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Comparison of EV Consumption Based on Simulation of Real Driving Condition

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Abstract. This work examines the impact of driving styles on the energy consumption of Electric Vehicles (EVs) against the backdrop of climate change and greenhouse gas emissions from the transportation sector. It presents a model estimating EV energy consumption, incorporating factors like traffic, weather, and driving behavior. A case study using a BMW i3 explores the energy consumption differences between aggressive and cautious driving styles in various urban, suburban, and highway scenarios. Results indicate that driving style significantly affects EV energy consumption, underscoring the importance of efficient driving practices in reducing emissions and enhancing the environmental benefits of vehicle electrification.

Keywords. BEV, EV driving style, simulation, sustainable mobility

1. Introduction

Climate change is a pressing global issue, with greenhouse gases being identified as one of the major contributors to this phenomenon, the reduction of anthropologic-related activity is now a priority for many policymakers [1]. The transportation sector, particularly in Europe, significantly impacts greenhouse gas emissions, with light-duty vehicles playing a substantial role, as today, transport emissions represent around 25% of the EU's total GHG emissions [2-3].

As a potential solution, the electrification of light vehicles has been proposed to mitigate the environmental impact of transportation [4]. However, the adoption of electric vehicles is slowed by some challenges such as range anxiety, which affects the perception and usability of battery electric vehicles [5]. Range anxiety not only influences the acceptance of electric vehicles but consequently limits the societal benefits they can offer [6]. Despite these challenges, private vehicle electrification is a crucial component of the strategy for reducing greenhouse gas emissions from light-duty vehicles [7]. Furthermore, the complete electrification of the transportation sector is deemed essential to decrease CO2 emissions and enhance air quality, particularly in densely populated urban areas [4].

In the context of Europe, alternatives to electrification pathways for light-duty vehicles have been explored, to make example, bio-fuels, synthetic fuel, and hydrogen fuel cells but most of the investments in Europe are connected to Battery Electric

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Vehicles (BEV) [8]. Additionally, the potential for electric vehicle adoption to mitigate extreme air quality events has been studied, emphasizing the role of electrification in reducing greenhouse gas emissions [9]. Moreover, the impact of fleet electrification on regional and urban air quality has been investigated, demonstrating the potential positive effects of electrification on environmental sustainability [10]. These findings underscore the significance of electrified vehicles in contributing to air quality improvement and addressing climate change concerns. Addressing climate change and reducing greenhouse gas emissions in the transportation sector, particularly in Europe, necessitates a comprehensive approach that includes the electrification of light vehicles. While challenges such as range anxiety persist, the potential environmental benefits of electrification are substantial, emphasizing the importance of further research and implementation in this area.

The work is structured as follows, section II is a short literature review on related topics, section III is about the description of the model developed to estimate the energy consumption of an EV, section IV describes the experimental campaign, section V contains comments on the results obtained both experimentally and by the virtual model and paragraph VI is a discussion on the outcome of this work.

2. Literature Review

A paper published in April 2017 [13] focused on driving styles and their impact on fuel consumption, collaborating with more than 500 drivers globally and using a neural network to elaborate data coming from OBD-II. The results indicate that aggressive driving leads to a significant increase in fuel consumption, with an average difference of 1.5 liters per 100 km compared to quiet drivers (about 20%).

Another journal in September 2022 [12] studied the instantaneous acceleration of the vehicle together with the pedal position. Based on a two-stage clustering algorithm, an instantaneous identification model for driving cycles and styles was established using an Artificial Neural Network.

A conference held in October 2022 [11], showed how the combination of SOM, K-Means, and GMM models can classify driving styles across different driving scenes. The experimental results indicated that, among the collected data, conservative drivers are the least common, while aggressive drivers are the most prevalent. This study also highlighted that the driving style of a person can vary across different driving scenes. For example, being conservative in low-speed scenes could shift to being aggressive in medium-speed and high-speed scenes. Conversely, some drivers consistently exhibit the same driving style across all three scenes.

