User Guide for the 30NOV2017 Version

of the

PHEV-BEV Power Train Model

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June 2018

TABLE OF CONTENTS

Acronyms

BEV	Battery electric vehicle
PHEV	Plug-in hybrid electric vehicle
Hyzem	An unofficial European transient driving cycle
NEDC	New European driving cycle
UDDS	Urban dynamometer driving schedule (U.S. city driving)
HWFET	Highway fuel economy test (U.S. highway driving)
WLTP	Worldwide harmonized light vehicles test procedure
BSFC	Brake specific fuel consumption
RPM	Revolutions per minute
N/V	Engine rotational speed over vehicle speed (in RPM/mph)
SOC	State of charge
SCL	Stationary charging loss

Variables Names

M	Vehicle mass (in kg)
A_F	Frontal area of vehicle (in m^2)
c_D	Aerodynamic drag coefficient
f_R	Rolling resistance coefficient
g	Acceleration due to gravity (in m/s^2)
ρ	Density of air (in kg/m^3)
$F_T(t_i)$	Force demand at tire patch at time t_i (in N)
$v(t_i)$	Vehicle speed at time t_i (in m/s)
η_Y	Energy conversion efficiency of device Y
ED_T	Energy demand of a given driving cycle at tire patch (in MJ/km)
$T_X(t_i)$	Torque demand at point X in the drivetrain at time t_i (in Nm)
$\Omega_X(t_i)$	Rotational speed demand at point X in the drivetrain at time t_i (in rad/s)
ED_m	Electricity demand of the motor (in MJ/100km)
E_{regen}	Recovered electricity from regenerative braking (in MJ/100km)
ED_{plug}	Plug electricity consumed in charge depleting mode (in MJ/100km)
$ED_{charge\ sustaining}$	Gasoline demand in charge sustaining mode (in MJ/100km)

1 How to use the Model

1.1 Enter vehicle specifications and driving cycle

The model simulates moving a specified vehicle through a specified driving cycle. The calculations behind the simulations can be found in Section 2 of this User Guide (How the model calculates vehicle energy demand). The role of each Excel spreadsheet is explained in Section 3. Only the 'Input Data' spreadsheet is required to use the Power Train Model.

All cells shaded blue on the 'Input Data' spreadsheet are input parameters. Figure 1 shows a screenshot of the vehicle specification sections of the 'Input Data' spreadsheet.

Inputs				
Vehicle Parameters				
Test Mass	kg	1512		
Battery mass	kg			75
(Test mass)-(battery mass)	kg			1437
Range for battery sizing	km (UDDS)	65		
Rolling resistance coeff.	-	0.007		
Acceleration due to gravity	m/s^2	9.81		
Frontal area	m^2	2.03		
Drag coefficient	-	0.250		
Air density	kg/m^3	1.225		
Spin loss coefficient	N/m/s	0.000		
DriveTrain Parameters				
Tire rolling radius	m	0.285		
Final drive				
Final drive ratio	-	6.00		
Final drive efficiency	-	0.95		
Transmission				
Gear	-	1	2	
Gear ratio	-	1.00	1.00	
Gear efficiency	-	1.00	1.00	
Shift duration	sec	0.75		
N/V (calculated)	RPM/mph	89.87	89.87	
Motor				
Maximum speed	RPM	7000		
Torque Scaling Factor	$T_{RESIZED}/T_{BASE}$	0.26		

Figure 1: Screenshot of the vehicle specification sections of the 'Input Data' spreadsheet

The spreadsheet is pre-populated with input data, which need to be changed to the values the user would like to use for the simulations. Some values are more likely to change than others.

Unlikely to change are *acceleration due to gravity* and *air density*, which are standard physical values. The user may also choose to use the pre-populated parameter settings for the *final drive* and the *transmission*. Those settings should only be changed if the user has values that are known to be a better fit for the specified vehicle than the preselected ones. The same is true for the input data shown in the blue shaded cells on the 'Battery Model' spreadsheet, which specify some aspects of the battery pack and the hybrid power train.

The input parameters that are most likely to be changed by the user are listed and discussed below:

Test (vehicle) mass, *rolling resistance coefficient*, *frontal area*, *drag coefficient*, *spin loss coefficient*, and *tire rolling radius*. These six parameters are required to calculate the tractive force demand at the tire patch of the vehicle and convert it to axle torque demand.

