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EXECUTIVE SUMMARY OF THE THESIS

Electric Vehicle Modelling, Simulation and Validation on Real Driving Conditions

TESI MAGISTRALE IN MECHANICAL ENGINEERING

AUTHOR: ANTONIO COVELLO

ADVISOR: CH.MA PROF.SA MICHELA LONGO

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1. Nomenclature

Name	Symbol
Mass of the vehicle	$M_{Vehicle}$
Mass of the passenger	$M_{Passengers}$
Equivalent Mass Coefficient	β
Equivalent Mass	m_{eq}
Rolling Resistance Force	F_{rr}
Rolling Friction Coefficient	f
Velocity of the Vehicle	v
Hill Climbing Force	F_{hc}
Slope of the Road	α
Aerodynamic Force	F_{ad}
Drag Coefficient	c_d
Frontal Area	S
Air Density	ρ
Inertia Force	$F_{Inertia}$
Acceleration of the Vehicle	a
Tractive Effort	F_{te}
Instantaneous Power Flow	P_{te}
Motor Efficiency	μ_m
Transmission Efficiency	μ_g
Torque	T
Angular Speed	ω
Tractive Power	P_{te}
Braking Power	$P_{braking}$
Power required by the motor	$P_{mot_{in}}$
Power of auxiliaries	$P_{auxiliaries}$
Power provided by the battery	$P_{battery}$
Instantaneous Energy profile	$E_{battery}$
Battery Capacity	$C_{battery}$

2. Introduction

Climate change and environmental concerns are now putting a higher focus than ever on sustainability in all aspects of modern life. The transition towards green energy and electrification must also involve the transportation sector, which is one of the major causes of emission all over the world. In this sense, great technological advancements have been in the road transports in modern years, with the development and evolution of Electric Vehicles (EV), whose popularity is strongly increasing, even if Internal Combustion Engine vehicles are still the most common vehicles used for road transportation. The EV annual sales tipped over the two-million-

vehicle mark for the first time in 2019, representing the 2,5% of the global market share. The reasons of the success of EVs can be found in sustainable policy support, public spending on subsidies and incentives and aggressive car electrification goals.
This background represents the starting point of the work of thesis, in which a methodology for the design of an EV model is described and its validation on a real-world vehicle system is presented, with detailed analysis of the results. This work is organized as follows. In section 2, the vehicle model is specified, focusing on the most important inputs. In section 3, the experimental campaign has been explored, with a particular consideration at the main parameters which affects the energy consumption, such as the definition of the route, and so the speed profile, the choice of the vehicle and the power of the auxiliary system. Finally, results were analyzed and compared.

3. Vehicle Model

The approach for designing and developing an EV model was firstly described in a previous work [1], and now, it is modified and corrected according to the literature, [2], [3], in order to give more accurate estimations of the outputs. To summarize, the model employs telemetry from a real-time speed profile acquisition across a fixed route to accurately calculate the energy consumption required. In order to simplify the explanation, the model has been broken into four blocks, which will be explored in detail below.

3.1. Speed Profile Model

The starting point of the model is the definition of the speed and the acceleration profiles. Since the goal of the model is to represent a true vehicle behavior through a fixed route, it has been decided to use a real speed profile acquisition.

3.2. Dynamic Model

After obtained speed and acceleration profiles, resistance (F_{rr}, F_{ad}, F_{hc}) and inertia ($F_{Inertia}$) forces had to be calculated (1).

$$\begin{cases} F_{rr} = f\,(M_{Vehicle} + M_{Passengers})g, \\ F_{ad} = \frac{1}{2}\,C_d\,S\,\rho\,v^2, \\ F_{hc} = (M_{Vehicle} + M_{Passengers})\,g\sin(\alpha), \\ F_{Inertia} = m_{eq} * a. \end{cases} \tag{1}$$

It is important to notice that α is the slope of the road and it has been calculated starting from the altitude profile acquired during the tests.
Afterwards, the tractive effort F_{te} has been computed summing all the forces.

