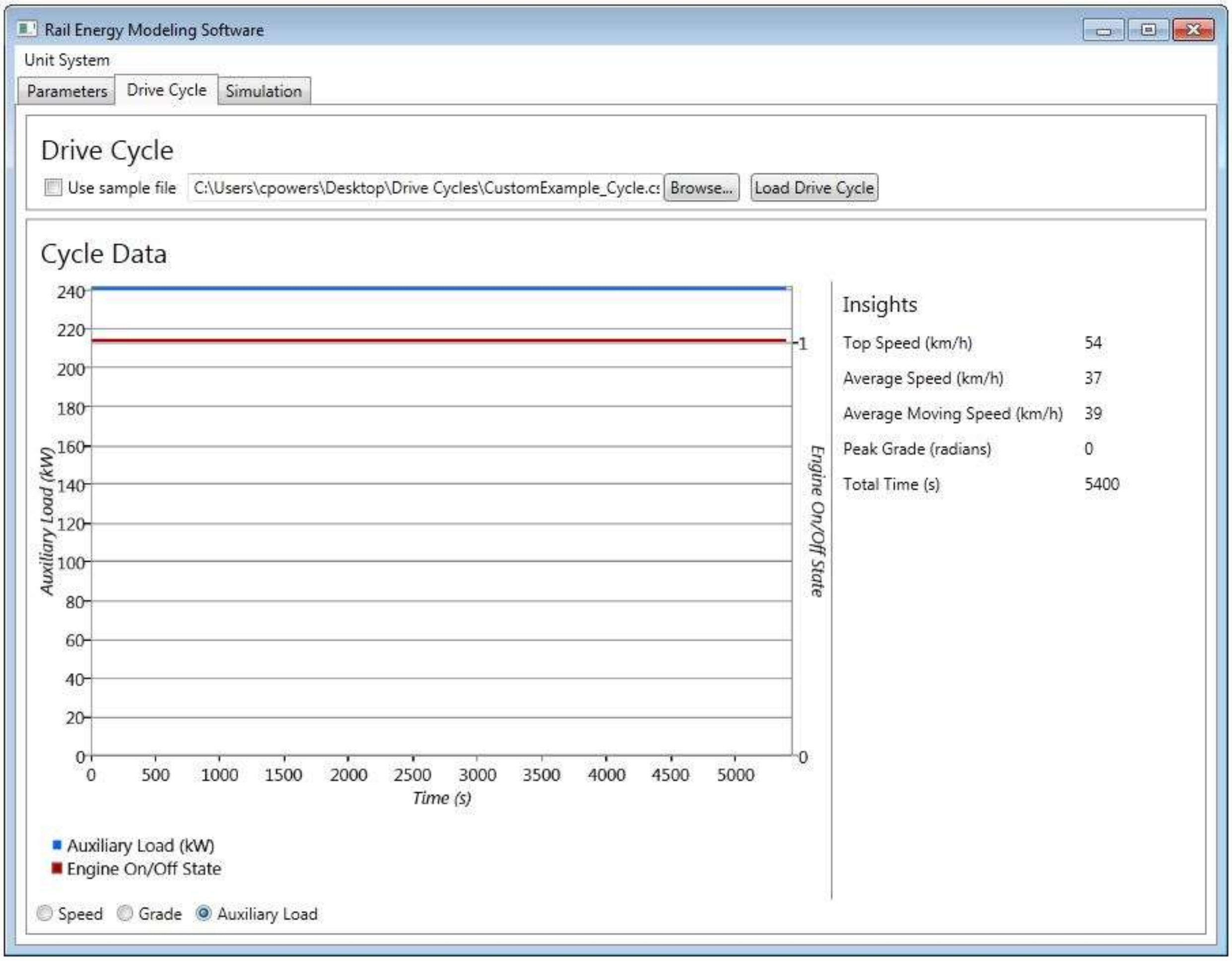


Figure 23. Viewing auxiliary operation profile

Since the tutorial uses an HEP and no AESS system, the engine and HEP are always on. Thus everything is working correctly.

