STUDY OF ELECTRIC VEHICLES WITH ADVISOR

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Abstract*: The main paper's purpose is to present how students and researchers can use the ADVISOR software in the design and simulation of electric vehicles. Not only electric vehicles but also hybrid, fuel-cell, or internal combustion engine vehicles can be simulated, this paper refers only to the former. Starting with the principal electric vehicle components such as the energy storage system and the electric motor, the user can choose them from the existing ones in the library or can compose/define new others. The software allows imposing different driving cycles (choosing from the library or user-defined) and calculates selected performances of the vehicle based on the simulation. Should emphasize the eloquent way of ADVISOR in presenting the results on the energy consumption of the main components as well as of the entire vehicle. Thus, it is easy to find how certain equipment affects the overall efficiency of the electric vehicle.*

1. INTRODUCTION

In recent years, one of the solutions to reduce the high level of air pollution, especially in large urban agglomerations, consists in vehicles electrification. It is well known that electric vehicles (EV) are not something new, their history starts somewhere in the first third of the 19th century. Much has been written about those who are considered the inventors of the first EV, also about when and who started EVs mass production. One of those accredited as a pioneer in the "large-scale" production of electric cars is William Morrison, a Scottish emigrant who lived in Iowa, a chemist with outstanding achievements in the development of electric batteries [1]. Thanks to his innovations, more powerful and lighter batteries were obtained, so such a battery pack was mounted on a carriage and powered an electric motor that drove one of its rear wheels. Of course, in this form, the success was quite limited, but the news about the horseless carriage spread quickly, and the development of electric vehicles took off.

In the last years of the 19th century and the first years of the 20th century, famous people like Porsche, Edison, and Ford were interested in the development of EVs. That is when the first hybrid vehicle appeared, produced by Porsche, powered by an electric motor and a gasoline engine. At the beginning of the 20th century, EVs were much more numerous than gasoline ones and almost as many as steam ones (about 40%). The heaviest blow received by EVs was given in 1908 by Henry Ford (who was initially interested in producing a cheap electric car) when he mass-produced a cheap car, the Model T, with a gasoline engine [2]. Because of some realities at that time - electric cars were approximately three times more expensive and had a much shorter range; petrol was cheap; internal combustion engine (ICE) starting was solved by introducing electric starters - EVs entered a dark period, and then they disappeared from the market altogether (the mid-'30s). This period lasted for more than half a century (for personal vehicles), until the beginning of the 70s when the price of oil increased, and the lack of gasoline was felt, the peak being considered the 1973 Arab Oil Embargo. Therefore, the search for alternative solutions began, with hybrid and electric vehicles again enjoying the attention of governments and researchers. The technologies of this period allowed the making of EVs with many disadvantages compared to ICEVs: reduced autonomy, long time for charging, and limited performance (maximum speed around 70 km/h). The research had to continue in an accelerated manner to be able to obtain performances for EVs comparable to those of ICEVs or better. Grants to research labs have increased, and big vehicle manufacturing companies have collaborated with governments to improve technologies. Testing new technologies from the design phase requires proper tools. It is unanimously recognized today that numerical simulations with dedicated software are the basis of the development of new products and technologies. Thus, it is not accidental that in the mid-90s, the Department of Energy (DOE) with the National Renewable Energy Laboratory (NREL) from the U.S.A together with industry partners (Ford, GM, and Chrysler) developed ADVISOR [3]. The software was intended as an analysis tool for the understanding and development of hybrid and electric vehicles.

2. VEHICLE MODEL AND MAIN PERFOMANCES

2.1. Vehicle model

Longitudinal vehicle model assumes only the forces that act longitudinally (*fig. 1*), in the direction of movement, the transverse forces and the internal forces (as the twists of the chassis and the vibrations within it) being neglected. Although it stands for a simplified 2D model, this is sufficiently correct in appreciating the most important performances of the vehicle including speed, acceleration, gradeability, and braking performance.

