Fuel consumption calculation utility and Electric Vehicle simulation

1 Introduction

This utility is designed whether to simulate a conventional powertrain or an electric vehicle (EV) over a driving cycle, permitting the evaluation of important parameters such as the fuel consumption and the electric range. The user interface has been set up to specify the most important parameters of the vehicle (e.g. rolling resistance, transmission ratios, battery size…); in this way, the user can immediately estimate the influence of a parameter on fuel economy or on electric range. Due to the quasi-static approach used for calculations, the results obtained with the present utility should be considered as a rough estimate. The evaluation of fuel consumption and of the electric range is obtained using steady state maps and curves, neglecting both the transient phenomena during accelerations and the thermal status. However, when "mild" driving cycles are simulated (e.g. NEDC cycle), results are good approximations of experimental data.

2 User interface: input data

The main window will appear like **Figure 1**:

Figure 1 – Main window

2.1 Vehicle Panel

In the ***Vehicle Panel***, depicted in **Figure 2**, the user should insert the information related to the vehicle drag and rolling resistance, as well as the vehicle mass.

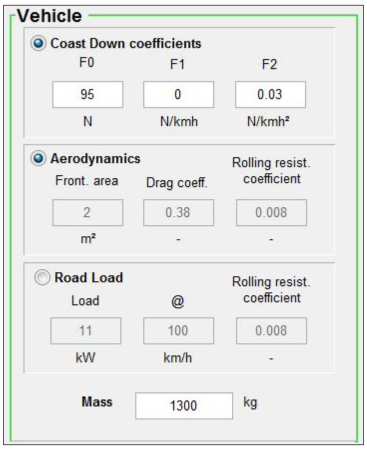

Figure 2 Vehicle Panel

Vehicle resistance can be defined in three ways:

- ***Defining the "coast down coefficients" F_0, F_1 and F_2***. The vehicle manufacturer generally provides these coefficients. Please insert the coefficient with the correct unit, as specified above each edit box. The resistive force calculated using these parameters is reported in (1);

$$F_{res} = F_0 + F_1 \cdot v + F_2 \cdot v^2 \ (1)$$

- ***Defining aerodynamic values***, which are the frontal area, the drag coefficient and rolling resistance coefficients. The resistive force calculated according these parameters is reported in (2).

$$F_{res} = m_{veh} \cdot g \cdot f + \frac{1}{2} \cdot \rho \cdot A \cdot C_x \cdot v^2 \ (2)$$

The rolling resistance coefficient ***f*** has no unit, and the correspondent force is defined in (3):

$$F_{roll}[N] = m_{vehicle}[kg] \cdot g \left[\frac{m}{s^2}\right] \cdot f[-] \ \ (3)$$

Note that sometimes ***f*** is provided in $\left[\frac{kg}{tons}\right]$; please insert the rolling resistance factor with no units (that is $\left[\frac{kg}{kg}\right]$), considering the equivalence shown in (4):

$$0.001[-] = 1\left[\frac{kg}{tons}\right] \ (4)$$

- ***Defining the "road load"***, i.e. the power required to move the vehicle at a constant speed; these data are sometimes provided, together with the rolling resistance factor, to define the vehicle drag and rolling resistance, which are used to calculate the resistive force according to (2).

2.2 Tyre Size Panel

In the ***Tyre Size Panel***, depicted in **Figure 3**, the user defines the tyre radius of the vehicle. If the wheel radius is unknown, it is possible to select a standard size in the popup menu by enabling the nearby radio button.

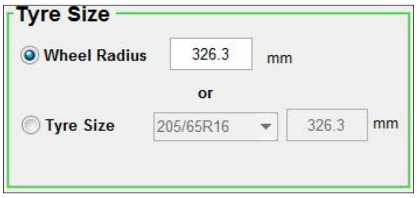

Figure 3 Tyre Size panel

2.3 Conventional Powertrain Panel

The simulation of a conventional powertrain is activated through the enabling of the radio button placed on the top of the red squares, as shown in **Figure 4**.

