COBEM 2021 26th International Congress of Mechanical Engineering
ABCM Associação Brasileira de Engenharia e Ciências Mecânicas
November 22-26, 2021, Virtual Congress, Brazil

COB-2021-1356
ENERGY EFFICIENCY COMPARISON BETWEEN ELECTRIC AND CONVENTIONAL POWERTRAINS EMPLOYED IN URBAN CONDITIONS

Lucas Alexandre Gonçalves Lima
lucasalglima@gmail.com
Hiran Williams de Almeida Júnior
hiran.junior@ime.eb.br
Elias Dias Rossi Lopes
elias.rossi@gmail.com
Gustavo Simão Rodrigues
simao@ime.eb.br

Instituto Militar de Engenharia – Praça Gen. Tibúrcio, 80 - Urca, Rio de Janeiro, Brazil

Abstract. *The debate over sustainable, eco-friendlier solutions gathers industry attention all over the world at present. In this framework, the emission of pollutants constitutes one of the main ecological concerns for the present society, especially when it comes to Global warming. Particularly, vehicles powered by fossil fuels play a large role in that matter, representing one of the main sources of carbon dioxide Emissions. Therefore, it is expected that the automotive industry looks for more sustainable, less environmentally harmful solutions. Indeed, many countries have already set deadlines for the end of sales for such vehicles. With that being said, pure electric vehicles comprise one sustainable alternative for modern mobility, not only embodying zero-emission vehicles (ZEV) but being also greatly more efficient when compared to fuel-powered vehicles. This paper aims to testify such an advantage over a standard urban driving cycle, comparing a single-gear electric vehicle to a conventional 5-speed gearbox vehicle through computational models based on, the MATLAB/Simulink environment. The control strategies (gear shifting for the ICE car and electronic control for the EV) shall be the best ones for each model so that the highest possible efficiency is achieved in each situation.*

Keywords: *Electric Mobility, Energy Efficiency, MATLAB/Simulink, Automotive Powertrains, Computational Simulation.*

1. INTRODUCTION

Electric cars do not share the huge success of cars powered by internal combustion engines due to the fact that these have enjoyed greater autonomy and greater ease of recharging. Nevertheless, it has not always been so, and this trend is now changing.

The first electric vehicles date from 1830 and, in fact, employed non-rechargeable batteries as their source of power (Larminie and Lowry, 2012). At the end of the 19th century, these first Electrical Vehicles were more used than cars powered by internal combustion engines (ICE) and those powered by steam engines. With the sharp reduction in the price of oil and with the arrival of autonomous-start ICE, however, vehicles with ICE started to predominate in the automobile market.

Besides the fuel price, the range was also a concern. Even though the electric motor efficiency was way higher than the ICE's, 90% against 20%, the specific energy of petroleum fuel was way higher if compared to the specific energy of a lead-acid battery. That's the reason why a car driven by an ICE would have a range of 50km with 4,5 liters of fuel (4kg) whilst an electric car would need a battery of 270kg to achieve the same range. Furthermore, it would take plenty more time for electric cars to be recharged, due to poor electrical recharging infrastructure at the time. At the same time, all it would take for a petrol car to be refueled was the filling of the gas tank, which took a matter of minutes. Moreover, batteries price would be considerably higher than the necessary investments for both the engine and the fuel reservoir, and they would also require an additional investment periodically, considering the life span of the battery (Larminie and Lowry, 2012).

However, this scenario has been changing in the last decade due to the growing concern with the environment, emissions, and the fact that there was a great development in rechargeable batteries, motors, and automatic controls. Besides the well-known environmental issues, electric cars are safer than ICEs. For they use a battery pack instead of a fuel tank, which is flammable, to store energy. Also, the way the batteries are being placed in EVs nowadays lowers the center of

gravity of the car, increasing further the roll stability of the vehicle.
As well as being safer, electric cars have cheaper maintenance costs because they use fewer mechanisms and rotating parts (Ehsani *et al.*, 2018). Moreover, electric motors are self-started, meaning they don't need another DC engine to help them start as it happens with ICE. On top of that, they don't need a complex transmission: An electronic inverter controls the single-speed transmission by adjusting the output power sequence. These characteristics provide torque even at the start of the motor and also give torque control, which leads to better car performance (Engineering, 2017).
In contrast with the past, electrified cars are becoming quite common. For the time being, most of them are hybrid, driven both by electric engines and ICE. And new technologies, such as the use of regenerative brakes, are making some of their previous downsides, such as the use of huge battery packs and exaggerated time to charge, less of an issue, opening space for electric cars on the market. Besides all these technological changes there's also legislation's forcing the use of more sustainable vehicles and the building cost dropping, which makes the belief of a future with more electric cars than ICE-driven vehicles more reasonable.

