Proposal of More Accurate Energy Model of Electric Vehicle For SUMO

Insaf Sagaama
National School of Computer Science
University of Manouba
Manouba, Tunisia
insaf.sagaama@ensi-uma.tn

Amine Kchiche
National School of Computer Science
University of Manouba
Manouba, Tunisia
amine.kechiche@ensi-uma.tn

Wassim Trojet
High Engineering School of Rouen ESIGELEC-IRSEEM
Normandie university
Rouen, France
wassim.trojet@esigelec.fr

Farouk Kamoun
National School of Computer Science
University of Manouba
Manouba, Tunisia
farouk.kamoun@ensi-uma.tn

***Abstract*—The attempts to reduce vehicle's CO2 emissions and fuel consumption are actually motivating the manufacturers in the transport and automotive sectors to focus their interests on Electric Vehicle (EV) concept. Battery autonomy and charging process are still a big issue for that kind of vehicles. The evaluation of EV's instantaneous energy consumption through realistic scenarios and based on consistent energy models are needed to take step forward on these issues. In this paper, we provide a deep insight on EV consumption dynamics and make a review of the energy model implemented in SUMO, one of the most popular traffic simulation framework used to evaluate vehicular technologies and strategies. We propose a set of energy consumption estimation improvements and show through simulation the achieved improvements in terms of accuracy compared to the sumo implementation.**

***Keywords*—Electric vehicle; vehicular networks; energy models; traffic simulation; energy efficiency**

I. Introduction

In recent years, the automotive industry has shown a big interest for EV technology as a solution to solve environmental problems related to CO2 emissions and fossil fuels crisis. To this end, Smart Cities infrastructures and systems aim to increase the energy efficiency through these vehicles by estimating the EV power consumption, route planning and charging stations deployment [1]. Therefore, several research studies based on Information and communication technologies (ICT) have been investigated to ensure reliable interaction between the connected EVs, EV driver and EV charging infrastructure [2][3][4]. In particular, such solutions aim to evaluate the areas related to routing, wireless communication, vehicular mobility, modeling and deployment of vehicular charging infrastructure [4]. Indeed, many projects have been reported in this context. For instance, the project "Intelligent Infrastructure of Electric Vehicle (ELVIIS)" [5] proposed a solution for reducing the complexity of EV charging process based on ICT systems. Moreover, the ARTEMIS EU project "Internet of Energy for Electric Mobility" [6] proposed an architecture based on ICT allowing communication between the charging infrastructure and connected EVs. Furthermore, FABRIC project [3] have proposed an advanced on-road charging infrastructure for EVs based on ICT. In the same context, we are working on a project "Urban Platform for Connected Electric Vehicles (PUVEC)" (in the CMCU project number 16G1404) [7]. The main goal of PUVEC is to create a simulation platform for the internet of EVs. It also aims to elaborate an energy map that will be used to propose innovative services for the optimization of battery consumption of connected EVs (choice of multi-criteria routes by adding the battery constraint as a criteria, estimation and prediction of energy consumption). Accordingly, the reliability of such solutions depends on the performance of road traffic simulation tools.

Several traffic simulators exist in literature and the "Simulation of Urban Mobility (SUMO)" is the most popular one [8]. SUMO is a portable open source software which is able to simulate several types of vehicles, vehicular communication, charging Infrastructure for EVs, microscopic and multi-modal traffic road networks [9]. Currently, it integrates a simple energy model for EVs [10] in order to perform traffic simulations taking into account the EV power consumption. However, this model needs improvements to ensure realistic urban traffic simulations for EVs. The aim of this paper is to ameliorate the actual EV energy model implemented in SUMO by taking into account ambient temperature which may dramatically affect energy consumption and by refining both electric-motor consumption and recuperation efficiency estimation.

This paper is organized as follows: section II discusses the previous related works about EV energy models that exist in the literature. Section III presents a set of improvements for the actual energy model implemented in SUMO. Section IV illustrates the result analysis to shows the gap between our proposed model, the actual model implemented in SUMO and real data experimentation results. Section V concludes the paper and presents perspectives of this work.

II. Literature review

The EV is a complex system [11].Thus, Several energy models have been proposed in the literature to estimate the EV energy consumption and relative needed charging operations among different scenarios and trajectories [10] [11][12].