The spin loss coefficient is determined empirically and quantifies the viscous forces generated in the drivetrain, which create a resistance force proportional to vehicle speed (rolling resistance is independent of vehicle speed; aerodynamic resistance is quadratic in vehicle speed). If no value for spin loss coefficient is known, it should be set to zero.

An important property of PHEVs and BEVs is their all-electric range, i.e. the total distance the vehicle can drive on a single electric battery charge. The input parameter is called *range for battery sizing*; its value is entered in kilometers. Using the energy demand of the specified vehicle in the UDDS driving cycle, the range is converted into battery size (in KWh) and battery mass (in kg).

Note that the test (vehicle) mass specified by the user includes the battery mass. Battery mass and vehicle mass without the battery are displayed on the 'Input Data' spreadsheet. The user needs to make sure that all mass values are realistic and consistent with each other.

The powertrain simulation is based on a motor map, which shows motor efficiency as a function of motor torque (in Nm) and speed (in RPM). The motor described by this map has a maximum torque of 650 Nm and a maximum power of 152 KW. If this is not the right motor size for the simulation, the user needs to resize it using the *torque scaling factor*, which scales the motor size up or down in a linear fashion. The resulting maximum engine torque and power is reported (in orange) under the Motor section on the 'Input Data' spreadsheet.

The user chooses the torque scaling factor which yields a desired vehicle specification, such as a desired 0-60 mph acceleration time or a desired maximum engine torque or power. This can be done using Excel's goal seek function which can be found under the Data Validation icon on Excel's Data tab. See Section 1.3 below for more info on how to use the goal seek function.

Finally, a driving cycle needs to be selected. This is done in the *select schedule* cell, which provides a drop down menu showing all currently available driving cycles.

1.2 Interpret results

Each time an input parameter value is changed or a different driving cycle is selected from the drop down menu, Excel instantly recalculates the simulation results.

All simulation results are displayed in orange, together with some info on the modeled vehicle. The most important results are, of course, the values for energy consumption/demand, which are all given in MJ per 100km. The model calculates results for two driving modes: In the 'Charge Depleting mode' only plug electricity is used for propulsion. In the 'Charge Sustaining mode' only gasoline is used for propulsion by employing an engine as electric generator. If the modeled vehicle is a BEV, only the charge depleting mode is relevant.

Four simulation results are calculated and shown for the charge depleting mode:

1. Electricity demand of the motor ED_m (called *Mech. energy consumption*)
2. Recovered electricity from regenerative braking E_{regen} (called '*Mech. energy regen*)
3. Net electricity demand of the motor $ED_m - E_{regen}$ (called *Net mechanical energy consumption*).
4. *Plug electricity consumed*, E_{plug}, which includes battery charging and discharging losses

The charge sustaining mode has just one simulation result, called *IC engine energy consumed*.

Other results are: *Acceleration time 0-60 mph calculated* and *calculated range on selected schedule*. The *Motor* section lists three additional specifications, which are designed to help the user select a suitable motor size: *Gradability in high gear at 60 mph, maximum motor torque,* and *maximum motor power*.

1.3 Conduct sensitivity and scenario analysis

Sensitivity and scenario analysis can be conducted simply by changing input parameter values and comparing old and new results.

Probably of highest interest to many users is the sensitivity of the vehicle energy demand with regard to vehicle mass. This sensitivity is simply calculated as the difference between old and new energy demand divided by the change in vehicle mass. It is expressed in MJ per 100km and 100kg mass reduction.

Vehicle mass reduction will not only reduce the fuel economy, but also the 0-60 mph acceleration time. One scenario of high interest is thus vehicle mass reduction plus resizing of the motor in order to keep the 0-60 mph acceleration time constant. This is done using Excel's Goal Seek function which can be found under the What-if Analysis icon on the DATA tab (Figure 2).