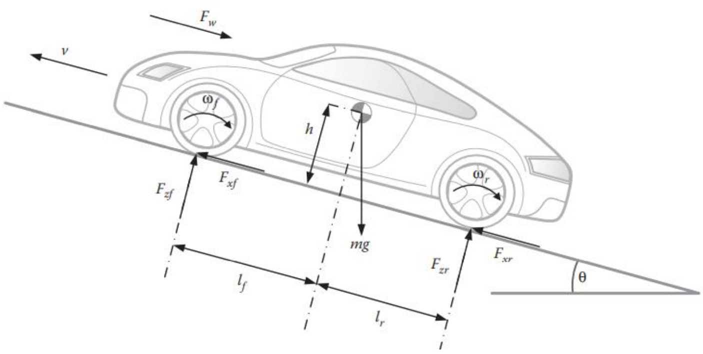


Fig. 1. Longitudinal forces acting on a vehicle [5]

As in every mechanical system, the acceleration force which starts the vehicle or increases the speed, is the difference between tractive force and resistant forces.

$$ma = F_t - F_w - F_g - F_r \tag{1}$$

Were noted: m – vehicle inertial mass, which can be approximated at 5% higher than real mass [6]; a – acceleration; F_t – tractive force; F_w – aerodynamic force or wind force; F_g – gravity force that must be overcome to climb a grade; F_r – rolling resistance force.

The wind force is a function of vehicle shape and size; it is proportional with air density, ρ, frontal area A and relative wind-car velocity, v, through drag coefficient, C_d; relative wind-car velocity represent the sum (when they have opposite sens) or difference (when they have same sens) between car velocity and wind velocity.

$$F_w = \frac{1}{2} C_d \rho A v^2 \tag{2}$$

The gravity force depends by incline angle of the road, θ, vehicle mass, m, and gravity acceleration, g.

$$F_g = mgsin(\theta) \tag{3}$$

The rolling resistance force, which is a friction force, function of vehicle mass, incline road angle and rolling resistance coefficient, C_r, which at its turn depends on tires and road surface.

$$F_r = C_r mgcos(\theta) \tag{4}$$

Another important characteristic that needs to be modeled, specific to hybrid and EVs, is the state of charge of the system battery (*SOC*). *SOC* is determined based of the system capacity (Q_0) [7], usually expressed in *Ah*.

$$SOC = \frac{Q(t)}{Q_0} \tag{5}$$

When simulating EVs, the *SOC* in every moment is in terms of the initial state of charge (SOC_0), coulombic efficiency (η_c) and the battery current [8].

$$SOC(t) = SOC_0 - \int \frac{\eta_c i(t)dt}{Q_0} \tag{6}$$

When the EV is in a regenerative braking regime, the sign of current is minus, and *SOC* increase. If the battery capacity is in *Wh*, there is the relation, *Wh/[Battery voltage]=Ah*.

2.2. Main performances

Among the main vehicle's performances are maximum speed, acceleration performance and gradeability [9]. Maximum electric vehicle speed is the constant cruising speed that the vehicle can develop at the maximum motor power on a flat road. This depends on the highest speed of the motor and total gear ratio of the transmission when the motor is sufficiently powerful.

$$V_m = \frac{\pi n_m r_d}{30 i_g i_0} \tag{7}$$

In (5) is noted: V_m – maximum vehicle speed; n_m – maximum motor speed; r_d – the effective radius of the drive wheel; i_g – gear ratio of transmission; i_0 – final drive gear ratio.

The acceleration performance is given by the acceleration time and the distance covered to increase the speed from zero to a certain high speed (eg. 100 km/h). In the case of EVs the highest acceleration is provided at low speed, and it depends on maximum motor torque (T_m), vehicle mass (m), effective radius of drive wheel (r_d), resultant of resistant forces (F_{tr}) and total gear ratio (i_t).

$$a = f\left(\frac{\frac{T_m i_t}{r_d} - F_r}{m}\right) \tag{8}$$

The gradeability is the largest incline angle of the road that the vehicle can overcome at a certain constant speed while in the case of heavy or off-road vehicles, usually, it is the maximum incline angle that the car can overcome at any speed. Fundamental parameters which influence the gradeability are the peak motor torque, total gear ratio, radius of drive wheel and friction coefficient (μ) between tires and rolling surface.

$$tg\theta = f\left(T_m, i_t, \frac{1}{r_d}, \mu\right) \tag{9}$$

3. METHODOLOGY

When the vehicle powertrain is analyzed, ADVISOR is focused on power flows among the components. So, to obtain results closer to the experimental measurements, the efficiency of each component in which the power flows must be as accurately estimated as possible, for the entire range of torques and speeds. In this sense, “industry and government experts were consulted to develop estimates of component performance, including "best case" and "conservative" estimates” [3]. Following these consultations, the results of ADVISOR simulations were very realistic, close to those obtained by other laboratories from industry or to measurements.

