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AN EVALUATION STUDY ON THE USE OF AN AUXILIARY ELECTRIC POWERTRAIN IN CONVENTIONAL VEHICLES: IMPROVEMENTS IN FUEL CONSUMPTION AND ACCELERATION PERFORMANCE

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Abstract. *The purpose of this study is to determine whether the addition of an auxiliary electric powertrain in a conventional lightweight vehicle is technically viable, quantifying the effects in fuel consumption and acceleration performance. In order to achieve these goals, a computational model was built using two different softwares working together. The main software was LMS Imagine.Lab AMESim (Advanced Modeling Environment for Simulations) in which most components were already modeled as well as the driving cycles, the driver and the longitudinal dynamics equations. The second software was MATLAB/Simulink where the control strategy and the new logic for the throttle pedal were implemented using C-codes that worked simultaneously with the model from AMESim. Initially a conventional car equipped with a 1.0 liter internal combustion engine (ICE), electric power steering and air conditioning system was modeled and used as reference for the comparisons with the hybrid proposals. The alternator has also been taken into account in order to simulate the mechanical load that it represents to the ICE. After achieving a fully functional and reliable reference model, a vehicle control unit (VCU), an electric motor, a power electronic converter and a small capacity battery pack were included. A heuristic control strategy was implemented in the Simulink-based VCU, always aiming at keeping things as simple as possible. Then, it was compared to the reference model in terms of fuel consumption and acceleration performance (0-60km/h and 0-100km/h). A significant decrease in fuel consumption was achieved and a considerable improvement in acceleration performance was observed in the hybrid model.*

Keywords: *hybrid powertrain, heuristic strategy, regenerative braking, fuel consumption, longitudinal dynamics.*

1. INTRODUCTION

Over the past few years, governments all over the world have increased their concerns about energy efficiency and greenhouse gases emissions. Since automobiles are intimately related to these two topics, more rigorous regulation have been elaborated and applied on this sector aiming at reducing gas emissions and decreasing the fuel consumption of the internal combustion engines, consequently improving the overall efficiency of new vehicles.

In Brazil, for instance, many programs have been created in order to stablish quantitative goals in these fields and they must be achieved by vehicle manufacturers in the years to come. The Inovar-Auto, for example, is a program that was approved by the Brazilian government in 2012 and encourages automakers to produce more efficient, safer, and technology-advanced vehicles while investing in the national automotive industry. In this program, automakers need to improve their corporate average vehicle efficiency by about 12% from 2012 levels by the end of 2017. An additional tax reduction of 1% and 2% are offered for those companies that achieve a gain of 16% and 19% in efficiency, respectively (ICCT, 2013).

In this quest for the reduction of fuel consumption and gas emissions, engineers often choose downsizing the ICEs which causes the desired effects of fuel economy and less emission, but also worsens the performance in terms of acceleration, since the power available to accelerate the vehicle is also significantly reduced. In the Brazilian automotive market it is very usual to see cars equipped with 1.0 liter engines that have approximately 75HP of peak power. This fact alone is not a problem, since the tradeoff between the gains and losses is positive. However, in order to fulfill a demand imposed by the consumer market, many of these vehicles are equipped with accessories like air conditioning and power steering systems. These accessories require energy to work properly and this energy comes from the same 75HP downsized engine that is used to accelerate the car and its passengers. The amount of power that is directed to these additional systems, in this case, might represent a fraction of up to 20% of the total mechanical power generated by the ICE. Thus, besides the significant drop in acceleration performance, the fuel consumption and the gas emissions are also negatively affected.

A possible solution to achieve both goals of fuel consumption reduction and a satisfactory acceleration performance might be the development of an auxiliary electric powertrain that can be assembled in a conventional car through a process named “hybridization”. The technology of hybrid and electric vehicles (HEVs) is not new, but it gained strength only in the last few years and has become a reality in the global automotive market, increasing its share of contribution in the sales of great automakers, year after year.

