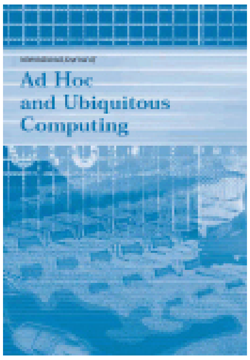


International Journal of Ad Hoc and Ubiquitous Computing

ISSN online: 1743-8233 - ISSN print: 1743-8225
https://www.inderscience.com/ijahuc

Energy consumption models in VANET simulation tools for electric vehicles: a literature survey

Insaf Sagaama, Amine Kchiche, Wassim Trojet, Farouk Kamoun

DOI: 10.1504/IJAHUC.2023.10052675

Article History:

Received:	01 November 2021
Last revised:	29 December 2021
Accepted:	22 January 2022
Published online:	16 December 2022

Energy consumption models in VANET simulation tools for electric vehicles: a literature survey

Insaf Sagaama* and Amine Kchiche

CRISTAL Laboratory,
ENSI,
University of Manouba,
Manouba, Tunisia
Email: insaf.sagaama@ensi-uma.tn
Email: amine.kechiche@ensi-uma.tn
*Corresponding author

Wassim Trojet

IRSEEM Laboratory,
ESIGELEC,
Normandie University,
Rouen, France
Email: wassim.trojet@esigelec.fr

Farouk Kamoun

CRISTAL Laboratory,
ENSI,
University of Manouba,
Manouba, Tunisia
Email: farouk.kamoun@ensi-uma.tn

Abstract: Electric vehicles (EVs) have been widely recognised as a key technology of the intelligent transportation systems (ITSs) to make both public and private transportation services more economic and ecological. The energy-saving in the case of EVs is a viable solution to promote smart navigation and extending the driving range. Realistic traffic simulations contribute to the large-scale diffusion of EVs in the future market. In particular, vehicular ad hoc networks (VANETs) simulation tools integrate often an energy model for calculating the vehicle energy consumption. Hence, the EVs raise a new challenge about integrating reliable and accurate energy models in the traffic simulators for this category of vehicles. In this paper, we present a thorough study about energy models elaborated in the automotive sector to provide valuable enhancements to VANET simulators. The main goal is to establish an accurate estimation of the EV consumption and recuperation in VANET simulation tools.

Keywords: electric vehicle; VANETs simulation tools; energy consumption models; energy recuperation; energy efficiency.

Reference to this paper should be made as follows: Sagaama, I., Kchiche, A., Trojet, W. and Kamoun, F. (2023) 'Energy consumption models in VANET simulation tools for electric vehicles: a literature survey', *Int. J. Ad Hoc and Ubiquitous Computing*, Vol. 42, No. 1, pp.30–46.

Biographical notes: Insaf Sagaama is a Doctor of Computer Science. She earned her Doctorate degree in 2020 from the ENSI, High Engineering School Manouba, Tunisia. She is a member of the CRISTAL Laboratory (RAMSIS Group) Tunisia since 2014. She received her research Master's and Engineering in Computer Science from the ENSI Manouba, Tunisia in 2013 and 2012 respectively. Her current research interests include vehicular networks, smart cities, electric vehicle, network simulation, energy efficiency and green intelligent transportation systems.

Amine Kchiche is currently an Associate Professor at the ISAMM, University of Manouba, Tunisia. He is a member of the CRISTAL Laboratory (RAMSIS Group), Tunisia. He received his Computer Science Engineering and DEA from the University of Karlsruhe in Germany in 2005. He received his PhD from the ENSI Tunisia in 2015. His work focuses on the role of infrastructure in vehicular ad hoc networks. His research interests include peer-to-peer, wireless, ad hoc and vehicular networks.

Wassim Trojet is an IT Associate Professor at the ESIGELEC, High Engineering School, Rouen University, France. He is a member of the IRSEEM Laboratory. He received his PhD and Master's in Computer Science at the University of Aix-Marseille, Marseilles, France. He is actually interested in security and safety issues in green intelligent transportation systems, especially the internet of electric vehicles.

Farouk Kamoun is currently the President of SESAME University and Professor Emeritus at the ENSI, Tunisia. He received an Engineering degree from the Ecole Supérieure d'Electricité, Paris, France in 1970 and PhD in Computer Science, in 1976 from UCLA, where he participated in the ARPA Network Project and obtained his research on design considerations for large computer communication networks. His research and interest areas deal with e-governance, cloud computing, internet of things and smart cities.

1 Introduction

Electric vehicles (EVs) are facing today to several challenges related to their relative limited battery's capacity. This constraint prevents EVs from achieving long distances without recharging their batteries. Such recurring operation would consume much time (i.e., a recharging operation lasts between 20 min and 8 hours) and would disturb the driver's journey. Many efforts are therefore required to ensure an optimised and sufficient deployment of charging station and also to minimise the vehicle energy consumption.

On the other hand, EVs have been seen as a promising technology, among others, thanks to the energy recuperation process which permits recapturing and storing a part of the dissipated inertial energy (Heydari et al., 2019). The energy recuperation process extends there by EVs driving range without any additional cost by around 15% (Heydari et al., 2019). Thus, it is crucial for the EV community to well understand, assess and estimate the energy consumption process of EVs to be able to address the above-mentioned challenges in a proper way.

Vehicular ad hoc network (VANET) simulation tools might be an efficient solution for the evaluation process of EV energy consumption. These tools need reliable models for computing realistic EV energy consumption to achieve reliable analysis that facilitate the EV diffusion. Therefore, accurately predicting the EV energy consumption in different VANET simulation scenarios is essential.

In particular, VANET simulation tools integrate often an energy model for calculating the vehicle energy consumption (SUMO, 2019). Hence, the EVs raise a new challenge about integrating reliable and accurate energy models in the traffic simulators for this new category of vehicles.

In practice, several existing VANET simulators have shown sufficient proficiency in simulating vehicles, traffic conditions, and even estimating fuel consumption and emission rates. Nevertheless, only few of them have integrated EV energy models which lack accuracy and need improvements to take into account the impact of several factors.

The present work aims to study the energy models for EVs in order to provide a better understanding of the energy consumption of EVs by identifying its main phases. This work aims also to evaluate the currently implemented models and to propose improvements that provide better estimations while maintaining a reasonable complexity level for a straightforward implementation.

The remainder of this paper is organised as follows. In Section 2, we conduct a thorough literature review about existing energy models for EVs. This study allowed us to gain a deep understanding of the consumption process of EVs. It focuses also on introducing the energy recuperation concept and it discusses recent related models. The main goal is to classify the different consumption and recuperation parts to evaluate the energy consumption models which are proposed by automotive energy specialists. In Section 3, we provide a literature review about the EV energy models which have been so far implemented and used by VANET simulation tools. A crosschecking against specialists' models, reviewed in the first part, will allow us to dress an objective evaluation of these implementations and to propose a set of improvements to have an accurate model for VANET simulators. Finally, Section 4 concludes the paper and identifies a number of perspectives for future research.

2 A literature review on energy models

In literature, various approaches have been discussed to accurately estimate the EV energy consumption and the related discharging mechanisms (De Cauwer et al., 2015; Fiori et al., 2016; Wu et al., 2015).

Energy models can be modelled by two main parts: the energy consumption part and the energy recuperation part. The energy consumption part reflects the real-time quantity of the energy consumed by an EV during a trip. The energy recuperation part represents the concrete quantity of energy recovered by an EV according to specific situations.

The following sections review studies on modelling the energy consumption part and the energy recuperation part.

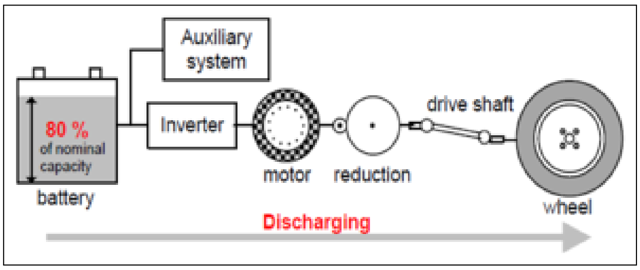
2.1 The energy consumption part

Several energy consumption models have been proposed in literature in order to simulate a realistic and accurate estimation of energy consumption for EVs (Fiori et al., 2016; Abousleiman and Rawashdeh, 2015; Kurczveil et al., 2013).

The energy consumption part represents the main part of the electric power derived from the battery and transformed into mechanical energy by the EV motor; a non-negligible part is consumed by an electrical subsystem (Maia et al., 2011). Accordingly, the consumption process can be mainly modelled through mechanical and electrical subsystems.

Figure 1 illustrates how the electric energy flows between these subsystems.

Figure 1 Electric power flow in EV (see online version for colours)



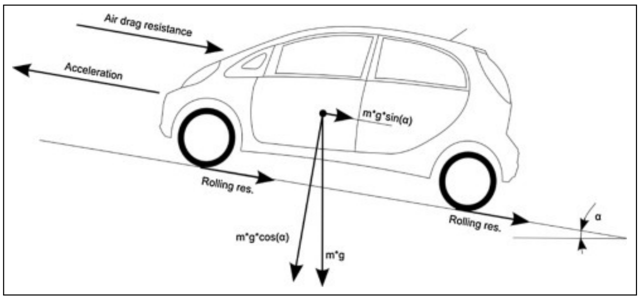
Source: Maia et al. (2011)

The mechanical subsystem represents a common core model for formulating the EV energy consumption. It reflects the power delivered to the wheels ensuring EV movement and it is based on the fundamentals of vehicle dynamics theory citeplarminie2012electric.

This power is defined specifically by the work of the tractive force necessary to overcome acceleration resistance, rolling resistance, air drag resistance and road gradient resistance (Maia et al., 2011).

The considered forces, as illustrated in Figure 2, include the internal tractive force that allows the movement and acceleration of the EV. The rolling resistance force refers to the friction of the tires on the road, the air drag resistance force covers the friction of the body moving through the air, and the road gradient resistance force is induced by the gravity and this force impacts the whole EV's behaviour (Larminie and Lowry, 2012).