2. LITERATURE REVIEW

In order to build a comparison between electric and conventional powertrains, it is necessary to understand the functioning and characteristics of each one. The main difference between these two types of architecture comes from how the power is transmitted from the propulsion system to the wheels. While fuel-powered cars include a list of rotating components in their systems, such as clutches (or torque converters) and multi-speed gearboxes, electric vehicles require much fewer moving components as a rule of thumb.

Traditional transmissions systems available for an ICE vehicle have, in fact, been widely known and employed for quite some time now. In such a manner, (NAUNHEIMER and RYBORZ, 2019) constitutes one of the main sources for fundamentals and design directives regarding the conventional powertrain.

On the other hand, electric vehicles, the way we see them today, are fairly recent and little-known worldwide (even though the first EVs date back from the end of the 19th Century). In this fashion, Larminie and Lowry (2012) provide an introductory view into electrified mobility. Furthermore, it comprises the essential working principles of an electric car, pointing out the main differences from its powertrain to a conventional one, aside from introducing the general fundamentals for an EV design.

Going further, (Ehsani *et al.*, 2018) encompass a methodological procedure for the sizing and the selection of the appropriate powertrain components for a purely electric vehicle. Indeed, it not only describes the process of selection for mechanical gears but also points out important design principles for the electronic controller unit related to the whole propulsion system.

It is possible, finally, to employ such skills and knowledge so as to develop a mathematical model to be used on computational simulation tools. The dynamic equations and transfer functions presented by (NAUNHEIMER and RYBORZ, 2019) and (Ehsani *et al.*, 2018) could be used to build computational models in numeric software for comparing the behavior of two different vehicles operating under similar external conditions.

That is, through the construction of one vehicle model for each type of architecture (conventional gas-powered vehicle and purely electric vehicle), it is possible to compare the energy consumption between the two, for a given urban driving cycle. The last one, de facto, constitutes the main objective of this paper.

3. THEORETICAL FOUNDATION

3.1 Modeling of Vehicle Dynamics

- Firstly, it is necessary to carry out the modeling of the vehicle, which takes into account the driving resistance, which is made up of (Wong, 2008)

- wheel resistance F_R,
- air resistance F_L,
- gradient resistance F_{St}, and
- acceleration resistance F_a.

Wheel resistance - Comprises the resisting forces acting on the rolling wheel. It is made up of rolling resistance, road surface resistance, and slip resistance. For a vehicle with a mass m_F, driven on a surface with rolling resistance coefficient f_R and gradient angle α_{St} the wheel resistance F_R is given by Eq. (1)

$$F_R = f_R \cdot m_F \cdot g \cdot \cos \alpha_{St} \tag{1}$$

Air resistance - The air resistance is made up of the pressure drag including induced drag, surface resistance, and internal resistance. Air resistance is calculated from the product of dynamic pressure and the maximum vehicle cross-section A multiplied by the dimensionless drag coefficient c_W, which is the coefficient of aerodynamic lift usually obtained from wind tunnel testing. Typical values of c_W for passenger cars vary in the range 0.2 - 0.5. (Wong, 2008). Therefore the air resistance F_L is calculated by Eq. (2):

$$F_L = \frac{1}{2}\rho_L \cdot c_W \cdot A \cdot v^2 \tag{2}$$

Gradient resistance - The gradient resistance relates to the slope descending force and is calculated from the weight acting at the center of gravity, as expressed by Eq. (3):

$$F_{St} = m_F \cdot g \cdot \sin \alpha_{St} \tag{3}$$

Acceleration resistance - The total mass of the vehicle m_F and the inertial forces that occur during acceleration and braking are the factors influencing the resistance to acceleration. Considering rotational inertia coefficient λ, which expresses the proportion of the total mass that is rotational, then the acceleration resistance is given by Eq. (4)

$$F_a = \lambda \cdot m_F \cdot a \tag{4}$$

Total driving resistance - The total driving Resistance is made up by the sum of all the equations mentioned previously, and is defined in Eq. (5):

$$F_D = F_R + F_L + F_{St} + F_a \tag{5}$$

Together with Equations 1, 2, 3 and 4, this may be expanded to Eq. (6)

$$F_D = m_F \cdot g \cdot (\sin \alpha_{St} + f_R \cdot \cos \alpha_{St}) + \frac{1}{2}\rho_L \cdot c_W \cdot A \cdot v^2 + \lambda_F \cdot a \tag{6}$$

3.2 Internal Combustion Engines

Internal Combustion Engines (ICE) are engines that generate motive power by the burning of gasoline, oil, or other fuel with air inside the engine, the hot gases produced being used to drive a piston or do other work as they expand.