As for ICE vehicles, the main factors influencing energy consumption and range for BEV are traffic, weather, infrastructural elements and driving style, which is the primary focus of the analysis. According to Donkers A., Yang D., Viktorović M. [14] aggressive driving style consumes 17% more energy due to higher speeds and up to 22% more energy due to speed oscillations and up to 30% more energy due to rapid accelerations with respect to an eco-driver.

Berglund E. [15] tested velocity and acceleration modified driving styles on five different situations. The analysis found that an increase in average velocity has huge impact on energy consumption, especially for highway routes, while has lower influence on urban environments. Contrariwise, urban drive cycles are more affected by aggressive accelerations than highway ones. Regenerated energy allows for lower energy consumption in urban routes, while have low-to-zero impact on constant high-speed trips. However, an important takeaway is that BEV, due to their high efficiency drivetrain, tend to maintain linear sensitivity of energy consumption and energy losses with respect to aggressive drive styles.

A publication [16] concluded that smooth and gentle behavior in reaching a stable velocity with gradual accelerations and decelerations produces a slow change in the SoC of a BEV. Conversely, aggressive driving styles with sudden speed variations and non-constant velocities lead to higher energy consumption, resulting in an overall shorter range.

3. Model Description

The model developed for evaluating the EV energy consumption requires as input the route and vehicle characteristics. For what concerns the route, all data are experimentally measured through GPS: the speed profile is the most important information and is used to compute vehicle acceleration and travelled distance, while altitude to estimate the slope.

On vehicle's side, it's required to provide data regarding mechanical and dynamic behaviour, namely curb weight, geometrical characteristics (Cx, frontal area, wheel radius), performances of the powertrain (maximum speed and torque, battery energy, maximum regenerative power, transmission ratio) and other information depending on the specific testing conditions (tire pressure, initial State of Charge, load).

Ambient temperature, assumed constant, is required to estimate air density and the power consumed by the cabin conditioning system.

From all these data the algorithm instantaneously computes the torque and power requirements of the vehicle, evaluating the forces resistant to the motion [22-23]:

- Aerodynamic resistance F_{aero}
- Rolling resistance F_{roll}, assuming tarmac road
- Inertia force F_i
- Gravity force F_{slope}, function of the estimated slope angle

A longitudinal dynamics model has been considered, assuming complete adherence conditions of the vehicle to the ground. After summing the contributions (1), the torque at the wheels is obtained as (2)

$$F_{tot} = F_{aero} + F_{roll} + F_i + F_{slope} \tag{1}$$

$$C_{tot} = F_{tot} \cdot R_w \tag{2}$$

with R_w being the wheel radius, neglecting any kind of tire deformation. Through the transmission ratio and the efficiency of the transmission, assumed 0,94 [17], the motor torque is computed. Finally, knowing the instantaneous rotational speed, the delivered mechanical power is found.

The actual electric power consumption to move the vehicle must include the losses in the motor and its controller. In the first the efficiency is evaluated as function of torque and speed through an efficiency map, while in the converter has been considered only as function of the speed [18]. The presence of regenerative braking imposes an important distinction between traction and braking phases. Its control strategy, strongly dependent on the vehicle type, is necessary because of some limitations in the recovery of mechanical energy. At SoC values close to 100% the regenerative braking is inhibited in order not to damage the battery, at low speed is limited by the very low torque provided to the motor and, in general, is controlled not to overcome the vehicle's maximum regenerative power. As in the traction case, the powertrain efficiency must be considered since it reduces the amount of recovered energy [19-20].

The overall electric consumption also considers the power required by many auxiliary components [21] on board the vehicle, such as driving control unit, energy management systems, lamps, power steering, infotainment, and vacuum servo pump. The energy requirement of air conditioning has been estimated more in detail, assuming the cabin temperature is controlled by a heat pump in both heating and cooling conditions. Its power consumption, computed at constant air flow rate, is function of both ambient and desired internal temperature, considering empirical values for the coefficient of performance of the heat pump [24-30].

The main outputs of the model, besides the overall energy consumption, are the torque and power profile, the instantaneous recovered energy, and the variation of the State of Charge (SoC) the battery, given the initial one. Figure 1 represents the scheme of the model.