3.3. Efficiency and Power Model

Once computed the total tractive force, F_{te}, the instantaneous power flow, P_{te}, required by the vehicle can be calculated. These values of the power profile can be either positive, P_{pos}, or negative, P_{neg}, when the vehicle is reducing its velocity. Furthermore, the power required by the motor, $P_{mot_{in}}$, can be calculated (2).

$$\begin{cases} P_{te} = F_{te} * v, \\ P_{tractive} = \dfrac{P_{pos}}{\eta_g * \eta_m}, \\ P_{braking} = P_{neg} * \eta_g * \eta_m * \eta_{reg.braking}, \\ P_{mot_{in}} = P_{tractive} + P_{braking}. \end{cases} \tag{2}$$

It is important to notice that at this point, the efficiencies of transmission, motor and regenerative braking, respectively η_g, η_m, $\eta_{reg.braking}$, play an important role.
As regard gear system efficiency, it is usually very high (considering inverter and transmission this efficiency can be around 0,95-0,99).
For the efficiency of the motor, several methods could be used:

- Usually the value of this efficiency ranges from 0,7 up to 0,95 and thus a typical mean value of 0,85 can be accepted, despite the fact that the precise number cannot be determined.
- The efficiency can be estimated with the Losses coefficients, using the dependence on motor speed ω and torque T (3).

$$\eta_m = \frac{T * \omega}{T * \omega + k_c * T^2 + k_i * \omega + k_\omega * \omega^3 + C} \tag{3}$$

- In order to better estimate the efficiency, another alternative could be to use the Efficiency Map of the specific motor of the vehicle used in the validation of the model.

Finally, the amount of power that the battery, $P_{battery}$, must provide to the vehicle during the route can be computed summing the contributions of the power required by the motor, $P_{mot_{in}}$, and the power of auxiliaries, $P_{auxiliaries}$.

3.4. Energy Model

As regards the computation of the energy consumption, the aim is to calculate the State Of Charge (SOC) of the vehicle needed to travel the fixed route. The calculation of the SOC is a complex task depending on several conditions. Anyway, since battery charge and discharge implicate complex physical processes and chemical reactions and considering that the instantaneous values of current and voltage are not very accurately measurable during the experimental tests, in this model a "macroscopic" approach has been used, considering only the power that the battery must provide during the route, and not the contribution of the quantities already mentioned above. Once obtained an instantaneous power profile of the battery, $P_{battery}$, also the instantaneous energy profile, $E_{battery}$, can be calculated with an integration. Making the cumulative sum of these instantaneous values, the energy consumption can be calculated, where of course the last value represents exactly the energy spent in order to travel the route chosen. Finally, knowing also the starting SOC of the vehicle and the capacity of the battery, $C_{battery}$, the SOC can be calculated (4).

$$SOC = SOC_{start} - \frac{EnergyConsumption}{C_{battery}} \tag{4}$$

4. Experimental Campaign

In order to validate the model, an experimental campaign on a fixed route has been executed, consisted in fifty experimental tests in a real-drive conditions, divided into two groups of twenty-five each, depending on the driver's behavior on the road.

The first driver, D1, represents a slow driver, with a maximum speed limited and eco-driving behavior, in order to take advantage of the energy recovery, helping to reduce unnecessary kilowatt consumption and bringing the motor closer to its maximum energy efficiency level.

The characteristics of the second driver, D2, instead, are quite the opposite: fast maximum speed and not limited by the eco-driving, rapid accelerations and slow down. Besides the velocities, other differences are the weight (60 kg for D1 and 100 kg for D2), and the hour of the tests, that is almost always in the morning for D1, and variable for D2.

The speed and the altitude profiles has been obtained using "TrackAddict", a data acquisition app which uses GPS to capture and analyze video and telemetry data.

4.1. Route: Speed and Altitude Profile

The analyzed route consisted in an about 31 km round trip between the cities of Trepuzzi (Le), from via Calvario 58C – A, and Lecce, to Istituto Presta-Columella - B, as showed in Figure 1. The choice of this route was due to simulate a typical journey that a worker may travel daily.