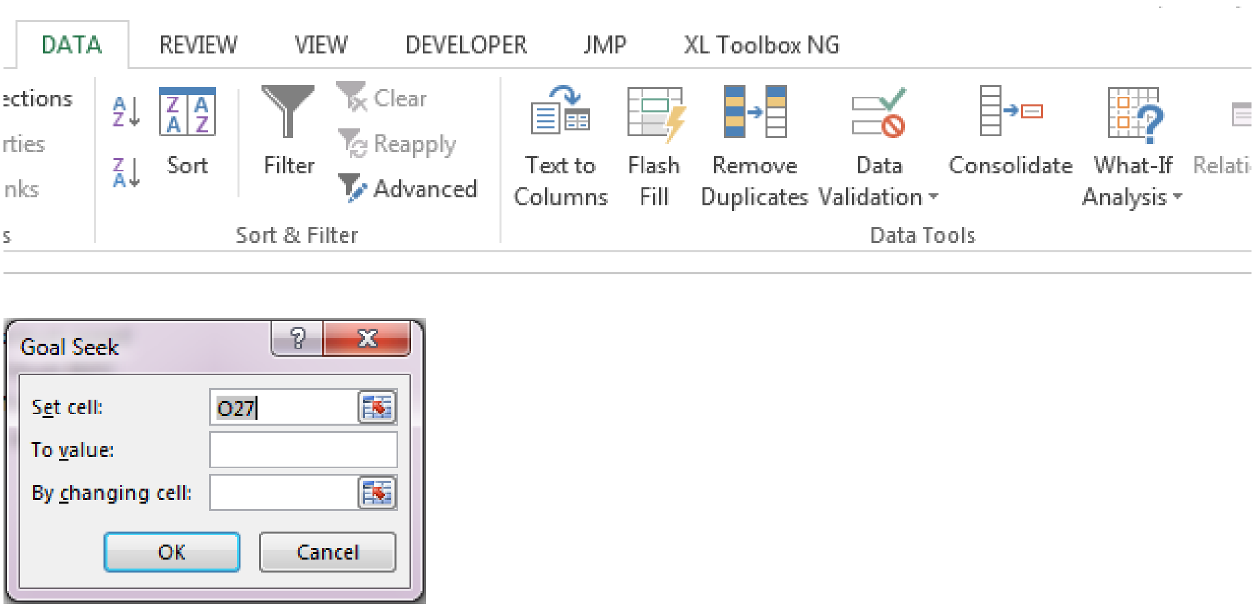

Figure 2: The Goal Seek function can be found under the What-if Analysis icon (DATA tab).

To resize the engine to keep 0-60 mph acceleration time constant, the user has to highlight the *acceleration time 0-60 mph calculated* cell (cell L2), open Goal Seek, enter the desired 0-60 mph acceleration time in the cell next to 'To value:', point the cell next to 'By changing cell:' to the *torque scaling factor*, and click the OK button. Goal Seek will find the torque scaling factor which yields the desired 0-60 mph acceleration time.

2 How the model calculates vehicle energy demand

Vehicle energy demand is given in Megajoules (MJ) of electricity or gasoline per 100km and calculated by moving a vehicle through a so-called driving cycle, which specifies vehicle velocity $v(t)$ (in meters per second) as a function of time t, typically given in time increments of one second t_i. The approach to powertrain modeling used here is to calculate the net tractive force demand F_T at the vehicle's tire patch for each time increment t_i and then determine the operating point of the power train that provides the required force under realistic operating conditions. The operating point of the powertrain, in turn, determines the efficiency of the motor and the battery. For a given driving cycle, the energy demand of the vehicle is obtained simply by summing up the energy demands of each time increment t_i and normalizing the result to 100 km.

Two objectives drive the selection of the modeling methods and choices. The first is to rely entirely on driving and powertrain physics and not use any engineering rules of thumb or approximations. The second is to obtain accurate results with a minimal number of vehicle and powertrain parameters. The latter objective aims at finding the sweet spot between model accuracy and modeling effort and complexity, a modeling approach sometimes called parsimonious.