3.1. ADVISOR software

A simple sketch of an EV is in the top left part while the map of the motor/controller efficiency and rated torque vs speed, is in the bottom left. In the right part are the labels and dialog boxes needed for configuration. Some boxes are active, others are not, this part of the interface being designed in such a way that all types of cars can be configured (electric, series or parallel hybrid, fuel-cell, or ICE).

Fig. 1 shows the main interface of ADVISOR when EV is selected for configuration.

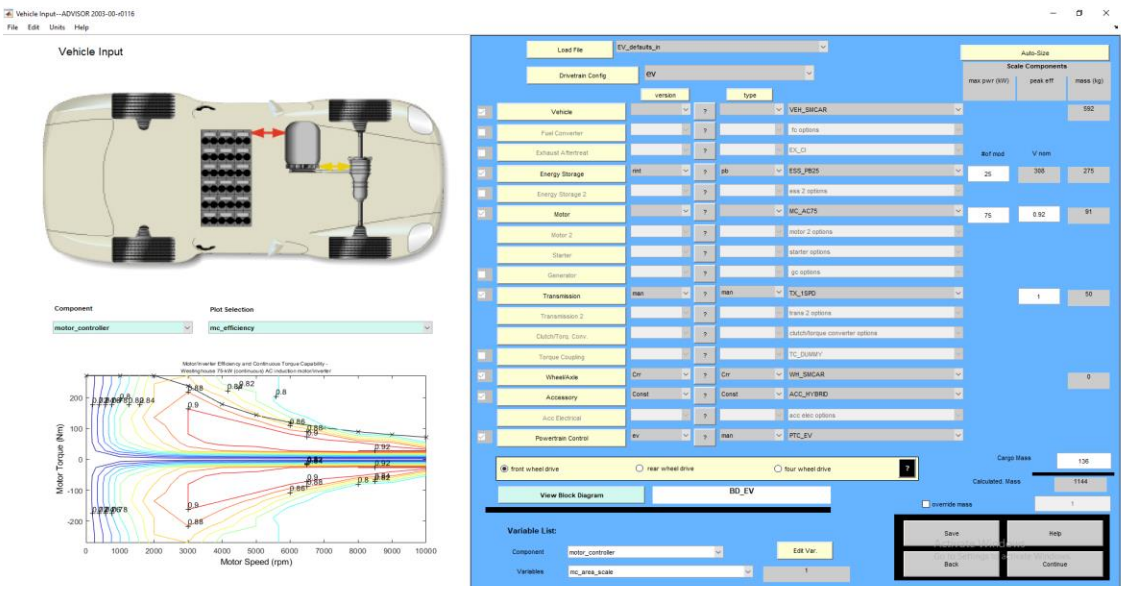
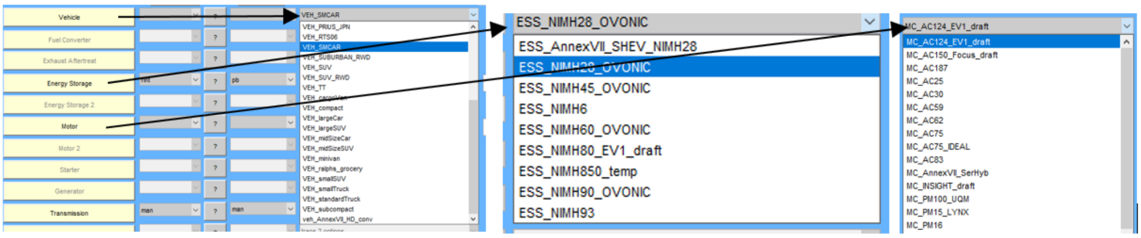


Fig. 1. ADVISOR interface, EV configuration

There is no big difference between the first two boxes, each of them allowing us to define the vehicle type or to choose a certain predefined model and brand. In the *Vehicle* box one can select the vehicle body (common or a certain model/brand, *fig. 2.a*). The next active box is for energy storage system choice (*fig. 2.b*) and the other for the motor (*fig. 2.c*). There are many types of energy storage systems, but the possibility of selection is a function of the selected file in the Load File box.



a) Vehicle body; b) Energy storage system; c) Motor.