A hybrid powertrain combines the best characteristics of ICEs and electric motors. There are many possible configurations for a hybrid vehicle, but all of them have one objective in common: improving the overall efficiency of the vehicle. The ICE allows the car to travel long distances without the need to fill up the tank for long periods and when it needs to be made, it does not take more than a few minutes. A pure electric vehicle, on the other hand, needs a lot of batteries to have a reasonable range and that is a disadvantage. However, while an ICE has an approximate average efficiency of 15%, an electric motor can easily achieve 80% of efficiency (Gallo, 2013). Another great advantage an electric motor has over an ICE is the capacity of recovering a great fraction of the energy during braking, storing it in the energy accumulator (usually made up of batteries) to use it again in a posterior acceleration. Therefore, a hybrid vehicle is able to combine the high efficiency of electric motors with the high range autonomy the ICEs provide.

Nevertheless, a hybrid vehicle also has a few disadvantages when compared to a conventional or a pure electric one. Since hybrid vehicles have both the ICE and the electric motor, they tend to be more complex and expensive. Besides that, the tractive batteries take up a lot of space, even though their weight and volume is much smaller than in a pure electric car (Bravo et al., 2014).

In this context, this work focuses on evaluating the use of an auxiliary electric powertrain in a car equipped with a 1.0 liter engine, air conditioning and power steering systems. In order to perform such study, a computational model is built using a standard urban driving cycle for the proposal made, having a same base in common to compare the simulation results between the hybridized model and the reference one. The control strategy proposed is designed to be as simple as possible and uses a heuristic approach in order to minimize the processing power required by the devices that will control this auxiliary system, reading the signals from other parts that are present in the car, processing the implemented strategy and sending the desired command signals to the electric powertrain components. The analysis will focus on fuel consumption and acceleration performance only, leaving aside the greenhouse and pollutant gases emissions.

2. ENERGY MANAGEMENT STRATEGIES

An energy management strategy (EMS) is usually implemented in the vehicle central controller and is defined as an algorithm with laws regulating the operation of the vehicle’s powertrain. Generally, its inputs are measurements of vehicle operating conditions such as speed, torque requested by the driver, current gear ratio, the state of charge (SOC) of the tractive batteries, brake command, catalyst temperature, among many others. The outputs of this kind of control strategy are basically decisions to turn ON or OFF certain components or to modify their operating regions by commanding local component controllers. The main objectives of hybrid energy management strategies are meeting the driver’s demand for the traction power, sustaining the battery charge and optimizing the powertrain efficiency, fuel consumption and emissions (Salmasi, 2007).

In the literature, there are two main categories for these control strategies: the first one is based on rules while the second comprehends the optimization-based methods. The main aspect involved in rule-based approaches is their effectiveness in real-time supervisory control of hybrid powertrains since they generally do not require a prior knowledge of the driving cycle. On the other hand, some of the optimization-based strategies (global optimization) can be performed only over fixed driving cycles making their application in real-time systems impossible and, even the ones that can be implemented in real-time applications, tend to be a lot more complex than the rule-based solutions. Nevertheless, optimization-based models can be used to design more efficient rules or to evaluate the quality of other control strategies through comparisons (Salmasi, 2007). Energy management strategies based on rules, therefore, can be designed based on heuristics, intuition, human expertise and even results observed from optimization-based models that, even not applicable in real-time applications, indicate actions that can be taken in order to increase the overall efficiency of a given hybrid powertrain.

Heuristic energy management strategies depend a lot on specific characteristics of the vehicle and powertrain configuration, but some recurrent features can be identified. One of these features, for example, refers to the SOC of the batteries: the battery discharge and recharge phases should be regulated such that the SOC stays within predefined thresholds, preventing the batteries from being damaged (Guzzella and Sciarretta, 2013). Another intuitive rule states that better fuel economy can be attained by having smaller accelerator commands, causing the ICE to operate at lower speed and torque (Baumann et al., 2000).

The main advantage of heuristic controllers is that they are intuitive to conceive and are able to directly translate control specifications. Two common approaches to implement these intuitive principles are the map-based (lookup tables) and the rule-based ones which can both provide good results in terms of fuel consumption reduction and charge sustainability. Unfortunately, the behavior of heuristic controllers strongly depends upon the choice of the thresholds and the maps, which actually can vary substantially with the driving conditions (Guzzella and Sciarretta, 2013).