Characteristics of ICEs The basic features of an internal combustion engine are shown in Fig. 1. The internal combustion engine starts operating smoothly at a certain speed (the idle speed). Good combustion quality and maximum engine torque are reached at an intermediate engine speed. As speed increases further, the mean effective pressure decreases because of growing losses in the air-induction manifolds, and the engine torque also declines. Power output, however, increases with an increase in speed up to the point of maximum power. Beyond this point, the engine torque decreases more rapidly with an increase in speed. This results in a decline in power output (Wong, 2008).

The problem with the internal combustion engine is that the whole shaded area in Fig. 3.2cannot be used without an additional output converter. The output converter must convert the characteristic of the combustion engine in such a way that it approximates as closely as possible the ideal of the traction hyperbola. That's the reason why 5-speed gearboxes are normally used, so the proportion of the shaded area is significantly smaller and the power potential of the engine can be better applied (NAUNHEIMER and RYBORZ, 2019).

Figure 3.2shows that increasing the number of speeds as much as possible gives a correspondingly better approximation to the traction hyperbola. With continuously variable transmissions, the traction hyperbola can correspond to the traction characteristic curve over the range of ratios. The problem with adding gears to the gearbox is that, as the number of gears is increased, so is the size and weight of the gearbox. It's a trade-off, therefore is necessary to verify which number of speeds deliver the best cost benefice. The automobile industry normally uses 5-speed gearboxes.

3.3 Electric Motors

An electric motor is an electrical machine that converts electrical energy into mechanical energy. In the case of an Electric Motor the input and output powers are straightforward to measure, the product of voltage and current for the input, and torque and angular speed at the output.

Electric Motor efficiency - The efficiency of an electric motor is not as simple to measure as might be supposed.The problem is that it can change with different conditions, and there is no single internationally agreed method of stating

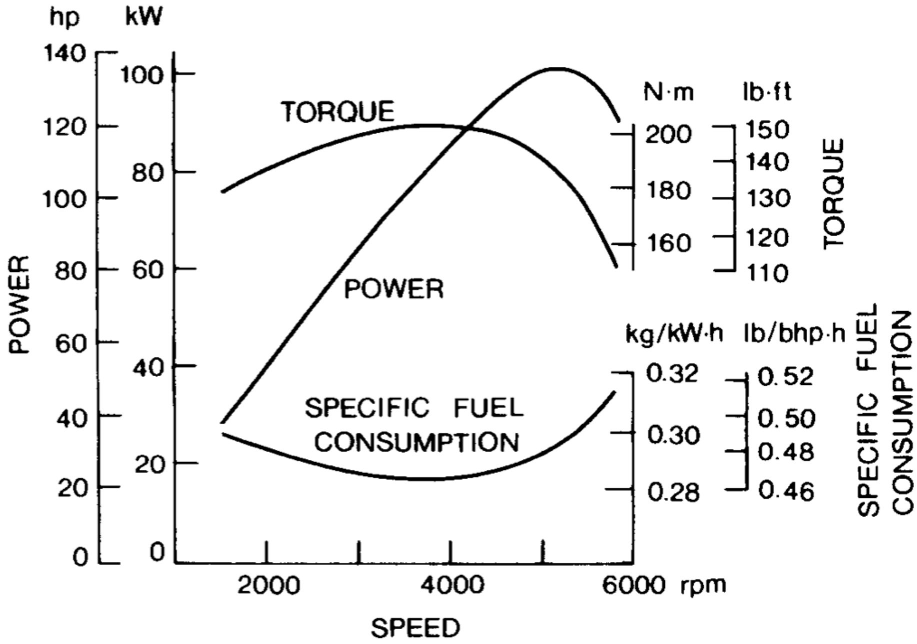

Figure 1. Performance characteristics of a gasoline engine. (Wong, 2008)