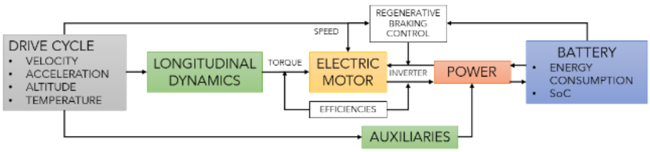


Figure 1. Scheme of the model

The model was then validated by observing the deviation within the trips made between the model results and the fuel consumption recorded by the car. The results showed great promise by being almost always in line with actual fuel consumption. Out of the six real cases collected, in four the results fell within the measurement error range of the vehicle's SoC, while in one the deviation could be explained by a complex weather condition, where within the same trip the automatic climate control system could have changed the direction of heat flow. Finally, in the sixth case, missing values did not allow this direct comparison. it is therefore possible to say that in validation the reliability of the model was >= 80%.

4. Case Study Description

4.1. Vehicle Description

The Electric Vehicle (EV) used to acquire data is the BMW i3 (Figure 2) owned by the Energy Department of Politecnico di Milano. In Table 1 are summarised the characteristics of the vehicle provided as input to the model.

Figure 2. BMW i3 used for the case study.

Table 1. Mechanical and technical parameter used in modelling the case study.

Parameter	Symbol	Value	Unit
Mass	m	1390	kg
Frontal area	A	2.8365	m^2
Aerodynamic coefficient	C_x	0.29	-
Wheel radius	Rw	0.3638	m
Maximum motor speed	RPM_{MAX}	11000	rpm
Maximum motor torque	T_{MAX}	250	Nm
Tire pressure	P_{tire}	2.3	bar
Transmission ratio	τ	0.1031	-
Maximum regenerative power	$P_{MAX\ reg}$	55	kW
Battery capacity	E_{batt}	42.2	kWh

4.2. Drivers

Two different drivers with a similar number of years of driving experience were involved in this phase. These can be considered intermediate. Both had no significant experience driving electric vehicles, which may have affected the non-smooth handling of certain vehicle functions, e.g., regenerative braking. It is important to note that neither driver was affected in their driving style; both were in the condition of not needing to reach their destination within a certain time limit. In addition, the experience on the roads traveled was on average high as they were often routes that had already been driven habitually. It can therefore be argued that despite the lack of driving experience with electric vehicles, the knowledge of routes.

As shown in Fig. 3, driver 1 tended to have few coasting phases, tending to keep the vehicle under acceleration or deceleration, as can be observed in Fig. Conversely, in driver 2, more cautious driving was observed, aimed at reaching a speed considered to be a target speed and maintaining it until the need to decelerate. Intuitively, one would expect from the literature analyzed a lower energy consumption when the vehicle is driven by Driver 2.

4.3. Route Conditions

In this comprehensive analysis, three distinct driving scenarios were methodically developed, each uniquely characterized by moderately low traffic conditions, thereby providing fertile ground for insightful observations and evaluations. The study meticulously delineates these scenarios, emphasizing their inherent characteristics and the resultant driving dynamics.

The first scenario unfolds within an urban setting, specifically driving from Cinisello Balsamo to Milano Bovisa.

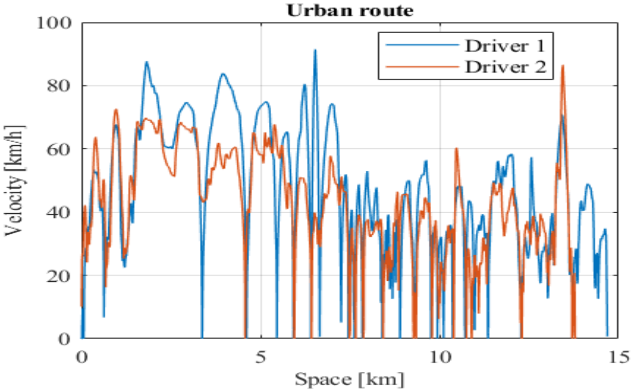


Figure 3. Drivers speed profiles comparison.

This route is distinguished by its dense concentration of traffic lights and intersections. Such infrastructural elements invariably lead to frequent vehicular stops or significant slowdowns, thereby presenting a challenging urban driving environment.

