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High-Fidelity Electric Vehicle Energy Consumption Modelling and Investigation of Factors in Driving on Energy Consumption

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***Abstract*— The ever-growing battery electric vehicle market (BEV) have reached several millions of sales annually, as a result of significant electrification of transport efforts globally. Accurate estimation of energy consumed by BEVs is of major importance especially for charging station selection, route planning and development of energy-efficient driving strategies in both manual and autonomous driving. One of the ways of achieving this is to conduct experiments on real BEVs, which is costly and labor intensive. An alternative to real life experimentation is to design high-fidelity mathematical models for energy consumption of BEVs and feed this model with experimental standardized driving cycles. This study develops and investigates the capabilities and advantages of a generic, detailed, modular BEV model. The effects of wide range of parameters on energy consumption of a BEV are analyzed comprehensively. The study is concluded by discussing the promising potential areas of use of the developed model.**

Keywords—driving cycle, electric vehicle, energy consumption estimation, range anxiety.

I. INTRODUCTION

Energy consumption of BEVs depend on several factors such as car's internal dynamics, driving behavior of the vehicle owner, the geometry of the route, traffic-road-weather conditions during the trip and other. An accurate estimation of vehicle energy consumption and improvement of energy savings in driving can reduce range anxiety of drivers, allow better EV charging coordination and pricing, improved fleet management, enhance battery health estimation and extension of batteries' effective lifetime, help improving hosting capacity of power grids and charging stations, help optimization of vehicle maintenance activities and allow effective identification of technical issues and abnormalities that affect vehicle's performance.

Energy consumption in BEVs is a result of the overall work done by the battery. Therefore, in order to calculate the energy consumption of a BEV, the power output of the battery (P_{out}) and the power input to the battery (P_{in}) over the duration of a driving cycle can be considered as in [1]. P_{out} is the sum of power exerted onto the wheels to overcome the net tractive force on the vehicle and the auxiliary power consumption which mainly consists of air conditioning, headlights, windshield, wipers etc. The researchers in [2] have determined that there are four tractive forces acting on the vehicle, which are rolling resistance force of the tires, aerodynamic drag force acting on the body of the BEV, gravitational force which depends on the slope of the road and acceleration force. The net sum of these forces multiplied by the velocity of the BEV is the power needed for the motion of the BEV. P_{in} is specifically regenerative breaking which significantly contributes to energy gains in electric vehicles as will be shown in the following sections of this study. Considering the losses, there is a loss due to the powertrain of the BEV. In [3], this issue is addressed by the use of a single coefficient $\eta_{powertrain}$.

The aforementioned tractive forces were modelled according to [4] except for the rolling resistance force. An equation with more detail that was used in [5] was selected to model the rolling resistance force. The equations are explained in details in section 2.

In this study, MATLAB/Simulink was used to develop a detailed model of BEV due its ease of use and library of readily available and widely used standard drive cycles to test the model. By changing the parameters in the model such as temperature, air density, wind speed and wind direction etc. the effects of these parameters can be investigated on the same drive cycle. Another use for the mentioned drive cycles is to compare the energy consumption per kilometer (kWh/km) in these differing scenarios, hence demonstrating the effects of different road types such as urban, rural or motorways.

The related studies in the literature use a similar method of calculating the energy consumption via calculating the power consumption first. However, the model developed in this study is designed to accommodate any drive cycle that can be fed to it, hence providing a mean for drawing conclusions on aspect of the energy consumption characteristics of BEVs. It should also be noted that, although there will be a greater margin of error, this model has the capability to predict energy consumption on a road without a drive cycle given that the acceleration and deceleration characteristics of the driver is provided.

Section 2 of the paper explains the inner mechanics of the model and how the model was designed. Section 3 of the paper explains the way drive cycles was fed into the model and presents the results of different scenarios, while section 4 of the paper is devoted to the discussion of the results and directions for future research.

II. MODELLING OF BATTERY ELECTRIC VEHICLES

This section of the paper mainly explains how the model was designed and how it works. Although the BEV Model can work with any given coefficients for any given vehicle, Tesla Model S 85 Signature 2013 is selected for the case study presented in section 3, parameters of which are taken from [6].