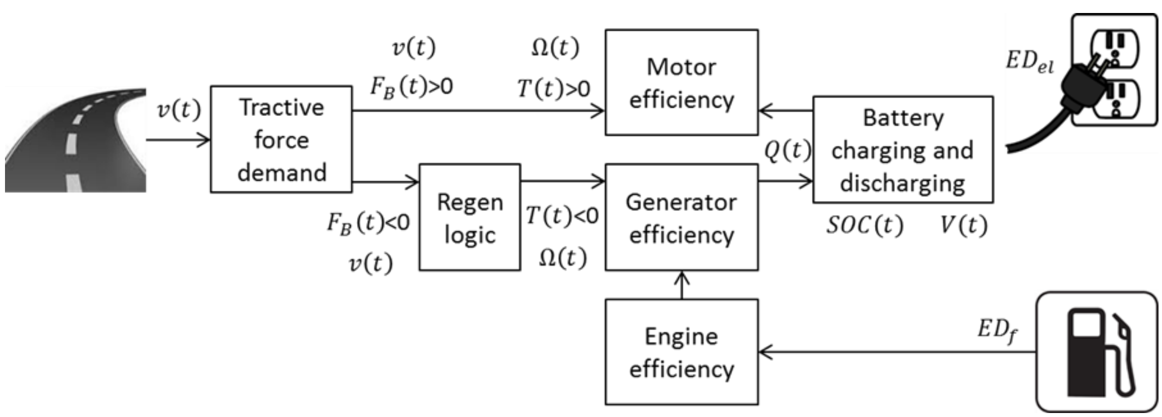

Figure 3: Overview of the PHEV-BEV powertrain model

2.1 Force demand at tire patch

The first step is to calculate the net tractive force that is required at the tire patch during each time step in order to move the vehicle through the drive cycle. In addition to the driving cycle $v(t)$, the minimal set of input parameters required to calculate tractive force demand are mass M, frontal area A_F, and aerodynamic drag coefficient c_D of the vehicle, as well as the rolling resistance coefficient of the tires f_R. The force demand at time t_i due to rolling resistance is calculated as $F_R(t_i) = Ma = Mgf_R$, with $g = 9.81 \frac{m}{s^2}$ being the acceleration due to gravity. The force demand at time t_i due to aerodynamic resistance is calculated as $F_D(t_i) = \frac{1}{2}\rho c_D A_F v(t_i)^2$, with $\rho = 1.225 \frac{kg}{m^3}$ being the density of air. The force demand at time t_i due to acceleration/deceleration is calculated as $F_A(t_i) = Ma = M \cdot \left(\frac{v(t_i)-v(t_{i-1})}{t_i-t_{i-1}}\right)$. Net force demand at the tire patch is calculated as $F_T(t_i) = F_R(t_i) + F_D(t_i) + F_A(t_i)$ and can be positive or negative, since the negative force of deceleration can be larger than the sum of the always positive rolling resistance and aerodynamic drag forces. A negative value of F_T indicates frictional or regenerative braking.

The powertrain model accounts for an additional tractive force demand, which is the spin loss of the drive train. Spin loss is a resistance force proportional to vehicle speed. An empirical way to measure the forces resisting forward motion is to estimate the coefficients in equation $M\frac{dv}{dt} = A + Bv + Cv^2$ through coast down tests. A is identical with the rolling resistance force $A = F_R = Mgf_R$. C is due to aerodynamic drag and thus calculated as $C = \frac{1}{2}\rho c_D A_F$. Spin loss coefficient B is related to the viscous forces generated in the drivetrain and determined empirically.

The resulting net force required during time increment t_i in order to move a vehicle through driving cycle $v(t_i)$ is now calculated as $F_T(t_i) = Mgf_R + Bv(t_i) + \frac{1}{2}\rho c_D A_F v(t_i)^2 + M\frac{v(t_i)-v(t_{i-1})}{t_i-t_{i-1}}$. The final part in this first modeling step is to convert translational speed $v(t_i)$ (in meter per second) and force demand $F_T(t_i)$ (in Newton) into rotational tire speed $\Omega_T(t_i)$ (in rad per second) and axle torque demand $T_T(t_i)$ (in Newton meter) according to the equations $T_T = r \cdot F_T$ and $\Omega_T = v/r$, with r being the rolling radius of the tire.

An interesting and useful intermediate result is the total energy demand at the tire patch, which is calculated as $ED_T = \sum_i F_T(t_i) \cdot v(t_i)$ and given in MJ per km.

2.2 Torque at motor or generator shaft

The next step is to model the drive train components between the tires and the motor or generator. For PHEVs and BEVs this only consists of a differential and, possibly, a transmission. The model calculations follow the power train backwards, or from left to right in Figure 1. The differential and transmission gears are defined by their gear ratios and their torque/energy conversion efficiencies, which are used to convert the required torque and rotational speed output (in Nm and rad/s) into the corresponding torque and rotational speed input. Required torque input into the differential is thus calculated as $T_{D-in} = T_T/(\eta_D \cdot R_D)$, with η_D being the energy/torque conversion efficiency, R_D being the gear ratio of the differential, and $T_{D-out} = T_T$. Speed input into the differential is calculated as $\Omega_{D-in} = R_D \cdot \Omega_{D-out} = R_D \cdot \Omega_T$.

