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Smart BMS for Enhanced Range and Eco-Friendly Driving in Electric Vehicles

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***Abstract*— The shift toward electrified road transport brings both exciting opportunities and complex challenges for the automotive industry. Designing and building energy-efficient electric powertrains is key to driving the widespread adoption of the next generation of electric vehicles (EVs). Merits to advances in high-performance lithium-ion batteries, EVs have taken a major step forward in making sustainable mobility a reality. Still, one of the main expectations from EV users remains the ability to travel longer distances without the need for frequent recharging. In this work, we explore the critical role that driving range plays in the appeal of electric vehicles. We propose strategies, along with a battery management system (BMS), aimed at optimizing energy usage. Through simulations, we analyse a range of factors including technical, environmental, driving behaviour, and design aspects, that affect the range of lithium-ion batteries. To further enhance efficiency, we developed an energy management system incorporating an eco-driving mode and driver assistance features.**

***Keywords*— Electrical vehicle; Smart BMS; SOC ; eco-driving; lithium-ion batteries.**

I. INTRODUCTION

Electric vehicles (EVs) have emerged as a foundation of sustainable transportation, offering a promising alternative to conventional internal combustion engine vehicles. Their adoption is driven by the urgent need to reduce carbon emissions, mitigate the effects of climate change, and improve air quality in urban environments [1]. Central to this transformation is the rapid advancement of lithium-ion battery technology, which has significantly enhanced the energy density, efficiency, and longevity required for modern mobility solutions [2]. These technological strides have positioned EVs at the forefront of global efforts to establish greener, more resilient transportation systems [3-4].

Nevertheless, while EVs continue to gain popularity, one of the main concerns among users remains the vehicle's driving range. The ability to travel long distances without frequent recharging is critical for the widespread acceptance of electric mobility. However, the achievable range is influenced by a multitude of factors, which can be broadly categorized into technical specifications, environmental conditions, driver behaviour, and vehicle design parameters. A comprehensive understanding of these factors is essential to optimize EV performance and meet user expectations.

Extensive research has been conducted to quantify these influences. Studies by Xie, Y. et al. [5] and Donkers, A. et al. [6] have demonstrated that ambient temperature significantly affects vehicle range, primarily through its impact on auxiliary systems such as air conditioning and heating. In extreme weather conditions, increased auxiliary loads can lead to a substantial decrease in available range. Additionally, Liu, K. et al. [7] have shown that road gradient is another critical variable, where uphill driving demands greater energy expenditure. Findings by Al-Wreikat, Y. et al. [8] further revealed that a 3% incline could result in a 50% increase in specific energy consumption. Beyond these factors, Wang, J. et al. [9] developed predictive models illustrating how driving speed, acceleration patterns, and road topography collectively impact energy consumption. Furthermore, Donkers, A. et al. [6] emphasized that aggressive driving behaviors, characterized by rapid acceleration and frequent braking, markedly elevate energy usage, thereby reducing the driving range.

In this study, we investigate the influence of these parameters on the range performance of an EV equipped with a permanent magnet synchronous motor (PMSM). The propulsion system includes a three-phase space vector pulse width modulation (SVPWM) inverter, powered by lithium-ion batteries managed through a charge and discharge

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control system [10]. To evaluate the range under varying conditions, simulations were conducted, monitoring the state of charge (SOC%) of the battery across different scenarios [11].

Our primary objective is to develop an advanced energy management strategy that encourages energy-efficient driving [12]. We propose the implementation of an eco-driving mode integrated with a suite of intelligent driving assistance tools. This system will enable drivers to select optimized driving profiles that constrain maximum speed and torque output, tailoring vehicle performance to real-time conditions. By dynamically adjusting these parameters based on factors such as road conditions, driving style, and environmental influences, the system aims to extend the effective driving range, enhance battery longevity, and promote a more sustainable use of vehicle resources. Ultimately, this approach contributes to improving the environmental footprint of electric transportation and advancing the sustainability of future mobility solutions.