8. Run the simulation by selecting the ***Simulate*** button in the Simulation Window (Figure 24).

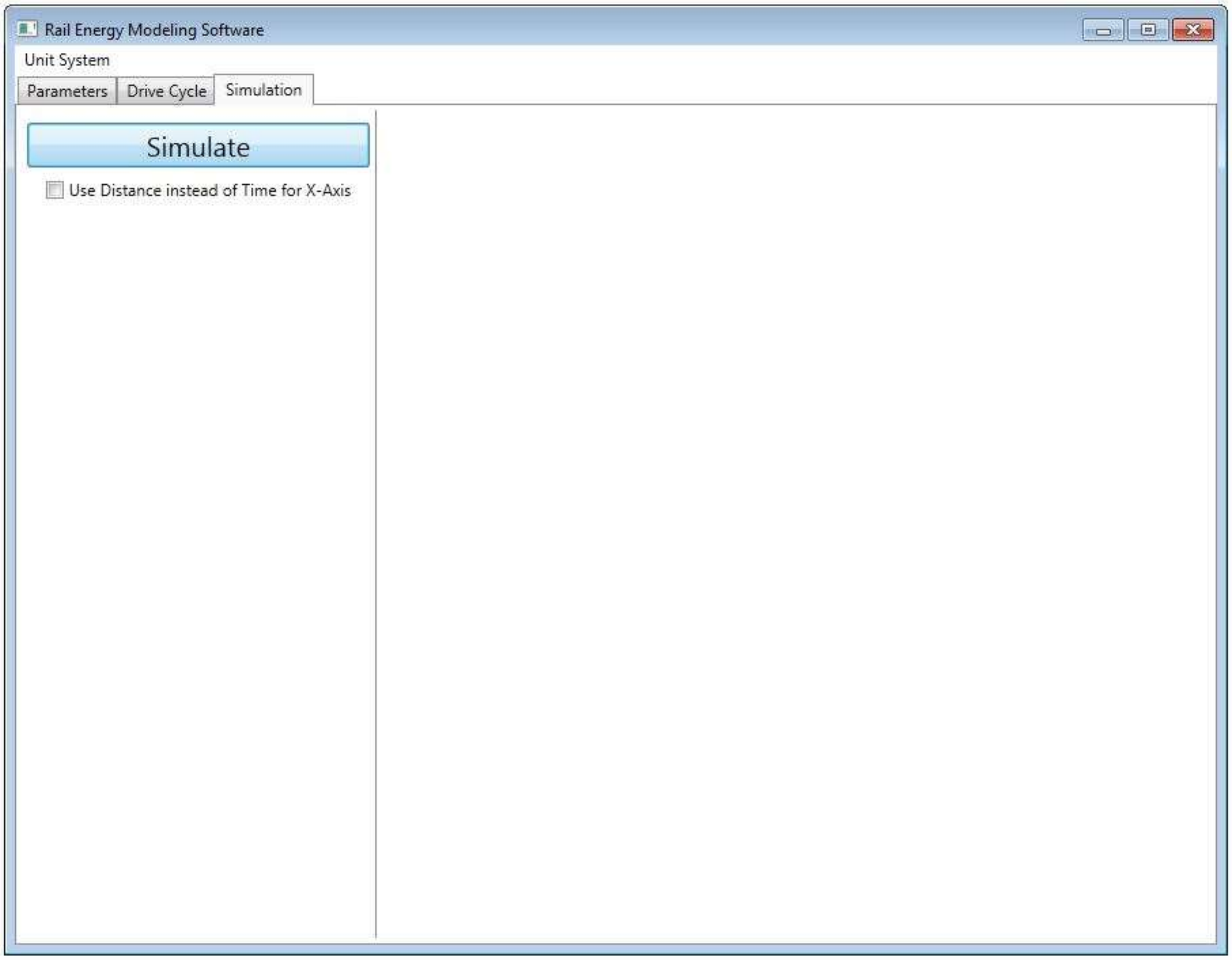
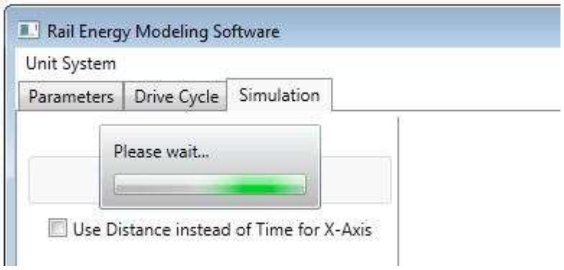


Figure 24. Running a simulation

A progress bar appears denoting that the simulation is running, and once the simulation finishes the progress bar displays which plots are being generated (Figure 25).

(a)



(b)

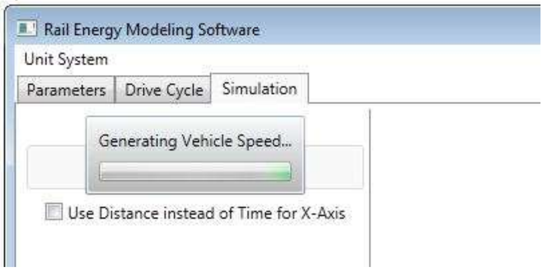


Figure 25. Progress bars for (a) an active simulation and (b) plot generation

When the simulation has finished the results are displayed (Figure 26).