Vehicle energy models aim to model two main parts: the energy consumption part and the energy recuperation part. The energy consumption part can be mainly based on modeling the mechanical and electrical subsystems.

Previous works and reviews showed that the mechanical subsystem represents a common core model for the EV, since it has been considered as the most important part of the EV energy consumption [12]. It reflects the power applied to wheels which insures the EV movement. Indeed, the mechanical subsystem have been modeled using the vehicle dynamics equation, presented in [11], which depends mainly on acceleration, rolling resistance, aerodynamic drag and road slope forces. Previous works on energy consumption models are mostly based on this force formula but with notable differences due to its impact on the energy model accuracy and the complexity of its implementation. For instance, Maia et al.(2011) [11] have employed the angle of road slope while Kurczveil et al.(2014) [10] have considered the elevation component in the evaluation of the driving forces applied on the EV. In addition, Cauwer et al. (2015) [13] and Shibata et al. (2015) [14] have employed aside the vehicle mass, the fictive mass of rolling inertia in the estimation of the acceleration force. Similarly, in the works of Abousleiman et al.(2015) [15] and Wang et al.(2015) [16] the aerodynamic drag force have been modeled with the wind velocity, and even they have integrated the average mass of vehicle and passengers for the calculation of the rolling resistance effort.

The electric subsystem modeling can be divided into two main parts: the energy consumed by auxiliary systems i.e. air-conditioning, heating, radio, etc. and the pure electric losses occurred when converting the power at the electric motor to the power at the wheels during the traction mode.

Concerning the estimation of the energy consumed by auxiliary systems, two different approaches have been defined: the first one consists of evaluating the auxiliary consumption part as a constant charge provided by vehicle constructor as shown in [11], [10] and [17]. The second one, presented by Cauwer et al. (2015) [13], which expressed this energy as a function of the outside ambient temperature due to its impact on the energy consumed by the auxiliary systems.

The pure electric losses modeling are based on two major approaches : the first one is based on detailed mathematical models. It is an accurate estimation of physical electrical-components [11], [18] (e.g. the current intensity, open circuit voltage from the battery, the internal Resistance, etc.). The second one is a sophisticated estimation based on constant efficiency percentage [14], [17] (e.g. inverter efficiency, battery efficiency, electric motor efficiency, etc.).

The EV integrates on the other side, the regenerative braking system which cover the recuperation part. During the energy recuperation mode, the electric motor acts as a generator through the transformation of the kinetic energy at wheels to electrical energy stored in the battery during the deceleration or driving downhill phases[17]. Indeed, most of proposed models focus on these subsystems due to their valuable impact on the EV power consumption.

Despite the importance of the regenerative braking process in the EV power consumption, the studies presented in [11], [13],[18] did not take into account this process. However, the works in [10] and [14] presented an estimation approach through a constant regenerative braking efficiency factor giving by the EV manufacturer. Fiori et al.(2016) [17] have modeled this process by an instantaneous braking energy regeneration formula. This formula depends mainly on the deceleration level and hence easy to include in the EV energy model. This formula was determined by using the " Least Square Optimization Method " and applying experimental analysis for five driving cycles and many types of EVs.

To sum up, the diagram illustrated by Fig. 1 presents the main subsystems composing the EV energy consumption model and the depended parameters for each subsystem.

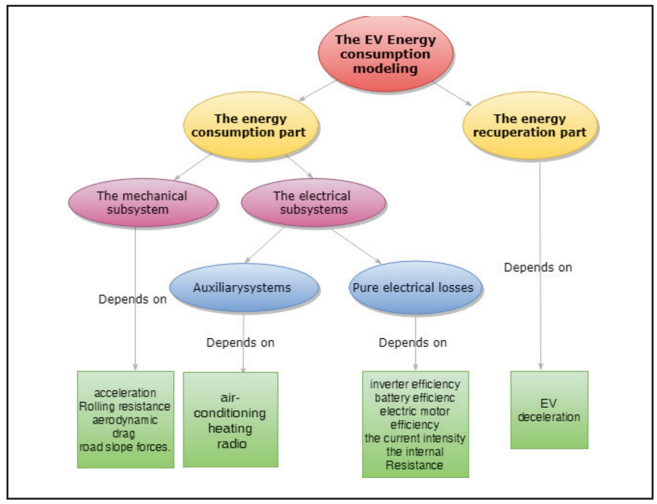


Fig. 1. EV energy model Components.