Fig. 2. Main components selection

In the *Transmission* box one can select the type of gear box. For EV, usually, 1-speed gear box is predefined, but the user can also select another type of gear box or can define a new one. For EV only manual type is possible. If not 1-speed gear box is selected, the user must alter the file *PTC_EV* which is the only selectable in *Powertrain Control* box. This is necessary because in this file is not defined the change of gear. Wheel/Axle refers to the coefficient of rolling resistance model, wheels, and axle types and in the *Accessory box*, the needed power is accounted. Also in this frame, one can select the driving wheels (front, rear or four).

After one pushed the *Continue* button, the new frame appears (*fig. 3*). In the left part are data about the selected cycling drive, and disponibile measuring units being *US* or *SI*. This stands for the speed-time graph which the car should fulfil during the simulation.

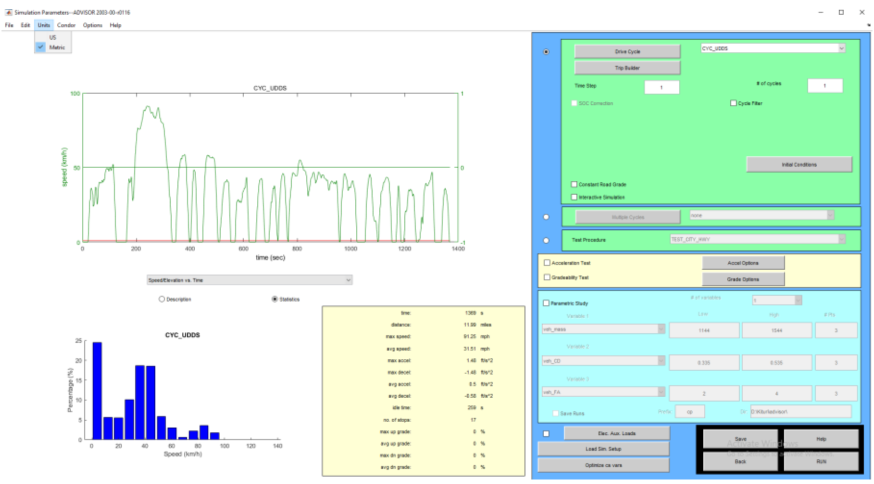


Fig. 3. Advisor second frame

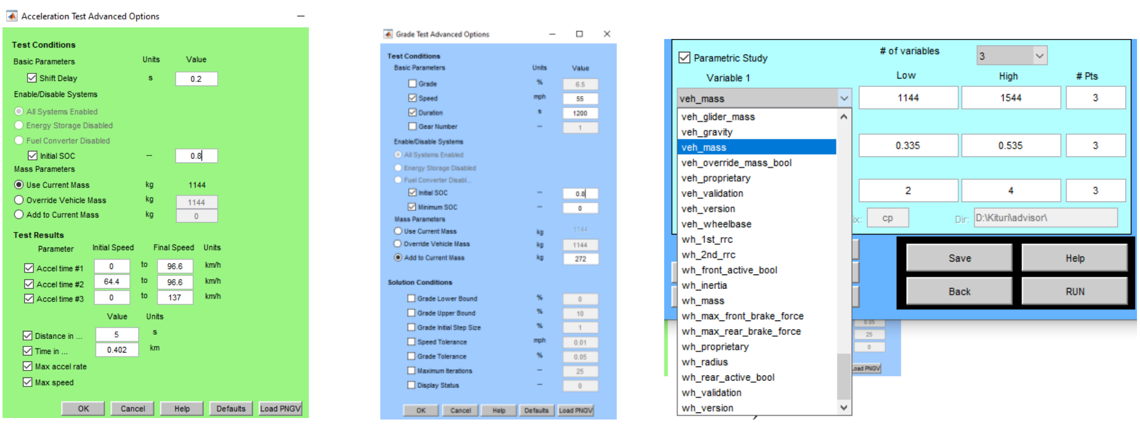
One can choose from the existing many cycles, define a new one, choose a test procedure or an interactive cycle. These cycles are like the used ones in experimental tests. As a main characteristic we can mention the driving specificity, some being for testing driving in city, on highway, combined cycle, and aggressive driving cycle. When a driving cycle (not test procedure) is chosen, one can impose a constant incline road, and defines the initial conditions as: ambient, motor and energy storage system temperature and *SOC*.