A. Net Tractive Force

In this study the preferred approach to calculate the energy consumption is to first calculate the net force acting on the vehicle. The net force F_{net} can be formulated as in (1).

$$F_{net} = F_r + F_{aero} + F_g + F_m \tag{1}$$

Where F_r is the rolling resistance force, F_{aero} is the aerodynamic drag force, F_g is the gravitational force and F_m is the acceleration force. The first of these forces, the rolling resistance force, is the force that acts on the wheels of the BEV. Although some related studies in the literature use a single friction coefficient for the tires, the developed model uses a more detailed formula that was introduced in [7] and given in (2).

$$F_r = mg\left(C_0 + C_1\left(\frac{V}{100}\right) + C_2\left(\frac{V}{100}\right)^4\right)cos\theta \tag{2}$$

Where m is the total mass of the BEV in kg, g is the gravity acceleration in m/s^2, θ is slope of the road in degrees and C_0, C_1 and C_2 are rolling resistance coefficients. The range value of C_0, C_1 and C_2 are given in Table I [8].

TABLE I. APPROPRIATE COEFFICIENTS FOR ROLLING RESISTANCE

Rolling Resistance Coefficients	Value
C_0	0.0072-0.120
C_1	0.00025-0.00280
C_2	0.00065-0.002

Another significant force that causes energy consumption is the aerodynamic drag force which can be written as in (3).

$$F_{aero} = \frac{1}{2}\rho C_d A(V - W)^2 \tag{3}$$

Where ρ is the air density in kg/m^3, C_d is the aerodynamic drag coefficient, A is the frontal area of the BEV in m^2, V is the velocity of the BEV in m/s and W is the wind speed in driving direction in m/s. The gravitational force is written as:

$$F_g = mgsin\theta \tag{4}$$

Where m is the total mass of the BEV in kilograms, g is the gravity acceleration in m/s^2 and θ is the slope of the road in degrees. The acceleration force is formulated as in (5).

$$F_m = \left(m + \frac{4J_w}{r^2} + \frac{J_m d^2}{r^2}\right)a \tag{5}$$

Where m is the total mass of the BEV and a is the acceleration of the BEV in m/s^2, J_w is the wheel inertia in kgm^2, J_m is the motor inertia in kgm^2, r is the tire radius in m, d is the gearbox ratio. It should be noted that, depending on the deceleration of the BEV or the slope of the road the gravitational force and the acceleration force can work in the driving direction.

B. Power Output and Power Input

The total energy consumption of a BEV is the total sum of the net power exerted on the BEV itself throughout the drive cycle i.e. integral of net power over time. However, the losses that occur due to power train should also be accounted for. Therefore, the result of the integral should be divided by the power train efficiency $\eta_{powertrain}$. The resulting equation can be written as in (6).

$$E_{tot} = \frac{\int \quad P_{out}(t)dt - \int \quad P_{in}(t)dt}{\eta_{powertrain}} \tag{6}$$

Regenerative brakes are a significant asset of BEVs. Unlike internal combustion engine vehicles (ICEV) BEVs can regenerate a portion of the vehicle's kinetic energy during breaking by using the motors that run the vehicle as a generator thus turning mechanical energy into electric energy that would otherwise be turned into heat in the breaks and be wasted. However not all of the energy can be recovered due to limitations of the battery. The maximum amount of energy that can be recovered is limited by the maximum charging current of the battery. Power output of the regenerative breaks can be formulated as in equations (7), (8), (9) and (10).

$$E = \frac{E_b}{x} \tag{7}$$

$$E_b = \left(\int_{traction} \quad P_o(\tau)d\tau - \int_{braking} \quad P_i(\tau)d\tau\right) \tag{8}$$

$$P_o = \frac{S_V.F_{Res}}{\eta_{Pt}} \tag{9}$$

$$P_i = k.P_{regen} \tag{10}$$

Where P_{regen} is the power output of the regenerative breaks in kW, E_b is the output of battery energy in (Wh), x is the distance in (m), F_{Res} is the forces opposed to the vehicle motion in (N), S_V is the speed of a vehicle in (m/s), η_{Pt} is efficiency of powertrain, α is the regained braking energy. It should be noted that in the BEV model there is a limit on P_{regen} due to aforementioned limitations of the battery.