Figure 2 Outside forces acting on an EV in motion



Source: Larminie and Lowry (2012)

Thus, the tractive Force F_{te} can be expressed by the following equation (Maia et al., 2011):

$$F_{te} = F_{rr} + F_{ad} + F_{hc} + F_{la} + F_{wa} \tag{1}$$

where

$$F_{rr} = \mu_{rr} \times m \times g \tag{2}$$

$$F_{ad} = \frac{1}{2} \times \rho \times A \times C_d \times v^2 \tag{3}$$

$$F_{hc} = m \times g \times \sin\alpha \tag{4}$$

$$F_{la} = m \times a \tag{5}$$

$$F_{wa} = I \times \frac{G^2}{\eta_g \times r^2} \times a \tag{6}$$

where m [Kg] is the total vehicle mass; v [m/s] is the vehicle speed; a [m/s^2] is the linear vehicle acceleration; g [m/s^2] is the gravitational acceleration; I [Kg.m^2] is the moment of inertia of internal rotating elements; ρ [Kg/m^3] is the variable air density; C_d [%] is the air drag coefficient; a [%] is the vehicle front surface area; μ_{rr} [%] is the rolling resistance coefficient; G [%] is the gear ratio of the system, α [°] is the angle of slope; η_g [%] is the gear system efficiency; and $r[m]$ is the tyre radius.

Previous related energy consumption models were mainly interested in specifying the tractive force formula, but with notable differences related to the complexity of its implementation, and hence impacting the accuracy of the energy model (Fiori et al., 2016; Maia et al., 2011; Van Roy et al., 2011). The mechanical subsystem does not fully account for the real world EV energy consumption. Special attention should be also given to the energy consumed by the electrical subsystem.

The electrical subsystem can be divided into two components: the energy consumed by auxiliary systems (i.e., air conditioning, heating, ventilation, radio, etc.) and the additional electric losses.

Regarding auxiliary systems consumption estimation, two different approaches are adopted; the first one, as matter of simplification, considers a constant energy consumption volume for auxiliary systems as expressed by equation (7) which get added to the total energy consumption (Fiori et al., 2016; Kurczveil et al., 2013).

$$\Delta E_{Aux,T}[t] = cst_{Aux} \times \Delta t \tag{7}$$

where cst_{Aux} [w] is a constant energy consumed by auxiliary systems per time unit.

The second approach integrates the real-time ambient temperature degree taking into account its impact on the energy consumed by auxiliary systems, especially the air conditioning and heating systems (De Cauwer et al., 2015; Shibata and Nakagawa, 2015). Indeed, experimentation results in Wang et al. (2017) proved that the EV would consume 6.7% more energy when the difference between the ambient temperature and the inside cabin is greater than 10°C, and 20.3% more energy when it is greater than 20°C difference.

The energy consumed by air conditioning and heating systems at each time step can be expressed as proposed in De Cauwer et al. (2015) by:

$$\Delta E_{Aux,T} = \beta \times |20 - T| \times aux \times \Delta t \tag{8}$$

where T [°C]: ambient temperature degree; β [%]: regression coefficient mapping HVAC consumption to ambient temperature which was estimated by De Cauwer et al. (2015); $aux = \frac{Duration\ of\ auxiliaries\ switched\ on}{Total\ duration\ of\ trip}$.

The second part of the electric subsystem introduces additional electric losses that occur due to the unstable power output of electric motors (Larminie and Lowry, 2012). According to several studies, two major approaches have been defined to estimate these additional losses. The first one is based on a mathematical model of the electrical subsystem (Wu et al., 2015). In this case, the power related to additional electrical losses can be expressed as illustrated in equation (9) (Wu et al., 2015):

$$P_e = I^2 \times r \tag{9}$$

where

$$I^2 = \frac{R^2}{K^2} \times F_{te}^2 \tag{10}$$

where I [A]: is the current intensity; R [m]: is the radius of the tire; r [Ω]: is the conductor resistance; $K = K_a \times \Phi_d$ (i.e., K_a is the armature constant and Φ_d is the magnetic flux); F_{te}: is the tractive effort as described in equation (1).

The second approach for estimating additional electric losses proposes a simplified estimation based on constant efficiency percentage (Fiori et al., 2016; Van Roy et al., 2011), mainly regrouping inverter efficiency, battery efficiency and electric motor efficiency. The effective electric power consumed corresponds to the force F_{te} and can be described by equation (11) (Shibata and Nakagawa, 2015).

$$P_m = F_{te} \times v \times \frac{1}{\eta_{BAT}} \times \frac{1}{\eta_{INV}} \times \frac{1}{\eta_{MOT}} \times \frac{1}{\eta_{TRA}} \tag{11}$$

where F_{te}: is the tractive force as described in equation (1); v [m/s]: is the vehicle speed; η_{BAT} [%]: is the battery charging and discharging efficiency; η_{INV} [%]: is the inverter efficiency; η_{MOT} [%]: is the electric motor efficiency; η_{TRA} [%]: is the power transmission efficiency.

To summarise, a core model based on mathematical and mechanical background is usually used to formulate the energy consumption part of the EV energy model. Nevertheless, energy models based solely on mechanical grounds underestimate the true EV energy consumption in real world. The energy recovery is an important feature that characterises EVs compared to internal combustion engine vehicles. Therefore, an accurate energy model should integrate an efficient model for the energy recovery process.

A review on the energy recuperation models will be discussed in the next subsection.

2.2 The energy recuperation part

The energy recuperation process is considered as one of the most inherent features of EVs. Its fundamental concept is about capturing a part of dissipated energy during the braking process without any additional costs. The recovered energy is stored in the EV battery and is then re-used when needed (Zou et al., 2015). Therefore, the energy regeneration is an important process that improves the EV efficiency and increases its driving range, especially in urban areas with heavy traffic (Xiao et al., 2016).

In this context, several research studies have shown that the energy recuperation can reduce the EV energy consumption by up to 32% (Lorf et al., 2013) and can increase the EV driving range by up to 20% (Shyrokau et al., 2013). Accordingly, incorporating the energy recuperation concept in the EV energy model has become a necessity.

Table 1 Comparative study between energy models

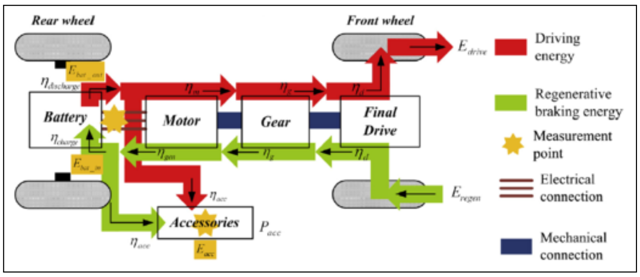
Authors	*Evaluation criteria*						
	Consumption part					*Recuperation part*	
	Mechanical subsystem	*Electrical subsystem*					
		Additional electrical losses		*Auxiliaries systems*			
		Simplified model	*Detailed model*	*Simplified model*	*Detailed model*	*Simplified model*	*Detailed model*
Larminie and Lowry (2012)	✓		✓	✓		✓	
Van Roy et al. (2011)	✓	✓		✓		✓	
Yi and Bauer (2014)	✓	✓				✓	
Schreiber et al. (2014)	✓						
Schellenberg et al. (2014)	✓			✓			✓
Wu et al. (2015)	✓		✓				
Shibata and Nakagawa (2015)	✓	✓			✓	✓	
De Cauwer et al. (2015)	✓				✓		
Wang et al. (2017)	✓	✓		✓		✓	
Abousleiman and Rawashdeh (2015)	✓			✓		✓	
Zhang and Yao (2015)	✓			✓			✓
Fiori et al. (2016)	✓	✓		✓			✓
Asamer et al. (2016)	✓	✓		✓		✓	

In the next subsection, we review recent researches on modelling the energy recuperation part.

2.2.1 *How does the energy recuperation process work?*

The EV is equipped with a regenerative braking system, that is able to recover a part of the dissipated energy to recharge the battery during the deceleration or driving downhill phases (Ye et al., 2008). The energy flow requires dual-directions, as shown in Figure 3. The green arrows reflect the input direction which represents the energy recuperation process, where Eregen is the energy recovered by regenerative brake during deceleration or downhill phases. The red arrows reflect the output direction which represents the energy consumption process, where Edrive is the energy consumed for driving the EV.

Figure 3 Energy recuperation process in the EV (see online version for colours)



Source: Lv et al. (2015)

During the recuperation process, the electric motor acts as a generator through the transformation of the mechanical energy at wheels (i.e., kinetic energy during deceleration and braking phases and/or potential energy during driving downhill phases) into electrical energy which gets stored in the battery and extends hence EV driving range (Spichartz and Sourkounis, 2016).

2.2.2 *A review on energy recuperation models*

Recently, different simulation models for energy recovery have been thoroughly proposed in literature (Van Roy et al., 2011; Hu et al., 2013; Genikomsakis and Mitrentsis, 2017; Zhang and Huang, 2018). In the main, the energy recuperation part can be modelled through two approaches.

The first approach provides a mathematical model based on the sum of the kinetic and potential energies. Some studies (Wu et al., 2015; Spichartz and Sourkounis, 2016; Li et al., 2015) proposed that the dissipated energy could be captured from the kinetic energy during deceleration phases and/or from the potential energy during downhill phases. The total energy recovery can be expressed as:

$$\Delta E_{recuperated}[t] = \Delta E_{kinetic}[t] + \Delta E_{potential}[t] \tag{12}$$

This approach assumes that the total dissipated energy is entirely converted to an electric power stored in the EV battery. However, it ignored the thermal energy dissipated due to the mechanical brakes, gear system, etc. (Maia et al., 2011; Spichartz et al., 2014). The second approach is based on an estimation approach represented by a regenerative braking efficiency factor (Hu et al., 2013; Genikomsakis and Mitrentsis, 2017; Yanan, 2016).

In this case, the total energy recovery formula corresponds to:

$$\Delta E_{recuperated}[t] = \eta_{recup} \times \Delta E_{consumed}[t] \tag{13}$$

where η_{recup} [%]: is the regenerative braking efficiency factor; $\Delta E_{consumed}$ [Wh]: is the instantaneous total energy consumed by the EV at the time step t.

Most researches have adopted this approach and have expressed the regenerative braking efficiency factor according to two main methods (Zhang and Yao, 2015; Sweeting et al., 2011; Ferreira et al., 2013).