The function of a transmission is to change torque and speed requirements of the wheel to values that are feasible and efficient for the power train. Electric motors have a wide range of efficient torque and speed values, so gears are not strictly necessary. The capability of the powertrain model to simulate a transmission is therefore currently not activated, which simplifies the simulation. For each time step t_i the resulting brake torque is simply $T_B(t_i) = T_{D-in}(t_i)$ and the resulting motor or generator speed is $\Omega_B(t_i) = \Omega_{D-in}(t_i)$.

2.3 Motor electricity demand

If $T_B(t_i) > 0$, the next step of the powertrain model is to convert the torque demand at the motor shaft into electricity demand. Motor efficiency is a complex function of motor torque and speed, $\eta_{motor}(T_B, \Omega_B)$. The relationship has been determined empirically, through motor tests, and the resulting data is stored and visualized in so-called motor maps. The energy conversion efficiency of the motor used in this powertrain model ranges from 62% to 97%.

For each time step t_i the powertrain model looks up the motor efficiency that matches the required brake torque and engine speed. Most of the motor map is stored as a data table with 50 Nm torque and 250 rpm speed intervals. To increase model precision, linear interpolation is used to calculate the efficiency of each motor operating point.

Once the conversion efficiency of the motor at time t_i is known, motor electricity demand at time t_i is calculated as $ED_m(t_i) = \Omega_B(t_i) \cdot T_B(t_i)/\eta_{motor}(t_i)$. The electric energy demand for the specified vehicle and driving cycle (in) is calculated as $ED_m = \sum_i ED_M(t_i)/(0.01 \cdot LDC)$ and given in MJ/100km. LDC is the length of the driving cycle in km and calculated as $LDC = \sum_i v(t_i)/1{,}000$. Motor energy demand ED_m excludes regenerative braking and battery charging/discharging losses.

2.4 Regenerative braking

If $T_B(t_i) < 0$, the next step of the powertrain model is to simulate deceleration. Vehicle braking is, in general, shared by friction braking and regenerative braking. In this simplified model, the split between the two types of braking is determined by the following two conditions.

Condition 1: The braking torque provided by the generator must be less than or equal the generator's capacity, $T_{Max-Gen}$. An example is shown in Figure 4.

Condition 2: For low speeds, braking is done solely by friction braking, for high speeds entirely by regenerative braking. The transition zone between the two regimes is implemented with a function that uses a so-called speed factor, $SF = T_{Reg-B}/T_B$ (see Figure 5).