In the following, *Acceleration test* and *Gradeability test* (*fig. 4.a, b*) should be set if they are desired. If the *Parametric Study* box is checked, from 1 to 3 parameters (chosen from a large list) can be varied between a minimum and maximum value (fig. 4.c).

After completing these stages, one should press the *Run* button which will start the simulations, and at the end, one can view the results. The possibilities of the presentation of the results will be shown with the case study.

3.2. Case study

The EV model was configurated choosing *EV_defaults_in* file in the *Load File* box and all boxes have been filled in automatically with proper data for EV type. After that, in the *Energy Storage* box, *ESS_PB91* has been chosen instead of *ESS_PB25*. This energy storage system models the *Electrosource Horizon 12N85* lead-acid battery, which has specific energy of 35 Wh/kg and specific power of 240 W/kg, the voltage is 308V and C/5 rate 91Ah. The parameters vary according to *SOC* and temperature. Although the voltage and the number of modules are the same, the amount of energy is almost four times higher than in *ESS_PB25* (while the mass is about 2.3 times). Another change compared to the defaults was the choice of the *MC_AC83* motor instead of the *MC_AC75*. Tis induction motor/inverter can develop 83 KW continuus power, has a 385 A maximum current, 200 V minimum voltage, and has the characteristics (the maximum continuous torque and efficiency vs speed) shown in *fig. 5*. With these changes a total vehicle mass (including 136 kg cargo mass) of 1511 kg resulted.



a) Acceleration *b) Gradeability* *c) Parametric study*

Fig. 4. Test options

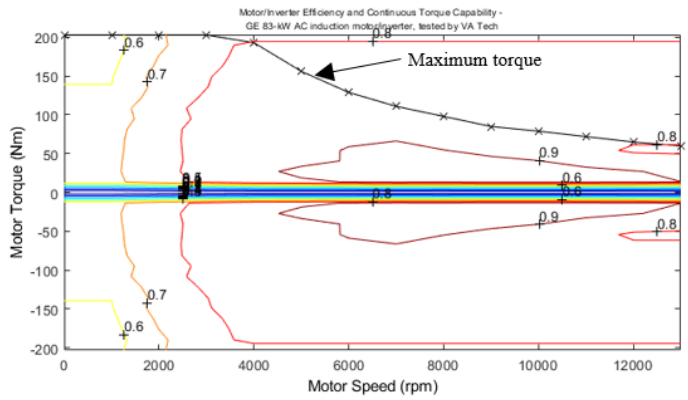
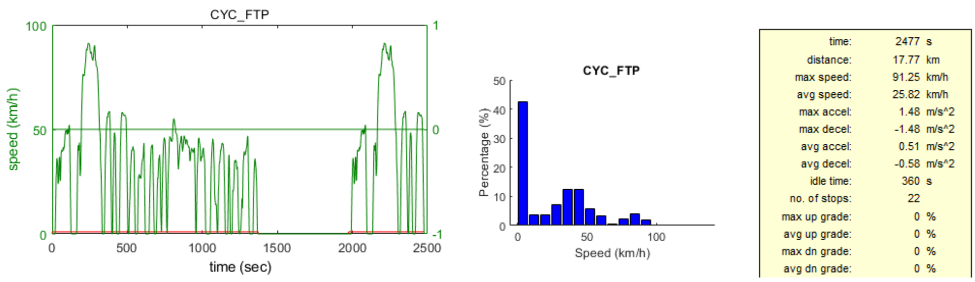


Fig. 5. Motor/inverter characteristics

In the next frame (fig. 3.) *CYC_FTP* drive cycle (federal test procedure in USA) has been chosen and it stands for city driving conditions for light duty vehicle testing having statisc data shown in *fig. 6*. An initial *SOC* of 0.8 was set, and gradeability and acceleration tests was checked. *Parametric study* was ignored in the first simulation.