II. EXAMINED EV POWERTRAIN

The EV architecture under investigation, is composed of several key components working together to enable propulsion and control. At the core of this system is the battery pack, which serves as the main energy source. This energy is delivered to an inverter that converts the direct current (DC) from the battery into alternating current (AC), necessary for operating the electric motor. The motor in question is a PMSM, which is mechanically coupled to a drivetrain consisting of elements such as the gearbox, axle, and wheels. Additionally, a central control unit is integrated into the system to manage the interaction between these components, ensuring efficient and coordinated operation of the entire vehicle system [10].

A. *Longitudinal Dynamics Vehicle Model*

The longitudinal motion of a vehicle is governed by a combination of external and internal forces that influence its acceleration and overall performance. These forces primarily include the traction force produced by the powertrain, the rolling resistance arising from tire-road interaction, the aerodynamic drag exerted by air resistance, and the gravitational component associated with the road's incline, commonly referred to as the road grade [10]. These forces interact to determine the vehicle's forward movement and are essential to understanding its dynamic behaviour.

The resulting motion along the longitudinal axis can be captured through a dynamic equation that accounts for the net effect of all these forces, offering a comprehensive description of the vehicle's behavior under various driving conditions.

$$\sum F = m\ddot{x} = F_t - F_{aero} - F_{rolling} - F_{gradient} \quad (1)$$

where m is the vehicle total mass, $\dot{x}$ is the acceleration and F_t is the total traction force needed to drive the vehicle.

- Traction force

$$F_t = \frac{\eta . N}{R_{wh}} . T_{em} \quad (2)$$

where T_{em} is the vehicle engine torque, $\boldsymbol{\eta}$ is the transmission efficiency, N is the total gear ratio, R_{wh} is the wheel radius.

- Rolling Resistance Force

The force required to overcome rolling resistance can be calculated using the equation (3):

$$F_{rolling} = C_{rr}.m.g \quad (3)$$

where g is the gravity acceleration, and Crr is the coefficient of rolling resistance.

- Aerodynamic Drag force

$$F_{Aerodynamic\_Drag} = \frac{1}{2}.\rho.(V + Vw)^2.C_d.A_f \quad (4)$$

where A_f , ρ, and C_d are the vehicle frontal surface, the air density, and the air resistant coefficient, respectively. V and Vw stand for vehicle velocity and wind velocity respectively.

- Gradient resistance force

The gradient resistance force is expressed as follows:

$$F_{gradient} = m.g.\sin(\alpha) \quad (5)$$

where α is the road grade

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B. *Battery model*

The battery model studied is presented by Olivier Tremblay. The controlled voltage source is described by the main equations for the general battery model for a Li-ion battery as:

Charging phase:

$$E_{ch} = V_c - K * \frac{Q}{i_t + 0.1 * Q} + A * e^{(-Bi_t)} \tag{6}$$

Discharging phase:

$$E_{disch} = V_c - K * \frac{Q}{Q - i_t} + A * e^{(-Bi_t)} \tag{7}$$

State of charge (SOC)

The SOC is commonly used to describe the current status of a used battery. SOC grading can help set criteria for each battery operation mode (i.e., charge or discharge), and overcharging and over-discharging can also be prevented. SOC is expressed as follows:

$$SOC(t) = Q - \int_0^t i(t)dt \tag{8}$$

Generally, it is solicited that the SOC of the battery be kept within appropriate limits;

20 % < SOC < 80 % ; to keep the battery performance.

III. FACTORS IMPACTING BATTERY RANGE

The driving range of a lithium-ion battery in EVs is influenced by several factors, generally grouped into technical, environmental, behavioural, and design-related categories. This study aims to assess the impact of each factor on the state of charge (SOC%) and overall battery autonomy. All simulations follow a standardized speed profile, comprising acceleration, constant speed, and deceleration phases.