Due to the practical appeal of this work and the idea of keeping things as simple as possible, a strategy based on simple rules defined heuristically will be adopted, even knowing this will not provide optimal results.

3. VEHICLE DYNAMICS AND DRIVING CYCLES

A number of approaches can be used to model vehicle dynamics depending on the overall simulation objectives. A single degree-of-freedom (DOF), point mass model, can be selected for an initial estimate of vehicle performance as different powertrain options are explored (Lin et al., 2001). Since the focus of this work is on the energy management strategy, the vehicle dynamics equations for this model are not presented here, but they can be found in Gillespie (1992).

A driving cycle represents the road characteristics and the manner the vehicle is supposed to be driven along a determined path. To put it in simple terms, it is defined as a sequence of vehicle target speeds along the time and, therefore, the vehicle acceleration can be obtained from the derivative of this speed profile with respect to time. Gathering some more information regarding specific vehicle characteristics such as masses, inertias and mechanical losses, it is possible to completely define the inputs (driving and braking forces) necessary to make the car follow a given speed profile (Corrêa, 2013).

Driving cycles are employed to compare the pollutant emissions and fuel economy of different vehicles on the same basis. They can be used both in simulations and on chassis dynamometers, where the scheduled speed profile is displayed on a monitor while a test driver controls the gas and brake pedals such that the vehicle speed follows these reference values within pre-specified error bands (Guzzella and Sciarretta, 2013).

There are several standardized test cycles that are commonly used and they are designed to represent both urban and extra-urban driving conditions: FUDS (urban driving cycle used in USA), FHDS (highway driving cycle used in USA), FTP-75 (USA), NEDC (Europe), NBR6601 (Brazilian urban cycle) and NBR7024 (Brazilian highway cycle), just to mention a few. Even though they are a powerful tool to compare different vehicles, real driving patterns are often much more complex and demanding than these test cycles. All automotive companies have their in-house standard cycles, which better reflect the average real driving patterns (Guzzella and Sciarretta, 2013).

For the purposes of this work, the employment of a standardized cycle is enough. The test cycle that was chosen by the authors to perform the simulations is the FTP-75, which represents an urban route without taking into account road elevations. The speed profile of this driving cycle is presented in Fig. 1.

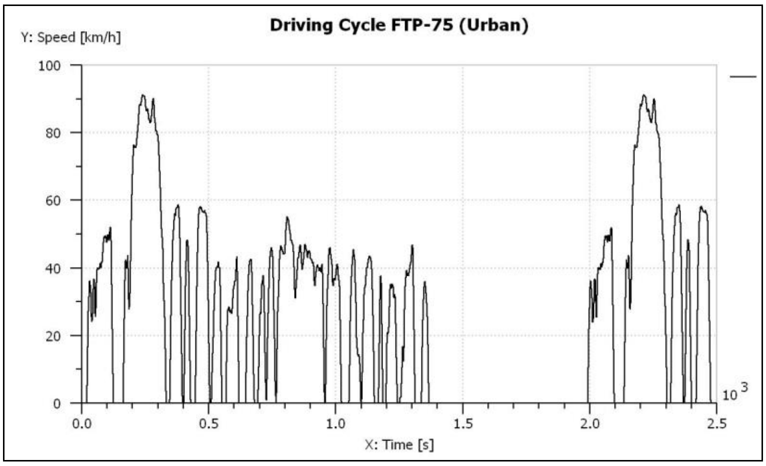

Figure 1 – Speed profile of the FTP-75 urban driving cycle.

4. THE AUXILIARY ELECTRIC POWERTRAIN: PROPOSAL AND MODELLING

This section provides an overview on the author's proposal and describes in detail the computational models built in AMESim as well as the energy management strategy implemented in the Simulink-based components.

4.1 Proposal overview

The main goal of this work is to study the effects caused by the installation of small (low torque and power) electric motors in the rear axle of a lightweight vehicle. In order to supply the energy required by these electric machines, a small capacity battery pack should be used. Since this auxiliary system is an add-on accessory that is supposed to be installed in a conventional vehicle which has never been thought to be hybrid, it is highly desirable that it does not interfere directly with the original components, i.e., the auxiliary electric powertrain should be as non-intrusive and independent as possible. Therefore, the energy management strategy cannot control directly any of the original systems of the car but it can read the signals from several sensors that are already present in the automobile (accelerator pedal position, vehicle speed, engine rotary speed, gear engaged, brake pressure, among others).