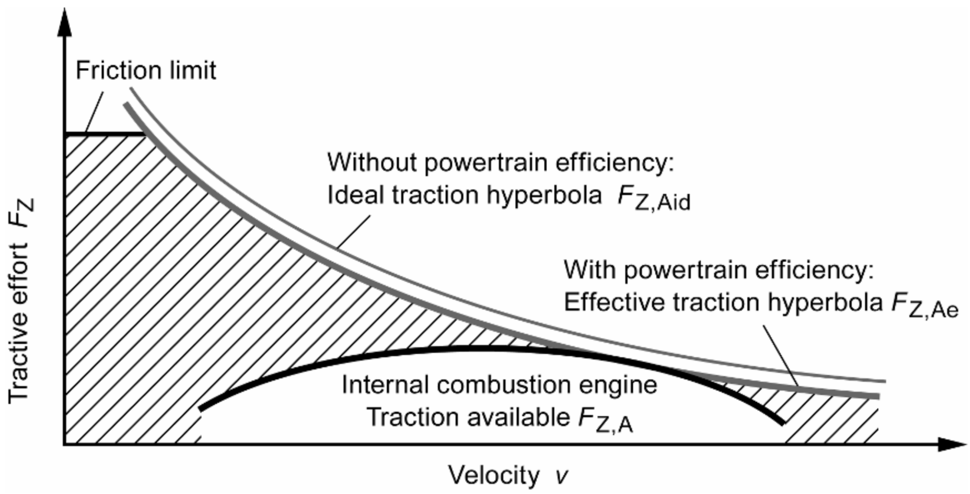

Figure 2. Traction Diagram of ICE without a gearbox

the efficiency of a motor (Auinger, 1999). Nevertheless, it is possible to state some general points about the efficiency of electric motors, the advantages and disadvantages of the different types, and the effect of motor size (Larminie and Lowry, 2012).

The first general point is that motors become more efficient as their size increases. Table 1 shows clearly the effect of size.

The second point is that higher-speed motors are more efficient than lower-speed ones as shown in fig. 4. The reason for this is that one of the most important losses in a motor is proportional to torque, rather than power (Larminie and Lowry, 2012). A third important factor is the cooling method to be employed. Motors that are liquid-cooled usually run at lower temperatures, which reduces the resistance of the winding and hence improves its efficiency.

The efficiency of an electric motor can also be calculated by an equation that takes all the four types of losses presented in all types of electric motors. These major sources of loss can be divided into four main types, as follows.

Copper losses - These are caused by the electrical resistance of the wires (and brushes) of the motor. This causes heating, and some of the electrical energy supplied is turned into heat energy rather than electrical work. Being K_c a constant depending on the resistance of the brushes and the coil, and also the magnetic flux Φ. And T the Torque provided, the cooper loss is defined by Eq. (7):

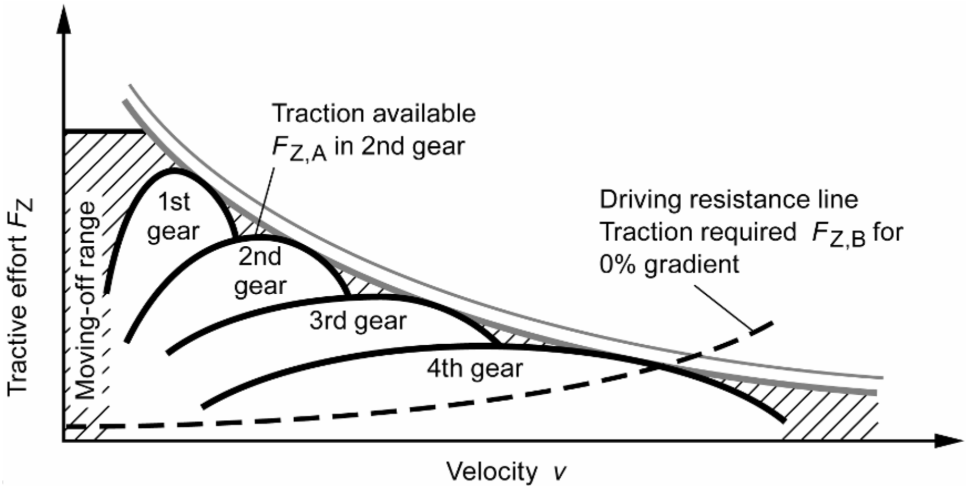

Figure 3. Traction Diagram of ICE with 4-speed gearbox
The role of Gearboxes in ICE Vehicles (NAUNHEIMER and RYBORZ, 2019).

Table 1. The minimum efficiency of a four-pole three-phase induction motor for it to be classified as Class 1 efficiency under EU regulations. Efficiency measured according to IEC 36.2.