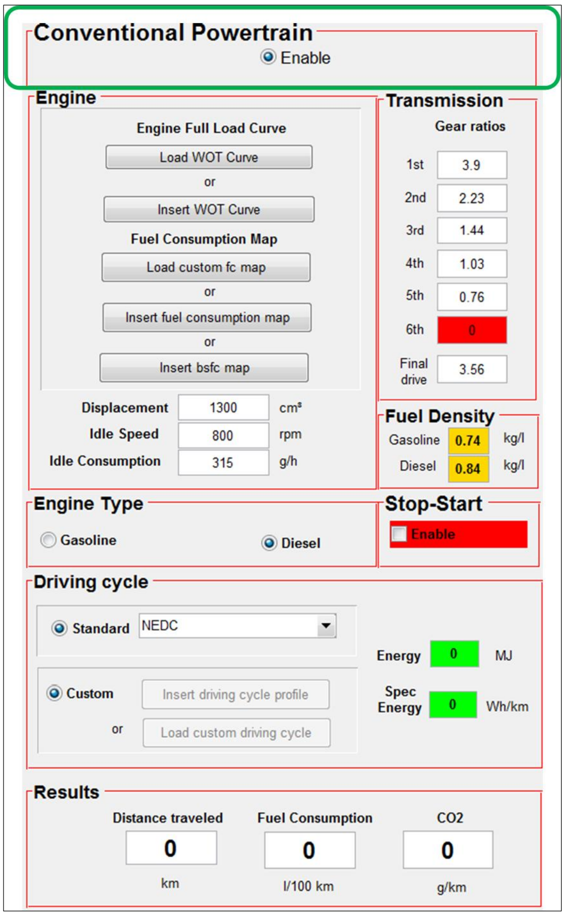

Figure 4 Conventional Powertrain Panel: enabling of the conventional powertrain simulation (green square)

Seven different subpanels compose the conventional powertrain simulation:

- Engine;
- Engine Type;
- Transmission;
- Fuel Density;
- Stop-Start;
- Driving Cycle;
- Results.

2.3.1 Engine Subpanel

In the engine panel, illustrated in **Figure 5**, the user should insert the engine Wide Open Throttle (WOT) curve, the engine fuel map, the engine displacement, the idle speed and the idle fuel consumption.

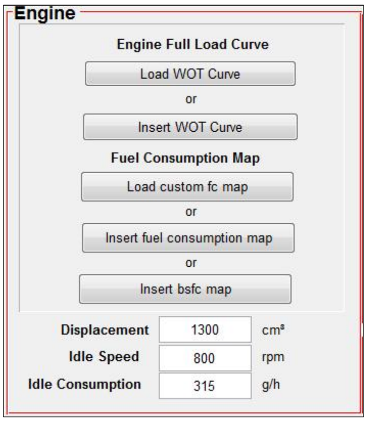

Figure 5 Engine Subpanel

The WOT curve is requested to limit for each instant of time the power demand to the Internal Combustion Engine (ICE) along the driving cycle. To insert the WOT curve, the user should press "***Insert WOT Curve***" and a window like **Figure 6** will appear:

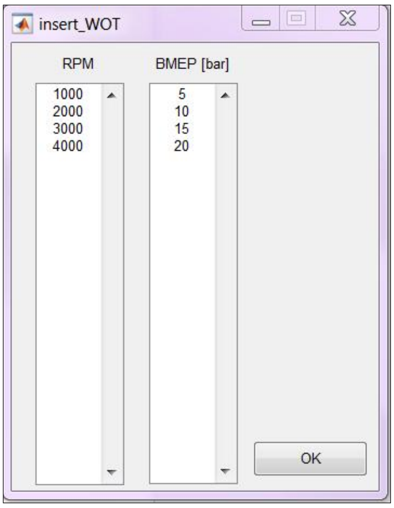

Figure 6 Custom WOT curve window

In this window, it is possible to paste the two columns related to RPM and BMEP, which are generally available as worksheet format. Please insert values using the correct units: [RPM] for engine speed, [bar] for engine BMEP. When the corrected values are inserted, by clicking on the "***OK***" button it will produce a plot of the WOT curve. The tool will ask to the user for saving the custom curve for a future use. This is recommended if a frequent use of the curve is requested. Selecting ***Yes***, a dialog box will appear asking a title for the WOT curve (e.g. 'my engine 2.0 L'). This will be the identifier name of the curve for a future loading. To load a previously saved custom WOT curve, click on "***Load WOT curve***" and select the name of a saved curve. The program will show the plot of the selected curve.