a) Speed vs time *b) Statistic data*

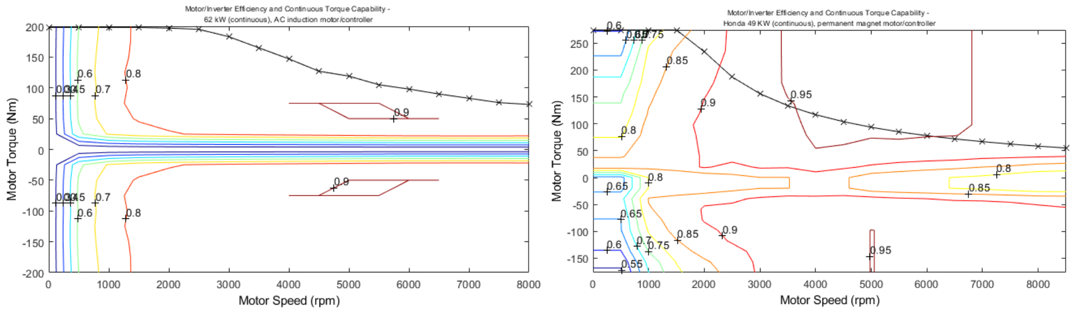
Fig. 6 FTP drive cycle

The second simulation was carried out with the same model, but the *Parametric Study* box was checked, and a single variable was taken into consideration, *gb_spd_scale*, which stands for the multiplication coefficient of the gear ratio in the gearbox. The influence of the gear ratio on the vehicle performance for different driving cycles has been also studied in [10]. Five values were imposed, between 0.8 - 1.2.

In the third simulation, two variables were imposed, adding *mc_spd_scale*, which stands for the multiplication coefficient of the motor speed, and three values were considered: 0.7, 0.85 and 1.

In the last simulation of this model, were imposed three variables: *gb_spd_scale*, *mc_max_crrnt* and *mc_min_volts*. The second stands for the maximum allowed motor current while the last is for the minimum allowed voltage. Three values (minimum, 200 A; the middle value; maximum 385 A, being rated value) were considered for the maximum current and the other three for the minimum voltage (200 V; the middle value, 225 V; 250 V).

The second EV model has been obtained based on the first, changing the *MC_AC83* motor with the *MC_AC62* motor.



a) AC62 *b) PM49*

Fig.7. Motor/inverter characteristics of the second and third model

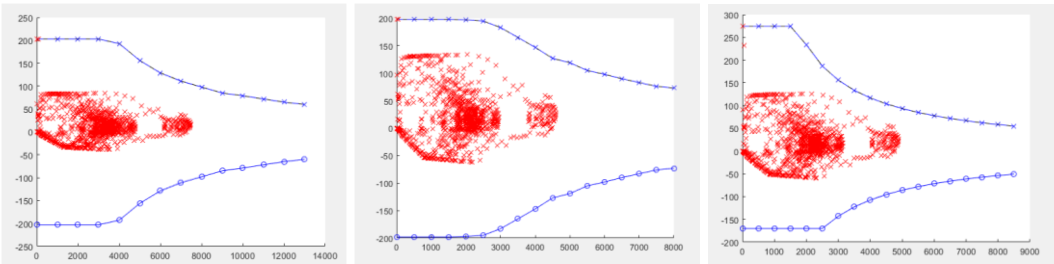
The last is also an induction motor and has the same maximum torque, but a reduced speed (and power, 62 kW), the motor characteristics are shown in *fig. 7a*.

The third studied model is also as first, but this time the chosen motor has been *MC_PM49*, which stands for a permanent magnets (PM) motor, having 49 kW continuous power and the characteristics from *fig. 7b*.

4. RESULTS

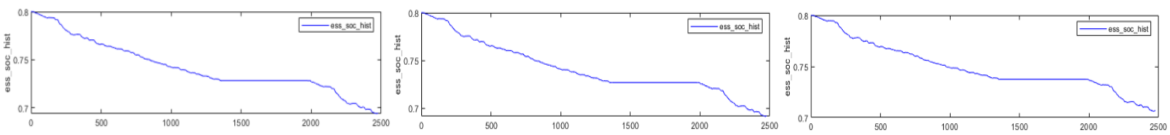
The simulation of the three models results in the operating points of the motors, shown in fig. 8 (on the *y* axis the measuring unit is *Nm*, and on the *x* axis is *rot/min*). As can be seen, all these motors can easily develop the needed power in this driving cycle. Variations of the *SOC* of the battery in the three cases are shown in *fig. 9*. This is approximately the same in the case of the two induction motors, and it is lower in the case of the PM motor.