The electric motors are supposed to provide extra power to the vehicle in order to decrease the amount of torque required from the ICE, this way contributing to an improvement in fuel economy and acceleration performance, mainly when an accessory like air conditioning is on. However, the electric motors alone, unlike seen in other hybrid vehicles, do not need to have enough torque to move the car on their own since the objective here is just aiding the original powertrain. Besides that, they should also be used to recover a fraction of the energy that is dissipated when the brake pedal is actuated or when the accelerator pedal is not being pressed, partially recharging the tractive batteries.

Finally, the system operation must be intuitive from the driver's perspective: the hybridized vehicle must present a dynamic behavior very similar to the conventional one.

4.2 Proposed strategy

The EMS proposed by the authors requires that the accelerator pedal have a fraction of its total travel reserved for the regenerative braking function. The original accelerator pedal is modelled linearly and the torque command for the ICE is proportional to the accelerator pedal position: when the pedal position sensor indicates 0% no torque is being demanded from the ICE, and when it indicates 100% it means that the maximum torque of the ICE is being requested by the driver (this logic is represented by the dashed line in Fig. 2(a)). In order to incorporate the regenerative braking function, a change is made in the accelerator command signal that goes from the pedal position sensor to the engine control unit (ECU), as represented by the continuous line in Fig. 2(a). Therefore, for the proposed strategy, the initial 10% travel of the pedal is reserved for the regenerative braking function and it has no effect on the ECU. Aiming at fulfilling the objective of dynamic behavior similarity between the conventional and the hybridized model, the regenerative braking was conceived in a way that it works intuitively like the ICE brake: as the driver decreases the pressure on the accelerator pedal, the ICE brake torque increases until a maximum that occurs at the pedal position of 10% (0% from an ECU perspective); if the driver continues decreasing the pressure and the pedal position sensor indicates a value lower than 10%, the regenerative braking then starts to actuate progressive and linearly, until it reaches its maximum braking torque at 0% of the pedal position.Thus, if the vehicle moves and the pedal position sensor indicates 0%, both the electric and the ICE will be operating at their highest braking torque. Figure 2(b) shows the proposed pedal curve for the electric powertrain.

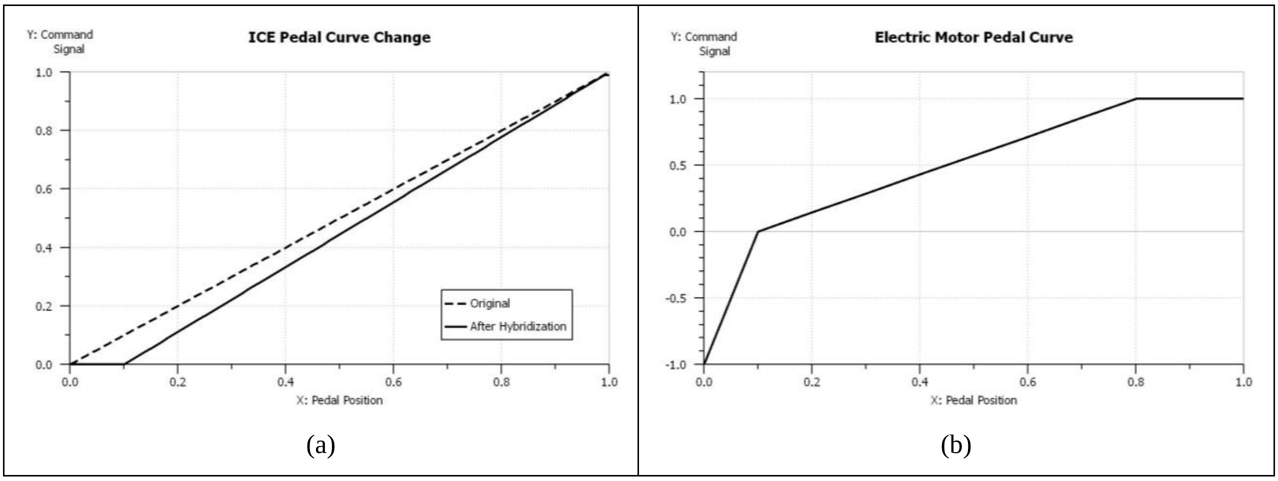

Figure 2 – Pedal curves: relation between pedal position and command signals sent to the ICE and to the electric powertrain. (a) Curve change to incorporate pedal travel for regenerative braking. (b) Electric motor pedal curve.