To insert the fuel consumption map the user should press "***Insert fuel consumption map***" and a window like **Figure 7** will appear:

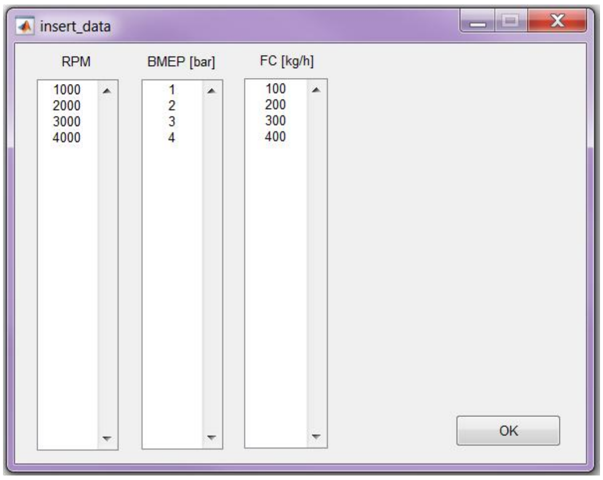

Figure 7 Custom fuel consumption map window

In this window it is possible to paste the three columns related to RPM, BMEP and Fuel Consumption (FC), which generally are available as worksheet format. Please insert values using the correct units: [RPM] for engine speed, [bar] for engine BMEP and [kg/h] for fuel consumption. When the correct values are inserted, clicking on the "***OK***" button will produce a plot of the calculated FC map. The tool will ask to the user to save the custom map for a future use. This is recommended if a frequent use of the map is requested. Selecting ***Yes***, a dialog box will appear asking a title for the map (e.g. 'diesel 2.0 L'). This will be the identifier name of the map for a future loading. If no fuel consumption data are available, it is also possible to insert BSFC data, clicking on "***Insert BSFC map***"; the code will calculate the corresponding FC value with the formula reported in (5):

$$Fuel\ Flow\left[\frac{kg}{h}\right] = bsfc\left[\frac{g}{kWh}\right] \cdot P_{ice}[kW] \cdot \frac{1}{1000} \quad (5)$$

Where

$$P_{ice}[kW] = \frac{bmep[bar] \cdot V_{tot}[cm^3] \cdot n[RPM]}{1200 \cdot 1000} \quad (6)$$

Where $\boldsymbol{V_{tot}}$ is the displacement of the ICE, which should be typed by the user in the specific box named "***Displacement***". Even in this case, a plot of the calculated FC map will appear, and user will have the possibility to save the map. It is possible to delete the saved custom maps (see **Reset data and Run Subpanels**). To load a previously saved custom map, click on "***Load custom fc map***" and select the name of a saved map. The program will show the plot of the selected map. Moreover, the user should insert the idle speed and idle fuel consumption respectively in the boxes "***Idle Speed***" and "***Idle Consumption***", which are used by the code to compute the fuel consumption in this particular condition. If the fuel map inserted by the user covers such condition, the model will not use this information for the computation of the instantaneous fuel consumption.

2.3.2 Engine Type and Fuel Density Subpanels

The user can choose the correct fuel to be used (Gasoline or Diesel) for the calculations, as shown in **Figure 8**. This information will change coherently the fuel density, which are listed in the fuel density subpanel (depicted in **Figure 9**), and the engine inertia parameters. The user cannot modify/fill the fuel density boxes, highlighted by the yellow background.