A. *Technical factor*

Impact of vehicle weight on the range

At a speed of 125 Km/h, we take three EVs with the same characteristics, only the weight is different. The aim is to study the evolution of the SOC for both vehicles, as shown in fig.1.

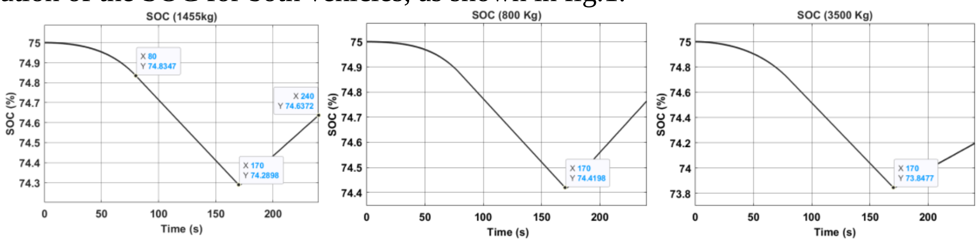

Fig. 1. Impact of vehicle weight

At a speed of 125 Km/h, an additional load of 1455 Kg, i.e. a 2045 Kg heavier vehicle, can reduce its range by 61.74%.

Heavy vehicles require more energy to move, which reduces range. For a heavy vehicle, reducing speed from 150 Km/h to 60Km/h gives 82.74% more range.

During deceleration, the motors used (PMSM) are reversible, enabling regenerative braking and ensuring part of the energy is recovered.

- **Impact of rolling resistance**

Test 1 : This test consists to measure the SOC for two values of the Crr rolling resistance coefficient(fig.2).

Test 2 : This test consists of keeping the rolling resistance coefficient (crr) value constant and measuring the SOC value (%) for two different EV speeds.

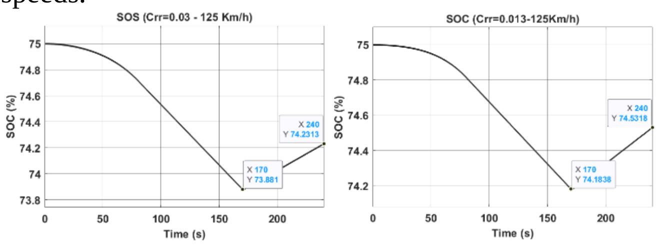

Fig. 2. Impact of rolling resistance at 125 Km/h

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We noticed from figures 2, with the same speed 125 Km/h, that the consumption increases if the coefficient of rolling resistance Crr increases.

Tires and their inflation condition influence rolling resistance, affecting energy consumption. By reducing the value of the rolling resistance coefficient, you can extend the range of the EV.

According to the second test, for Crr of significant value, reducing speed from 125 Km/h to 60Km/h gives greater range (82.74% saving).

B. Driving factors

This factor includes the EV user's behavior on the road, which has an impact on speed and acceleration, and consequently on energy consumption and battery ageing. Aggressive driving behavior leads to more frequent speed variations and greater acceleration. This leads to higher energy consumption.

- Variation of the speed

We change the speed, and the evolution of the SOC (%) is given by figures 3.

Speed has a direct effect on EV energy consumption.

By reducing the speed from 150 Km/h to 125 Km/h, the range is extended by 55.63%.

- Variation of the acceleration

For two different accelerations a1 and a2, verifying a1 > a2, the SOC measurements are given in figures 4