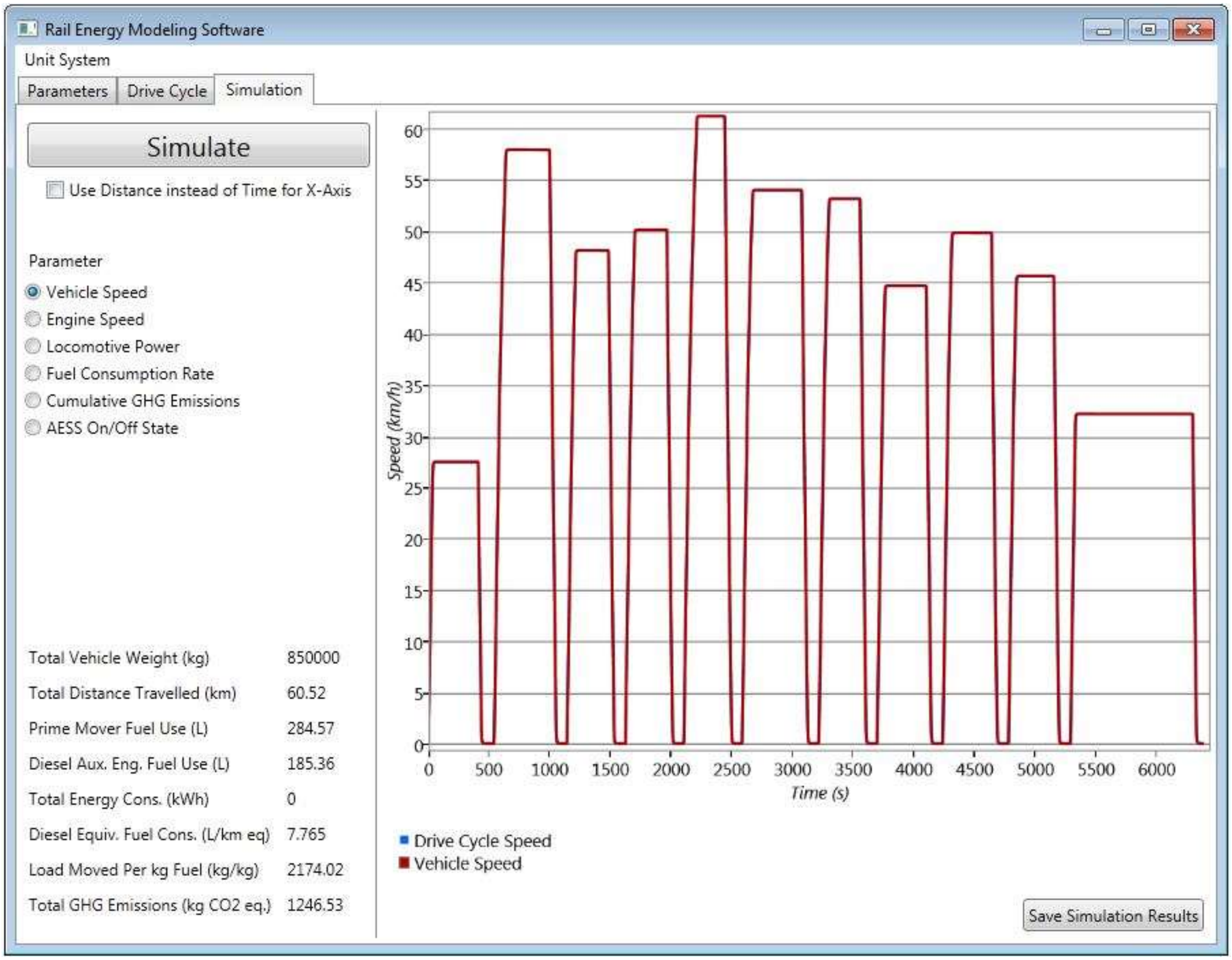


Figure 26. Viewing vehicle speed results of first simulation

The simulation summary containing the more important results is found in the bottom left corner of the window. Since this tutorial details rapid simulation for comparing fuel consumption between two topologies, the diesel equivalent fuel consumption is recorded as 7.765 L/km.

For a more detailed review of simulation results, the radio buttons to the left of the graph can be used to view different plots of the simulation results; such as ***Fuel Consumption Rate*** (Figure 27).

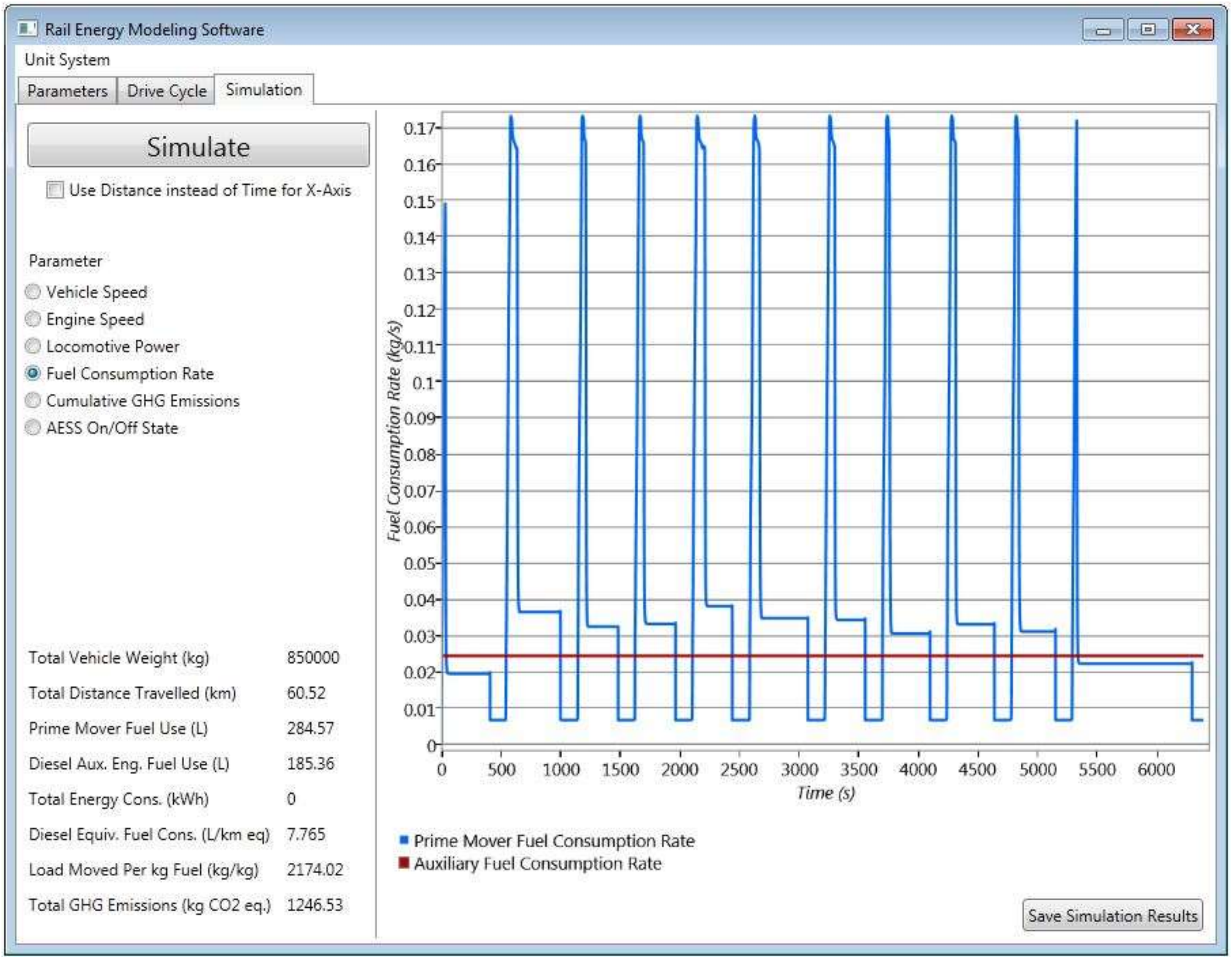


Figure 27. Viewing fuel consumption results of first simulation

9. Save the results by selecting the ***Save Simulation Results*** button, entering a file name, selecting the file type, and selecting the ***Save*** button (Figure 28). In this case the data is saved as a '.mat' file, but it could also have been saved as a '.csv'.