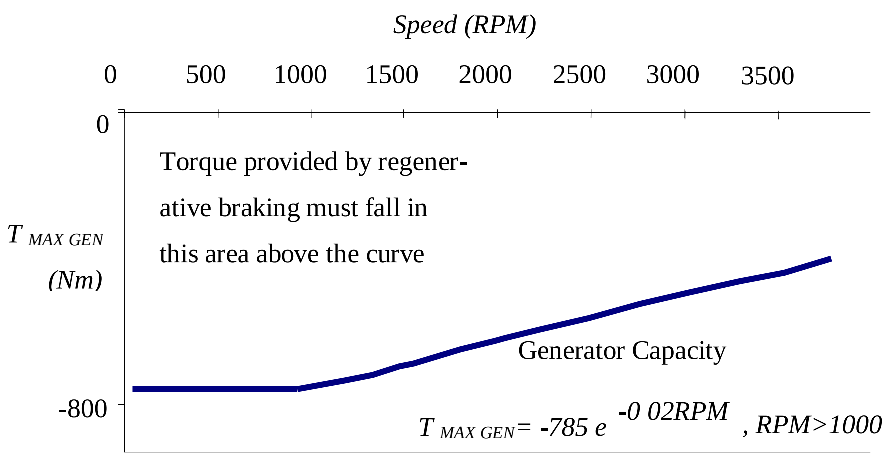

Figure 4: Condition 1 for regenerative braking

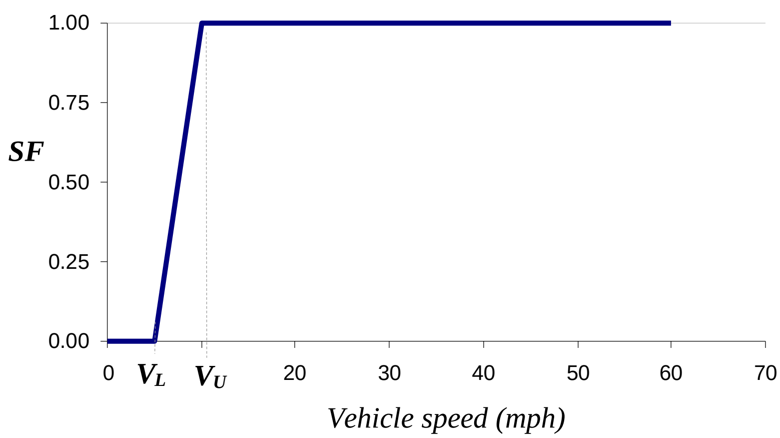

Figure 5: Condition 2 for regenerative braking

For a given brake torque demand T_B, the regenerative braking torque, T_{Reg-B}, is calculated as $T_{Reg-B} = Min[-SF \cdot T_B, -SF \cdot T_{Max-Gen}]$.

The product of T_{Reg-B} and generator rotation speed is the mechanical power at the generator input shaft. Multiplying this mechanical power by the generator efficiency yields the electric power available for battery charging. Generator efficiency is a complex function of generator torque and speed, $\eta_{gen}(T_B, \Omega_B)$. The relationship has been determined empirically and the resulting data is stored and visualized in a generator map. The energy conversion efficiency of the generator used in this powertrain model ranges from 25% to 95%.

Once the conversion efficiency of the generator at time t_i is known, generator electricity generation at time t_i is calculated as $E_{regen}(t_i) = \Omega_B(t_i) \cdot T_{Reg-B}(t_i) \cdot \eta_{motor}(t_i)$. For the specified vehicle and driving cycle, the total amount of electricity generated due to regenerative braking is calculated as $E_{regen} = \sum_i E_{regen}(t_i)/(0.01 \cdot LDC)$ and given in MJ/100km. LDC is the length of the driving cycle in km and calculated as $LDC = \sum_i v(t_i)/1{,}000$. Recovered electric energy E_{regen} excludes battery charging/discharging losses.

2.5 Battery discharging and charging

Battery charging or discharging is the conversion of electrical energy into chemical energy and back into electricity. Both conversions are not 100% efficient, and the PHEV powertrain model thus needs to quantify the charging and discharging losses.

Like all other powertrain processes, charging and discharging is simulated in one second increments. Energy losses during discharging are modeled through a drop in terminal voltage. Energy losses during charging are modeled through over-potentials at the battery terminal. Voltage drops and over-potentials are assumed to depend only on state of charge (SOC) and power in- or output. Voltage drops are taken from discharge curves of existing lithium-ion cells. Over-potentials are assumed to be symmetrical to voltage drops under equal power and SOC. The cell used in the default model is the ANR26650 M1-B from A123.

The calculation process is as follows:

1. Power demand from or supply to the battery during second *i* is $P_i = ED_M(t_i) + E_{regen}(t_i)$.

2. Use electric power demand/supply P_i during second i and SOC_i at beginning of second i to look up voltage drop/over potential during second i: $\Delta V_i = f(P_i, SOC_i)$
3. Calculate the terminal voltage as $V_i = V_{nominal} - sign(P_i) \cdot \Delta V_i(P_i, SOC_i)$.
4. Calculate resulting current during second i as power / voltage: $A_i = P_i / V_i$
5. Calculate charge (in Ah) removed from or added to battery during second i as current (in A) divided by 3,600: $\Delta Q_i = \frac{A_i}{3600sec}$.
6. Calculate new battery charge (in Ah) at begin of second $i + 1$ as $Q_{i+1} = Q_i - \Delta Q_i$.
7. Calculate state of charge at beginning of second i+1: $SOC_{i+1} = \frac{Q_{i+1}}{Q_0}$
8. If $SOC_{i+1} < DOD$ then set SOC_{i+1} back to initial state of charge SOC_0. This simulates a full stationary recharge of the battery from an electrical outlet.
9. Repeat for every second of the driving cycle.
10. At the end of the driving cycle, bring SOC from SOC_{end} back to SOC_0 through one final stationary recharging of the battery.