Power, kW	Minimum efficiency, %
1.1	83.8 %
2.2	86.4 %
4	88.3 %
7.5	90.1 %
15	91.8 %
30	93.2 %
55	96.2 %
90	95.0 %

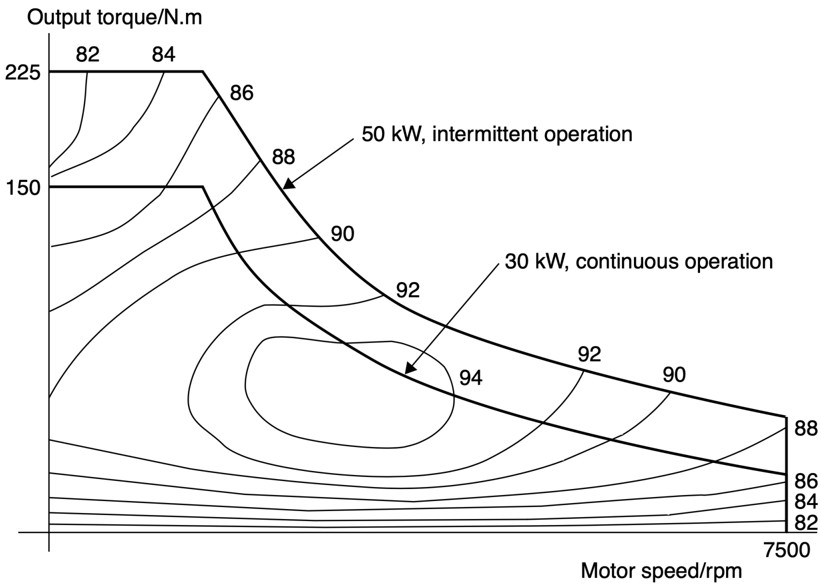

Figure 4. The efficiency map for a 30 kW Brushless DC motor. (Larminie and Lowry, 2012)

$$C_L = K_c \cdot T^2 \tag{7}$$

Iron losses - They are caused by magnetic effects in the iron of the motor, particularly in the rotor where the magnetic field is continually changing and thus affecting the iron. Therefore the loss is proportional to the frequency with which that magnetic field changes which is directly proportional to the speed of the rotor. As K_i is a constant, then Eq. (8) holds:

$$I_L = K_i \cdot w \tag{8}$$

Friction and windage - The rotor also faces a wind resistance that will increase with the square of the speed. K_w is a constant depending mainly on the size and shape of the rotor, and whether or not a cooling fan is fitted. The power involved in these forces is then given by Eq. (9):

$$W_L = K_w \cdot w^3 \tag{9}$$

Constant losses - Occur even if the motor is stationary, and vary neither with speed or torque. In the case of the separately excited motor, these are definitely not negligible, as current must be supplied to the coil providing the magnetic field. The letter C is used to designate these losses. Therefore, combining equations 7, 8 and 9 the total losses is achieved by Eq. (10)

$$T_L = K_c \cdot T^2 + K_i \cdot w + K_w \cdot w^3 + C \tag{10}$$

That being said, the motor efficiency can be described by Eq. (11):

$$\eta_m = \frac{output_{power}}{input_{power} + losses} = \frac{T \cdot w}{K_c \cdot T^2 + K_i \cdot w + K_w \cdot w^3 + C} \tag{11}$$

4. MODELING

At first, were developed two models employing the Simscape Physical Library, which provides physical-mathematical modeling describing the different aspects and relations inherent to Multi-body systems, as in the case of Automotive Powertrains.

These two models were not necessarily based on any particular real vehicle.

Later on, the analysis concentrated on one of the most fuel-efficient ICE vehicles available on the market as of 2021, and how would a loosely designed EV stack up against it.

4.1 Modeling of Powertrains in Simulink environment

ICE Vehicle Modeling

The ICE Powertrain model was based on the components available within the Simulink Powertrain Blockset.

The vehicle was then modeled employing an inherent Simscape Engine (based on the Torque x Speed and Fuel consumption maps). The engine was mechanically coupled with the transmission system through a Torque Converter, which in turn was connected to a 5-speed gearbox. Finally, the power was transferred to the differential, the final drive, powering the tractive wheels of the vehicle.

An overly simplified view of the model is shown in Fig. (5). The gear shifting strategy and each relation are detailed ahead, inputting the appropriate relation at each time to the Transmission, representing the Gearbox. As for the brake and acceleration commands, they were controlled by a PID Controller, allowing the vehicle to follow the speed desired in each standard Driving Cycle.