On the one hand, the works in Kurczveil et al. (2013), Maia et al. (2011), Lv et al. (2015), Hu et al. (2013), Yanan (2016) and Shibata and Nakagawa (2015) opted to consider a constant regenerative braking efficiency factor specified by the EV manufacturer. This factor is expressed in terms of charge/discharge efficiency, gearbox efficiency, etc. (Lv et al., 2015; Maia et al., 2011). Some studies estimated the value of these factors through a set of simulation results [i.e., 60% for the study in Yanan (2016)]. On the other hand, recent studies (Fiori et al., 2016; Zou et al., 2015; Zhang and Huang, 2018) have modelled this factor by an instantaneous braking energy regeneration formula, which depends on the deceleration level, EV weight, speed, etc. (Fiori et al., 2016; Zou et al., 2015; Zhang and Huang, 2018).

For instance, in the work of Fiori et al. (2016), the regenerative braking efficiency factor formula has been expressed as:

$$\eta_{recup}[t] = \left(e^{\left(\frac{0.0411}{|a[t]|}\right)}\right)^{-1}, \forall a[t] < 0 \tag{14}$$

where a [m.s^{-2}] is the instantaneous acceleration.

This model was experimentally validated by the authors for a Nissan Leaf car. The objective was to propose an accurate formula that could be also easily integrated into the EV energy model. The second method, with an explicit formula of the regenerative braking efficiency factor, turns out to be more accurate especially when the parameters related to various factors (i.e., deceleration rate, road slope, etc.) are included (Liu et al., 2017; Bian and Qiu, 2018; Bingham et al., 2012). Next, the main features of a realistic and accurate energy model as well as the associated requirements of each subsystem are discussed in more detail.

2.3 *Summary and evaluation*

In this subsection, we provide a detailed comparative study of the aforementioned EV energy models according to the accuracy and completeness of the proposed model as shown in Table 1.

Two different representations to describe each subsystem are presented in this study: the first one consists of a simplified model with different efficiency factors presenting constant values. The second one is a detailed model with variable parameters depending on various factors impacting EV energy consumption (i.e., current intensity, ambient temperature, acceleration rate, etc.).

As stated in Subsection 2.1, all models do share a common model core for the EV, namely the mechanical subsystem. This is expected, since mechanical traction represents the most important part of energy consumption. Therefore, as mentioned in Table 1, all works have managed to completely model the forces related to that part but with notable differences. In particular, the tractive force is depending mainly on rolling resistance, air drag resistance, road gradient resistance, and acceleration resistance forces. Differences appeared at the level of used parameters to estimate these forces. For instance, De Cauwer et al. (2015) and Shibata and Nakagawa (2015) have considered the fictive mass of rolling inertia aside the vehicle mass to estimate the energy required for acceleration. Abousleiman and Rawashdeh (2015) and Wang et al. (2017) considered the wind velocity in the estimation of the air drag resistance force. They also took account of the whole average mass of vehicle and passengers for the computation of the rolling resistance force. All these differences have of course an impact on the accuracy of the model but also on the complexity of its implementation. The electrical subsystem is the part that represents the largest part of differences. Approaches for modelling additional losses varied from accurate estimation, based on detailed mathematical models to simplified models based on efficiency percentage. Therefore, two different approaches have been considered.

The first one is an exact evaluation of the physical characteristics of the electrical components (e.g., the current intensity, the internal resistance, the magnetic flux, open circuit voltage from the battery, etc.) (Wu et al., 2015; Maia et al., 2011). The second one is an estimation based on subsystems efficiency estimation (e.g., inverter efficiency, power transmission efficiency, electric motor efficiency, battery efficiency, etc.) (Fiori et al., 2016; Wang et al., 2017). This abstraction makes the model easier to implement and makes it also closer to the reality at the same time.

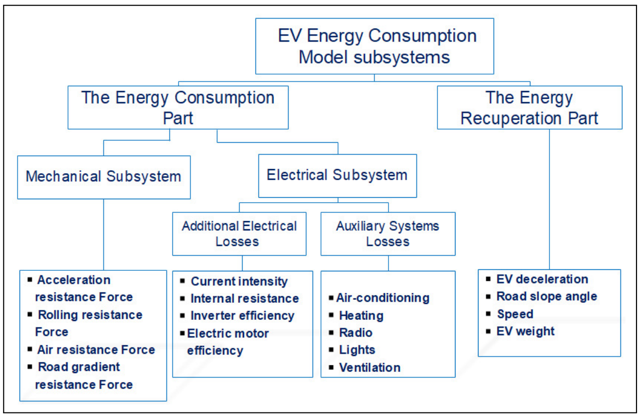
The additional electrical losses consumption represents a significant part of the whole EV consumption and it should be considered in EV consumption model, unlike works such as De Cauwer et al. (2015), Schellenberg et al. (2014) and Zhang and Yao (2015). Modelling this part by an efficiency estimation factor, provided by the EV constructor, is accurate enough to be preferred to exact calculation in order to keep simulations scalable and as simple as possible to be implemented. Auxiliary systems have been in most cases restricted to the air conditioning system. Such simplification is reasonable, as it is the most significant consumer of energy among other auxiliaries (i.e., radio, lights, etc.) (Shibata and Nakagawa, 2015). Auxiliary energy consumption has been in most cases evaluated as a constant charge provided by the vehicle manufacturer as shown in Fiori et al. (2016) and Schellenberg et al. (2014). Some works go deeper by taking into account the impact of external factor on auxiliary consumption, such as ambient temperature as shown in De Cauwer et al. (2015). Indeed, the temperature and time dependent formula presented by De Cauwer et al. (2015) is more simplified than the formula presented by as Shibata and Nakagawa (2015) which allows its straightforward implementation in simulators.

Regarding the energy recuperation part, several studies such as De Cauwer et al. (2015), Wu et al. (2015) and Shibata and Nakagawa (2015) did not model the regenerative braking process despite its importance in the EV energy consumption process.

As introduced in the in Subsection 2.2, two main approaches for modelling the energy recuperation are selected. An estimation approach represented by a constant regenerative braking efficiency factor, provided by the EV constructor as shown in Shibata and Nakagawa (2015) and Wang et al. (2017).

The second one is an exact evaluation approach modelled by an instantaneous regenerative braking efficiency factor formula. The energy recuperation part was modelled by Fiori et al. (2016) in terms of the EV deceleration and is simple to integrate in the energy model. Finally, the diagram illustrated by Figure 4 summarises the main subsystems of EVs. In summary, a detailed literature review of modelling the EV energy consumption is provided by automotive energetic community. This review can be a good support for the researchers of the network community in order to integrate and implement a realistic and accurate energy model for EVs in VANET simulators.

Figure 4 The EV energy model main subsystems (see online version for colours)



In the next section, we will focus on VANET simulators and we will carry out an in-depth review of the implemented energy models for EVs in these simulators. A confrontation between the theoretical energetic models presented in the first part of this chapter with those found to be used by VANET simulators will allow us in the last part of this chapter to evaluate their relevance, accuracy and eventually to decide which improvements have to be done.

3 A literature review on EV energy models implementations in VANET simulation tools

Deploying and testing different applications in the context of intelligent transportation system (ITS) related to eco-routing, eco-driving assistance systems, charging stations deployments, etc. is a very difficult task due to its high cost and environmental physical limitations. Indeed, testing these applications for research purpose requires several real-world experimental data for any predefined scenario. However, the experimentation task is often expensive and even impossible in the case of particular scenarios such as traffic conditions, mobility models, weather conditions, critical traffic situations, etc.

Moreover, some required measurements need significant efforts and are not repeatable. VANETs simulations might be an efficient solution for these problems (Schilling, 2005). These tools are required to test and evaluate the performance and QoS of various simple or complicated applications and protocols before implementing them.

In fact, VANETs can be considered a subclass of the MANETs. VANET is a promising technology for ITS that has the potential in spreading widely wireless communication to exchange information between vehicles, and RSUs. It is an emerging field that increases road safety with more efficiency regarding driving experience, road congestion and road navigation. Additionally, it allows commercial and comfort applications to the road users such as path planning, accurate local weather information dissemination, internet accessibility, etc. (?Ahmed et al., 2019).

VANET simulation is basically different from MANETs simulation since vehicular environment in VANET has raised new issues and potential requirements (i.e., road topology constraints, trip models, traffic flow models, energy-efficient routing, driver profile modelling, etc.). Currently, VANET simulation tools can be classified into three different categories as shown in Figure 5. These are

a mobility simulators

b network simulators

c VANET simulators.

Mobility simulators are used for generating realistic vehicles movements on roads to improve the realism level in VANET simulations. The traffic generation in mobility simulators depends on various factors such as road map, road topology, driver's behaviour, vehicle density, etc. The output files are imported into a network simulator as an input to assess the performance of network protocols and innovative solutions in a variety of conditions.

Network simulators are used to test the performance of network protocols. It performs packet-level simulation of source, destination, route, background load, data traffic transmission, links and channels. Finally, VANET simulators link the mobility simulator and the network simulator by the means of a middleware to provide a complete environment for testing communication networks build upon vehicular networks. The next subsections investigate the properties of the most well-known mobility simulators, network simulators and VANET simulators while focusing on the energy models they are using for EVs.

3.1 Mobility simulators

The transportation engineering researchers provide a lot of well-known mobility simulators or mobility generators to generate realistic mobility traces for vehicles. The mobility generation depends mainly on the vehicle model specifications, the driver's behaviour, the road topology, the traffic conditions, etc. However, only few mobility generators are interested in studying the EV concept and especially the energy model component. In this case, the mobility simulator generates vehicular mobility trace files with the energy consumption information of each EV at each simulation time step.