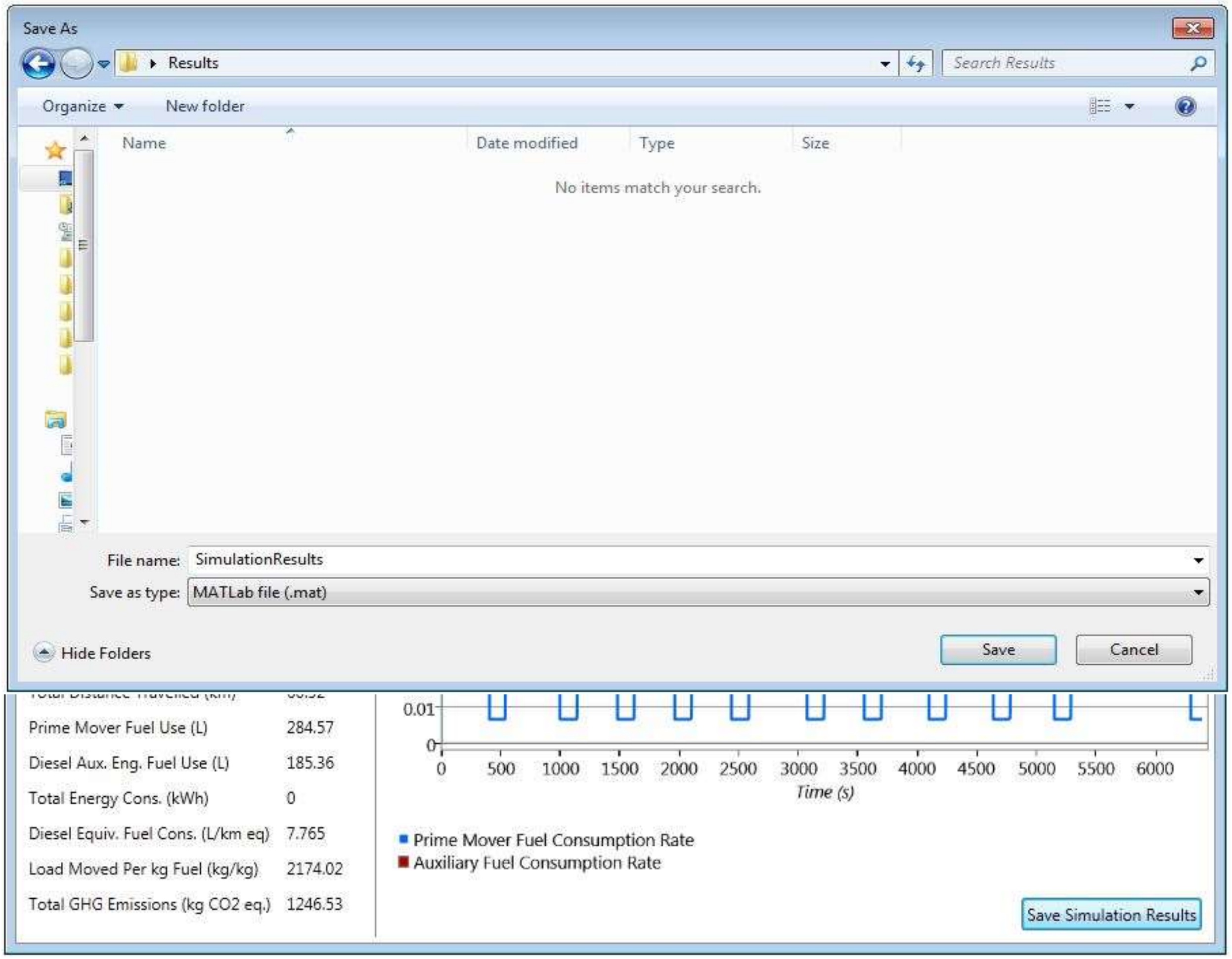


Figure 28. Saving results of first simulation

10. Set up the second simulation by navigating back to the Parameters Window to change the powertrain type from an ***Engine Electric*** to a ***Fuel Cell Ultracapacitor*** hybrid (Figure 29).