The pedal curve shown in Fig. 2(b) refers exclusively to the electric powertrain and determines, in a direct way, the total amount of torque that must be provided to the rear axle of the vehicle by the electric motors for a given position of the accelerator pedal. This suggestion was defined arbitrarily and implemented in the Simulink-based VCU in order to have its simulation results compared to the ones of the reference model.

The SOC of the batteries is another important parameter that must be used to determine whether certain commands can be given by the VCU, based on the strategy algorithm. Minimum and maximum thresholds for the SOC must be defined in order to prevent the batteries from being damaged due to overcharge or over-discharge. Every battery manufacturer recommends safe limits for their products, depending on diverse characteristics of the battery cells. In this work, an inferior SOC limit of 20% is adopted. The maximum acceptable SOC threshold for operating conditions is 90%, except for the case in which the batteries are being recharged connected to an electricity source (a charging station, for instance).

So based on all the information gathered until this moment, a simple set of rules is proposed:

1. If SOC ≤ 20% , the electric motors can operate only in regeneration mode until the SOC reaches or exceeds 30% again (SOC ≥ 30%);
2. If SOC ≥ 80%, the regenerative capacity must be decreased by 10% for every advance of 1% in the SOC (when SOC ≥ 90% the regeneration capacity is null);
3. The regeneration mode starts only 3 seconds after the accelerator pedal enters the "regenerative zone" (from 0% to 10%), and when it starts it must be made progressively. This rule prevents abrupt deceleration from happening during gearshifts;
4. If the brake pedal is actuated, the 3-seconds rule must be ignored, but the regeneration still needs to be made progressively;
5. The amount of electric torque (positive for acceleration or negative for regeneration) must be determined exclusively by the accelerator pedal position according to the curve shown in Fig. 2(b).

In order to insert this strategy in the computational model, a C-code has been written and implemented in Simulink.

4.3 Computational model

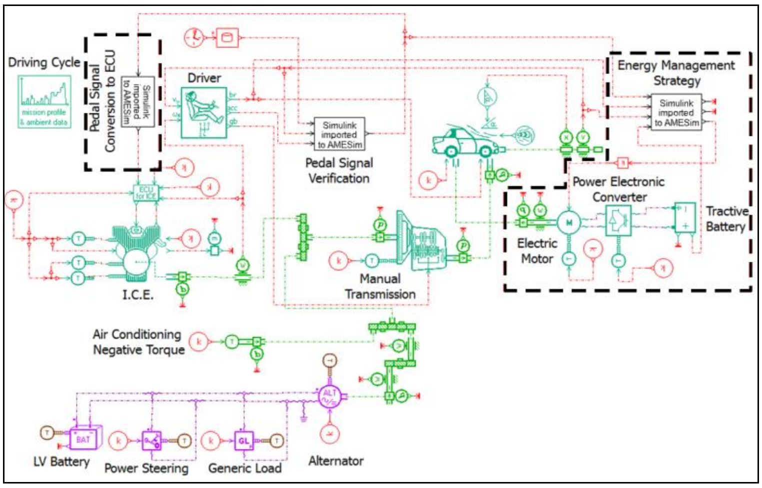

Figure 3 – Hybridized model built in AMESim with Simulink-based components.

