Analysis of the modes of operation of an electric vehicle on energy consumption

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***Abstract*— This manuscript presents a comprehensive analysis of the modes of operation of an electric vehicle (EV) and their impact on energy consumption. The study focuses on investigating the influence of three different drivers and three distinct road inclinations on the energy efficiency of an EV via simulation in MATLAB Simulink. The objective of this research is to gain a deeper understanding of the factors that affect energy consumption in various operational scenarios, ultimately contributing to the optimization of EV performance, range, and battery state of health (SOH). The obtained results (namely battery state of charge, battery current, motor torque) were analyzed in detail to assess the patterns associated with each driver type and road inclination scenario. Statistical techniques were employed to identify significant differences in energy efficiency among the various modes of operation. Additionally, insights were gained regarding the impact of driver behavior and road inclination on the EV's energy consumption.**

Keywords— electric vehicle, MATLAB Simulink, energy consumption, driver behavior, road inclination

I. INTRODUCTION

The introduction and large-scale use of electric vehicles in traffic (especially in the urban environment) represents the solution adopted at the global level for the reduction/elimination of pollution caused by the polluting emissions of internal combustion engines. From the very beginning, electric vehicle manufacturers had to solve the major problems (barriers) caused by customer requirements, especially related to the driving range for a full charge of the battery. For this reason, research has become numerous in the direction of increasing the energy efficiency of the battery through: the development of new materials and electrochemical technologies, intelligent command and control systems of energy flows, reducing the weight of vehicles, efficient thermal management systems, etc.

A simple bibliographic analysis of the articles published on the topic of increasing the performance of electric vehicles shows that there is a lack of studies and research related to the influence of the driver's driving style on the overall energy efficiency of the electric vehicle. The researches and studies published so far mainly refer to the analysis of the main factors of influence that influence the driver's behavior and to the way in which (using different techniques) fuel consumption can be reduced and implicitly the reduction of pollution.

The main links between driver behavior and fuel consumption underlined by different studies can be considered the following [1- 4]:

- acceleration and braking: Frequent and aggressive acceleration and braking consumes more fuel. Rapid acceleration and hard braking waste energy and increase fuel consumption. Smooth and gradual acceleration, as well as gentle braking, can improve fuel efficiency.
- speeding: Driving at high speeds increases aerodynamic drag and requires more fuel to maintain the vehicle's speed. Fuel efficiency tends to decrease significantly at higher speeds. Adhering to speed limits and driving within a reasonable speed range can help conserve fuel.
- idling: Keeping the engine running while the vehicle is stationary, such as during long periods of idling, wastes fuel. Turning off the engine when parked or waiting for extended periods can save fuel.
- constant speed: Consistently maintaining a steady speed, especially on highways, promotes fuel efficiency. Avoiding unnecessary speed fluctuations or sudden changes in speed can help conserve fuel.
- planning routes: Efficient route planning can reduce fuel consumption. Minimizing the distance traveled, avoiding congested areas, and choosing routes with fewer stops and traffic lights can improve fuel efficiency.
- vehicle maintenance: Neglecting vehicle maintenance, such as ignoring engine tune-ups, underinflating tires, or using poor-quality motor oil, can negatively impact fuel efficiency. Keeping the vehicle properly maintained helps optimize fuel consumption.

In addition to the technical approach to the problem of efficient use/exploitation of a vehicle (presented above), in general, it can be considered that several key factors influence driver behavior (Fig. 1) [5 – 9]:

- cognitive factors: Attention, perception, decision-making, and reaction time are cognitive processes that impact driver behavior. Distractions, fatigue, and impaired mental states (e.g., due to alcohol or drugs) can significantly affect these factors.