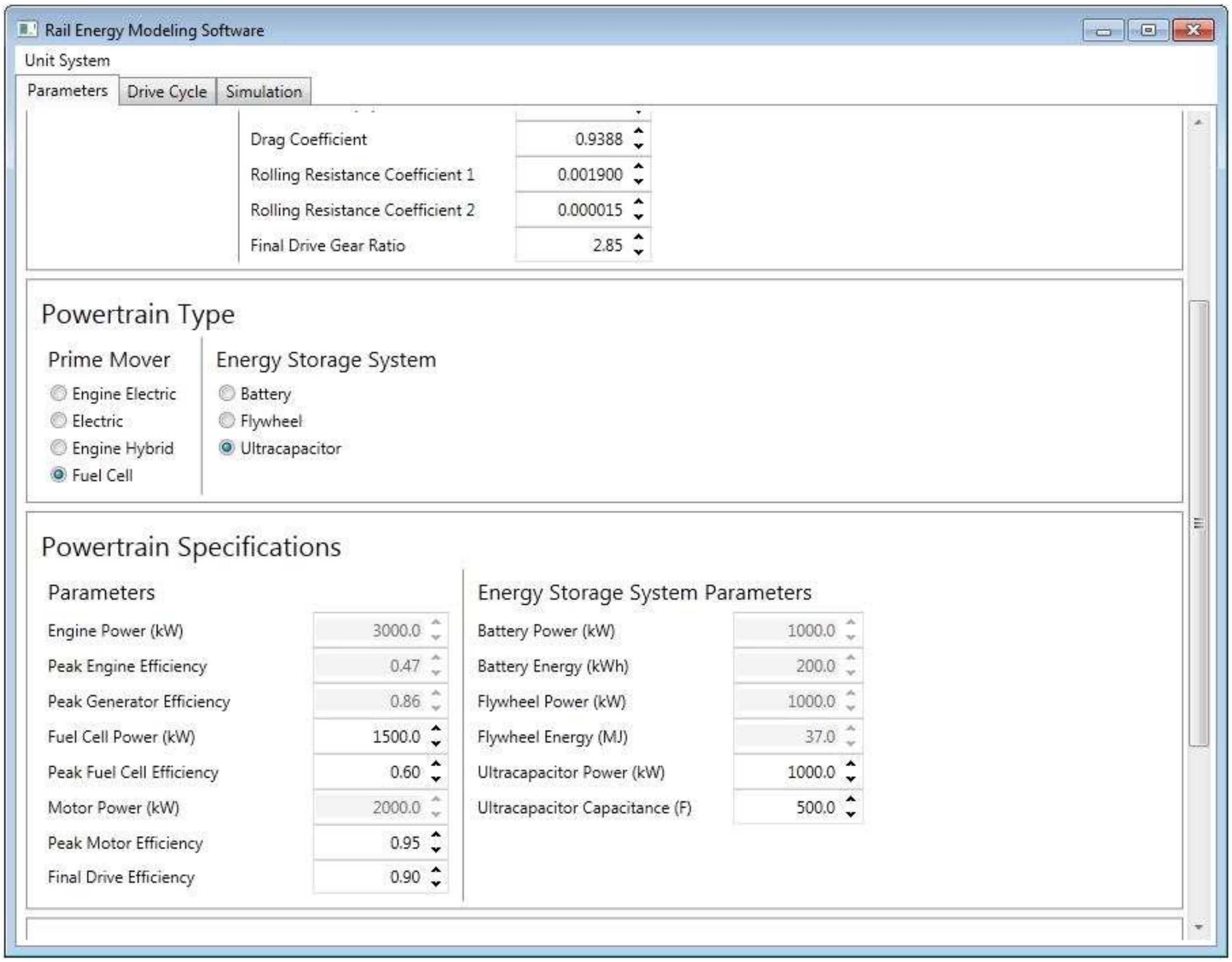


Figure 29. Defining second locomotive

11. Skip the ***Drive Cycle*** tab since the same drive cycle is being used and the drive cycle is already loaded. Remember, if the auxiliary systems were altered in the Parameters Window, then the drive cycle must be reloaded.
12. Navigate to the Simulation Window and run the new simulation by selecting the ***Simulate*** button again (Figure 30).

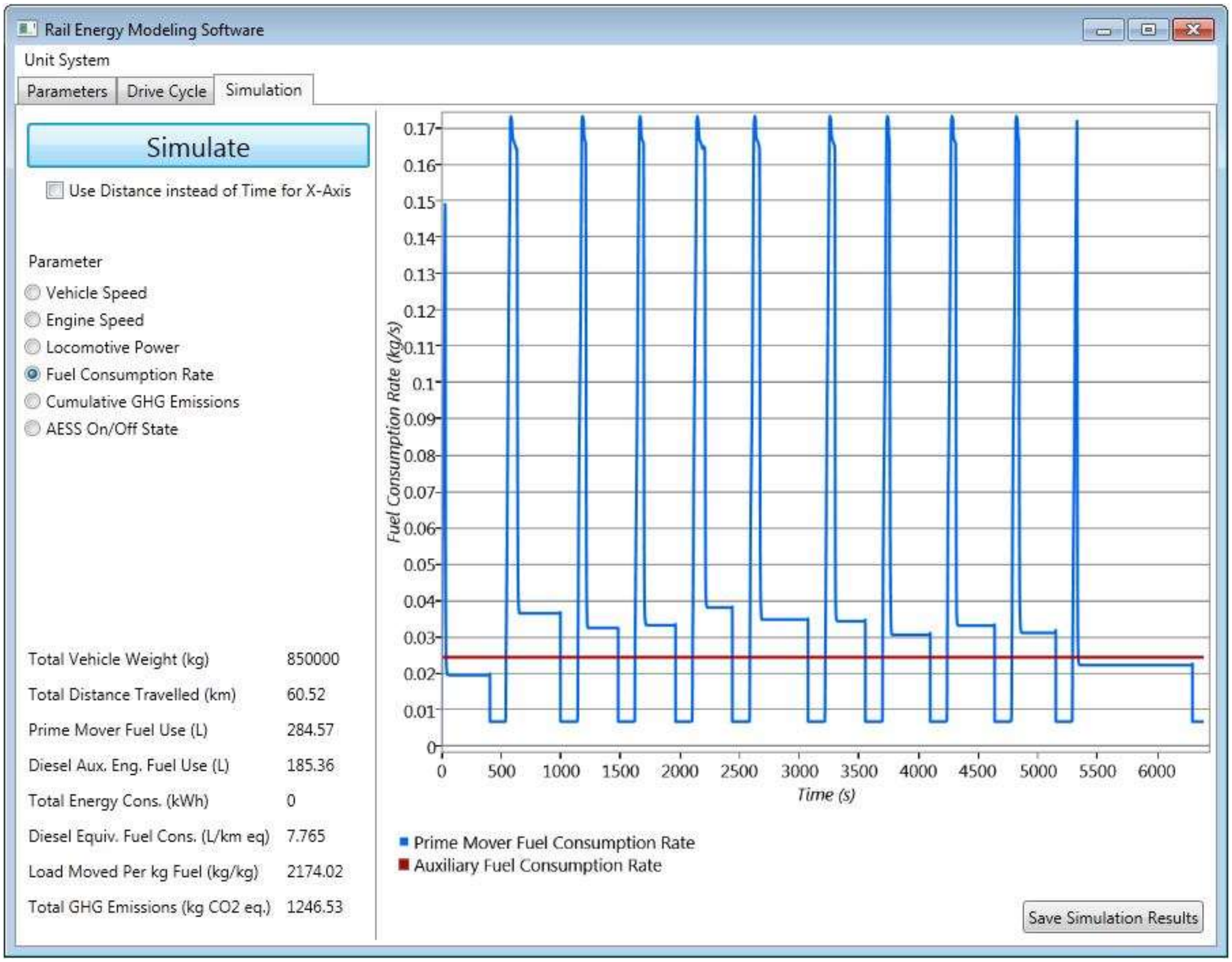


Figure 30. Simulating second locomotive

The simulation finishes and the new results are displayed (Figure 31).