This scenario is emblematic of typical metropolitan driving conditions, where drivers must constantly navigate through a maze of stop-go traffic, thus testing the vehicle's responsiveness and the driver's decision-making skills under constrained urban settings. The speed profile of the second driver is shown on the map in Fig. 4, green corresponds to maximum speed and red to zero speed.

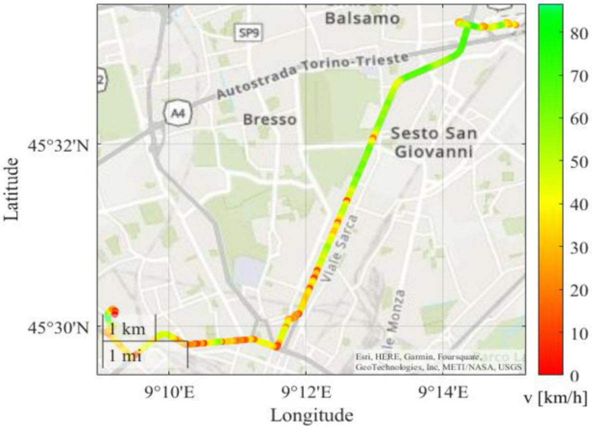


Figure 4. Urban route and speed profile.

In contrast, the second scenario represents a suburban driving experience. This route, extending from the periphery of Milan to Bollate, is marked by a distinctly different traffic flow compared to the urban scenario. Here, the presence of roundabouts facilitates smoother traffic transitions, and the larger, high-visibility roads contribute to a more fluid driving experience.

Additionally, the lower population density in this suburban landscape further alleviates traffic congestion, offering a setting where one can evaluate vehicle performance in conditions that strike a balance between urban congestion and open-road driving. The speed profile of the second driver is shown on the map in Fig. 5.

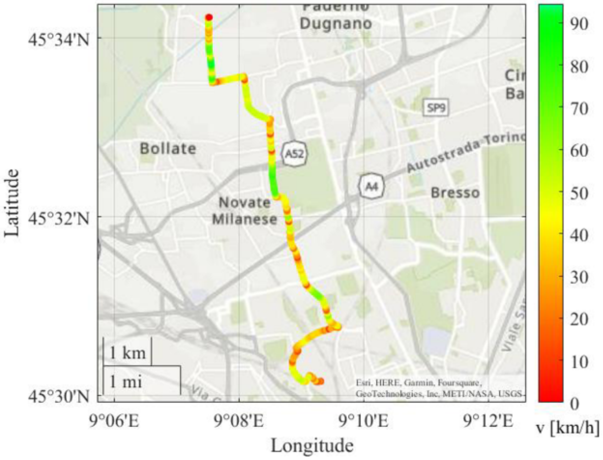


Figure 5. Suburban route and speed profile.

The third scenario is an example of highway or motorway driving, tracing a path from Bollate to Cinisello Balsamo via the Tangenziale Nord. This setting is characterized by its majority of motorway traffic, which is typically free-flowing and maintains almost constant speeds. It offers a unique opportunity to assess vehicle dynamics in a high-speed, less obstructive environment. Such a scenario experiences critical for understanding a vehicle's performance in terms of stability, fuel efficiency, and comfort over extended periods of high-speed travel. The speed profile of the first driver is shown on the map in Fig. 6.