The first step of this work consisted in building the reference model: a lightweight vehicle equipped with a 1.0 liter engine, manual transmission, air conditioning and power steering systems. This reference model was tuned through the variation of its input parameters until presenting reliable results. Then, the auxiliary electric powertrain was implemented on the reference model, keeping all the parameters of the conventional vehicle exactly the same, except the vehicle total mass that increased from 1000kg (conventional vehicle) to 1100kg (hybridized vehicle) due to the addition of auxiliary electric powertrain components, such as batteries and electric motors. Therefore, through direct comparison between the simulated results of the hybridized model and the reference one, the authors were able to evaluate the viability of their proposal in terms of fuel consumption and acceleration performance. Figure 3 shows the hybridized model in which the auxiliary electric powertrain components are highlighted with bold dashed lines. If these highlighted components are removed, the reference model is what remains.

The electric motor submodel selected in AMESim is a generic model that works both as motor and generator and is independant from the technology of the motor and its converter. In order to fully characterize it, four parameters are required: the maximum power, the maximum torque, the mean efficiency and the maximum rotary velocity. The parameters used in the electric powertrain and the values adopted for each one of them are presented in Tab. 1.

Table 1 – Parameters used in the electric powertrain components.

Parameter	Value
Maximum electric torque in the rear axle	200 Nm
Maximum electric power in the rear axle	15 kW
Electric motor mean efficiency	85%
Power electronic converter efficiency	90%
Tractive battery voltage	48V
Battery pack configuration	15s2p
Battery pack capacity	1980 Wh
Rated capacity of the battery	40 Ah

5. RESULTS

In this section, the auxiliary electric powertrain and its EMS are evaluated in terms of acceleration performance and fuel consumption. The simulation results of the hybridized model are always compared to the results of the reference model in order to quantify the gains and losses of the proposed system in relation to the conventional one.

5.1 Acceleration performance

The acceleration performance simulations were performed considering five different scenarios. These scenarios took three aspects into account: the powertrain (conventional or hybrid), if the accessories (air conditioning and power steering) are active or not and the tractive batteries SOC. The results are presented in Tab. 2.

Table 2 – Overall acceleration performance comparison.

Scenario	Time [s] (0-60km/h)	Reduction [%]	Time [s] (0-100km/h)	Reduction [%]
1. Conventional with accessories	6,6	-	16,9	-
2. Conventional without accessories	5,9	10,6	14,8	12,4
3. Hybrid with accessories (Initial SOC = 100%)	5,7	13,6	12,6	25,4
4. Hybrid without accessories (Initial SOC = 100%)	5,1	22,7	11,4	32,5
5. Hybrid with accessories (Initial SOC = 25%)	6,9	-4,5	17,9	-5,9

As expected, the accessories have a negative influence on the acceleration performance since they subtract power from the ICE. The auxiliary electric powertrain causes the desired effect when the SOC of the tractive batteries allows the electric torque to be applied on the rear axle and one thing deserves to be pointed out: the hybrid vehicle with accessories (scenario 3) presents better results than the conventional vehicle without accessories (scenario 2). The hybrid model with accessories and low SOC has the worst results because no electric torque can be applied on the rear axle of the vehicle when the SOC is too low and the new components added to the original vehicle (batteries, motors, inverters) increase the total mass to be accelerated only by the ICE, in this specific case.

5.2 Fuel consumption

In order to demonstrate the influence of accessories (air conditioning and power steering) in the fuel consumption of the reference model, simulations with these systems activated and deactivated were performed according to the standard FTP-75 driving cycle. As expected, the vehicle with these accessories consume a lot more fuel (31,9%) than the one without them. The results of this simulation are presented in Tab. 3.

Table 3 – Fuel consumption of the reference model with and without accessories.

Model	Displacement [km]	Fuel consumed [kg]	Fuel consumption [l/km]	Increase [%]
With accessories	17,08	0,9233	0,0721	31,9
Without accessories	17,35	0,7109	0,0546	

Since these accessories have great influence on fuel consumption, all the simulations performed to evaluate the viability of the proposed auxiliary electric powertrain consider that both air conditioning and power steering systems are active. Three analysis are made considering different initial values for the SOC of the tractive batteries. The first scenario represents the conventional model. The second and best scenario is the one in which the car starts the FTP-75 driving cycle with fully charged batteries (SOC = 100%). The fourth and worst scenario happens when the vehicle starts its motion in the driving cycle with a SOC equals to 20% since the electric motors cannot be used to accelerate the vehicle but only to regenerate energy when the brake pedal is actuated or when there is no pressure being applied on the accelerator pedal. In this situation, the SOC first needs to reach 30% so that the electric motors can be used to aid the ICE to accelerate the vehicle. The third analysis is made for an intermediate situation in which the initial SOC is 60%. The results of the four scenarios, in terms of fuel consumption, are presented in Tab. 4.