C. Driver Model

The model works by following a drive cycle. In the case of this study, a drive cycle is consisting of velocity and an acceleration reference information. For the model to simulate the drive cycle accurately the driver should be modelled such that the vehicle velocity tracks the velocity reference (i.e. the drive cycle). In order to accomplish this task, the driver has been modelled as a PI controller as in (11)

$$PI(s) = \left(P + \frac{I}{s}\right) \tag{11}$$

Where P is the proportional gain coefficient and I is the integral gain coefficient. The aforementioned coefficients have been tuned manually to track the drive cycle. Another reason to pick a PI controller as a representative of the driver is that it allows the opportunity to further demonstrate different driving styles by changing the parameters.

D. Auxillary Power

Any modern vehicle has entertainment systems, air conditioning, headlights etc. While each of these systems could have negligible effects on the overall energy consumption rate; when combined, the effects can be significant. Therefore, it is important to consider these additional power consuming systems.

III. ANALYSIS OF ENERGY CONSUMPTION CHARACTERISTICS

This section of the paper demonstrates the capabilities of the BEV Model when it comes to understanding the wide range of factors that have impact on energy consumption of a BEV. The primary benefit of using a mathematical model to analyze the effects of individual factors such as temperature, rain, wind, road type, traffic etc. is that, unlike real life experimentation, each factor can be isolated and impact on energy consumption can be solely investigated. In addition, by using preexistent drive cycles the labor and cost of such analyses is considerably reduced. A quadruple of such drive cycles is the Common Artemis Driving Cycles (CADC, or shortly Artemis) consisting of four separate drive cycles. These drive cycles are Artemis Urban, Artemis Rural and Artemis Motorway 130 shown in Figure 1, Figure 2 and Figure 3 respectively.

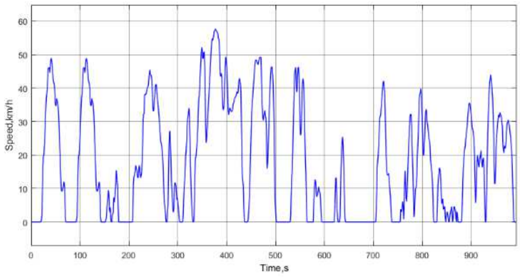

Fig. 1. Artemis Urban Drive Cycle

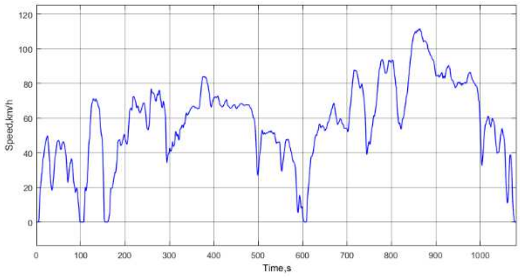

Fig. 2. Artemis Rural Drive Cycle

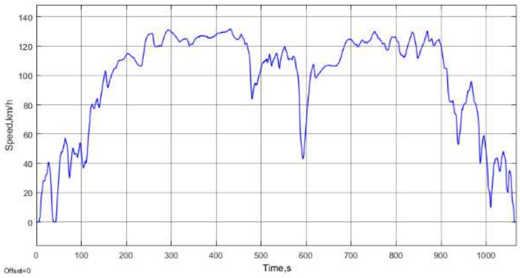

Fig. 3. Artemis Motorway 130 Drive Cycle

Artemis drive cycles, developed within the European Artemis (Assessment and Reliability of Transport Emission Models and Inventory Systems) project are de facto industry since they represent a set drive cycles with a wide array of useful scenarios based on statistical analysis of real-world driving patterns. Table II gives the characteristics of the Artemis cycles in detail.