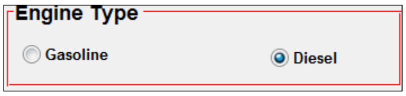

Figure 8 Engine Type Subpanel

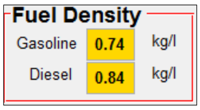

Figure 9 Fuel Density Subpanel

2.3.3 Transmission Subpanel

In this panel, as shown in **Figure 10**, it is possible to define the transmission gear and the final drive ratios. The transmission efficiency, as well as the tyre inertia, is internally defined and not changeable. The efficiency is set to 0.96 for the transmission and 0.98 for the final drive; the tire inertia is equal to 0.685 $kg\ m^2$ for a single tire.

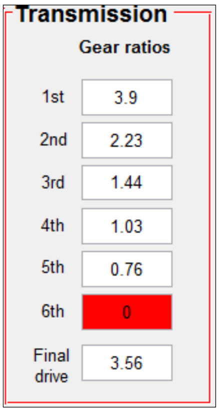

Figure 10 Transmission Subpanel

<u>The red background in correspondence of the sixth gear advises the user to pay attention to the number of gears. If the requested gearbox has five ratios, the user should type in the sixth ratio box the value 0, otherwise the desired value.</u>

2.3.4 Stop-Start Subpanel

The user has the possibility to evaluate the impact on fuel consumption of stop-start technology, by marking the box enable, as illustrated in **Figure 11**. When the stop-start is enabled the background colour is green, otherwise it will be red, as shown in **Figure 11**.

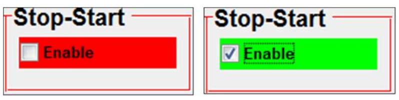

Figure 11 Start-Stop Subpanel: Left stop-start disabled, Right: stop-start enabled

2.3.5 Driving cycle Subpanel

In the driving cycle panel, depicted in **Figure 12**, user should select the vehicle mission over which it is required to estimate the fuel consumption.

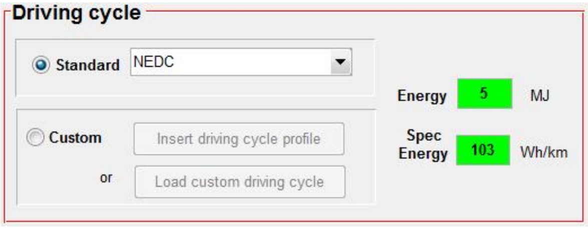

Figure 12 Driving Cycle Subpanel

Some standard driving cycles are loaded by default:

- NEDC
- ECE
- EUDC
- FTP
- Artemis – Urban
- Artemis – Road
- Artemis – Motorway

The NEDC cycle is selected by default and in this case, and off course for the ECE and EUDC, depending on the number of gear ratios considered, the code automatically selects between the six gear profile or the five one. The utility offers the possibility to choose the US FTP driving cycle or the Artemis cycles, which are more representative of "real world" driving. All of the default driving cycles are sampled with a time-step of 1 second. It is also possible to insert a custom driving cycle, selecting "***Custom***" and then clicking on "***Insert driving cycle profile***". A window like **Figure 13** will appear:

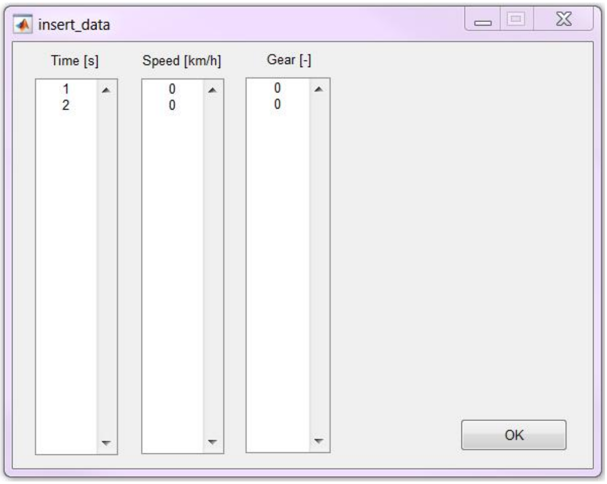

Figure 13 Custom driving cycle

User should paste three columns reporting time, speed and gear profile in the proper boxes. Once data are inserted, a plot will show speed and gear shifting profiles, and the user will have the possibility to save the custom driving cycle for a future use. To load a previously saved driving cycle, select "***Custom***" and then click on "***Load custom driving cycle***" and select the name of a saved profile. It is not necessary to use a constant time step for the inserted profiles, but it is suggested to insert the time profile with steps of 1 second; however, the code will consider one working point for each of the user defined steps.