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▪ individual characteristics: Personal traits such as age, gender, experience, attitude, and risk perception can affect driver behavior. For example, younger and less experienced drivers may exhibit riskier behaviors compared to older and more experienced drivers.
▪ social and cultural factors: Cultural norms, social pressures, and peer influence can shape driver behavior. For instance, cultural attitudes towards speeding or seat belt usage can impact individual driver choices.
▪ environmental factors: Road and traffic conditions, weather conditions, and infrastructure design can influence driver behavior. Heavy traffic, poor road conditions, or adverse weather can increase stress levels and affect decision-making.
▪ legal and regulatory factors: Traffic laws, enforcement, and penalties play a role in shaping driver behavior. Strict enforcement and harsh penalties for traffic violations can act as deterrents and promote safer driving practices.
▪ Vehicle characteristics: The design, performance, and condition of a vehicle can impact driver behavior. Factors such as vehicle speed, handling capabilities, and advanced safety features can influence driver choices and actions.

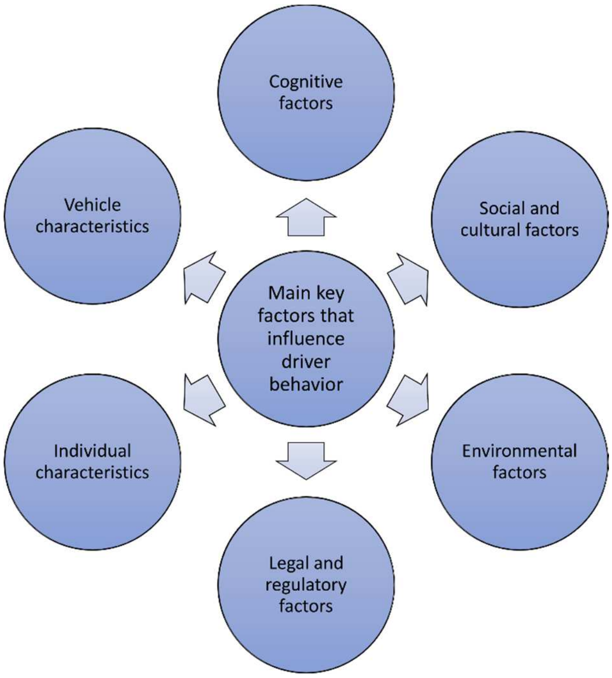

Fig. 1. Key factors that influence driver behavior

It is important to note that driver behavior is a complex interplay of these factors and can vary significantly among individuals, and in this context, the question arises whether the operating mode of a vehicle with an internal combustion engine has an effect or not when the driver switches to an electric vehicle.

In the case of electric vehicles, it is found that battery state of health (SOH) indicates a point of its lifetime and evaluates the health level of the present specific performance compared with the initial state, being an important factor in the operating time of an electric vehicle. One of the important factors regarding the functional degradation mechanism of the battery is the peak of the charge/discharge current [10 - 12].

The purpose of this article is to analyze the energy efficiency of an electric vehicle in a particular traffic case, by numerical computer simulation (MATLAB Simulink). Several scenarios are considered related to the departure from the spot (from the traffic light stop) for different situations of actuation of the accelerator pedal, in the mode: aggressive, normal and defensive. The analysis parameters taken into account were motor torque, battery state of charge and battery current; and the conclusions drawn were based on two major directions of analysis of the energy efficiency through the autonomy of the electric vehicle and the effect on the requests of the energy source (of the battery), conclusions that allowed issuing some solutions related to the studied problem.

II. SIMULATION MODEL

The simulation model is made in MATLAB Simulink (namely EvReferenceApplication from MATLAB Library, under University license), and consists of an electric vehicle made with:

▪ a longitudinal driver subsystem that uses the closed loop variant;
▪ the environment subsystem that includes the road gradient, wind velocity and atmospheric conditions;
▪ controller subsystem that includes the powertrain control module;
▪ passenger car subsystem, that has a Simscape electric plant with 3 degrees of freedom vehicle body, longitudinal wheel model, differential and the powertrain that consists of a mapped motor, the EV (electric vehicle) battery and all wheel drive;