TABLE II. CHARACTERISTICS OF ARTEMIS DRIVE CYCLES

Characteristic	Urban	Rural	Motorway 130
Duration (s)	993	1082	1068
Distance (km)	4.9	17.3	28.8
Av. Speed (km/h)	17.7	57.5	96.9
Max. Speed (km/h)	57.3	111.1	131.4
Speed Distribution (speed=s)			
Idle	21%	2%	1%
Low Speed / 0<s≤50	77%	32%	15%
Mid Speed / 50<s≤90	2%	59%	14%
High Speed / s>90	0%	7%	70%

A. Effects of Different Road Types

In this study Artemis Urban, Artemis Rural Road and Artemis Motorway 130 drive cycles are evaluated using the BEV Model in order to observe the effects of different traffic conditions on energy consumption of a BEV. Artemis Urban is a good representation of a road with traffic due to 21% of the drive cycle being idle (i.e. V=0 km/h) indicating frequent stops. On the other hand, Artemis Rural and Motorway 130 represent a road without too much traffic, but with different average speeds. All of the other conditions were kept equal and under normal conditions (assuming no change in elevation, ideal ambient and vehicle conditions, no additional auxiliary power etc.). The results are shown in the figures below.

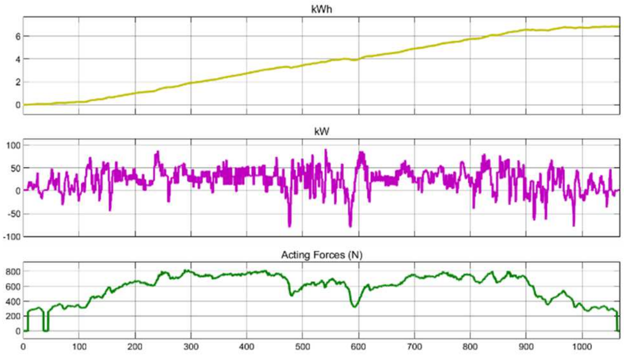

Fig. 4. Artemis Motorway 130 Drive Cycle simulation results

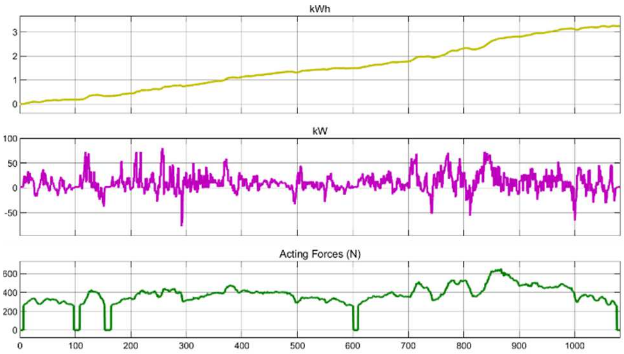

Fig. 5. Artemis Rural Drive Cycle simulation results

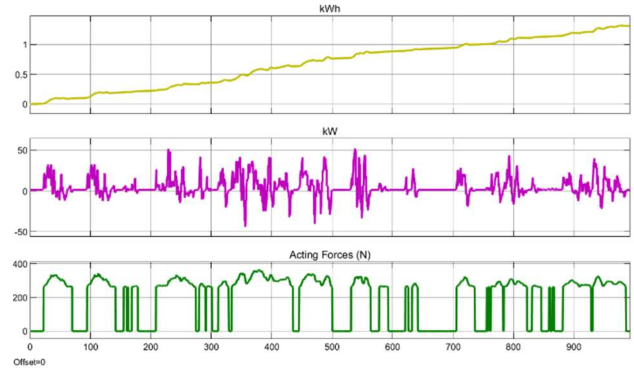

Fig. 6. Artemis Urban Drive Cycle simulation results

The figures 5, 6 and 7 present the total energy consumption in kWh, motor power in kW and instantaneous acting forces on BEV that would solely impact the motor torque output. It can be seen that, there are instants where the motor output power and acting forces are both non-existent in Figure 6. In reality, acting forces has a constant impact on the vehicle however in this model, when the vehicle stalls, these forces are substituted with braking force of the BEV.

B. *The Impacts of External Conditions*

By changing the parameters within the BEV Model, the influences of external conditions such as temperature, rain, wind speed and direction can also be observed. The results are shown on the simulation of the same drive cycle; but with only one of the parameters changed.