The gearbox relations for the 5 speeds are stated in table 2. The final drive relation, stated as F_D, is also presented.

Table 2. Gearbox ratios final drive

Speed	Transmission ratio
1	2.3321
2	1.8670
3	1.4947
4	1.1966
5	0.9580
F_D	3.74

The gear shifting strategy was implemented so that the fuel consumption was as low as possible. To do so, the gear would shift upwards as soon as the engine speed surpassed the speed of maximum torque. The gear shift control was implemented in Simulink through *Stateflow*, which represents a State-Machine, as showed in figure 6.

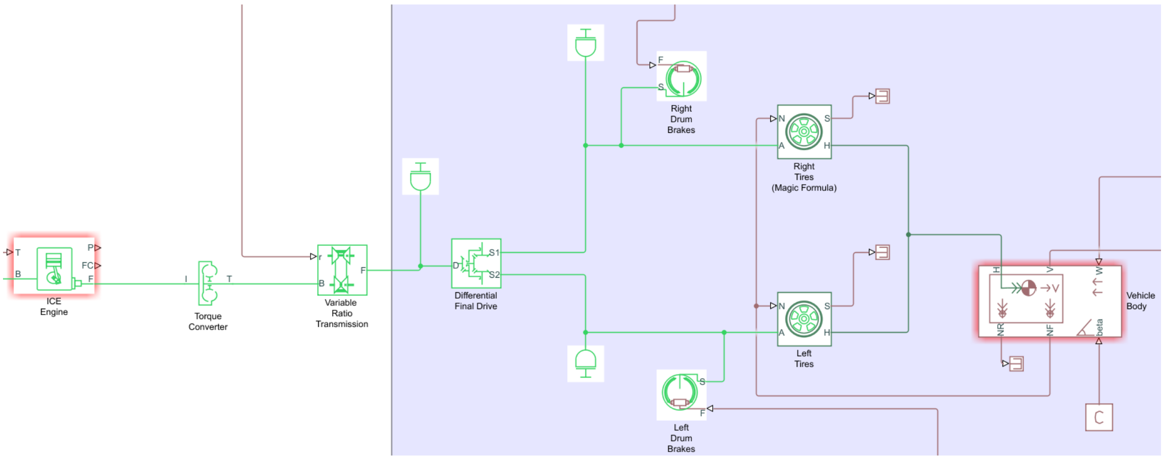

Figure 5. A simplified view of the Modeling in Simulink

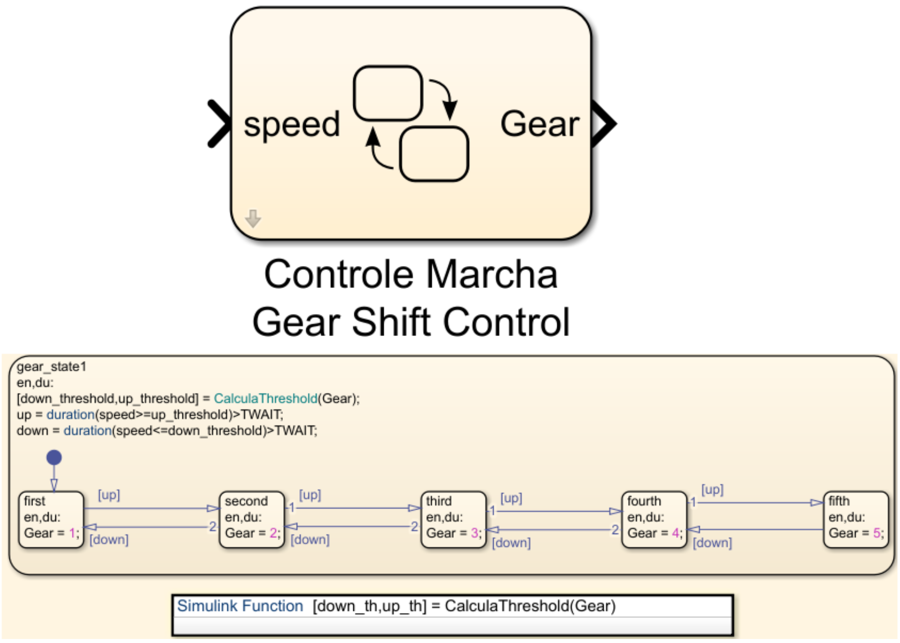

Figure 6. Gear shifting strategy implemented

General/geometric parameters

Furthermore, the most relevant vehicle parameters used in the simulation are showed in Tab. (3). These were kept constant for both the ICE and Electric vehicle, to maintain the maximum number of parameters unchanged between models. The only exception constitutes the vehicle's mass, which might be higher for EVs due to the necessary battery.