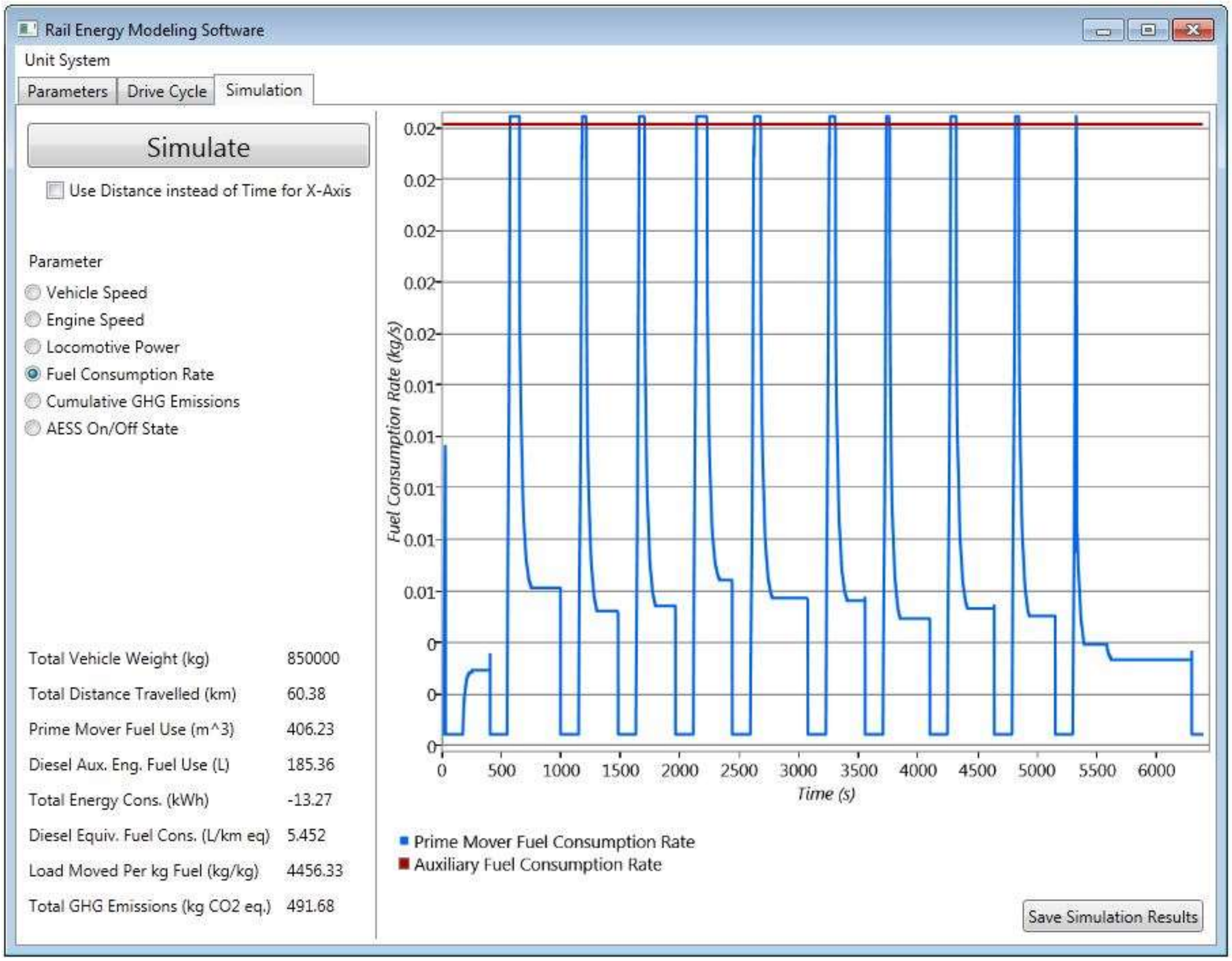


Figure 31. Viewing fuel consumption results of second simulation

The diesel equivalent fuel consumption for the fuel cell ultracapacitor hybrid powertrain is 5.452 L/km which is lower than the 7.765 L/km of the engine electric powertrain. This is because the fuel cell ultracapacitor powertrain has a higher overall efficiency compared to the engine electric powertrain.

13. To convert the results into US imperial units (Figure 32):
    a. Select ***US Imperial*** from the ***Unit System*** dropdown menu in the application's toolbar.
    b. The units of the summary results should change immediately, but the plots will not.
    c. Since the units were changed after the simulation, a warning message appears saying that the graphs need to be reloaded because of the unit change.
    d. Select the ***Reload*** button to regenerate the plots in the new unit system. Do not select the ***Simulate*** button since the simulation does not need to be re-run.

If the unit system is changed before a simulation is performed, there is no need to reload the plots.