3.1.1 MOVE

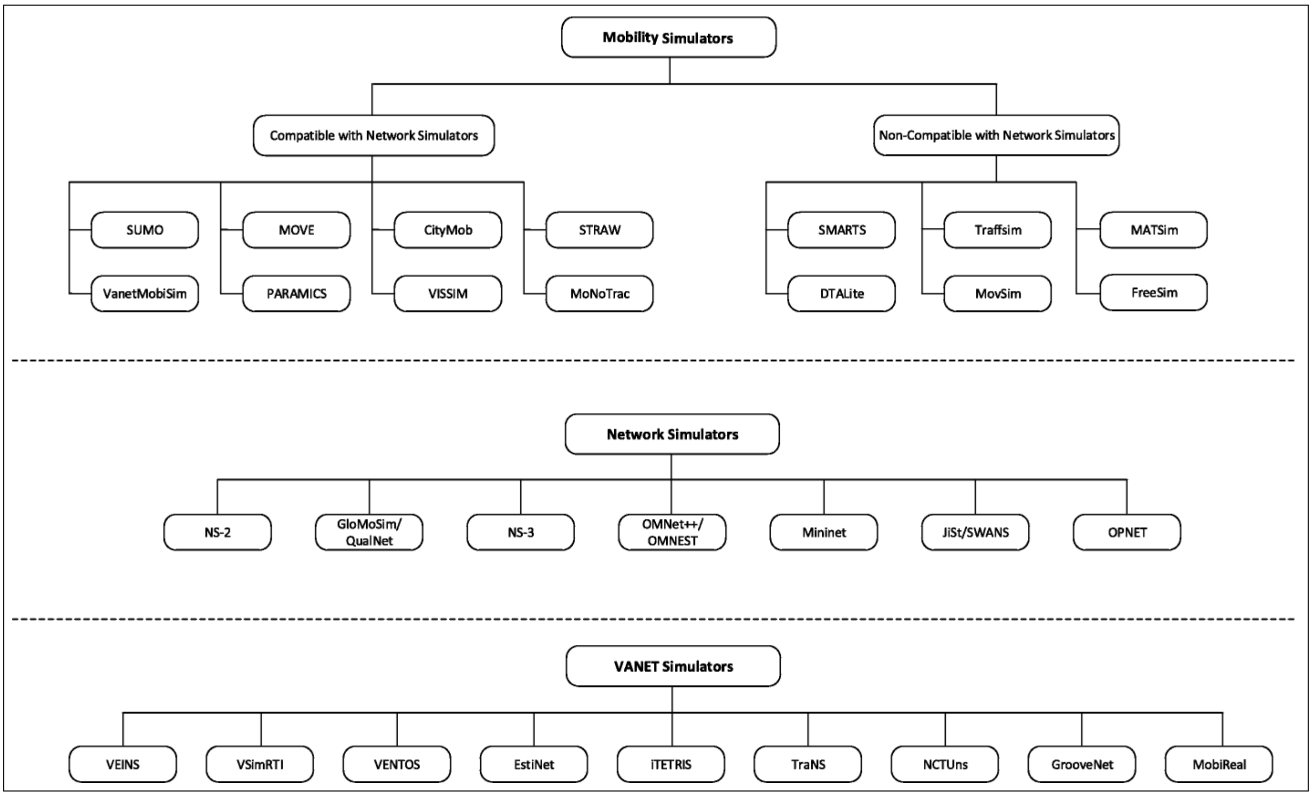
MOVE (Lan, 2010) is a tool based on Java programming language and used to generate a realistic traffic and mobility models for VANET simulation. MOVE is built on top of micro-traffic simulator SUMO. It provides a GUI to facilitate the traffic generation, and then it saves the user time and effort without writing traffic generation scripts. It also the allows user to import mobility models of vehicles and road maps for simulation scenarios using SUMO. The output files are used as inputs for the network simulator like NS-2 or QualNet to assess the performance of different VANET protocols under various conditions. However, MOVE did not provide a specific energy model for calculating instantaneous energy consumption of EVs.

3.1.2 VanetMobiSim

VanetMobiSim (Härri et al., 2006) is an open source Java-based traffic generator used to generate vehicular mobility models at both macroscopic and microscopic levels. It is an extension of the CanuMobiSim simulator which has been extended to cover realistic simulation of vehicular mobility (Harri and Fiore, 2006).

VanetMobiSim has many features like the IDM/LC, intersection steering, traffic light control, car following model, routing selection, multi-lane roads, etc. It is compatible directly with several network simulation tools like NS-2, GloMoSim and QualNet. VanetMobiSim focuses on vehicular mobility and does not provide a standard energy model for calculating the energy consumption of each EV in simulation scenarios. Otherwise, VanetMobiSim could be used in the context of EVs to build a communication framework based on VANETs (Li et al., 2018) for making charging-discharging decisions, the state of parking place (i.e., free or busy situations), etc.

Figure 5 Taxonomy of VANET simulation tools' list



Source: Ahmed et al. (2019)

3.1.3 VISSIM

VISSIM (Fellendorf and Vortisch, 2010) is a closed paid free-flowing and microscopic multi-modal traffic generator developed by PTV AG group. It is a time driven microscopic simulation package used for simulating private and public transport operations under different constraints such as vehicle composition, traffic signals, lane configuration, public transportation stops, etc. Besides, VISSIM can be used to resolve several transportation problem settings. Each vehicle in the simulation has its own driver model. The driver model is the mobility model that provides the desired speed of the driver, the required acceleration and the lane angle. These properties are later depended by the performance limits of the vehicle. In this context, Obaidat et al. (2014) have proposed and developed a simulation framework integrating an energy model for VISSIM to compute EVs energy consumption.

The proposed energy model requires as inputs the vehicle design parameters. The simulation scenario requires roadway information that include traffic state, road type, road gradient, etc. to generate vehicular traffic in VISSIM. Then, the traffic simulation scenario output data are a time series of the distance travelled, lane changes, EV velocity, EV acceleration, energy consumption, etc. These data and mainly the resulting energy consumption data of each EV are collected and analysed through statistical regression.

Regression analysis is used to build a meta-model of EV energy consumption to estimate the energy consumption per distance travelled by each EV during the simulation scenario.

The proposed energy model is based on modelling auxiliary systems consumptions and the mechanical part consumption. Thus, the energy consumed on a road segment is expressed by equation (15) of the form:

$$E = P \times t + W \times d \tag{15}$$

where E [Wh]: is the energy consumed; P [W]: is the power consumed by accessory loads; W [J]: is the work of tractive force [equation (1)] applied on the EV; t [h]: is the time step and d [m]: is the traveled distance.

The proposed model is over-simplified and unable to reflect the reality when it is used for various scenarios. In addition, it does not consider the impact of weather conditions such as ambient temperature on accessory loads. Moreover, the proposed model does not model the energy consumed by additional electrical losses. Finally, the proposed energy model for the VISSIM simulator does not reflect the energy recuperation aspect of EVs.

In summary, the proposed model can be considered as over-simplified since it models only the mechanical subsystem and auxiliary loads. It does not consider the additional electrical losses and the energy recuperation part modelling.

3.1.4 FreeSim

FreeSim (Miller and Horowitz, 2007) is an open source, portable, microscopic and macroscopic traffic simulator. It is licensed under the GNU and GPL. FreeSim is mainly used for simulating various mobility models of vehicles, determining shortest and fastest paths using specific algorithms, etc. FreeSim allows simulating different vehicular traffic scenarios and path planning to be easily integrated and executed for individual vehicles or nodes or lanes or for the entire network. Real-time data gathered by the transportation organisation can be also loaded and used by the FreeSim simulator for traffic generation. Additionally, FreeSim is an ideal solution for ITS simulation as it enables vehicles to communicate autonomously with the system monitoring the traffic on the highways. However, it has limitations as it does not compatible with network simulators (e.g., NS-2, QualNet, SWANS, OMNeT++, etc.). Moreover, it does not integrate a realistic energy model for calculating EV energy consumption.

3.1.5 PARAMICS

PARAMICS (Smith et al., 1995) is a microscopic and commercial traffic simulation software. It was developed and proposed by Quadstone Ltd. It has been widely used in commercial and academic research fields. PARAMICS is often used for simulating ITS applications. Besides, it could be used to provide fast vehicular network construction, simulation and visualisation. It could offer large-scaled traffic generation by simulating large number of vehicles in various and complex road traffic networks (i.e., urban area, work zone, highways and intersections, etc.). It provides straightforward outputs for end users (i.e., instantaneous speed, acceleration, fuel consumption, etc.). PARAMICS includes the tightly CME/EC model (Barth et al., 2001) which was designed for ITS evaluation.

The CME/EC model is used for to predicting emissions and fuel consumption for each vehicle at every second during simulation scenarios. The CME/EC model was designed for 26 different categories of light duty vehicles (Barth et al., 2001). However, CME/EC model is not a generic model since it cannot be applied on various types of vehicles such as EVs. It only addresses light duty vehicles. Jansuwan et al. (2021) proposed an evaluation framework AET that addresses the challenges associated with EVs (i.e., battery capacity, energy-saving, range, cost, etc.). The AET was developed within the PARAMICS simulator. This study aims to make the roadway itself a potential source of energy by delivering energy on demand and in real-time to vehicles in motion. AET suggested transferring the electricity via WPT pads to continuously electrify the highway networks. AET system is mainly based on three measures of effectiveness: the energy savings, the system capacity and emission reduction. In this context, this study proposed an energy model for PARAMICS simulator to compute the total energy consumed by AET vehicles which are HEVs and EVs. However, the proposed energy model is basic since it is mainly based on the vehicle dynamics modelled through the mechanical forces applied to an EV in motion. Additional electrical losses, auxiliary loads and also the recuperation process were not modelled in the AET model. Therefore, the proposed model cannot reflect real-world energy consumption.