Table 3. Parameters used in simulation

Parameters	**Values**
C_d	0.33
A	$2m^2$
m_f	1400
f_r	0.015

EV Modeling

The electric vehicle model, on the other hand, was modeled with a single gear transmission, followed directly by the differential. The parameters for the BEV's Powertrain are shown in Tab. (4).

Table 4. Electric Vehicle parameters

Parameters	**Values**
Maximum velocity	1132 [rpm]
Nominal velocity	800 [rpm]
Power	65Kw (87Hp)
Nominal Voltage	370 V
Additional battery weight	450 kg

It is important to note that, in order to permit a fair comparison between the two types of cars, an estimated 450 kg of Li-Ion battery was added as cargo to the BEV, assuring the same distance range for both architectures.

5. SIMULATION RESULTS

The simulation was based on the standard FTP-75 Driving Cycle, shown in Fig. (8), for this represents one of the main tests used across America (including Brazil) to certificate fuel consumption and emissions. It is defined by the US Environmental Protection Agency (EPA)

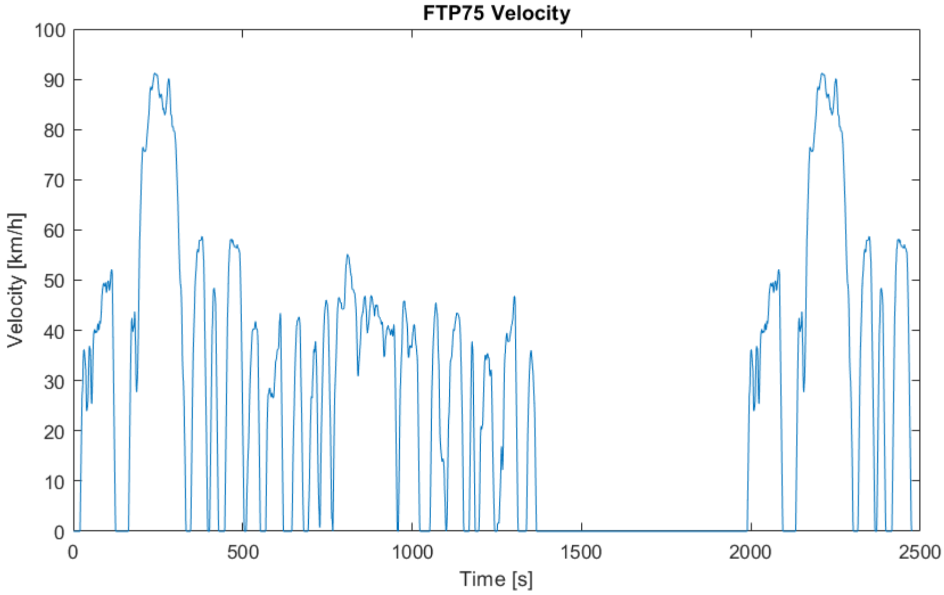

Figure 7. FTP Cycle employed

As aforementioned, in order to achieve the desired speed profile, the acceleration and brake inputs (ranging from 0 to 1 in both cases) were controlled by a PID controller. The results for the ICE Vehicle are shown in figure

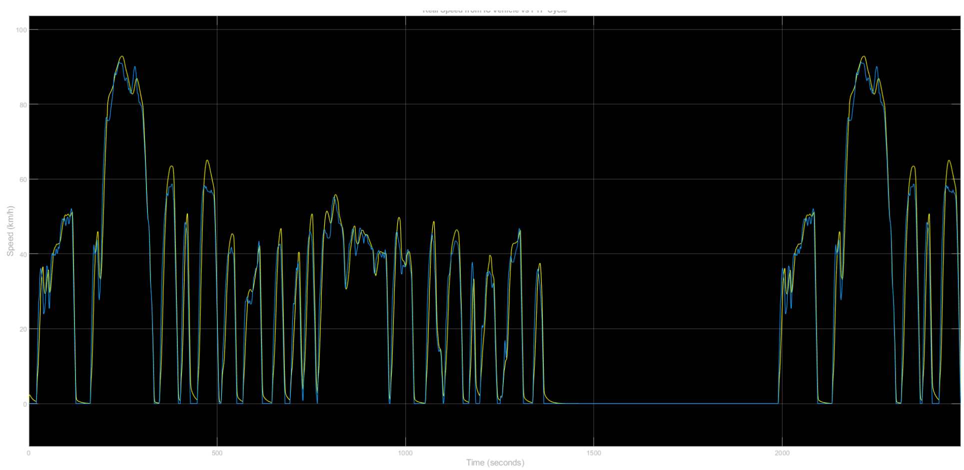

Figure 8. FTP Cycle plotted against the simulated car performance

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For the FTP Cycle and for both architectures previously shown, the results are as follows in Tab. (5):