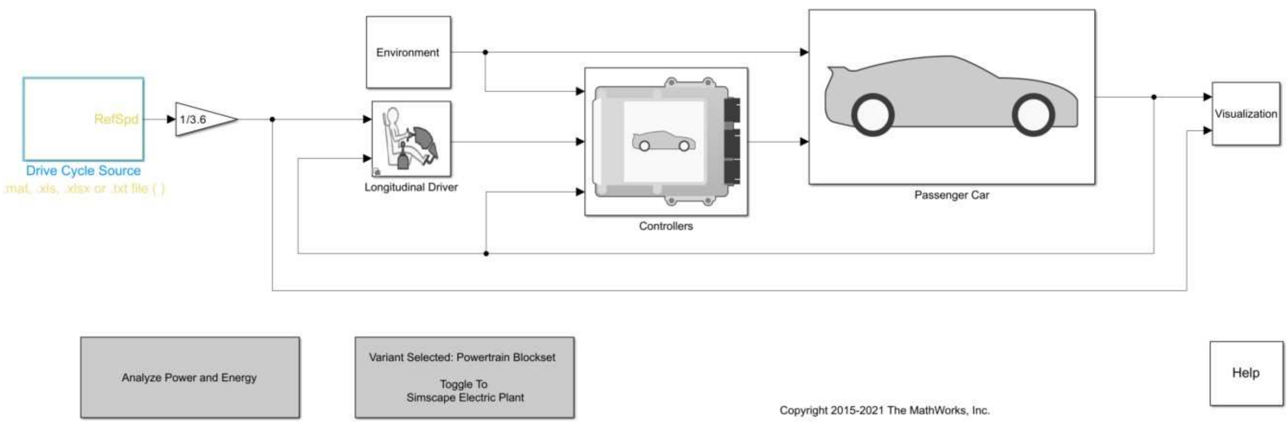

Fig. 2. Model used for simulation of the electric vehicle

The EV battery subsystem is a datasheet battery [13] that uses the following formula for the SOC calculation:

$$SOC\ [\%] = SOC_0[\%] + \frac{1}{C}\int_0^t I_b dt \qquad (1)$$

where SOC_0 is the initial charge of the battery, C is the rated capacity of the battery and I_b is the battery current.

The main input for the model, demand velocity in kilometers per hour, was changed using a signal builder block and sent to the driver that compares the demand velocity with the actual velocity of the vehicle and acts accordingly. The second input factor was the gradient of the road. Three gradients were considered, 0%, 5% and 10% respectively.

The simulation was run for three different drivers: aggressive, normal and defensive, with the three gradients. The demand velocity profiles for the three drivers were created (Fig. 3): for the normal driver (Velocity_dem_norm [km/h]), a linear demand of velocity from stand still to 100 kilometers per hour in 100 seconds, while for the aggressive driver (Velocity_dem_agr [km/h]), a parabolic with higher-than-normal velocity demand was used, but after 100 seconds demand stabilizes at 100 kilometers per hour, and for the defensive driver, a parabolic with lower-than-normal velocity demand was used (Velocity_dem_def [km/h]).

The state of health of the battery, is expressed in percentage and can be calculated as:

$$SOH\ [\%] = \frac{Q_{max}}{C} 100 \qquad (2)$$

where Q_{max} is the maximum available charge of the battery.

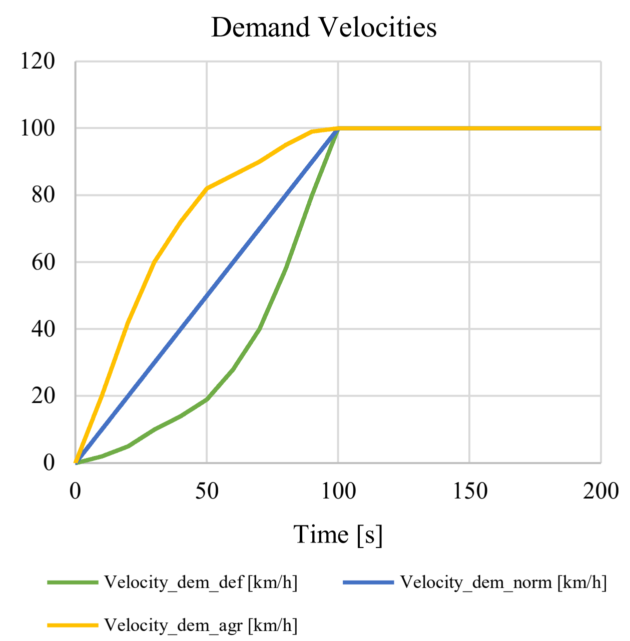

Fig. 3. Demand velocities for the three driver types

III. RESULTS

The simulation data were exported from Simulink to MATLAB workspace and processed.