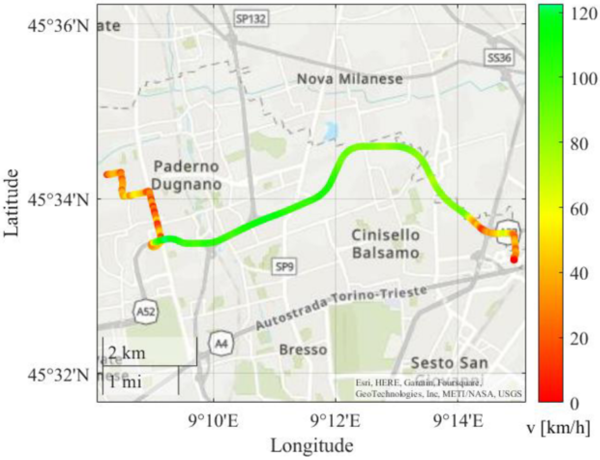


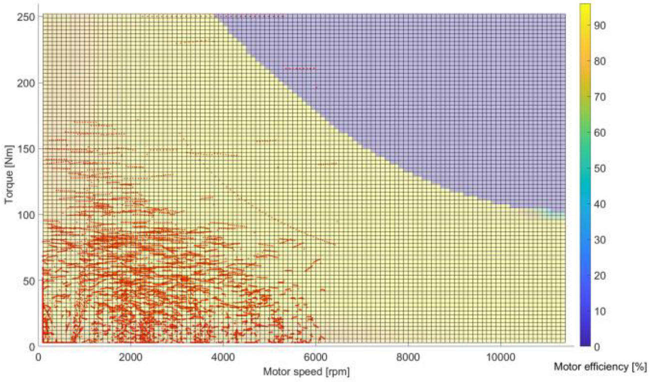
Figure 6. Highway route and speed profile.

Each of these scenarios presents a distinct set of challenges and opportunities for both the vehicle and the driver, enabling a comprehensive assessment of vehicular performance across varied traffic conditions. The selection of these specific routes and conditions reflects a deliberate and thoughtful approach in designing a study that encapsulates the multifaceted nature of everyday driving experiencees. This thorough analysis not only contributes to our understanding of vehicle dynamics in different traffic scenarios but also offers valuable insights for urban planning and traffic management strategies. The highway route represented in the image above has not been considered for the comparison, due to traffic reason and external factors.

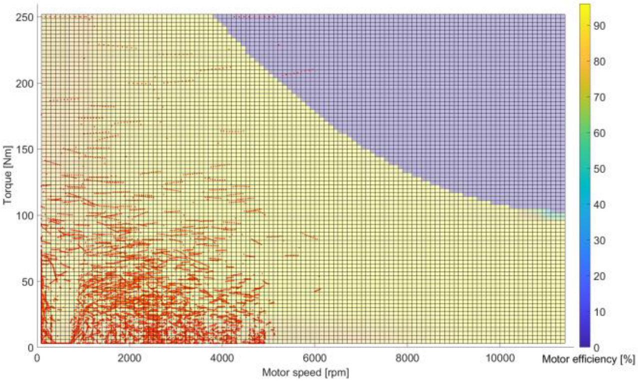
5. Analysis of Results

To better understand the differences between driving styles, four comparison images are reported below, in the background there is the efficiency map of the motor [22].

The first couple shows the operating points of the BMW i3 motor, respectively of the first and second driver, as shown in Fig. 7.



(a)



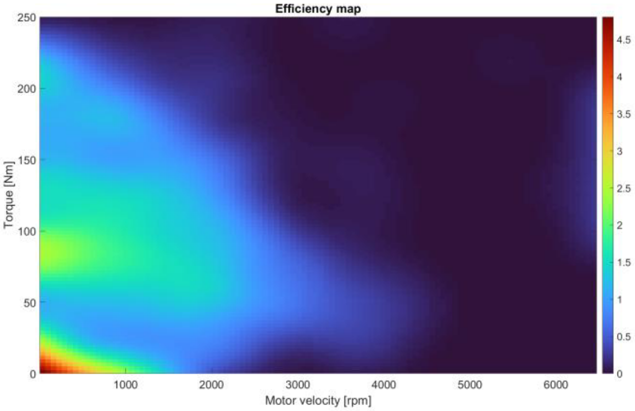
(b)