Table 4 – Fuel consumption comparison between hybridized and conventional models.

Scenario	Displacement [km]	Fuel consumed [kg]	Fuel consumption [l/km]	Fuel economy [%]
1. Reference	17,07	0,9233	0,0721	-
2. Hybrid (initial SOC = 100%)	17,03	0,8294	0,0649	9,96
3. Hybrid (initial SOC = 60%)	16,94	0,8758	0,0689	4,42
4. Hybrid (initial SOC = 20%)	16,78	0,9166	0,0728	-0,99

From the results shown in Tab. 4, it is possible to conclude that for the scenario in which the car starts the simulation with the batteries fully discharged (SOC = 20%), there is an increase of 1% in the fuel consumption that is due, probably, to the increase of the vehicle total mass since the hybrid model has more components than the conventional one. However, in the other two scenarios (SOC = 60% and SOC = 100%), significant gains are observed. For the case in which the car starts the driving cycle with its batteries fully charged, a drop of almost 10% in fuel consumption is achieved. As expected, the higher the value of the initial SOC, the better are the results achieved by the vehicle in terms of fuel consumption. The battery discharge behavior along the FTP-75 driving cycle, for the three last scenarios analyzed, is shown in Fig.4.

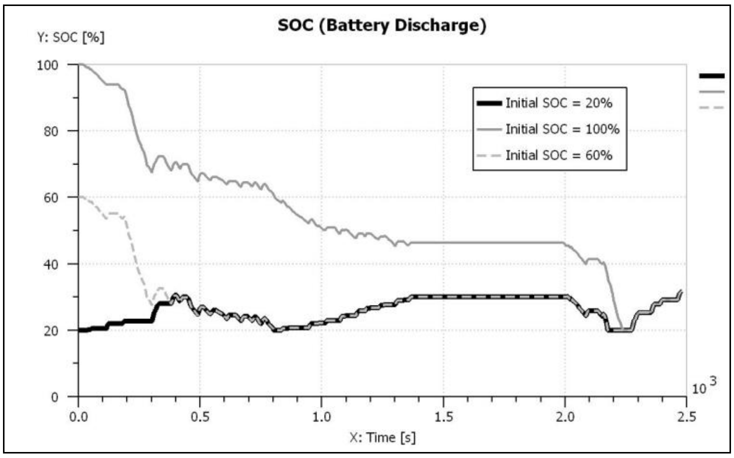

Figure 4 – Tractive battery SOC along the FTP-75 driving cycle for the different scenarios analyzed.

For this specific driving cycle (FTP-75) the proposal of the authors demonstrated great results, reaching up to 10% in fuel economy. However, in order to make a more robust analysis, it is necessary to include other driving cycles and to repeat the same procedure presented here comparing the new simulated results with the ones exposed in this work. Besides that, an important factor that may influence the results and should be included in future studies is the presence of elevations along the path the vehicle moves along, once the electric motors can recover a fraction of the vehicle's gravitational energy.

6. CONCLUSION

The author's proposal proved to have a great potential in the reduction of fuel consumption and improvements in acceleration performance, even though more studies are necessary before assuring this.

The goals stablished initially were achieved and a simple and effective solution was proposed. In this case study, results of up to 10% in fuel economy were achieved and expressive gains in acceleration performance were observed. As stated previously in this work, this solution is far from being optimal, but due to its simplicity it has a great potential to be implemented in a real time application at a low cost.

Nowadays, great efforts have been made to improve fuel efficiency in internal combustion engines, but these efforts are often rewarded with small gains. Hybrid powertrains, on the other hand, can easily provide better results than the ones obtained with the internal combustion engines only.

There is still a lot to be explored in terms of hybrid powertrains to optimize fuel economy, performance and gases emissions, but a simple hybridization process like the one proposed in this work is highly feasible and already provides significant gains, as demonstrated in the previous pages of this article.

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