At the end of the simulation, the two green boxes, represented in **Figure 12**, related to the cycle energy [MJ] and the specific cycle energy [Wh/km] will be written off in order to give to the user an evaluation of the cycle energy request.

2.3.6 Results

Once all input data have been correctly inserted, clicking on "***Calculate"*** button, shown in **Figure 26**, will start the data processing. As output, user will see in the proper boxes the following values:

- Total travelled distance;
- Specific fuel consumption $^{l}/_{100km}$;
- CO_2 emissions $^{g}/_{km}$.

Selecting the "***Plots***" checkbox, shown in **Figure 26**, the user can see the following graphs:

- Vehicle speed, engine speed, BMEP, instantaneous fuel flow, total fuel consumption vs time;
- Contour plot of FC map vs, RPM, BMEP with engine operating points.

2.4 Electric Vehicle Panel

The simulation of an EV is activated through the enabling of the radio button placed on the top, as shown in **Figure 14**.

Figure 14 EV Panel: enabling of the EV simulation (red square)

Five different subpanels compose this panel:

- Motor-Generator;

- Transmission;
- Battery-Auxiliary;
- Driving Cycle;
- Results.

The simulation of the battery is based on the data of a fixed cell with a capacity of 60 [Ah] and a nominal voltage of 3.7 [V], based on the data of a Superior Lithium Polymer battery of Kokam (info: kokam.com). The simulation of the battery is done using a circuit-based modelling, which represents the battery behaviour as an equivalent electrical circuit, needing a limited number of data and a lower computation time. The equivalent circuit implemented in the model is illustrated in **Figure 15**.

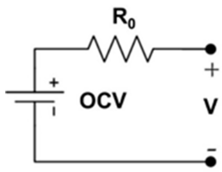

Figure 15 Equivalent circuit model of the battery

Where ***OCV*** is the voltage at the battery terminals when no load is applied, $\boldsymbol{R_0}$ is the internal resistance representative of the Ohm losses inside the battery and ***V*** is the terminal voltage between the battery terminals, correlated between them through the Ohm's law (7).

$$V = OCV[V] - R_0[Ohm] \cdot I[A] \ (7)$$

The OCV and the internal resistance vary depending on the load demand, on the temperature and battery State of Charge (SOC). In this case, they are supposed variable only as function of the SOC, as depicted on **Figure 16**.

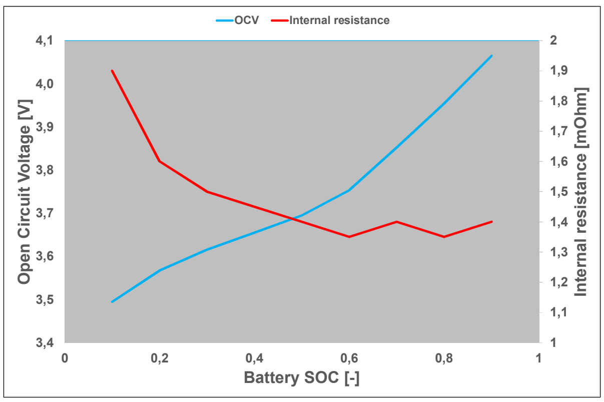

Figure 16 OCV and internal resistance of the Kokam cell

The computation of the battery SOC is done according the following formula (8):

$$SOC = SOC_0 - \frac{\int_0^t I[A]dt}{3600C_{batt}[Ah]} \ (8)$$

Where ***SOC₀*** is the starting SOC level, ***I*** is the battery current and ***C_batt*** is the battery capacity. In this formulation, the current is supposed positive during the discharge phases and negative during the charging events.