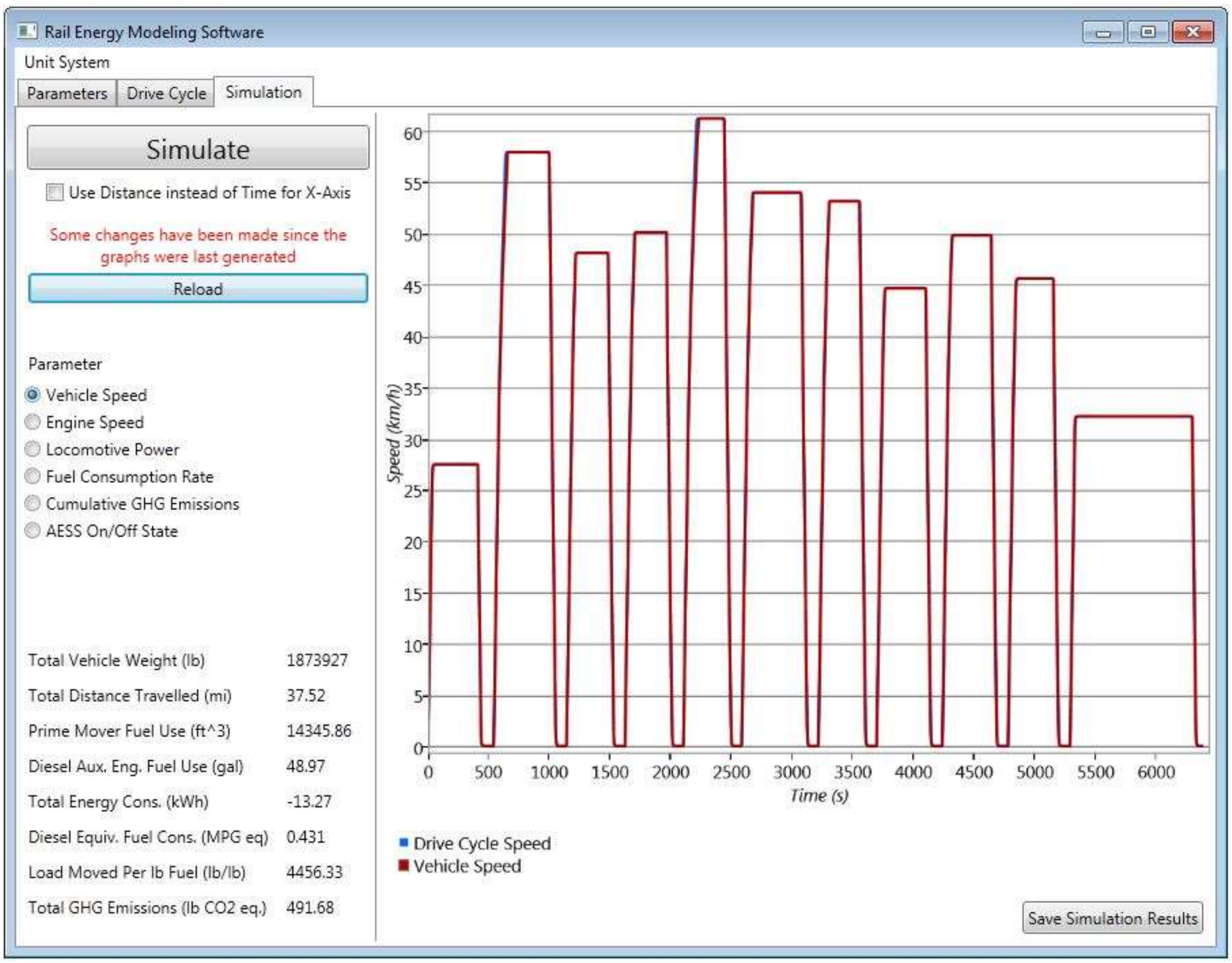


Figure 32. Changing unit system

After a few moments, the plots are updated to the new unit system (Figure 33).