The net amount of charge removed from the battery during the driving cycle is $\Delta Q_{total} = \sum_{i=1}^{end} \Delta Q_i$. The total amount of energy lost during all stationary charging, *SCL*, is calculated as

$$SCL = n \cdot \frac{\Delta V(P_{min}, SOC_0) + \Delta V(P_{min}, 1 - DOD)}{2} \cdot \frac{(SOC_0 - 1 + DOD)\Delta Q_{batt}}{1{,}000} + \frac{\Delta V(P_{min}, SOC_0) + \Delta V(P_{min}, SOC_{end})}{2} \cdot \frac{\Delta Q_{total}}{1{,}000}$$

n denotes the number of times the battery has to be fully recharged to complete the driving cycle. The total amount of electricity withdrawn from the plug is calculated as $E_{plug} = \left(\frac{V_{nominal} \cdot \Delta Q_{total}}{1{,}000} + SCL\right) / (0.01 \cdot LDC)$. LDC is the length of the driving cycle in km and calculated as $LDC = \sum_i v(t_i) / 1{,}000$. E_{plug} is the total energy demand, including battery discharging and charging losses, in charge depleting mode.

Driving in charge sustaining mode assumes that the on-board engine and generator are used to provide all charge removed from the battery ΔQ_{total}, which means that no plug electricity is used and $SOC_{end} = SOC_0$. The total gasoline energy demand in charge sustaining mode is calculated as

$$ED_{charge\ sustaining} = \frac{V_{nominal} \cdot \Delta Q_{total}}{1{,}000 \cdot \eta_{generator} \cdot \eta_{gears} \cdot \eta_{engine} \cdot 0.01 \cdot LDC}$$

η denote the efficiencies of generator, gear train, and engine (operated at maximum efficiency).

2.6 Vehicle performance and motor resizing

Comparative environmental assessments of vehicles need to make sure that functionally equivalent cars are compared. One pertinent example is that, all other things being equal, the performance of a vehicle will increase when its mass is reduced. A common approach to reestablishing functional equivalence is to downsize the motor of the mass-reduced vehicle, so that it has the same 0-60 miles per hour (mph) acceleration as the baseline car.

To implement such engine resizing, the power train model calculates the 0-60 mph acceleration time for the vehicle specified by the model user. It does so by calculating the time intervals it takes to accelerate the vehicle by 1 mph increments. For each speed increment, $x\ mph\ \rightarrow x+1\ mph$, the model selects the gear that provides the maximum torque, converts this engine torque into force at the tire patch, and uses the net force demand equation to calculate the time it takes to increase vehicle speed by one mile. The time it takes to accelerate from 0 mph to 60 mph is simply the sum of the 60 time increments. The model also accounts for tire slip beyond a set maximum force, and the time it takes to shift gear.

The resizing of the motor is modeled using a torque scaling factor, $T_{resized}/T_{base}$. Motor resizing is modeled by taking the motor map and scaling the torque axis be a constant factor, while leaving everything else the same.

The process of engine resizing after vehicle mass reduction to achieve equal performance is as follows: Enter all input data for the baseline vehicle and note the calculated 0-60 mph acceleration time. Reduce vehicle mass input data; the calculated 0-60 mph time will decrease as a result. Use the Excel goal seek function to set the 0-60 mph time back to the baseline value by changing the torque scaling factor, i.e. simulating a downsizing of the engine (see Figure 2). The result is a mass-reduced vehicle with the same 0-60 mph acceleration as the baseline vehicle.

3 Description of the additional spreadsheets

3.1 Selected Schedule

This spreadsheet contains all driving cycles which are available for simulation. All driving cycles are given as second by second velocity profiles $v(t)$. The velocity data are available in the original units, e.g. mph and km/h, and also in meters per second. The spreadsheet picks the pertinent vehicle specifications and the driving cycle that have been selected by the user and displays the velocity data in column B of the spreadsheet. It then calculates the net force demand at the tire patch for each second and shows the data in column D of the spreadsheet. Integrating over the velocity profile yields the total distance covered by the selected driving cycle (shown in cell C7). Integrating over the net force demand yields the total energy required at the tire patch in order to move the specified vehicle through the selected driving cycle. The ratio of those two values yields the energy demand at the tire patch in MJ per km (shown in cell E7).