The EV simulation takes into account the effect on the battery energy balance of the regenerative braking event, by supposing a brake force distribution of 60% on the front axle and of 40% on the rear, considering the electric machine positioned on the front axle.

2.4.1 Motor-Generator Subpanel

In the engine panel, illustrated in **Figure 17**, the user should insert the motor mechanical characteristic curve and the engine efficiency.

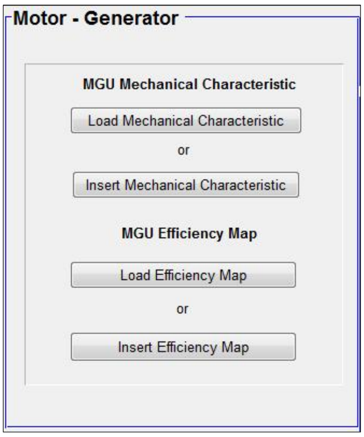

Figure 17 Motor-Generator Subpanel

The mechanical characteristic curve is requested to limit for each instant of time the power demand to the Motor Generator Unit (MGU) along the driving cycle. To insert the MGU curve, the user should press "***Insert Mechanical Characteristic***" and a window like **Figure 18** will appear:

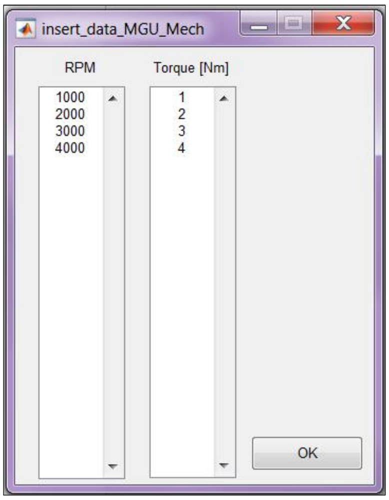

Figure 18 Custom Mechanical Characteristic curve window

In this window, it is possible to paste the two columns related to RPM and torque, which are generally available as worksheet format. Please insert values using the correct units: [RPM] for MGU speed, [Nm] for MGU torque ***only related to the first Cartesian quadrant***. The model will mirror the curve on the fourth quadrant, which is representative of the regenerative braking condition. When the corrected values are inserted, by clicking on the "***OK***" button it will produce a plot of the MGU mechanical characteristic curve. The tool will ask to the user for saving the custom curve for a future use. This is recommended if a frequent use of the curve is requested. Selecting ***Yes***, a dialog box will appear asking a title for the WOT curve (e.g. 'my MGU 35 kW'). This will be the identifier name of the curve for a future loading. To load a previously saved custom

MGU curve, click on "***Load Mechanical Characteristic***" and select the name of a saved curve. The program will show the plot of the selected curve.

To insert the MGU efficiency map the user should press "***Insert Efficiency Map***" and a window like **Figure 19** will appear:

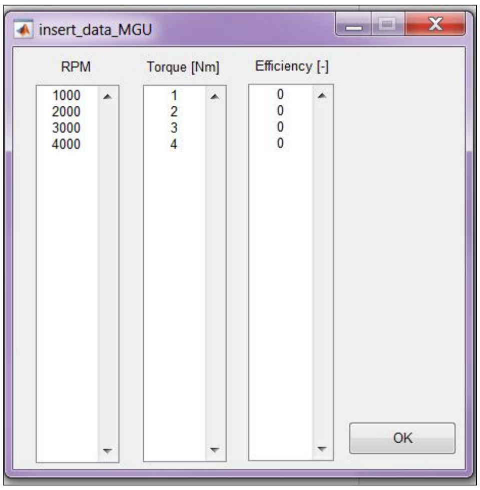

Figure 19 Custom MGU efficiency map window

In this window, it is possible to paste the three columns related to RPM, torque and efficiency, which generally are available as worksheet format. Please insert values using the correct units: [RPM] for MGU speed, [Nm] for MGU torque and for the efficiency a fraction [-]. When the correct values are inserted, clicking on the "***OK***" button will produce a plot of the calculated efficiency map. The tool will ask to the user to save the custom map for a future use. This is recommended if a frequent use of the map is requested. Selecting ***Yes***, a dialog box will appear asking a title for the map (e.g. 'my MGU 35 kW'). This will be the identifier name of the map for a future loading.