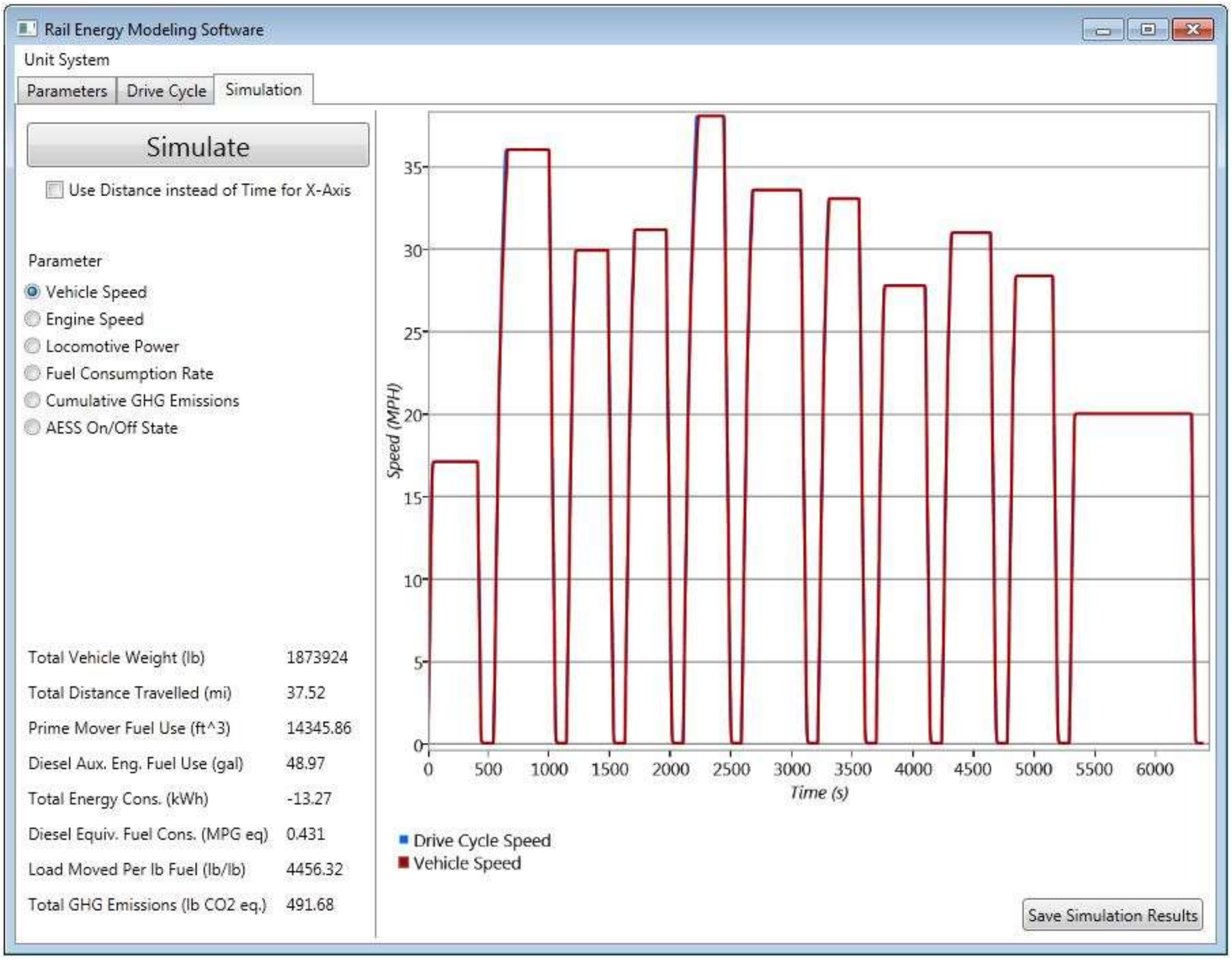


Figure 33. Viewing vehicle speed results in US imperial unit system

5.0 Model Validation

There was very little public data available to validate the accuracy of the models. The best source was found to be a thesis by Skoglund [1], which performed testing of an engine electric locomotive and recorded performance specifications, a speed trace, and the route that the testing was performed on. Section 5.1 describes the model validation performed using this data. This validation effort led to confidence in the engine electric model components as well as the many lower level components of the train such as the wheels and final drive. The other component models were created based on component datasheets, as discussed in Section 5.2.

5.1 Engine-Electric Validation

The engine electric powertrain topology was validated to the data found in Skoglund's thesis. The paper provides the specifications of a T-44 locomotive that was used for testing, the route the testing was carried out on, and the fuel consumption of the trip (Figure 34).

Figure 34. Route used for validation to real world data [1]

This information was gathered and the drive cycle was duplicated, thus allowing the modeling of that specific train. The train was simulated on the drive cycle from the paper and the two speed traces were plotted together (Figure 35).

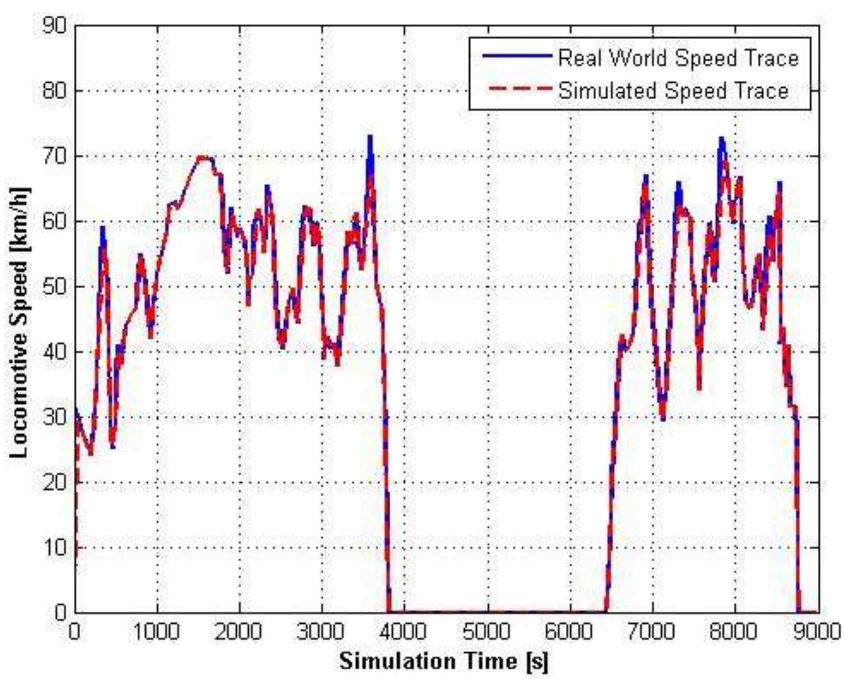


Figure 35. Simulation results of speed trace of validation cycle (Vansbro, Sweden - Borlänge, Sweden)

Results from the simulation were compared against the real world results (Table 5). The simulation achieved a fuel consumption rate of 2.718 L/km, which yielded a percent error of 0.43% from the real world 2.706 L/km; assuming a diesel density of 0.815 kg/L [1].

Table 5. Validation results for comparing real world source parameters to simulation parameters and outputs

Parameter	Validation Source [1]	Simulation
Diesel Engine Power (kW)	1235	1235
Maximum Locomotive Speed (km/h)	100	100
Total Loaded Weight (kg)	915000	915000
Wheel Radius (m)	0.5075	0.5075
Mean Engine Efficiency (%)	25-40	25
Mean Motor Efficiency (%)	90-93	90
Mean Generator Efficiency (%)	90-93	90
AESS Present (Y/N)	N	N
APU/HEP Present (Y/N)	N	N
Trip Length (km)	85	84.53
Fuel Consumed (L)	230	229.72
Fuel Consumption (L/km)	**2.706**	**2.718**
Fuel Consumption Percent Error (%)	**-**	**0.43**

The train parameters were tuned to match those provided in the paper. Since the train used for testing was manufactured between 1968 to1987, the low ends of all efficiencies were used as the mean efficiencies in the simulation. The train would have had an old, inefficient engine, and the high ends of the efficiency ranges represent modern, more efficient engines [1].

5.2 Component Modeling

The other components were modeled based on data from real-world components, as shown in the following table (Table 6).

Table 6. Validation of powertrain components

Model Component	Validation
Diesel Engine	Fuel consumption of Vansbro to Borlänge trip
Generator	Fuel consumption of Vansbro to Borlänge trip
Motor	Fuel consumption of Vansbro to Borlänge trip
Final Drive	Fuel consumption of Vansbro to Borlänge trip
Wheels	Fuel consumption of Vansbro to Borlänge trip
Train Body	Fuel consumption of Vansbro to Borlänge trip
CNG Engine	Cummins L10-300
LNG Engine	John Deere 8.1L
Battery	A123 M1/26650 cells scaled to a pack

Flywheel	120 kW Flywheel from Flywheel Energy Systems Inc.
Ultracapacitor	Maxwell P125 Ultracapacitor from Maxwell Technologies Inc.
Fuel Cell Stack	50 kW Direct Hydrogen PEM Fuel Cell Stack from Argonne National Lab

6.0 References

[1] M. Skoglund, "Evaluation of Test Cycles for Freight Locomotives," KTH Electrical Engineering, Stockholm, 2011.