3.1.6 SUMO

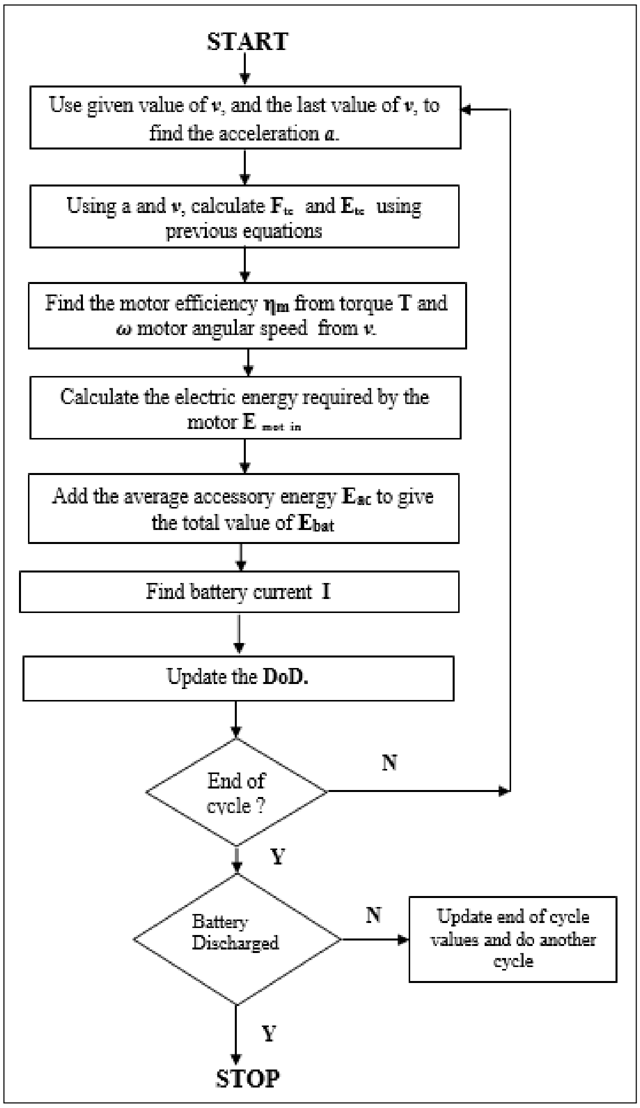
SUMO (Behrisch et al., 2011) is an open source and a highly portable road traffic simulator. It is developed by the Institute of Transportation Systems at the German Aerospace Center (DLR) and implemented in C++. It is supported by the most of operating systems. SUMO is designed to handle intermodal traffic systems including road vehicles. The main characteristic of SUMO are the portability and the ability to perform microscopic simulations. Indeed, each vehicle is modelled separately and explicitly to have its own route and to move individually through the network.

The main features of SUMO simulator are:

- Supporting many tools that can be used to find and visualise a route, import a road network, calculate vehicle emissions, collision free vehicle movement.
- Supporting OpenGL GUI.
- Importing different network formats such as OpenStreetMap and NavTeq, and also converting networks from other mobility simulators such as VISUM and VISSIM.
- Supporting different vehicle types, especially EVs.
- Supporting unlimited network size and unlimited number of simulated vehicles.
- Using a portable library.

SUMO have supported the first version of an energy model for EVs proposed by Maia et al. (2011) since version 0.24.0. The energy model is considered as a component added to EV to calculate its energy consumption at each simulation time step. The model proposed by Maia et al. (2011) was mainly based on the energy consumption part and especially the mechanical and electrical subsystems. The mechanical subsystem is presented by the tractive force as described in equation (1). The electrical subsystem and especially the additional electrical losses were represented by a detailed model based on a specific formula in terms of the current intensity I. The energy consumed by auxiliary systems was presented by a constant power supposed to be provided by the vehicle manufacturer. The energy recuperation part was not modelled by an explicit formula but rather through motor and gear system efficiency factors. The diagram illustrated by Figure 6 explains the steps to follow in order to calculate the DoD output (i.e., percentage of the battery that has been discharged relative to the overall capacity of the battery) when the EV is moving at each simulation time step. Actually, the second version of the EV energy model implemented in SUMO was proposed by Kurczveil et al. (2013). They presented a simple model to decrease the runtime of EV energy consumption calculations in traffic simulations compared to the first version proposed by Maia et al. (2011). Indeed, the mechanical subsystem can be modelled at each time step by the energy gained ΔE_{gain} between t and $t+1$.

Figure 6 The diagram for the simulation of the energy model



This energy is calculated by summing kinetic, potential, and rotational energies, and by subtracting the energy losses related to the work of the resistance forces (i.e., air drag resistance, rolling resistance, road gradient resistance, etc.). The energy consumed by auxiliary systems is added to the energy losses. Thus, the energy gained ΔE_{gain} is expressed as:

$$\Delta E_{gain}[t] = \Delta E_{veh}[t+1] - E_{veh}[t] + \Delta E_{loss}[t] \quad (16)$$

$$\begin{aligned} E_{veh}[t] &= E_{kin}[t] + E_{pot}[t] + E_{rot,int}[t] \\ &= m/2 \times v^2[t] + m \times g \times h[t] + \frac{J_{int}}{2} \\ &\times v^2[t] \end{aligned} \quad (17)$$

$$\begin{aligned} \Delta E_{loss}[t] &= \Delta E_{air}[t] + \Delta E_{roll}[t] + \Delta E_{curve}[t] \\ &+ \Delta E_{Aux}[t] \end{aligned} \quad (18)$$

where

$$\begin{aligned} \Delta E_{air}[t] &= \frac{1}{2} \times \rho_{air} \times A_{veh} \times C_w \times v^2[t] \\ &\times |\Delta s[t]| \end{aligned} \quad (19)$$

$$\Delta E_{roll}[t] = C_{roll} \times m \times g \times |\Delta s[t]| \quad (20)$$

$$\Delta E_{curve}[t] = C_{rad} \times \frac{m \times v^2[t]}{r[t]} \times |\Delta s[t]| \quad (21)$$

$$\Delta E_{Aux}[t] = E_{Aux,const} \times \Delta[t] \quad (22)$$

The underlying Table 2 explains the introduced parameters.

Table 2 Physical parameters input for the energy model

Constants	*Meaning*
m	Total vehicle mass
$v[t]$	Time variant vehicle speed
$a[t]$	Instantaneous vehicle acceleration
g	Gravity acceleration
$h[t]$	Time variant vehicle altitude
J_{int}	Moment of inertia of internal rotating elements
ρ_{air}	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

Depending on its sign, $\Delta E_{gain}[t]$ represents the amount of energy consumed (i.e., $\Delta E_{gain} < 0$) or recovered (i.e., $\Delta E_{gain} > 0$) based on the EV movement. Therefore, the energy contained in the vehicle battery can be calculated by equations (13) and (14) by introducing constant efficiency factors. The first efficiency factor is used for representing the additional electric losses and the second one reflects the energy recuperation part. In particular, the additional electric losses are modelled through η_{prop} factor and the remaining energy in the battery E_{Bat} is hence expressed through the following formula:

$$E_{Bat}[t+1] = E_{Bat}[t] + \Delta E_{gain}[t] \times \eta_{prop}^{-1} \quad (23)$$

where η_{prop} [%]: is the efficiency factors for propulsion, and E_{Bat} [Wh]: is the remaining energy in the battery.

The energy recuperation is modelled by a constant regenerative braking efficiency factor η_{recup}. Thus, the remaining energy in the battery E_{Bat} can be expressed as:

$$E_{Bat}[t+1] = E_{Bat}[t] + \Delta E_{gain}[t] \times \eta_{recup} \quad (24)$$

In summary, the model proposed by Kurczveil et al. (2013) is mainly based on the mechanical subsystem. They presented the electrical subsystem by a simplified model through introducing a constant efficiency parameter for propulsion provided by the EV constructor. This parameter represents the additional electric losses that come out of the battery and get dissipated while accelerating. This representation minimises the complexity of the energy consumption computation. In addition, they represented the energy consumed by auxiliary systems as a constant energy provided by the vehicle manufacturer. Regarding the energy recuperation part, Kurczveil et al. (2013) proposed a constant regenerative braking efficiency factor. This parameter depends only on the EV specifications and should be provided by the vehicle manufacturer.

In brief, MOVE, VanetMobiSim and FreeSim exhibit good software characteristics (i.e., portability, open source, modular structure, etc.) but these simulators did not include an energy model for EVs and are not under active development. Only the following three simulators integrate energy models that might be interesting for our research study: VISSIM, PARAMICS and SUMO simulators.

3.2 Network simulators

Network simulators are employed to simulate and analyse the performance of different VANET protocols under various scenarios. Network simulators allow researchers to test various scenarios in cost effective manner. Researchers can then personalise the simulator to achieve their specific analysis needs.

In this subsection, we have selected the most commonly used simulators for VANET networks simulation which consist of: OMNeT++ (Varga and Hornig, 2008), OPNET (Sethi and Hnatyshin, 2012), NS-2 (NS-2 Simulator, 2020) and NS-3 (Chaudhary et al., 2012).

3.2.1 OMNeT++

OMNeT++ (Varga and Hornig, 2008) is an open source object-oriented modular simulator based on C++ language. It is available under Academic Public License. It is used for simulating a large set of scenarios including new features such as VANET protocols, communication networks, wireless networks (e.g., VANETs or sensor networks), smart metering applications, smart grid and other distributed systems.

OMNeT++ is a discrete-event simulator based on the ‘module’ concept. Each module is written in C++ to reflect a different entity that can be reusable. The communication links between the different modules are modelled based on virtual gates.

The INET framework is the most known network simulation model framework for OMNeT++ that has been developed at the University of Karlsruhe. It has evolved from the protocol IPSuite. It provided a set of detailed OMNeT++ modules in the different network layers for the TCP, UDP, IPv4, IPv6, ARP and several other protocols. In particular, the INET framework provides an independent and extensible power model for designing power-sensitive protocols (e.g., routing protocols and MAC protocols) with power management features.

The INET power model consists of three components:

1 the energy generation models
2 the energy storage models
3 the energy consumption models.

The energy generation model is an OMNeT++ simple module that implements the energy generation of hardware devices over time (e.g., solar panel). It is integrated as a submodule in network nodes to provide the power or to generate current during simulation.

The energy storage model is an OMNeT++ simple module which represents physical phenomena used for storing power produced by generators and supplying power for consumers. The main goal is to compute the amount of available charge or energy at the simulation time.

The energy consumption model is an OMNeT++ simple module implementing the energy consumption of devices over time (e.g., hardware devices or software processes, etc.). For instance, this model could account the energy consumed due to radio transmissions and receptions, the CPU consumption when network protocol forwards a packet, transceiver consumption when it sends or receives a signal, etc. The energy consumption model could be integrated as a submodule in the compound module of the software components or the hardware devices. In particular, this model can be integrated as submodule in the node representing the EV as a regular moving and transmitting node. However, this module was not designed for calculating the electric motor consumption of EV. Therefore, the INET energy model can be used as an additional component for the EV node during the network simulation but it cannot be used to account for the EV energy consumption.