The actual EV energy model implemented in SUMO has been proposed by Kurczveil et al.(2014) [10]. They have presented a simple model aiming to improve runtime of energy consumption calculations in traffic simulations. Thus, their model is based on the mechanical subsystem model. They oversimplified the electric losses modeling by introducing a constant efficiency parameter for propulsion giving by the EV constructor. This constant represents the part of energy losses that comes out of the battery and is dissipated into drag components during the EV movement. In addition, they presented the auxiliary energy losses by a constant power provided by the vehicle manufacturer. Concerning the recuperation part, they proposed a constant regenerative braking efficiency factor that depends on the vehicle model and no explicit formula was proposed. These simplifications reduced model accuracy.

The main goal of this study is to elaborate a realistic, easily implementable and an accurate energy model in order to insure realistic traffic simulations and producing valuable results. An easy implementable model becomes capable to speed up the traffic simulation runtime. An accurate model can be applied on various types of EVs and under different conditions. In the next section, we will propose a set of improvements needed to be applied in the actual energy model implemented on SUMO [10].

III. PROPOSED ENERGY MODEL

The objective of this paragraph is to propose a set of improvements for the SUMO energy model implemented by [10], to take into account the evaluation results/findings of the previous section. SUMO [8] is considered today as one of the most reliable traffic simulators used especially for vehicular networks and hence for EV scenarios. To our sense, the current implementation of the consumption model [10] lacks accuracy, as we explained in the previous section. The ideal implementation should combine accuracy and simplicity to achieve a good modeling of a real system while maintaining a reasonable complexity level.

To achieve such requirements, we propose to enhance the model implemented by [10] with more accurate evaluation of each consumption subsystems modeling:

- *Ambient-Temperature-aware*: we propose to express the power consumed by the auxiliary systems in terms of ambient temperature and time-dependent formula as described in [13] in order to quantify the impact of auxiliary system on the energy consumption model.

  The energy consumed by auxiliaries in each time-step Δt corresponds then to:

  $$\Delta E_{Aux,T}[t] = E_{Aux,const} \times \Delta t + \beta \times |20 - T| \times aux \times \Delta t$$

  Where:

  $E_{Aux,const}$**[W]:** is the minimum base energy consumed by these auxiliary systems : radio, light system, etc. at 20°C [19].

  T: Ambient temperature in °C.

  β: regression coefficient mapping HVAC consumption to ambient temperature which was estimated by [13] through experimentations.

  $$\mathbf{aux} = \frac{\text{Duration of auxiliaries switched on}}{\text{Total duration of trip}}$$

- *Accurate Electric losses estimation*: The energy at the electric motor can be estimated, given the mechanical power at the wheels, and considering an accurate efficiency estimation, as presented in the previous section. This approach keep the implementation and simulation steps as less complex as possible to be able to afford scalability whiles emulating large vehicular scenarios. The efficiency-coefficient based approach shown through[14], might be of significant support.

  The electric losses could be hence expressed through the following formula:

  $$\Delta E_{Bat}[t+1] = \Delta E_{Bat}[t] + \Delta E_{gain}[t] \times \eta_{BAT} \times \eta_{INV} \times \eta_{MOT}$$

  Where: η_{BAT}: *battery charging & discharging efficiency;* η_{INV}: *inverter efficiency;* η_{MOT} *: electric motor efficiency.*

- *Deceleration-dependent recuperation modeling*: We propose to include an accurate energy recuperation model that depends on the deceleration level as it was physically demonstrated and experimentally estimated in[17] in order to improve the accuracy of the overall energy modeling [10].