3.2 Fuel Cons Calc-Max eff

This spreadsheet converts vehicle speed and net force demand at the tire patch into motor speed and torque and then looks up the corresponding efficiency from the motor map. It does this for each second of the driving cycle, so each row after row 28 contains identical calculations, just for a different time increment of the driving cycle. The calculations are described in Sections 2.2 and 2.3 of this user guide. In summary, the calculations follow the drivetrain backwards from the tire patch to the engine (see Figure 3 on page 5), going through differential and transmission. The differential is characterized by its drive ratio and energy loss. Each gear is characterized by its gear ratio and energy loss.

On important modeling decision is to determine which gear the vehicle is in during each second of the driving cycle, taking into account that some gears may require engine speed and torque combinations that the specified engine cannot deliver. Many different gear shifting logics could be implemented. The current default setting assumes that the vehicle has no gears, which simplifies the simulation.

For each second of the driving cycle the selected gear is shown in column T; the resulting required engine speed in column U, and the required engine torque in column V. The resulting motor electricity demand for each second is calculated in column W. The simulation also checks and reports how many times the required torque is not possible with the selected engine. Cell W25 calculates the total fuel consumption for the entire driving cycle by simply summing over all values in row W. Dividing this value by the length of the driving cycle yields the fuel economy (in MJ/100km). This value is reported in cell X25 and also forwarded to the 'Input Data' spreadsheet.

3.3 Energy Regen Calc-Max eff

The starting point of this spreadsheet is the velocity data and all negative values of the net tractive force demand data. For all other time steps net tractive force demand is set to zero. Based on this data the sheet calculates the electrical energy that the generator is able to recover from the available deceleration energy through the process of regenerative braking. Regen Speed Factor parameters are input on this sheet.

3.4 Battery Model

This sheet calculates the following:

1. Energy losses from discharging the battery to provide the electricity required by the motor.
2. Energy losses from charging the battery through regenerative braking or from the plug.
3. Fuel required to continuously charge the battery with the gasoline generator in the charge-sustaining mode.
4. The spreadsheet also calculates the battery size (in Wh and kg) required to achieve the all-electric UDDS range specified by the user on the 'Input Data' spreadsheet.

All battery pack design parameters and all variables used to calculate battery size are also contained in the spreadsheet. Battery charging and discharging losses are calculated based on a table of voltage drops / over potentials, which are given as function of battery state of charge (SOC) and power demand / supply.

3.5 Accel Perf Calculations

This sheet calculates the 0-60 mph acceleration time. It is assumed that at each time, the motor is at maximum torque, and the gear which maximizes tractive force is selected. It is further assumed that if tire slip occurs, it is for a negligible time period. The shift duration input on sheet 'Input Data' is added to the time at each shift point.

3.6 Gradeability Calculations

This sheet calculates low and high gear gradeability. This information is to aid in selecting appropriate low and high gear ratios and final drive ratios. It is not directly used in energy consumption or acceleration calculations. Gradeability is calculated at a user specified speed and grade which are entered on this sheet (at test mass for high speed gradeability, and gross vehicle mass for low speed gradeability). The available-to-demanded torque is calculated.

3.7 Motor Eff

This sheet contains the motor map, i.e. motor efficiency as a function of motor speed and torque.

3.8 Motor T vs. N

This sheet contains maximum motor torque and speed data for the same motor as in the sheet 'Motor Eff'. Motor speed, *N*, and torque, *T*, are shown as a table. The acceleration performance calculation on sheet 'Accel Perf Calculations' uses a third order polynomial fit for the *T*-*N* relationship. Excel calculates the polynomial coefficients and displays them on a *T vs. N* graph, but the user must enter the coefficients into the blue cells.

3.9 Gen Eff

This sheet is similar to sheet 'Motor Eff' but for the generator mode.

3.10 Gen T vs. N

This sheet is similar to sheet 'Motor T vs. N' but for the generator mode.

3.11 Battery discharge curves

This sheet contains so-called battery discharge data. Data tables and figures show voltage drops as a function of battery power demand and SOC. The data are used on the spreadsheet 'Battery Model'.

3.12 Benchmark data

This sheet contains benchmark data for several electric vehicles in production.