2.4.2 Transmission Subpanel

In this panel, as shown in **Figure 20**, it is possible to define the final drive of the EV, which differently of the conventional powertrain does not request a gearbox. The transmission efficiency is set to 0.98 and it is not editable by the user. The inertia of all the rotating parts is supposed equal to the 3% of the vehicle mass.

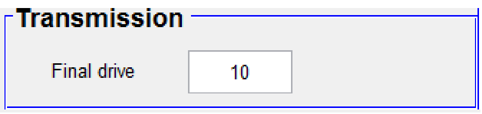

Figure 20 Transmission Subpanel for the EV simulation

2.4.3 Battery-Auxiliary Subpanel

The user in the battery-auxiliary subpanel, illustrated in **Figure 21**, defines the layout of the battery, the allowed SOC swing, the power adsorbed by the auxiliary components (lights, infotainment, etc.) and the equivalent CO_2 emissions from the grid, related to the electric energy production. The user defines the number of cells connected in series by compiling the "***N° Cell Series***" box and the number of cells in parallel filling the "***N° Cell Parallel***" box, depicted in **Figure 21**. Moreover, the user can define the SOC swing, which defines the maximum allowed use of the battery energy, by filling the two boxes "***SOC Max***" and "***SOC Min***", expressed as a percentage. The model allows a maximum SOC value of 90% and a minimum of 15% to be representative of the constraints implemented in a real Battery Management System (BMS) in order to limit the battery ageing. The user in the "***Auxiliary Power***" box defines the power adsorbed from the auxiliary components as [kW], which will be added at each instant of time to the traction power requested to the battery.

Finally, the user can define the equivalent CO_2 production from the grid, expressed as [g/kWh] by filling the "***CO_2 from grid***". This parameter is important to perform a meaningful comparison with a conventional powertrain.

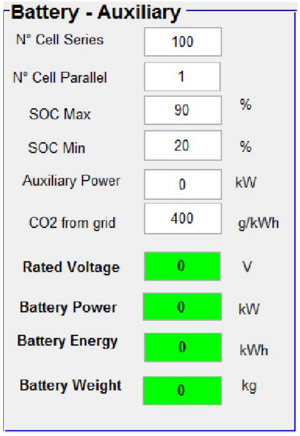

Figure 21 Battery-Auxiliary Subpanel

During the simulation of the configured EV, the model provides as output the rated voltage, the power, the energy and the weight of the configured battery, which are shown in the four green boxes that cannot be edited by the user. For the evaluation of the battery weight, it is supposed a specific weight of 15 [kg/kWh], which cannot be modified by the user.

2.4.4 Driving cycle Subpanel

In the driving cycle panel, depicted in **Figure 22**, user should select the vehicle mission over which it is required to estimate the fuel consumption.

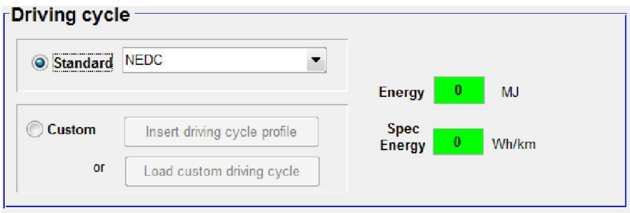

Figure 22 Driving Cycle Subpanel

Some standard driving cycles are loaded by default:

- NEDC
- ECE
- EUDC
- WLTC
- FTP
- Artemis – Urban
- Artemis – Road
- Artemis – Motorway