Figure 7. Operative points of the motor for both (a) driver 1 and (b) driver 2

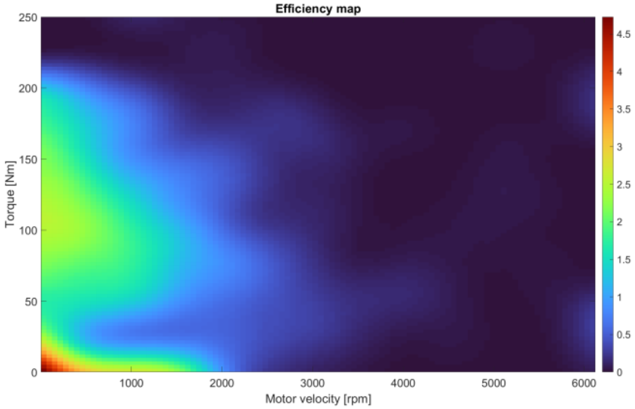
It is easily noticeable that the second tends to drive at lower speeds, almost never exceeding 5000 rpm, while the first reaches quite often the 6000 rpm mark. Furthermore, in the first figure the points are less concentrated towards the bottom-left section, with respect to the second one. Points in the blue zone are not real operative conditions, but come from derivative errors of the algorithm.

The following images show heatmaps representing the same driving conditions of above, and the observations regarding the points distribution are similar. Heatmaps have been scaled on the horizontal axis based on the maximum motor regime reached by the driver, thus they do not reach the maximum engine speed of 11500rpm. In the colorbar, red represents high occurrence of operative points on the efficiency map. As before, Fig. 8(a) is for the first driver, while Fig. 8(b) for the second.

Regarding the difference in energy consumption between the two drivers, the main results are show in the Table 2.



(a)



(b)

Figure 8. Heat map of the operative points for both (a) driver 1 and (b) driver 2.

Table 2. Energy consumption results from the speed profile and simulation for the two drivers.

Driver	Energy consumption [kWh]
1	2.175
2	1.879

According to the model, the first driver consumed 15.75% more than the second. Since the environmental conditions between the two tests were almost the same, the difference in energy consumption can be only due to the different driving style.

6. Discussion of Results

The proposed model is useful to estimate the consumption of an EV given its physical characteristics and speed time history. As seen, this last input is intrinsically representative not only of the kind of road and traffic situation but also of the driving style. Being the consumption estimation based on the major sources of mechanical and electrical power dissipation, it could be employed to highlight the consequences of different driving patterns. In this the tool offers the possibility to evaluate various alternatives of driving strategy aiming at a more efficient use of the available energy. The comparison of the same route carried out with different driving styles shows how the final consumption in real life conditions is determined by the different energetic requirements, coming directly from the input data. Indeed, the driver's behavior in accelerating and decelerating, reaching a maximum speed, and engaging the brakes can be identified in the speed profile and relate to the power utilization.

Since the idea was to develop a robust and simple model, the need to find a tradeoff between all the involved variables and specificities was of primary importance. Of course, the attempt to make it general in terms of vehicles leads to errors, mostly because of the approximations made to face the different technical solutions available on the market. Note that this strategy may make the results diverge from reality, especially when the vehicle moves quite constantly in some very specific conditions. For example, a real electric motor may be designed to be particularly efficient at high rpm, while another at high torque. The model assigns to every vehicle the same efficiency map, and that could be harmful when operating most of the time in a condition with a real efficiency particularly different from one of the algorithms. Moreover, peculiar behaviors, such as driving with the car windows open, can't be perceived by the algorithm from the provided data. In other words, even if the tool worked perfectly given precise input, lots of minor phenomena wouldn't be considered.

To sum up, having a precise estimation isn't always guaranteed given the complexity of the real world. However, this model offers guidelines for a vast variety of possible applications, above all in helping the mobility's transition to electric. In that scenario, it may be interesting to assess if, regarding the impact on energy consumption, different driving styles have the same outcome both for conventional and electric vehicles. A similar analysis has already been conducted by [31]. Especially in the current scenario, it could be fundamental to be more aware of how to employ the available energy in a more efficient way.

7. Conclusions and Future Work

This paper analyses the behavior of a B-segment BEV driven with two different driving styles, following the same route. Along with the speed profiles and maps of the route, the calculation of the energy consumed by the BEV has been performed. The energy calculation has been carried out through a model developed during research in MATLAB and Simulink. As expected, the aggressive driving style led to an increase in energy consumption. Further improvements include the perfection of the consumption model, increasing its accuracy, and a higher number of road tests with different cars and environments to confirm the results.

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