First of the parameters, impact of which on vehicle energy consumption was explored in this study is the effect of the temperature. Under normal conditions the auxiliary energy consumption is 180Wh/km [9]. When it is extremely cold (-5°C) or extremely hot (40°C), it can be assumed that air conditioning (AC) will be on. This will have an effect on the energy consumption of the vehicle. In the case of extreme cold weather this roughly corresponds to an additional 1000 Wh/km of energy consumption and in the case of extreme hot weather this corresponds to an additional 1500 Wh of extra energy consumption [9]. However, as the weather gets hotter the air density decreases. This phenomenon causes to BEV to withstand less drag. Under normal conditions (UNC) and with Motorway 130 Drive Cycle, BEV spends 230.4 Wh/km. In cold weather the energy consumption rate increases to 241.4 Wh/km without AC and 257 Wh/km with AC. In hot weather energy consumption rate decreases to 225.4 Wh/km without AC and 235.7 Wh/km with AC. Figure 4 shows all the simulation results with different drive cycles.

The second external factor that was simulated was the wind. According to Beaufort Wind Force Scale winds with a speed between 29 km/h and 38 km/h are categorized as wind force 5. The land description of wind force five winds is “Small trees in leaf begin to sway” as per [10]. In order to observe both the negative and positive effect of wind, a headwind of 36 km/h (in opposite direction to the BEV) and a tailwind of 36 km/h (in the same direction as the BEV) was selected.

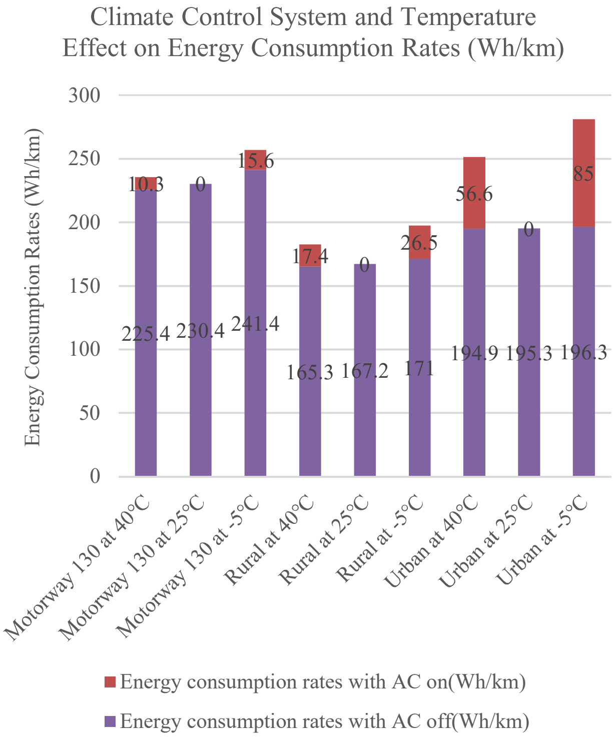

Fig. 7. Simulation results for climate control system and temperature effect

On the Motorway 130 drive cycle with the headwind the energy consumption rate was 295 Wh/km and the energy consumption rate with the tailwind was 172.4 Wh/km. While the headwind causes an additional 28.03% increase in energy consumption rate the tailwind decreases the energy consumption rate by 25.17%. The simulation results can be observed in Figure 8.

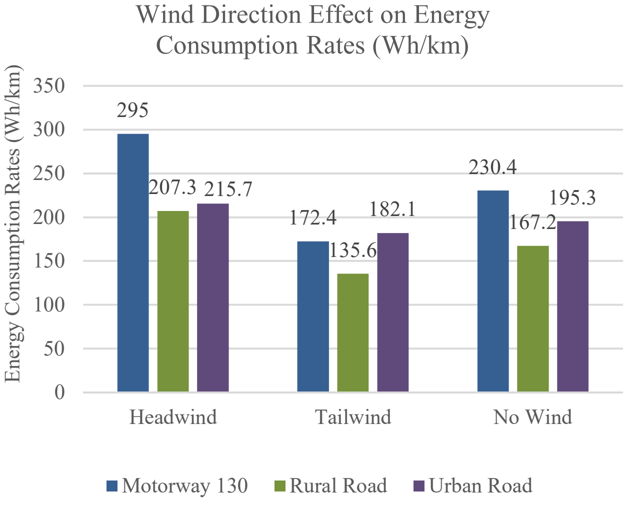

Fig. 8. Simulation results for wind speed and direction effect.