  The energy recuperation part could be injected as following in the model formula: in regenerative case ($\Delta E_{gain}[t] > 0$):

  $$E_{Bat}[t+1] = E_{Bat}[t] + E_{gain}[t] \times \eta_{recup}[t]$$

  Where the recuperation part could be estimated by:

  $$\eta_{recup}[t] = \left[e^{\left(\frac{0.0411}{|a[t]|}\right)}\right]^{-1} \quad ; \forall a[t] > 0 \quad , [17]$$

The entire proposed PUVEC energy consumption model is then expressed by the classical mechanical consumed energy [10] on which we do apply the proposed improvements:

$$\Delta E_{gain}[t] = E_{veh}[t+1] - E_{veh}[t] - \Delta E_{loss}[t]$$

$$E_{veh}[t] = E_{Kin}[t] + E_{pot}[t] + E_{rot,int}[t]$$

$$= \frac{m}{2} . v^2[t] + m . g . h[t] + \frac{J_{int}}{2} . v^2[t]$$

$$\Delta E_{loss}[t] = \Delta E_{air}[t] + \Delta E_{roll}[t] + \Delta E_{curve}[t] + \Delta E_{Aux,T}[t]$$

Where:

$$\Delta E_{air}[t] = \frac{1}{2} . \rho_{air} . A_{veh} . C_w . v^2[t] . |\Delta s[t]|$$

$$\Delta E_{roll}[t] = C_{roll} . m . g . |\Delta s[t]|$$

$$\Delta E_{curve}[t] = C_{rad} . \frac{m . v2[k]}{r[k]} . |\Delta s[t]|$$

The underlying Table I explains the introduced parameters.

TABLE I. PHYSICAL PARAMETERS INPUT FOR THE ENERGY MODEL

Constants	Meaning
m	Total vehicle mass
v[k]	time variant vehicle speed
a[k]	instantaneous vehicle acceleration
g	gravity acceleration
h[k]	time variant vehicle altitude
J_{int}	moment of inertia of internal rotating elements
ρ_{air}	variables air density
C_w	Air drag coefficient
A_{veh}	vehicle front surface area
C_{roll}	rolling resistance coefficient
C_{rad}	curve resistance coefficient
T	Outside Ambient temperature in °C
η_{BAT}	battery charging & discharging efficiency
η_{INV}	inverter efficiency
η_{MOT}	electric motor efficiency

IV. RESULTS ANALYSIS

In the previous sections, a detailed model of the EV electric motor power consumption has been presented, analyzed and some, to our sense, critical enhancements, have been proposed. To evaluate the proposed modeling, we conducted a series of simulations based on almost real conditions, consisting of real vehicle description parameters applied on standardized driving cycles. The obtained results have been compared to experiment results, in order to evaluate the accuracy of the new improved model compared to the currently available SUMO model.

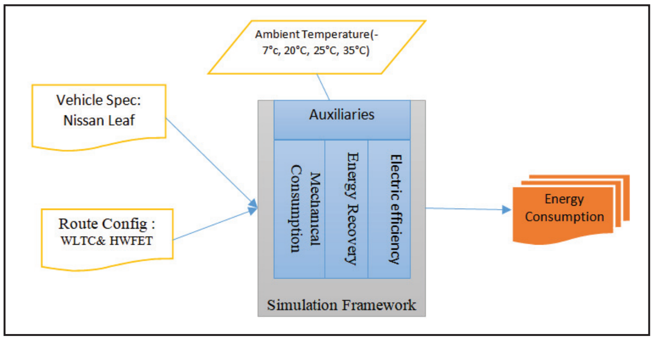
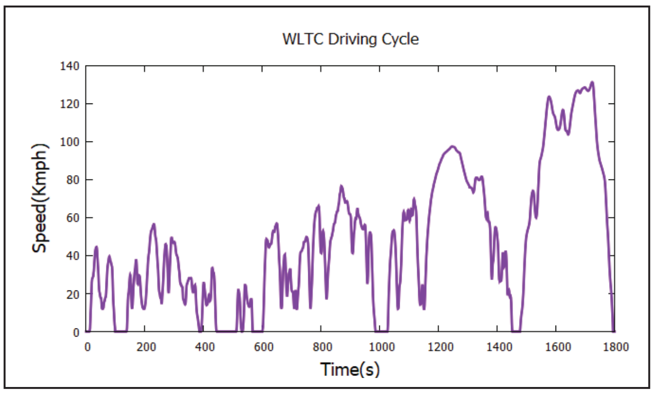
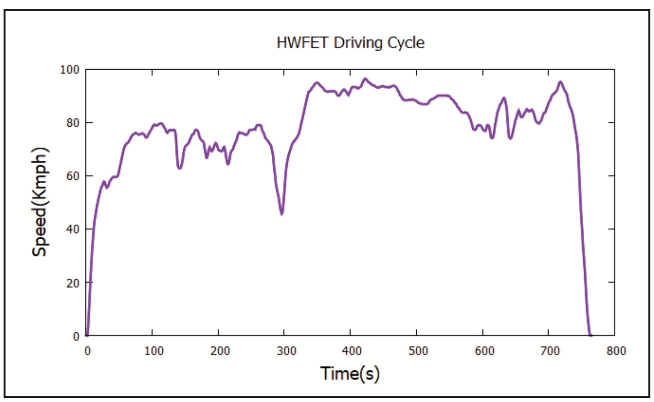