3.2.2 OPNET

OPENT (Sethi and Hnatyshin, 2012) is a discrete event commercial network simulation tool. It is licensed under Riverbed technologies. OPENT enables modelling both wired and wireless networks including routers, switches, servers and several protocols. It has the ability to support a wide spectrum of wireless technologies and standards (e.g., satellite networks, IEEE 802.11, IEEE 802.15.1, IEEE 802.20, etc.). Unlike OMNeT++ simulator, OPNET does not support any energy model or simulate any energy aspects related to EVs. In literature, OPNET simulator was used to simulate the communication network in charging stations of EVs (Ye et al., 2014). Besides, OPNET was considered as an efficient tool to study the communication network aspect between EVs and base stations while parking based on the vehicle to grid (V2G) technology (Kiokes et al., 2015). OPNET was hence used for the evaluation of the wireless networking performance system but till now no energy models were provided to study energy efficiency in such networks.

3.2.3 NS-2

NS-2 (NS-2 Simulator, 2020) is a discreet event, object oriented, portable and open-source network simulator. It was implemented by the VINT project research group at Carnegie Mellon University. It is licensed under GPL. The simulation kernel is written in C++ and the simulation modelling is written in OCTL. It was frequently used in networking research community for studying the dynamic nature of communication networks. Besides, it is used for the simulation of wired and wireless networks (e.g., MANET and VANET networks). Moreover, it provides a significant support for the simulation of IP protocols, routing and multicast protocols (e.g., TCP, UDP, SRM, RTP, etc.). The NS-2 extension integrates an energy model to notify the simulated nodes about their instantaneous energy level (Er-Rouidi et al., 2016). The main purpose of the energy model is to measure the amount of energy during data transmission (i.e., transmission, reception, controlling packets, etc.). The energy model is mainly based on three components: the initial energy, the transmission power and the reception power. The energy consumed during transmission is calculated by multiplying the transmission power by the time required to transmit a packet.

The energy model component cannot be used to compute the total energy consumed by a simulated EV while traveling. It is used to calculate the energy consumed at the network level, especially during data transmission and/or data reception to show how the energy consumption could be affected in such scenario.

3.2.4 NS-3

NS-3 (Henderson et al., 2008) is a discreet-event, open source network simulator written entirely in C++ with an optional Python scripting API. It is especially targeted to networking researchers and educators for studying Internet protocols and large-scale systems in a controlled environment. NS-3 is not the replacement of NS-2 simulator. It is a new simulator, written from the ground up and it does not support NS-2 API (Chaudhary et al., 2012). It is an open source software that motivates community contribution, peer review, and validation process.

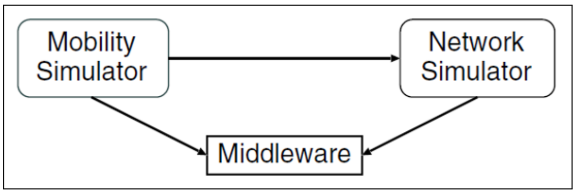
Wu et al. (2011) proposed an energy framework for NS-3 by modelling energy consumption as well as energy sources. The main goal is to incorporate the energy aspect into network simulations. The network simulator NS-3 includes energy models that reflect devices energy consumption (e.g., Wi-Fi radio). It enables calculating the energy consumption related to specific tasks in network simulations. In particular, this model focuses mainly on calculating the energy consumption related to network related events such as packet transmission and/or reception. Therefore, NS-3 was used to design and simulate both power and communication networks for smart grid applications (Mets et al., 2011). The proposed energy consumption model does not represent the different computation tasks on a node during network simulations such as the total energy consumption at a battery powered node. Therefore, NS-3 does not include a specific model for calculating the total energy consumption on a node representing an EV in VANET.

In summary, network simulators provide energy models at the network level to account for energy consumption in energy-critical scenarios (i.e., sensor networks) but till now, none of them provides an energy model for EV even though, the concept of EVs (as a specific node type) was already integrated in some of them.

3.3 VANET simulators

VANET simulators provide a high level of maturity for both network and traffic flow simulation without the need to run different types of software at the same time. Mobility and network simulators communicate with each other via a Middleware as illustrated by Figure 7. In this subsection, we review simulators and frameworks that integrate both mobility and network simulators. We will consider only the following VANET simulators, as they are the most common used in vehicular networking research area, and they was also used in the context of EVs: GrooveNet (Mangharam et al., 2006), TraNS (2019) and VEINS (2020).

Figure 7 VANET simulators structure



Source: Ahmed et al. (2019)

Next, we will present a detailed description of GrooveNet, TraNS and VEINS simulation platforms.

3.3.1 GrooveNet

GrooveNet (Mangharam et al., 2006) is an open source hybrid VANET simulator developed by Carnegie Mellon University which is composed of both mobility and network simulators. GrooveNet is a modular event based simulator with a good model interface for adding new modules. GrooveNet's modular architecture integrates mobility models and supports models for message broadcast systems, etc. The main features of GrooveNet are that it has the capability to simulate a very large number of vehicles. Besides, it provides user friendly interface and supports V2V and V2I communications. Moreover, it enables adding various new models with regard to applications, security, networking and vehicles interactions.

The GrooveNet framework was used for developing frameworks in the context of EVs (Diaz, 2012; Mangharam, 2012) (i.e., implementing energy efficient routing algorithms for EVs, allowing communications between EVs, etc.). However, GrooveNet did not include an explicit energy model for calculating energy consumption of vehicles and especially EVs.

Table 3 Comparative study between energy models implementations in mobility simulators

Mobility simulator	*Authors*	*Evaluation criteria*						
		Consumption part					*Recuperation part*	
			Electrical subsystem					
		Mechanical subsystem	*Additional electrical losses*		*Auxiliaries systems*			
			Simplified model	*Detailed model*	*Simplified model*	*Detailed model*	*Simplified model*	*Detailed model*
VISSIM	Obaidat et al. (2014)	✓			✓			
PARAMICS	Jansuwan et al. (2021)	✓						
SUMO	Maia et al. (2011)	✓		✓	✓		✓	
	Kurczveil et al. (2013)	✓	✓		✓		✓	

3.3.2 TraNS

TraNS (2019) is a GUI-based open-source VANET simulator that combines the mobility simulator SUMO with the network simulator NS-2. It was developed by Swiss Federal Institute of Technology in Lausanne for VANET simulation environment. The main goal of TraNS is to generate realistic VANETs simulations. The real-time interaction between the traffic simulator SUMO and the network simulator NS-2 is performed through two-way link established by the TraCI protocol. Besides, TraCI adopts client/server architecture which SUMO acts as the client of TraCI and NS-2 acts as the server of TraCI. SUMO and NS-2 intercommunicate through TCP/IP. The communication between SUMO and NS-2 is controlled by NS-2. Indeed, NS-2 sends a command to the traffic simulator SUMO and then SUMO adjusts rapidly the movements of all vehicles according to the received command by the network simulator. However, the Trans framework does not support the latest version of SUMO and NS-2 and is not under active development.

3.3.3 VEINS

VEINS (2020) was developed by the University of Erlangen. It is an open source, robust and highly scalable software that is based mainly on the two widely known simulators: SUMO as the mobility simulator for traffic mobility generation and OMNeT++ as the network simulator. VEINS enables online re-configuration and re-routing of vehicles in reaction to the network simulator. During a VEINS simulation scenario, the mobility simulator SUMO and the network simulator OMNeT++ are running in parallel. It is bidirectionally coupled between traffic and network simulators that has the ability to model the impact of road traffic on network traffic and vice versa via the protocol TraCI. TraCI enables both simulators to be connected via a TCP link to establish a communication via a socket in client-server architecture. OMNeT++ acts as the server of TraCI and SUMO as the client of TraCI. The network simulator OMNeT++ allows individual vehicles in the simulation to change their speed and routes by sending a set of commands. Moreover, the mobility simulator SUMO sends periodically updated mobility traces. Consequently, the network simulator makes a reaction by updating positions, instantiating new nodes and deleting nodes that have reached their final destinations. Therefore, these properties make the VEINS simulation scenarios more dynamic and realistic. To sum up, only TraNS and VEINS have explicitly adopted the EV concept (i.e., energy model, charging station deployment for EVs, etc.) since they supported the mobility simulator SUMO.

3.4 Summary and evaluation

In the last subsection, we have reviewed the most widely known VANET simulators those can be used for performing VANET simulations in the context of EV. This work can help researchers of the network community to pick up the right tool for their study. These simulators have been classified into three categories namely mobility simulators, network simulators and VANET simulators. Indeed, network simulators integrate energy models to compute the energy expended at the network level, especially during vehicular communications, packet transmissions, etc. We are particularly interested in energy models that compute the total energy consumed for EVs at each simulation time step. Some of mobility simulators incorporate different components relative to the EV area, such as charging stations deployment, EV energy models, etc. However, only three mobility simulators (i.e., VISSIM, PARAMICS and SUMO) have so far integrated consistent energy models to characterise the environmental and energy effects of EVs on large and complex urban network environments. A comparative study between these mobility simulators is presented with respect to the various metrics and the differences illustrated by Table 3.

Other important metrics that are not listed in Table 3 should be taken into consideration, namely, open source, modular and under active development while selecting the most efficient tool for a network research study. Indeed, an efficient simulation tools should be open source and provide the necessary documentation. The aim is to allow researchers of the network community to criticise the validity of the proposed models design and its implementation. Particularly, VANET simulation programs should possess a modular and customisable structure to allow the developer to analyse single pieces of the simulation process. The design of modular simulation models gives the simulation tool potential to grow, simulate mixed scenarios and define more details to bring additional requirements and provide larger applications. Furthermore, the VANET simulation tools should be under active development to meet more stringent future requirements in VANET simulation. The aim is to provide high level of maturity in both mobility and network simulation areas.