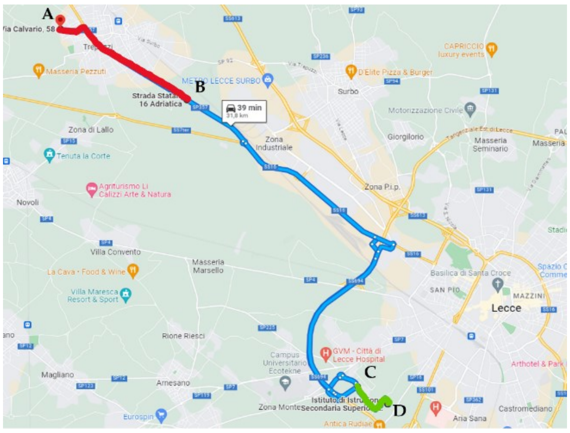

Figure 1: Google Maps visualization of the route.

The route can be divided into three zones:

- A 7,2 km urban road, in the small city of Trepuzzi, with all the characteristics of a city road: limited maximum speed, full of stops and fast accelerations due to the congestion and the traffic-lights, and with an elevation more or less constant (A-B).
- A 2,2 km country-side road, near the Istituto Presta-Columella, that is also a slow street due to characteristics of the road and the presence of pedestrians and other vehicles (C-D).
- An extra-urban road in between them, which represents the biggest contribution to the travel (about 21,5 km). This is a faster street, with an important difference in elevation, but some roundabouts or junctions are present, which make the vehicle speed slow down (B-C).

These zones can be seen also looking at the speed profile, which is showed in Figure 2 together with the altitude profile.

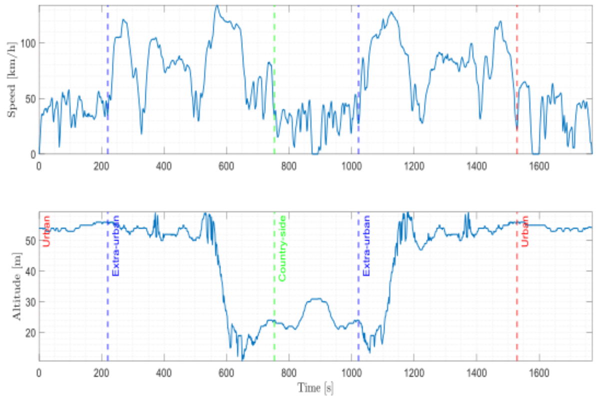

Figure 2: Speed and Altitude Profile with indication of the three zones.

From the graph, it can be clearly seen how the elevation is quite constant in the urban zone. Furthermore, in the first part of the extra-urban road, the altitude remains more or less constant, with some exceptions: a bridge and a road junction to enter the high-speed road are present. In the second part of the extra-urban road, a massive reduction in elevation can be noted, which will be recovered in the last part of the travel, i.e. the country-side. The opposite is valid for the return journey. Moreover, it can be noted that urban and country-side environments are both characterized by low or limited speed and common stops and fast accelerations, which make them far different from the extra-urban road. Thus, in order to simplify the analysis, these two zones are considered together and combined.

A critical point of this route is the presence of a 1 km long tunnel. During the travel of this, a lack of GPS signal could happen, giving wrong acquisition of data of both speed and altitude. The speed profile has been corrected and reconstructed considering the real velocity on the street, Figure 3, to have the more life-like speed profile.

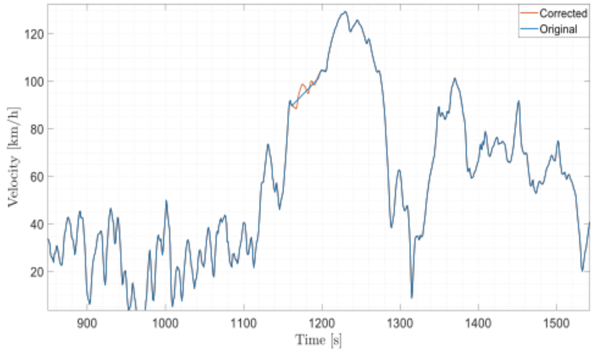

Figure 3: Comparison between the original and the corrected speed profiles, with a zoom on the different region.

As regards the altitude profile, it has been modified and corrected using Google Earth as a reference, Figure 4, to avoid or minimize the measurement errors, which could give wrong values of the slope force. Finally, it is important to notice that this problem did not happen in all the tests, or it happens only for 32 seconds over the whole duration of the travel, thus the mistake given by the wrong approximation is quite minimum.