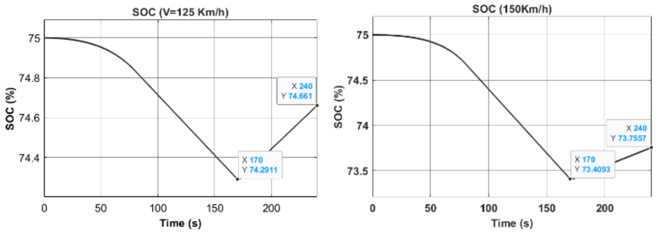

Fig. 3. Impact of EV speed

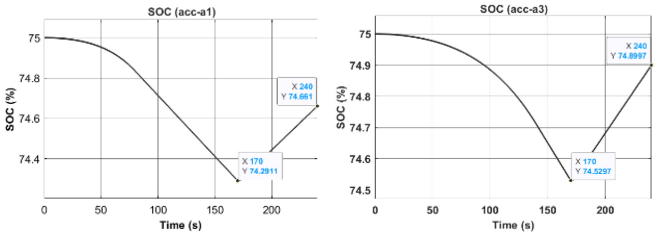

Fig. 4. Impact of the acceleration

The number and intensity of accelerations affect energy consumption. In fact, by reducing acceleration, we'll have a more extended range.

Busy traffic increases the number of accelerations and decelerations, which in turn increases energy consumption. The Range is affected by signal-related stops and intersections, which increase the number of accelerations.

C. Environmental factors: Impact of metrological condition

- Impact of the wind

Wind has a direct effect on the EV's aerodynamic drag, depending on wind direction. This factor impacts energy consumption at high speeds. Air resistance also changes with temperature and pressure.

- Factors related to road conditions

Slope has an effect on energy consumption. On the way up, the EV's consumption increases, and on the way down, the energy recovery system recovers some of the potential energy.

In the absence of a slope, we'll have extended autonomy of 69.1%.

IV. BMS AND PROPOSED INTELLIGENT EMS FOR ELECTRIC VEHICLE BATTERIES

A battery management system (BMS) is an essential part of any energy storage system. It controls battery charging and discharging, manages optimal operating conditions, regulates safety limits, executes battery charge and health algorithms, monitors battery parameters and communicates with other associated devices. The diagram in figure 5 shows the effective measures to be taken.

To increase battery range, reduce consumption and promote sustainable driving behavior, we propose a EMS whose functionalities are defined according to each of the factors influencing battery range, and based on simulations carried out previously.

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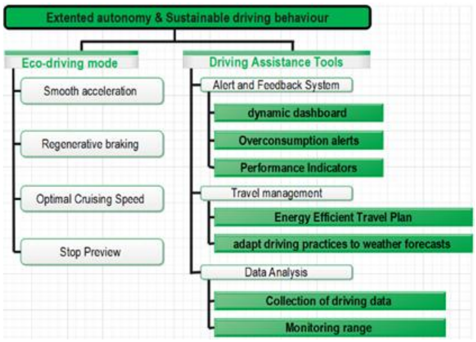

Fig. 5. Proposed intelligent EMS with the following functionalities

Vehicle weight: According to tests 1 and 2 in section III, at higher speeds, the EV consumes more energy.

-The proposed EMS requires a reduction in speed to obtain greater range.

-The proposed EMS incorporates a load analyzer to inform the driver of the impact of additional loads on range.

Rolling resistance: The proposed EMS provides tire pressure monitoring, ensures regular analysis of tire condition and checking whether they are suitable for road conditions or not.

Speed and acceleration control: The proposed EMS ensures Intelligent Speed Limitation by automatically adjusting speed according to road speed limits and battery status. It presents a Driving Intelligence system that provides alerts when the driver is accelerating too quickly, displaying advice to slow down.

Road conditions : That we see in simulation result, wind has an effect on the vehicle aerodynamic drag. This factor impacts energy consumption at high speeds. The proposed EMS should advise speed adjustments based on integrated wind speed and direction information. It must have anadvanced GPS system. Knowing topographic data, it provides alerts for the driver on slopes and driving adaptation.

V. Conclusions

The proposed Energy Management System (EMS), integrating eco-driving modes and Driver Assistance Systems, presents an effective strategy for reducing energy consumption EVs. It accounts for multiple influencing factors, including technical parameters, environmental conditions, driving behavior, and vehicle design. While simulation results confirm the potential of this approach, future work will focus on real-world deployment and testing to evaluate its effectiveness and provide experimental validation.

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