As we have explained in the last subsection, the energy model proposed for the simulator VISSIM (Obaidat et al., 2014) is based on the basic properties of the mechanical subsystem. The electrical subsystem was represented only by a constant power reflecting auxiliary systems consumption. Therefore, this model lacks accuracy as it does not reflect the impact of weather conditions on EV auxiliary systems consumption. It does not also model the additional electrical losses. Therefore, this model could not reflect real world EV energy consumption and achieve valuable results. The energy model proposed for the PARAMICS simulator (Jansuwan et al., 2021) is mainly based on modelling The mechanical forces applied to EV dynamics. It does not reflect the energy consumed by auxiliary systems. Neither additional electrical losses nor the energy recuperation process were modelled in this model. Therefore, there are very limited components modelled in the implementation of this model, so the PARAMIC model provides unrealistic results as it remains unable to simulate realistic EV energy consumption. Moreover, the documentation for both VISSIM and PARAMICS software is incomplete and the source code is inaccessible, making it difficult to propose, simulate and validate more accurate and realistic models for EV energy consumption.

SUMO is the most widely known mobility simulator used by the researchers of the network community. Actually, it integrates a simple energy model for EVs proposed by Kurczveil et al. (2013) which models the majority of components of a realistic energy model. However, this model lacks accuracy as it does not reflect the impact of weather and environmental conditions on EV energy consumption and recuperation. In particular, auxiliary systems consumption was represented by a constant power provided by the vehicle manufacturer. However, this power underestimates the energy consumed by auxiliary systems in real-world. Moreover, such formula does not reflect the impact of environmental factors on the energy consumed by auxiliary systems. It is obvious that the factors related to the environment have a significant impact on the auxiliary energy consumption and subsequently on the EV performance, especially the outside ambient temperature (De Cauwer et al., 2015; Shibata and Nakagawa, 2015). Nevertheless, only few studies have been conducted to estimate the EV performance depending on the ambient temperature. In fact, experimentations presented in De Cauwer et al. (2015) and Fiori et al. (2016) have proved through simulation results that the EV energy consumption might increase by up to 32% under the influence of such an environmental factor. In brief, it is crucial to express the energy consumed by auxiliary systems in terms of the ambient temperature due to its valuable impact on the accuracy of the EV energy consumption estimation.

Regarding the energy recuperation part, a constant value of the regenerative braking efficiency factor was presented. However, this parameter is not presented by an explicit formula that depends by an internal and/or an external factor related parameters. Therefore, the existing energy model in SUMO does not reflect the energy recuperation in real-world. Special attention towards incorporating an explicit formula for modelling the energy recuperation part should be paid to reflect the impact of external factors (i.e., EV deceleration, road gradient, etc.) on the total EV energy consumption estimation.

To sum up, the simplifications proposed by Kurczveil et al. (2013) seem to make the actual SUMO energy model lacks accuracy and underestimates the EV energy consumption in real world. A set of improvements can be attributed mostly to the energy consumed by auxiliary systems formula, and to the energy recuperation modelling. These improvements are important as they enhance the accuracy of the EV energy consumption model in mobility simulators. Obviously, it is crucial to investigate and characterise the impact of various other factors that impact the EV energy consumption and recuperation to provide more realistic formula for such model. Moreover, the simulator SUMO documentation is widely available and the source code is accessible. Therefore, SUMO could be considered as the best simulator in its category that meets our research study requirements, but it needs significant improvements to achieve more realistic results. Exploring recent studies in the automotive energy research domain could be beneficial for the SUMO energy model.

4 Future challenges and directions

Developing a realistic and accurate EV energy model for traffic simulations becomes a necessity to enhance the design and the diffusion of EVs into the consumer market. Such model is the core of energy optimisation algorithms (e.g., eco-routing, eco-driving) that could be employed by energy-oriented navigation systems (i.e., EV driver assistance systems).

As mentioned in Section 2, the energy model for EVs can be presented according to two main parts: the energy consumption part and the energy recuperation part. If we can claim that the mechanical consumption part is quite modelled and that its estimation is enough accurate, it is not the case for the recovery part. Indeed, researchers began by considering a constant efficiency recuperation factor (Genikomsakis and Mitrentsis, 2017), then a formal simplistic model depending on the deceleration parameter (Fiori et al., 2016), to finally recognise a multifactor dependency (Sarrafan et al., 2016). To be able to handle complex factors combinations, traditional approaches, such as fuzzy logic (Bathala et al., 2020), could be employed. Nonetheless, this technique presumes a complete knowledge and mastery of the interactions that govern the considered factors which is far to be the case in such highly dynamic and sensitive context.

A new approach that could be explored to cope with this complexity, is the machine learning one. In fact, the heterogeneity and independency of the factors that could impact the recovery process, could be explored and expressed through machine learning based models. Some works are already underway (Bathala et al., 2020), and we think further research on the same way should follow. Additionally, the same thought and idea could be applied at a macro level. Indeed, the whole consumption estimation could be managed by a machine learning process. The same above-mentioned reasons could be again evoked. This direction is reinforced by the fact that the recovery process is actually not totally separated from the consumption process in the EV motor and that many external factors (e.g., environmental factors) should be considered in the estimation process (Liu et al., 2017; Ma et al., 2015; Iora and Tribioli, 2019).

In that context, machine learning models are more suited than mathematical models to represent the correlation between the different factors and to accurately model and estimate the whole consumption process. This approach has been already adopted by several research works and should be further strengthened in the near future. However, we believe that these works should be better organised and classified according to the granularity and heterogeneity of the considered factors and could achieve better results by considering temporal dependency.

5 Conclusions

The increasing popularity and attention in VANETs have prompted researchers to develop realistic and efficient simulation tools that deal with the EV concept. In particular, to accurately estimate the energy consumption for EVs, an accurate energy model must be existed in traffic simulations.

The aim of the present work was to evaluate the existing energy models in VANET simulation tools to specify the main requirements needed for elaborating a realistic and accurate energy model ensuring realistic traffic simulations and producing valuable results. Accordingly, a deep understanding of EV energy consumption and recovery processes and related influencing factors (e.g., ambient temperature) is needed to build a reliable and faithful energy model for EV.

In this paper, we have reviewed the existing energy models related to the automotive energy domain. The review structures the different parts that represent the energy model and points out the commonly used models for each part. We particularly distinguished between the consumption part and the recuperation part that characterise any accurate energy model for EVs. The conducted theoretical analysis revealed many optimisations and recommendations that should be applied when implementing a realistic and accurate EV energy model. An efficient energy model implementation should combine accuracy and simplicity to achieve a good modelling of real-world EV energy consumption while maintaining a reasonable complexity level. Then, the second part of this paper is dedicated to explore the different energy models implementation in VANET simulation tools. Thereafter, the VANET simulation tools have been classified into three categories, namely the mobility simulators, the network simulators and the VANET simulators. Only mobility simulators integrate energy models for EVs. In particular, we have selected the simulator SUMO as the most reliable simulator that incorporates a consistent energy model for calculating EV energy consumption at each simulation time step. However, such model lacks accuracy and requires a set of improvements to accurately compute EV energy consumption. The conducted theoretical analysis revealed two main recommendations that should be applied when implementing such energy model. The first one consists of enhancing the auxiliary systems consumption model to reflect the ambient temperature impact. The second one focus on representing the energy recuperation model by an explicit formula to reflect the driver profile impact.

In the next step, these propositions will be implemented and evaluated through a set of simulation scenarios in SUMO.

References

Abousleiman, R. and Rawashdeh, O. (2015) 'Energy consumption model of an electric vehicle', in *2015 IEEE Transportation Electrification Conference and Expo (ITEC)*, IEEE, pp.1–5.

Ahmed, B., Malik, A.W., Hafeez, T. and Ahmed, N. (2019) 'Services and simulation frameworks for vehicular cloud computing: a contemporary survey', *EURASIP Journal on Wireless Communications and Networking*, No. 1, p.4.

Asamer, J., Graser, A., Heilmann, B. and Ruthmair, M. (2016) 'Sensitivity analysis for energy demand estimation of electric vehicles', *Transportation Research Part D: Transport and Environment*, Vol. 46, pp.182–199.

Barth, M., Malcom, C. and Scora, G. (2001) *Integrating a Comprehensive Modal Emissions Model into Atmis Transportation Modeling Frameworks*, California Partners for Advanced Transportation Technology, UC Berkeley [online] https://escholarship.org/uc/item/6248p2dr (accessed 1 August 2001).

Bathala, P., Srivasthav, B.S., Reddy, Y.S.S. and Deepa, K. (2020) 'Estimation of regenerative braking force in electric vehicles for maximum energy recovery', in *2020 IEEE 17th India Council International Conference (INDICON)*, IEEE, pp.1–7.

Behrisch, M., Bieker, L., Erdmann, J. and Krajzewicz, D. (2011) 'SUMO – simulation of urban mobility: an overview', in *Proceedings of SIMUL 2011, The Third International Conference on Advances in System Simulation*, ThinkMind.

Bian, J. and Qiu, B. (2018) 'Effect of road gradient on regenerative braking energy in a pure electric vehicle', *Proceedings of the Institution of Mechanical Engineers, Part D: Journal of Automobile Engineering*, Vol. 232, No. 13, pp.1736–1746.

Bingham, C., Walsh, C. and Carroll, S. (2012) 'Impact of driving characteristics on electric vehicle energy consumption and range', *IET Intelligent Transport Systems*, Vol. 6, No. 1, pp.29–35.

Chaudhary, R., Sethi, S., Keshari, R. and Goel, S. (2012) 'A study of comparison of network simulator-3 and network simulator-2', *International Journal of Computer Science and Information Technologies*, Vol. 3, No. 1, pp.3085–3092.

De Cauwer, C., Van Mierlo, J. and Coosemans, T. (2015) 'Energy consumption prediction for electric vehicles based on real-world data', *Energies*, Vol. 8, No. 8, pp.8573–8593.

Diaz, S. (2012) 'ProtoDrive: simulation of electric vehicle powertrains', *NSF Summer Undergraduate Fellowship in Sensor Technologies*, Binghamton University.

Er-Rouidi, M., Moudni, H., Mouncif, H. and Merbouha, A. (2016) 'An energy consumption evaluation of reactive and proactive routing protocols in mobile ad-hoc network', in *2016 13th International Conference on Computer Graphics, Imaging and Visualization (CGiV)*, IEEE, pp.437–441.

Fellendorf, M. and Vortisch, P. (2010) 'Microscopic traffic flow simulator VISSIM', in *Fundamentals of Traffic Simulation*, pp.63–93, Springer.