All outputs have the following annotations:

- def – defensive driver;
- norm – normal driver;
- agr – aggressive driver;
- g0 – road gradient 0%;
- g5 – road gradient 5%;
- g10 – road gradient 10%.

Fig. 4 presents the motor torque for the three driver types, with a road gradient of 0%. It can be seen that for the aggressive driver, the torque demand is high at the beginning (first 20 seconds) of the cycle, with a maximum torque of 49.19 newton meters, and for the defensive driver, there is a high torque demand (max 56.01 newton meters) from second 80 to 100 of the simulation, while for the normal driver, the motor torque increases gradually from 24.61 newton meters to 38.6 newton meters. For all driver types, after 100 seconds, the motor torque stabilizes at 24.44 newton meters since the velocity demand is constant for all drivers.

Another output is the battery current (Fig. 5), for the three driver types on different road gradients.

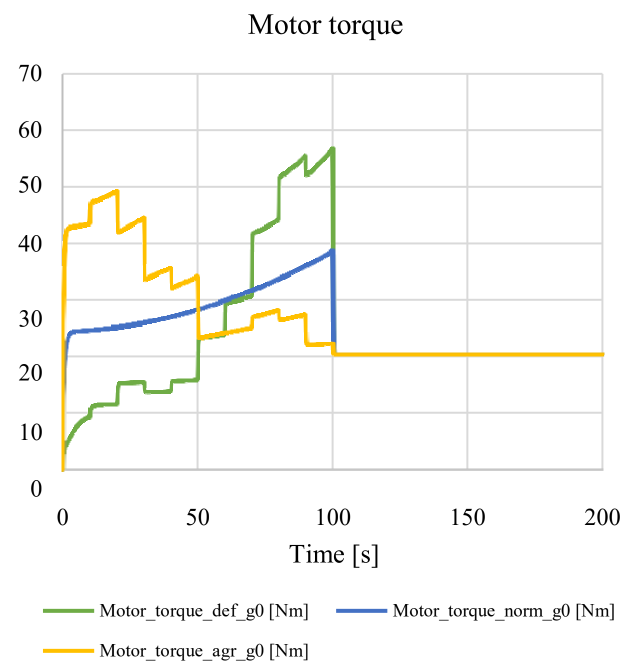

Fig. 4. Motor torque for the three driver types, with 0% road gradient

Table I presents the maximum values for the battery current in amperes.

TABLE I. MAXIMUM BATTERY CURRENT

Road gradient	Max battery current [A]		
	Aggressive driver	*Normal driver*	*Defensive driver*
0%	56.46	80.65	114.88
5%	161.50	187.60	228.71
10%	284.70	314.24	362.03

Fig. 6 presents the battery SOC for all simulations, all starting from 75% SOC.