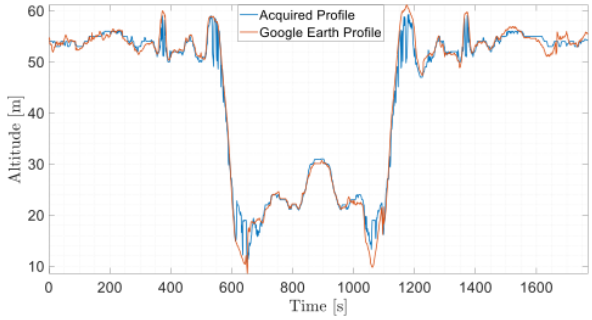

Figure 4: Comparison between the acquired altitude profile and Google Earth profile.

4.2. Choice of the Vehicle

The vehicle chosen for this study a Renault Twingo E-Tech Electric. This vehicle represents the perfect city car: small but comfortable, useful in urban conditions by reason of regenerative braking. However, due to its low battery capacity, the range is limited at only 160 km, which makes this model not to be one of the best-selling EV. The choice of vehicle determined numerous parameters, such as:

- The mass of the vehicle was at over 1133 kg. The equivalent mass was fixed at 104% to consider the inertial effects of the wheels, of the motor and of the drivetrain. This equivalent mass is essential for the calculation of the inertial forces produced during the acceleration and deceleration of the car. To have an estimation of the equivalent mass coefficient, a preliminary calculation on the inertial effects of the wheels was performed and it was found to be around 4%. Hence, this typical value has been used.
- Aerodynamic drag coefficient is 0,32 and the frontal area of the vehicle is set to 2,11 m^2.
- In order to calculate the rolling resistance force, the formula (5) for the rolling coefficient f has been used. The tires pressure was set at 2,5 bar.

$$f = 0{,}005 + \frac{1}{P_{Tires}}\left(0{,}01 + 0{,}0095\left(\frac{v}{1000}\right)^2\right) \quad (5)$$

- The slope force has been computing using the altitude profile acquired during the tests.
- Slip condition has been checked, even though no slip occurred during the experimental tests.
- As regards the motor efficiency, the loss coefficients method has been used for D2 with

a value of transmission efficiency of 0,97. For D1, instead, the typical value of 0,85 has been chosen, considering both efficiencies. This is due to the fact that D1 travels with eco-driving behavior, and so the motor works almost always in the optimal point; instead, for D2 there are some sections in which the vehicle travels at its maximum speed available and the efficiency will not be optimal. In Table 1, the values of the loss coefficients and the quantities used for the calculations are reported.

- Regenerative braking efficiency was set at 0,85, but it has been allowed only above 12 km/h.
- The battery capacity is 22 kWh, which is a low-medium value for modern e-cars. However, even if this is a brand-new EV and the State Of Health (SOH) is 0%, the net available capacity is assumed a bit lower at 21,5 kWh.

Table 1: Parameters for the calculation of the motor efficiency with Loss Coefficients Model.

		Value	Unit
Simple Fixed Gear Ratio	G	9,7:1	
Tire Radius	r	0,289	m
Copper Losses Coefficient	k_c	0,12	$\frac{\mathrm{s}}{\mathrm{kg\ m^2}}$
Iron Losses Coefficient	k_i	0,01	J
Windage Losses Coefficient	k_ω	$5 * 10^{-6}$	$\mathrm{kg\ m^2}$
Constant Losses	C	600	W

4.3. Power of Auxiliaries

The other important parameter in the simulation is the power of auxiliaries, which can be significantly different from time to time, depending if air cooling, lights and other utilities are switched on or off. For this reason, there cannot be unique of fixed values for this power. To simplify the model, this power has been generally classified into three classes, which represent the energy consumption of the auxiliaries during the tests, Table 2.

Table 2: Auxiliaries Power Conditions used in the model.

Auxiliary Power Condition	Energy Consumption [W]
Poor	100
Moderate	500
High	900

However, it is important to notice that these values are only a starting point, since it can happen that some auxiliaries are switched on only for a limited period and not for the whole duration of the travel.