Fig. 2. Simulation Process For the Energy model Validation.

The simulation process is shown in Fig. 2. The Nissan Leaf EV Model was chosen given its popularity and the availability of related detailed technical specifications that were integrated in our simulation environment.



a) WLTC Driving Cycle speed profile.



b) HWFET Driving Cycle speed profile.

Fig. 3. WLTC and HWFET Driving Cycles speed profile.

The corresponding experimental results of the considered scenarios have been taken from the[17]. As a travel scenario, we applied two driving cycles: the Worldwide harmonized Light vehicles Test Cycles (WLTC), illustrated in Fig. 3 and the Highway Fuel Economy Test cycle (HWFET) illustrated by Fig. 4. The WLTC driving cycle was developed by European, Japanese and Indian experts in order to replace the NEDC cycle in 2013-2014 and was intended to evaluate the pollutants and emissions, the fuel economy but also the electric range of light duty vehicles (passenger cars). The corresponding electric consumption data were reported by the Joint Research Centre (JRC) of the European Commission[20]. The HWFET driving cycle was developed by the US Environmental Protection Agency (EPA) and is usually used to assess fuel economy over highway driving cycle. The corresponding electric consumption validation data were collected by the DOE's Advanced Vehicle Testing Activity (AVTA) of the Idaho Nation Laboratory (INL) [21].

A. Overall Impact: Average consumption

The first aspect, we were interested on, was the validation of the whole model, while excluding the temperature aspect. The following table compares the average electrical consumption between SUMO default model and our PUVEC model while taking experimental results from [20][21] as reference. The simulation was applied to the two above-mentioned driving cycles.

The results, as shown in Table II, are unequivocal: 1% deviation from the experimentation results for the PUVEC model against 23% for the SUMO model in the HWFET driving cycle case and 4% deviation against 28% in the WLTC driving cycle case. Let us point out that a minor difference from the experimental results is to be expected due to the difficulty to integrate exact vehicle parameters and simulation conditions. The registered improvement achieved by the PUVEC model can be explained by a refined recuperation process model and a more accurate efficiency parameter integration as explained in section III.

TABLE II. AVERAGE ENERGY CONSUMPTION (25°C HVAC OFF).

The Nissan Leaf Electric Car					
Energy consumption (Wh/Km)	***Real Experiments (AVTA/ JRC)***	***PUVEC Energy model***	***Error[%] PUVEC Vs Real Experiments***	***SUMO Energy model***	***Error [%] SUMO Vs Real Experim ents***
HWFET	149.6	147.34	-1.51	114.36	-23.55
WLTC	178.4	171.16	-4.05	127.55	-28.5

B. Ambient Temperature Impact: a refined model.

As detailed in section II, the other part that is expected to have an important impact on EV consumption is the Air Conditioning subsystem. AVTA and JRC experimental results revealed already such impact [20][21][22]. In addition, the experimentations presented in [23] and [17] have proved through simulation results that the power consumption might increase by up to 32% depending on the ambient temperature.