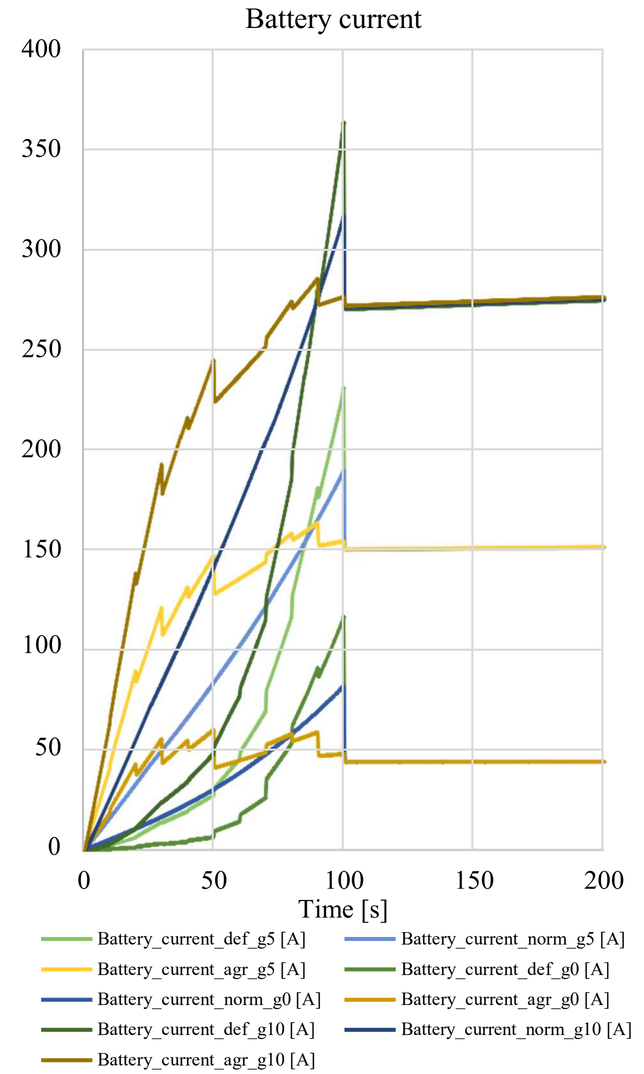

Fig. 5. Battery current for the three driver types with three road gradients

TABLE II. BATTERY SOC AFTER 200 SECONDS

Road gradient	Remaining battery SOC [-]		
	Aggressive driver	*Normal driver*	*Defensive driver*
0%	73.37	73.35	73.56
5%	69.98	70.56	71.06
10%	66.14	67.18	68.20

Fig. 7 presents the average battery current that was calculated for the given cycles.

IV. CONCLUSIONS

The expected conclusion of the simulations was that the defensive driver should be the best at preserving the battery, from the SOC and SOH perspective. Due to the imposed premises: all drivers must reach 100 kilometers per hour in 100 seconds, the conclusions are as follows:

- regarding the state of charge, at a road gradient of 0%, the SOCs are very similar no matter the behavior of the driver; for 5% and 10% road gradient, the defensive driver has the most SOC, but also has the biggest battery current requirement (228.71 amperes and 362.03 amperes respectively), which means that from a holistic point of view, the normal driver would exploit the vehicle in a better way, however, when looking at the average of the battery current values the defensive driver has the lowest values and therefor the recommendation stands – defensive drivers exploit electric vehicles in a more economical way;