5. Analysis and Discussion of the Results

For every experimental test, two photos of the vehicle dashboard have been captured, one before and the other after the travel. In this way, it has been possible to find out the indication of the SOC of the vehicle, and so the value of energy consumption for the route.

The first results showed that in general the model accurately estimated the experimental outputs, since the average error between the two results is quite small, with a maximum error value of 1,16% and 0,88% respectively for D1 and D2. However, some outbounds were present for both groups: it has been noticed how the energy consumption for the tests starting with a full charged battery was significantly small, far below the average specific energy consumptions. It was found in literature [4] that when the SOC is higher than 90%, the energy discharged by the battery is higher. Hence, the model has been modified.

5.1. D1 results

After the full-charged-battery correction, all the simulations match the output of the test, since the error is almost always lower than 1%. In general, for D1 group, the model seems to underestimate a bit the experimental results, with an acceptable value of average error of -0,37%, Table 3: Comparison between experimental and model average results for D1 and D2.Table 3.

Table 3: Comparison between experimental and model average results for D1 and D2.

Average Quantities	D1	D2
Experimental SOC Difference	15,72	21,06
Model SOC Difference	15,35	21,24
Error	-0,37	0,18

5.2. D2 Results

In the case of D2 group, the model seems to better estimate the experimental result, with a value of average error of 0,18%,

Table 4. Anyway, few outbounds are still present. This could be due by the SOC sensors of the vehicle

that have a sensitivity of 1%, thus, the measured values of SOC have a tolerance of ±0,5%. Moreover, only for D2 group a correlation between SOC and mean speed can be found when the speed is higher, so it is the energy consumption. This is not valid for D1 tests, for which the power of the auxiliaries gives a more significant contribution to the energy consumption since the velocities are much lower.

5.3. Comparison for the same power of auxiliary system

To make a further analysis, a pair of simulations with the same auxiliary's power consumption has been compared, in order to find out supplementary critical issues of the model. However, also in this case, the model better estimates the experimental results. Simulations with similar speed profile characteristics, if have the same power of auxiliaries, will give also similar energy output, and vice versa.

5.4. Comparison between D1 and D2 results

Lastly, a further comparison has been made. This time, the two groups were compared according to the sections of route. It has been found that for the urban zone, since the speeds are quite similar, Figure 5, the energy output are similar too,

Table 4.

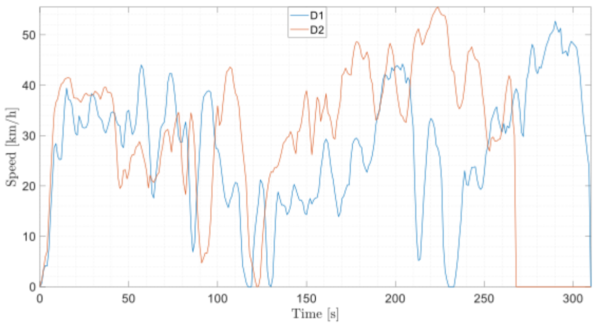

Figure 5: Comparison between D1 and D2 urban speed profiles.

Table 4: Average quantities of urban section for D1 and D2.

Average Quantities	D1	D2
Maximum Speed [km/h]	47,5	57,7
Mean Speed [km/h]	24,8	32,0
Specific Energy Consumption [kW/100km]	11,39	12,19

The opposite is valid for the extra-urban zone: the difference in mean and maximum speeds makes the energy consumption to significantly increase, with a mean difference value of about 4kWh/100km for only 10km/h. This is of course also due to the long periods in which the vehicle travelled at its maximum speed (around 130 km/h).

6. Conclusion

The purpose of this work is the development of an EV model and its validation through an experimental campaign. To conclude, this model seems to accurately estimate the energy consumption and so the SOC of a chosen vehicle, since the average error between the two results is quite small. It has been established how the speed profile and the power consumption of the auxiliaries are the main parameters, respectively at high and low velocities. Thus, future possible developments and modifications could be a more accurate evaluation of the power of auxiliaries and a more appropriate estimation of the efficiency of the vehicle, since these two are very significant and case-dependent parameters.

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