The last external factor that was studied was the road condition. In order to simulate road quality, the rolling resistance coefficient was changed. Under normal conditions the rolling resistance coefficient of an average asphalt road is 0.0135 [11]. Rolling resistance coefficients of various road types are calculated under the influence of [12]. These variations of rolling resistance coefficients cause the energy consumption rate of the Motorway 130 drive cycle to change, as represented in Figure 9.

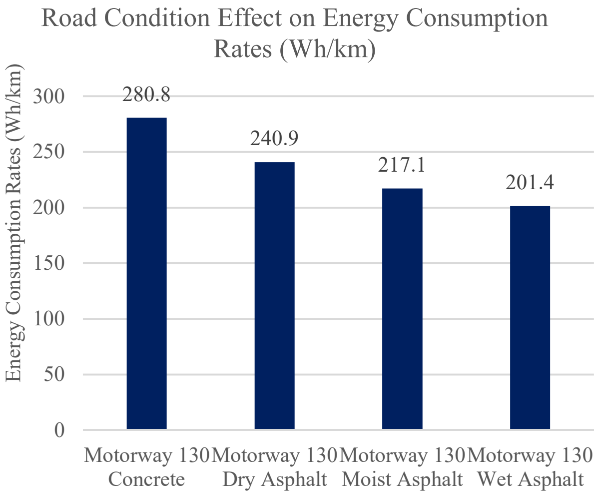

Fig. 9. Artemis Motorway 130 Drive Cycle Simulation Results

IV. CONCLUSIONS

This paper provided insights about power consumption characteristics of BEVs and demonstrated the uses of a compatible and generalized mathematical model for BEVs. The main advantage of such a high-fidelity model is the simplicity and efficiency it offers at determining the significance and the effect of differing conditions when it comes to energy consumption rate of a BEV. The first of the factors studied was the effect of different road types on energy consumption rates. Under normal conditions the energy consumption rates of Artemis Motorway 130, Rural Road and Urban are 230.4 Wh/km, 167.2 Wh/km and 195.3 Wh/km respectively. The reason that the biggest energy consumption rate is at Motorway 130 drive cycle is that as per Table II during that cycle vehicle is moving at high speed 70% of the time. This in return creates a bigger drag force thus drastically increasing the energy consumption rate. However, it is observed that the energy consumption rate of Urban Road drive cycle is smaller than Urban drive cycles energy consumption rate despite the fact that the average speed of Rural Road drive cycle is more than three times faster in average in comparison to Urban drive cycle. This is due to idle time. When the BEV is not moving, although there is no energy consumption due to the motion of the BEV the auxiliary systems continue to consume energy hence increasing the overall energy consumption rate. It should be noted that the model also provides the means to analyze the effects of external conditions as well as per Section III Part A. First of the external conditions analyzed in this study is the effect of ambient temperature on the energy consumption rate of a BEV. The change in energy consumption rates are mainly a result of the increased auxiliary power usage due to air conditioning. As shown in figure 7 as the ambient temperature gets colder or hotter in comparison to normal circumstances (25°C) the effects of increased auxiliary power usage become more distinct. However, the biggest change is at Urban drive cycle. This is again due to idle time, since during that time although no road is traversed the AC continues to use power hence increasing the overall energy consumption rate of the BEV. The following external factor that was studied was the effect of wind. Looking at figure 8 it can be concluded that the energy consumption rate with a headwind of 36 km/h is roughly 70% more than the energy consumption rate with a tailwind of 36 km/h. The effect of wind was studied despite the intuition that a head wind would cause higher rates of consumption since it could provide an insight for future studies when it comes to the level of certainty or uncertainty wind has when it comes to predicting the energy consumption and it can be concluded from this study that wind has a significant effect when it comes to energy consumption rate of a BEV. The last of the external factors that was studies was the road condition. As it is shown in figure 9 as the road gets wetter the energy consumption rate decreases. This is due to the rolling resistance coefficients decreasing as the road gets wetter. However, it should be noted that rolling resistance is directly corelated with the grip of a BEV. In future studies different road materials can be analyzed to determine the efficiency of that road type with regards to energy consumption rates of vehicles along with other factors such as humidity, frontal area of the BEV, air drag coefficient of the vehicle etc. In conclusion a high-fidelity BEV model further improves the understanding on energy consumption rate of BEVs and provides insights on both external and internal factors that have an effect on said energy consumption rate.

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