Of course, a low *SOC* at the end of the cycle means more consumed energy or less overall efficiency.



a) AC83 *b) AC62* *c) PM49*

Fig. 8. Operating points of the motors



a) AC83 *b) AC62* *c) PM49*

Fig. 9. SOC variation in driving cycle

For the considered driving cycle, with the same energy storage system and the same vehicle (the differences being only given by the different weights of the motors), the overall vehicle efficiency was: 0.368 for the model with *AC_62*; 0.382 for the model with *AC_83*; and 0.425 for the model with *PM_49*. Although the *AC_83* motor is larger than the *AC_62* so the vehicle is heavier, due to the higher performance of the first motor, the total efficiency is also higher. The best motor/controller of the three is the PM_49, which has an average efficiency of 0.88 (as the motor) and 0.85 (as the generator); the next is AC_83 with 0.82 and 0.73 respectively; the last is AC_62 with 0.78 and 0.69 respectively. Regarding the performance of the analyzed models, the results are shown in table 1. Inasmuch for the first simulated model a parametric study was carried out, in the belows figures some of the results are shown.

Table 1. Performances of the models

Parameter \ Motor type	AC_83	AC_63	PM_49
Gradeability at 88.5 km/h [%]	18.8	13.4	10.4
Acceleration 0-100 km/h [s]	10.3	15.1	16
Acceleration 65-100 km/h [s]	5.1	6.9	9
Acceleration 0-135 km/h [s]	18.8	27.8	34.3
Maximum acceleration [m/s^2]	3.8	2.3	3.5
Maximum speed [km/h]	157	157.6	157.9

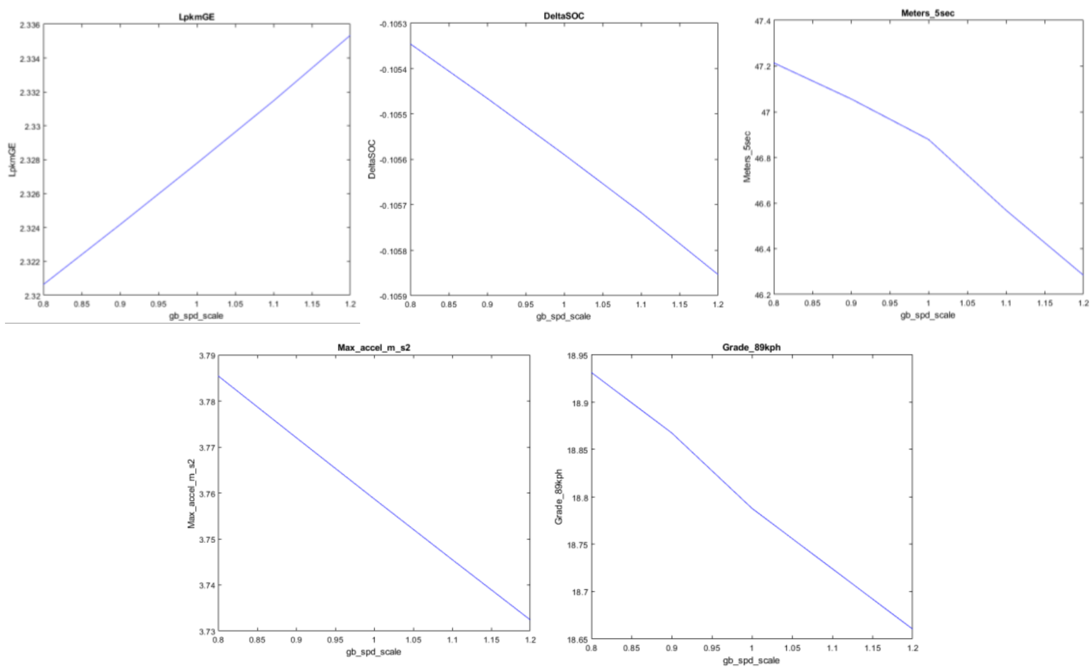


Fig.10 Parametric study considerring a single variable (gb_spd_scale). LpkmGE – gasoline equivalent in liter/km; DeltaSOC- variation of the SOC; Meters_5sec – distance in 5 secons, in meters; Max_accel_m_s2 – maximum acceleration (m/s^2); Grade_89kph – gradeability at 89 km/h