Simulation results, which compare SUMO and PUVEC models do confirm the importance of integrating such awareness in the EV model. In fact, Fig. 5 illustrates the Energy consumption variation according to the ambient temperature. Experimental results show a consumption increase of about 55.8% (between 20°C and -7°C) due to the heating system consumption. In the other hand, SUMO model stays insensitive to the temperature factor, whereas PUVEC model prove its ability to reflect the air conditioning consumption impact. Fig. 6 illustrates the consumption evolution over the time while considering the WLTC driving cycle and clearly shows how the gap of consumption increases for different temperatures (25°C ,35°C and -7°C), compared with the static SUMO consumption model.

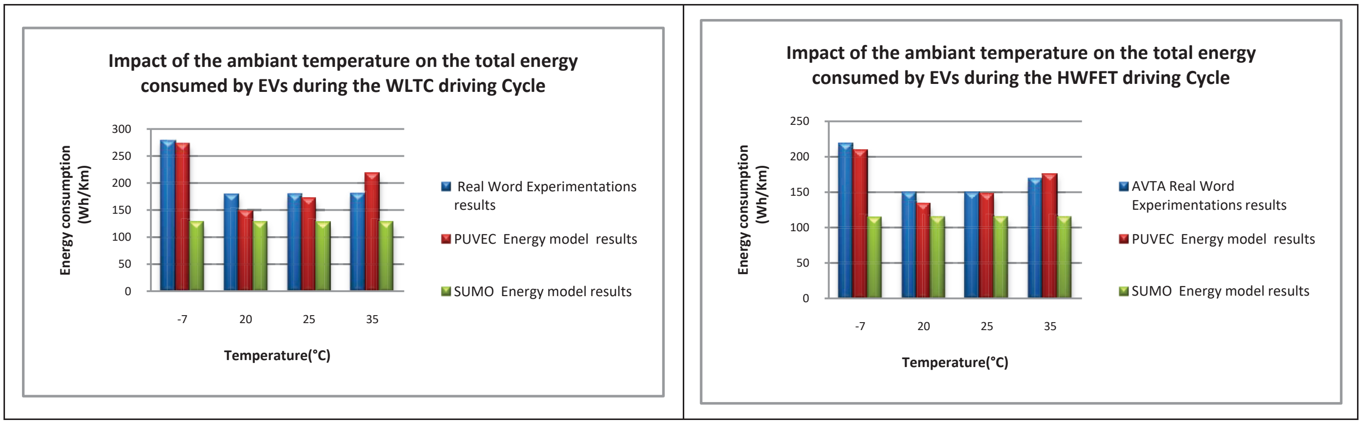


Fig. 4. Impact of the outside Temperature on the total energy consumed.

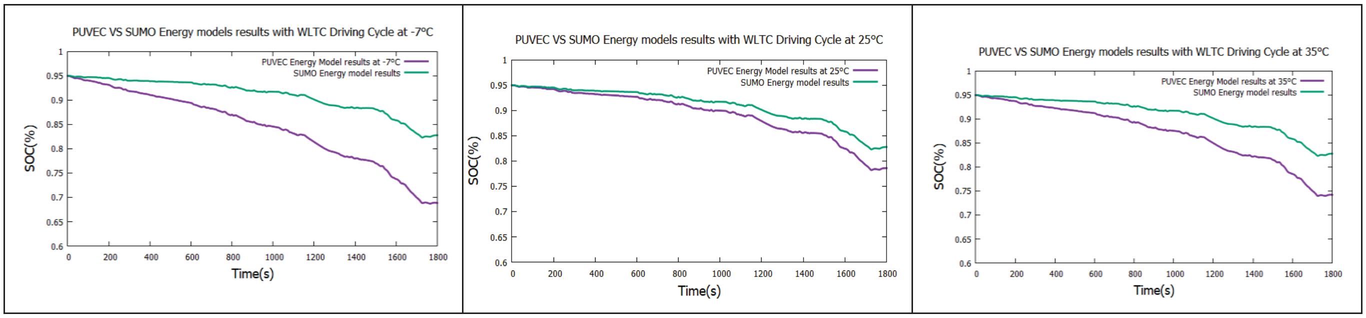


Fig. 5. Combination of the SOC profile graphs related to (1) PUVEC energy model and (2) the actual energy model available in SUMO at different temperatures.