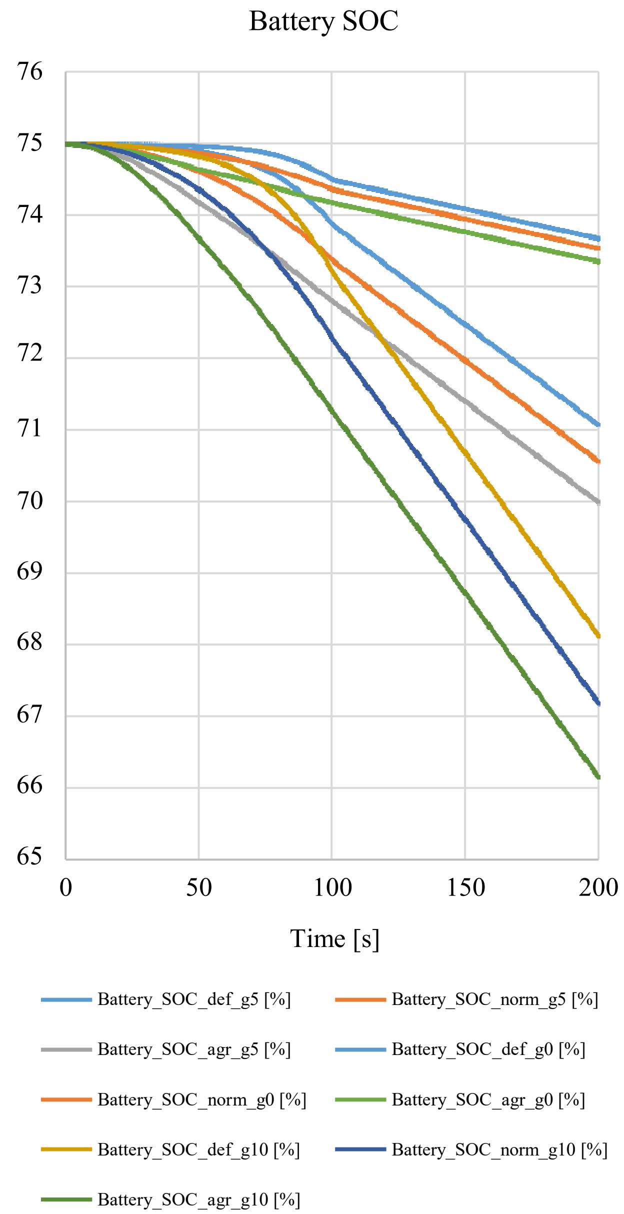

Fig. 6. Battery SOC for the three driver types with three road gradients

- regarding the state of health of the battery (SOH), since it is a measurement that indicates the level of degradation and remaining capacity of the battery, and is influenced by "SOC, temperature and the methods of charge and discharge" as mentioned by Li in [14], it can be concluded that in order to preserve the battery and prolong its life, the defensive driver is recommended so that the variations of the average battery current are smaller during exploitation; even though the defensive driver needs a higher torque towards the end of the acceleration and the aggressive driver uses high torque at the very beginning of the simulation.

For further development of the current manuscript, the imposed velocity will be kept at 100 kilometers per hour, but the limit and the differences between the three drivers will be the maximum allowed acceleration, so that the defensive driver will take as long as it needs to reach the desired velocity. Also, a real urban driving scenario will be implemented with limited velocity to 50 kilometers per hour.

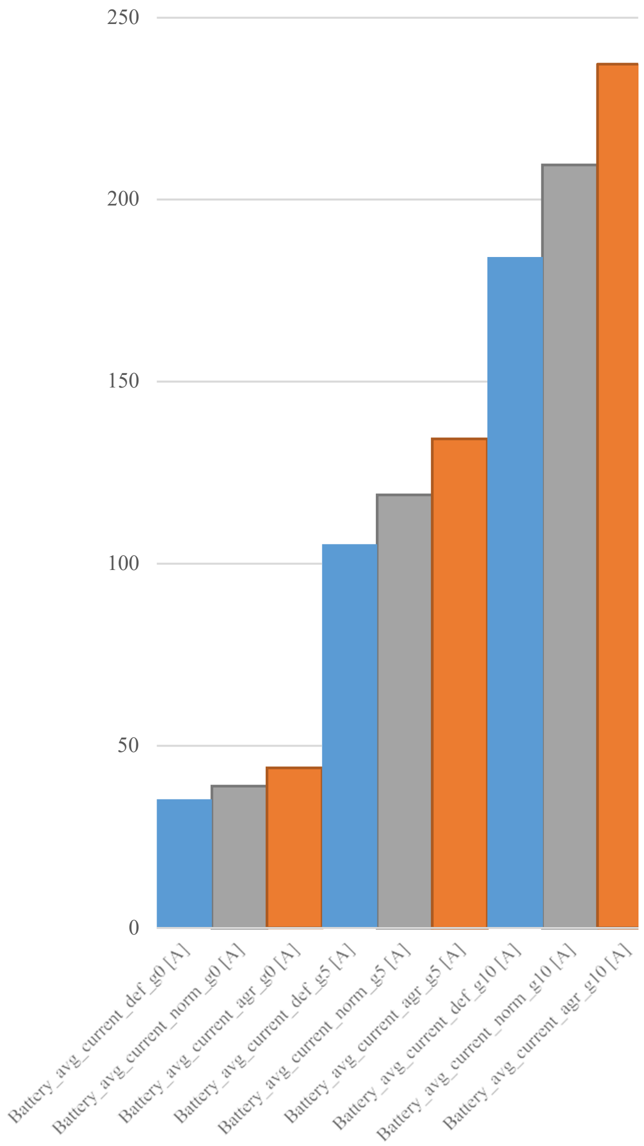

Fig. 7. Average battery current for the three driver types with three road gradients

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