Table 5. Simulation results: Energy Consumption

Parameters	Values
ICE Vehicle	13 [km/l]
BE Vehicle	3 [km/kWh]

The great advantage of the electric vehicle, however, presents itself at the financial sheet, as in Tab. (6). The specific power prices were determined by the average price in the state of Rio de Janeiro, Brazil. The energy fee was recorded for the consumption of 150–300 kW during the so-called *"Red Flag"* for electric energy: when the unit energy has reached its most expensive cost.

Table 6. Comparison between ICE and EV vehicles.

Vehicle Type	Consumption (100km)	R$/Power	Final Price (R$/100km)
ICE	7.7 L	5,78	44,506
EV	33 kWh	0,83864	27,68

In this simulation, the cost for recharging/refueling was at least 37,8% cheaper.

It is clear that, even for a BEV equipped with a motor not designed for the vehicle (and consequently working at a relatively low-efficiency operating point), the financial benefits presented by Electrical vehicles to consumers are explicit.

As a matter of fact, one of the most fuel economic ICE cars produced in 2020 was the Mitsubishi Mirage, which achieved around 4–5 L/100 km for the NEDC or WLTP cycles. It is capable of accelerating from 0 to 100 km/h in 12.6 seconds (without cargo). With its 35 liters gas tank, it would be capable of traveling roughly 700 km without refueling.

On the other hand, Tesla's Model 3, an economical electric sports car, is claimed to have a regular energy consumption of 18 km/kWh. The manufacturer also has claimed that the car has an estimated range of around 657 km in its Long Range model, putting the vehicle quite closely to Mirage on this matter.

The comparison in consumption between both vehicles is shown on Tab.(7)

(It should be noted, however, that such comparison should be taken solely as a matter of information, since many parameters between both vehicles are different, such as Drag Coefficient, Mass, max speed).

Table 7. Comparison between real ICE / EV vehicles.

Vehicle	(0–100 km/h)	Max. Speed	Cons. (100km)	R$/Power	Final Price (R$/100km)
Economic ICE (Mirage Hatch)	12.6 s	180 km/h	4–5 L	5,78	23,12–28,90
Sport EV (Tesla 3)	4.6 s	233 km/h	18 kWh	0,83864	15,10

In this scenario, it would be at least 34,6% cheaper to travel with the BEV, as compared to the ICE car.

6. CONCLUSION

The development of reliable and highly efficient electric motors, associated with the great progress already achieved in Battery development, has made it possible for electric vehicles to become a clear alternative for Urban mobility. The environmental need to turn away from fossil fuels reinforces this fact.

Due to the intrinsic characteristics of Electric Motors, EVs don't usually require a multi-speed gearbox. If the vehicle is intended only for urban areas i.e. low-speed regions, a one-speed gearbox could suffice, as (NAUNHEIMER and RYBORZ, 2019) state. Moreover, the continuous operating range of E-motors allows BEVs to be designed without clutches/Torque converters, further simplifying the Powertrain and also removing a possible source of energy losses.

It is possible to summarize all main sources of energy losses which are taken away from E-Cars, in order to comprehensively understand the upsides presented by electrified vehicles:

- Considerably higher efficiency of E-Motors, especially compared to combustion engines;
- Performance characteristics of motors ideally match the ideal power curve desired for optimal vehicle performance;
- E-Cars allow for simplified transmission systems/Gearboxes, by reducing the number of gears necessary and thus reducing meshing losses;
- Continuous operation of electric motors removes the need of a clutch, which is also a source of mechanical losses.

Bearing in mind all these factors, it is no surprise the advantage of Electric cars over ICE vehicles in terms of energy usage. In fact, it has been seen that such upside reflects itself in the regular costs for the driver, being considerably cheaper to recharge an EV in Brazil when compared to a so-called "conventional" car.

As a consequence, when E-Cars, in fact, reach a production cost similar to Conventional ones, due to increasing progress in Battery development, the adoption of Electric Mobility would be a benefit not only for the environment: it would also represent big savings for the everyday driver.

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