1.1 Impact on the Driving Range

As stated in previous sections, EV limited driving range, coupled with long recharging times and limited number of charging stations, is one of the main constraints for the proliferation of EV. Fig. 7 shows that the driving range is significantly affected by the Air conditioning subsystem (decrease up to 31.2% in driving range in the case of -7°C compared to the 20°C conditions). The SUMO model shows a wrong estimate of about 96.7 Km in the WLTC driving cycle at -7°C (similar result were also registered in the HWFET driving cycle), which makes this model unreliable for analyzing EV consumption.

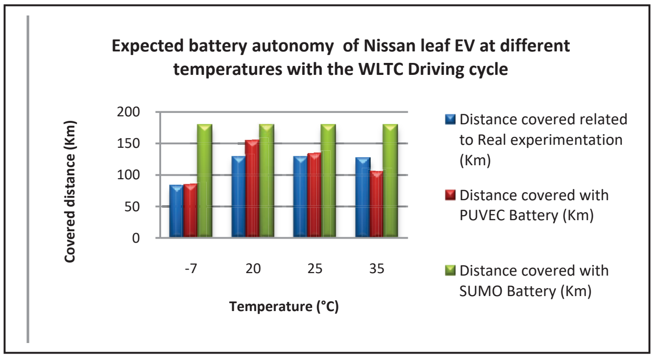


Fig. 6. WLTC driving cycle: Expected battery autonomy of the Nissan leaf EV at various temperature degrees.

Our proposed model, on the contrary, achieves a better estimation, with a distance error percentage of 20.17% in the worst case. Such results could be used with confidence while studying EV consumption and may help mitigating driver range anxiety.

To summarize, we showed that the air conditioning subsystem may have a significant impact on the EV energy consumption (33,2% of the total energy in -°7C temperature range), which instantly affects its driving range. As shown in Fig. 9, auxiliaries' consumption (mainly HVAC in our case) may represent a significant proportion of the whole EV consumption. A proper and accurate estimation of its amount is essential otherwise the EV distance range estimation and all related services could be distorted. The EV HVAC system may require a complex modeling of the air flow behavior and the climate control system. Nevertheless, we showed that a simple linear model could give a good enough estimation of the induced consumption.

The recovery process is also very important and an oversimplified model such the one used in SUMO may mislead the estimation, as revealed in Fig. 8. Finally, a faithful specification of efficiency factors (battery, propulsion, inverter, recovery.) is also important as it consumes a considerable part of the whole energy (16,3% in the last scenario)".

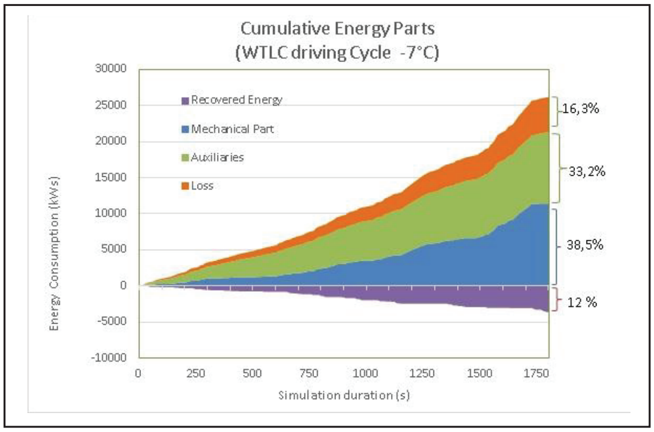


Fig. 7. Cumulative energy components of The Nissan Leaf EV during the WLTC Driving Cycle at -7°C.

V. Conclusion and Future Work

In this paper, we presented a literature review of energy consumption models for EV. We recalled in a first step the different forces acting on an EV and deduced the different energy consumption parts that should be considered while establishing an accurate energy model for EVs.

The conducted theoretical analysis revealed many optimizations and recommendations that should be applied when implementing EV energy consumption models with regards to scalability, efficiency, and accuracy. Therefore, We proposed a set of improvements that should be integrated in the currently implemented energy model in SUMO. We showed through a set of simulation scenarios, whose results were compared with experimental data, that the proposed enhancements make a worthwhile contribution to achieve reliable and accurate energy consumption estimations.

Future work includes considering real experimentations on different road shapes with different elevations to further study the regeneration impact on the EV energy consumption model.

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