The NEDC cycle is selected by default. The utility offers the possibility to choose the US FTP driving cycle, the WLTC and the Artemis cycles, which are more representative of "real world" driving. All of the default driving cycles are sampled with a time-step of 1 second. It is also possible to insert a custom driving cycle, selecting “Custom” and then clicking on “***Insert driving cycle profile***”. A window like **Figure 23** will appear:

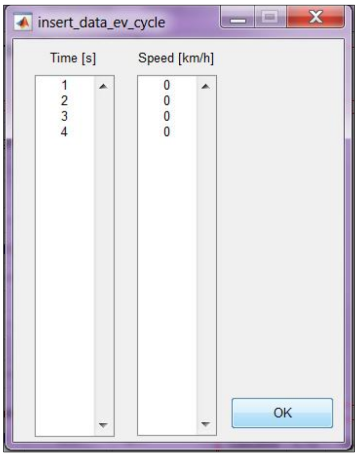

Figure 23 Custom driving cycle

User should paste two columns reporting time, speed in the proper boxes. Once data are inserted, a plot will show the speed profile, and the user will have the possibility to save the custom driving cycle for a future use. To load a previously saved driving cycle, select “***Custom***” and then click on “***Load custom driving cycle***” and select the name of a saved profile. It is not necessary to use a constant time step for the inserted profiles, but it is suggested to insert the time profile with steps of 1 second; however, the code will consider one working point for each of the user defined steps.

At the end of the simulation, the two green boxes, represented in **Figure 22**, related to the cycle energy [MJ] and the specific cycle energy [Wh/km] will be written off in order to give to the user an evaluation of the cycle energy request. The user cannot fill these two boxes.

2.4.5 Results

Once all input data have been correctly inserted, clicking on “***Calculate***” button will start the data processing. As output, user will see in the proper boxes the following values:

- Electric range;
- Battery energy consumption in ${Wh}/_{km}$;
- Equivalent CO_2 emissions ${g}/_{km}$.

Optionally by selecting the “***Plots***” checkbox shown in **Figure 26**, it is also possible to see the following plots:

- Vehicle speed, MGU torque, battery current, voltage, SOC vs time;
- Contour plot of MGU efficiency map vs, RPM, torque with the electric motor operating points.

2.5 Reset data and Run Subpanels

Clicking on “***Clear custom data***” inside the Reset Data subpanel, shown in **Figure 24**, this button will open a dialog box that allows the user to choose which of the saved custom maps, curves and cycles have to be deleted.

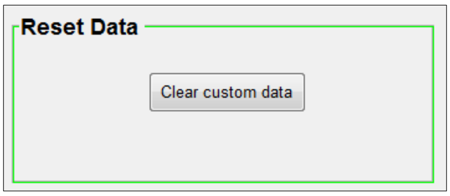

Figure 24 Reset data Subpanel

In the dialog window shown in **Figure 25**, the user should press the "***OK***" button to delete the selected data or "***Cancel***" to move forward to the next window.

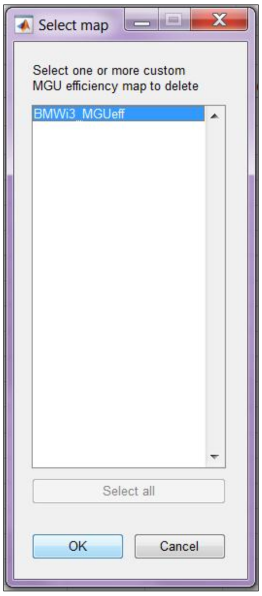

Figure 25 Reset data Subpanel: MGU Efficiency map selection

The Run subpanel is depicted in **Figure 26**, where the user can run the simulation of the defined vehicle model by pushing the "***Calculate***" button. Moreover, the user can consult the manual by pushing "***Help***", and this guide in Pdf format will appear.

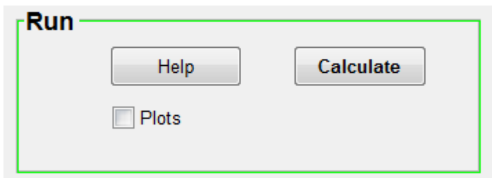

Figure 26 Run Subpanel