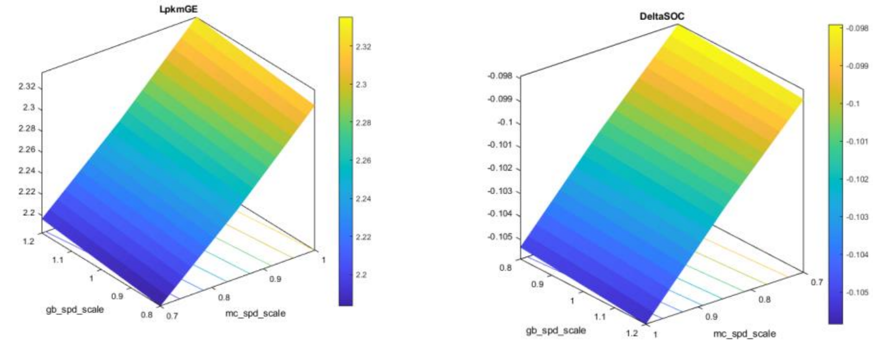


Fig. 11. Parametric study with two variables

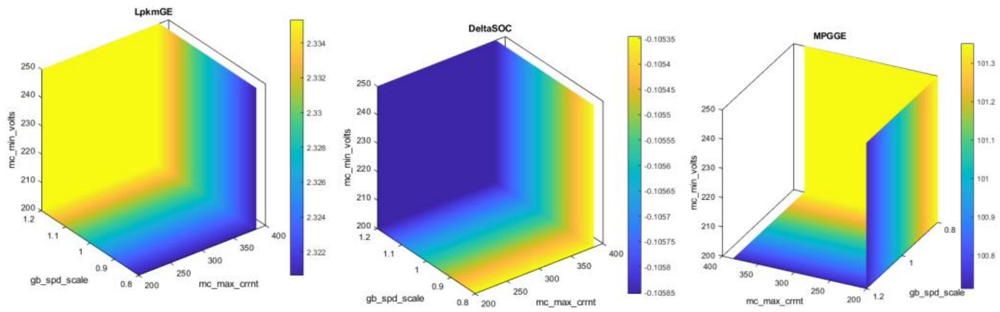


Fig. 12. Parametric study with three variables
(MPGGE - drive cycle miles per gallon gasoline equivalent)

5. CONCLUSION

In this study, the main steps needed to configure the model of an EV and then its simulation in different conditions were presented. For the same vehicle body, cargo mass, and energy storage system, three different motors were considered to find the best solution from the overall efficiency point of view, for a specific driving cycle. The surprise is not that the PMs motor is more efficient in this city-specific driving cycle, but the fact that a high-power induction motor offers higher overall efficiency than a low-power induction motor, even if the first is a less loaded. However, if one looks at the efficiency-speed map, is observable higher efficiency for the AC_83 motor/controller and it is known, the motor is the main consumer of the EV.

The transmission ratio of the gearbox is calculated so that at a slip of 10%, the car can reach a maximum speed of 144.8 km/h (90 miles/h). So, the gear ratio is 8.67 for AC_83, for AC_62 this is 5.34, and for PM_49 it is 5.67. Even though PM_49 has the highest maximum torque and can develop the highest maximum acceleration (table 1), the times in the acceleration test are the highest (low performances). This is caused by the fact that this maximum torque is only available in a limited speed range (the lowest power of the three).

Parametric Study allows one to study the influence of a variable parameter on the vehicle performance. A maximum of three variables can be set at the same time. *Fig. 10* shows the influence of the gear ratio on the other parameters characteristic of vehicle performance. The influence of the gear ratio and the motor's maximum speed on the same parameters is shown in *fig. 11*. A minimum 2.18 l/km gasoline equivalent is obtained when the two variables are the lowest and increases when any of them increase. The last simulation considered three variables for parametrization (fig. 12), but only one of them, *gb_spd_scale*, affects the selected parameters.

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