Ferreira, J.C., Monteiro, V. and Afonso, J.L. (2013) 'Dynamic range prediction for an electric vehicle', in *2013 World Electric Vehicle Symposium and Exhibition (EVS27)*, IEEE, pp.1–11.

Fiori, C., Ahn, K. and Rakha, H.A. (2016) 'Power-based electric vehicle energy consumption model: model development and validation', *Applied Energy*, Vol. 168, pp.257–268.

Genikomsakis, K.N. and Mitrentsis, G. (2017) 'A computationally efficient simulation model for estimating energy consumption of electric vehicles in the context of route planning applications', *Transportation Research Part D: Transport and Environment*, Vol. 50, pp.98–118.

Harri, J. and Fiore, M. (2006) 'VanetMobiSim – vehicular ad hoc network mobility extension to the CanuMobiSim framework', *Institut Eurécom Department of Mobile Commu.*, Vol. 6904, pp.1–19.

Härri, J., Filali, F., Bonnet, C. and Fiore, M. (2006) 'VanetMobiSim: generating realistic mobility patterns for VANETs', in *Proceedings of the 3rd International Workshop on Vehicular Ad Hoc Networks*, pp.96–97.

Henderson, T.R., Lacage, M., Riley, G.F., Dowell, C. and Kopena, J. (2008) 'Network simulations with the NS-3 simulator', *SIGCOMM Demonstration*, Vol. 14, No. 14, p.527.

Heydari, S., Fajri, P., Rasheduzzaman, M. and Sabzehgar, R. (2019) 'Maximizing regenerative braking energy recovery of electric vehicles through dynamic low-speed cutoff point detection', *IEEE Transactions on Transportation Electrification*, Vol. 5, No. 1, pp.262–270.

Hu, X., Murgovski, N., Johannesson, L. and Egardt, B. (2013) 'Energy efficiency analysis of a series plug-in hybrid electric bus with different energy management strategies and battery sizes', *Applied Energy*, Vol. 111, pp.1001–1009.

Iora, P. and Tribioli, L. (2019) 'Effect of ambient temperature on electric vehicles' energy consumption and range: model definition and sensitivity analysis based on Nissan leaf data', *World Electric Vehicle Journal*, Vol. 10, No. 1, p.2.

Jansuwan, S., Ryu, S., Freckleton, D., Chen, A. and Heaslip, K. (2021) 'An evaluation framework of an automated electric transportation system', in *Transportation Research Part E: Logistics and Transportation Review*, Vol. 148, p.102265, Elsevier.

Kiokes, G., Zountouridou, E., Papadimitriou, C., Dimeas, A. and Hatziargyriou, N. (2015) 'Development of an integrated wireless communication system for connecting electric vehicles to the power grid', in *2015 International Symposium on Smart Electric Distribution Systems and Technologies (EDST)*, IEEE, pp.296–301.

Kurczveil, T., López, P.Á. and Schnieder, E. (2013) 'Implementation of an energy model and a charging infrastructure in SUMO', in *Simulation of Urban Mobility User Conference*, Springer, pp.33–43.

Lan, K-C. (2010) 'Move: a practical simulator for mobility model in VANET', in *Telematics Communication Technologies and Vehicular Networks: Wireless Architectures and Applications*, pp.355–368, IGI Global.

Larminie, J. and Lowry, J. (2012) *Electric Vehicle Technology Explained*, John Wiley & Sons.

Li, Y., Zhang, L., Zheng, H., He, X., Peeta, S., Zheng, T. and Li, Y. (2015) 'Evaluating the energy consumption of electric vehicles based on car-following model under non-lane discipline', *Nonlinear Dynamics*, Vol. 82, Nos. 1–2, pp.629–641.

Li, G., Boukhatem, L., Zhao, L. and Wu, J. (2018) 'Direct vehicle-to-vehicle charging strategy in vehicular ad-hoc networks', in *2018 9th IFIP International Conference on New Technologies, Mobility and Security (NTMS)*, IEEE, pp.1–5.

Liu, K., Yamamoto, T. and Morikawa, T. (2017) 'Impact of road gradient on energy consumption of electric vehicles', *Transportation Research Part D: Transport and Environment*, Vol. 54, pp.74–81.

Lorf, C., Martínez-Botas, R.F., Howey, D.A., Lytton, L. and Cussons, B. (2013) 'Comparative analysis of the energy consumption and CO_2 emissions of 40 electric, plug-in hybrid electric, hybrid electric and internal combustion engine vehicles', *Transportation Research Part D: Transport and Environment*, Vol. 23, pp.12–19.

Lv, C., Zhang, J., Li, Y. and Yuan, Y. (2015) 'Mechanism analysis and evaluation methodology of regenerative braking contribution to energy efficiency improvement of electrified vehicles', *Energy Conversion and Management*, Vol. 92, pp.469–482.

Ma, H., Xie, H., Huang, D. and Xiong, S. (2015) 'Effects of driving style on the fuel consumption of city buses under different road conditions and vehicle masses', *Transportation Research Part D: Transport and Environment*, Vol. 41, pp.205–216.

Maia, R., Silva, M., Araújo, R. and Nunes, U. (2011) 'Electric vehicle simulator for energy consumption studies in electric mobility systems', in *2011 IEEE Forum on Integrated and Sustainable Transportation Systems*, IEEE, pp.227–232.

Mangharam, R., Weller, D., Rajkumar, R., Mudalige, P. and Bai, F. (2006) 'GrooveNet: a hybrid simulator for vehicle-to-vehicle networks', in *2006 Third Annual International Conference on Mobile and Ubiquitous Systems: Networking & Services*, IEEE, pp.1–8.

Mangharam, R. (2012) 'The car and the cloud: automotive architectures for 2020'.

Mets, K., Verschueren, T., Develder, C., Vandoorn, T.L. and Vandevelde, L. (2011) 'Integrated simulation of power and communication networks for smart grid applications', in *2011 IEEE 16th International Workshop on Computer Aided Modeling and Design of Communication Links and Networks (CAMAD)*, IEEE, pp.61–65.

Miller, J. and Horowitz, E. (2007) 'FreeSim – a free real-time freeway traffic simulator', in *2007 IEEE Intelligent Transportation Systems Conference*, IEEE, pp.18–23.

NS-2 Simulator (2020) [online] https://www.isi.edu/nsnam/ns/ (accessed 25 January 2020).

Obaidat, M.S., Filipe, J., Kacprzyk, J. and Pina, N. (2014) *Simulation and Modeling Methodologies, Technologies and Applications*, Springer.

Sarrafan, K., Muttaqi, K.M., Sutanto, D. and Town, G. (2016) 'Improved estimation of the impact of regenerative braking on electric vehicle range', in *2016 IEEE International Conference on Power System Technology (POWERCON)*, IEEE, pp.1–6.

Schellenberg, S., Berndt, R., Eckhoff, D. and German, R. (2014) 'A computationally inexpensive battery model for the microscopic simulation of electric vehicles', in *2014 IEEE 80th Vehicular Technology Conference (VTC2014-Fall)*, IEEE, pp.1–6.

Schilling, B. (2005) *Qualitative Comparison of Network Simulation Tools*, Technical Report, Citeseer.

Schreiber, V., Wodtke, A. and Augsburg, K. (2014) 'Range prediction of electric vehicles', in *Shaping the Future by Engineering: Proceedings; 58th IWK, Ilmenau Scientific Colloquium*, Technische Universität Ilmenau, 8–12 September, Vol. 58.

Sethi, A.S. and Hnatyshin, V.Y. (2012) *The Practical OPNET User Guide for Computer Network Simulation*, CRC Press.

Shibata, S. and Nakagawa, T. (2015) 'Mathematical model of electric vehicle power consumption for traveling and air-conditioning', *Journal of Energy and Power Engineering*, Vol. 9, No. 6, pp.269–275.

Shyrokau, B., Wang, D., Savitski, D. and Ivanov, V. (2013) 'Vehicle dynamics control with energy recuperation based on control allocation for independent wheel motors and brake system', *International Journal of Powertrains*, Vol. 2, Nos. 2–3, pp.153–181.

Smith, M., Duncan, G. and Druitt, S. (1995) *PARAMICS: Microscopic Traffic Simulation for Congestion Management*, IET.

Spichartz, P. and Sourkounis, C. (2016) 'Assessment of recuperation strategies for electric vehicles by simulations and measurements', in *2016 International Symposium on Power Electronics, Electrical Drives, Automation and Motion (SPEEDAM)*, IEEE, pp.1226–1231.

Spichartz, P., Dost, P. and Sourkounis, C. (2014) 'Recuperation strategies for electric vehicles', in *2014 Ninth International Conference on Ecological Vehicles and Renewable Energies (EVER)*, IEEE, pp.1–7.

SUMO (2019) *Simulation of Urban Mobility* [online] http://www.dlr.de/ts/en/desktopdefault.aspx/tabid-9883/16931_read-41000/ (accessed 15 April 2020).

Sweeting, W.J., Hutchinson, A.R. and Savage, S.D. (2011) 'Factors affecting electric vehicle energy consumption', *International Journal of Sustainable Engineering*, Vol. 4, No. 3, pp.192–201.

Traffic and Network Simulation Environment Simulator (TraNS) (2019) [online] https://www.isi.edu/nsnam/ns/ (accessed 28 December 2019).

Van Roy, J., Leemput, N., De Breucker, S., Geth, F., Tant, P. and Driesen, J. (2011) 'An availability analysis and energy consumption model for a flemish fleet of electric vehicles', in *European Electric Vehicle Congress (EEVC)*, Brussels, Belgium, 26–28 October.

Varga, A. and Hornig, R. (2008) 'An overview of the OMNeT++ simulation environment', in *Proceedings of the 1st International Conference on Simulation Tools and Techniques for Communications, Networks and Systems & Workshops*, ICST, p.60.

Vehicles in Network Simulation (VEINS) (2020) [online] http://veins.car2x.org/ (accessed 12 April 2020).

Wang, J-b., Liu, K., Yamamoto, T. and Morikawa, T. (2017) 'Improving estimation accuracy for electric vehicle energy consumption considering the effects of ambient temperature', *Energy Procedia*, Vol. 105, pp.2904–2909.

Wu, H., Nabar, S. and Poovendran, R. (2011) 'An energy framework for the network simulator 3 (NS-3)', in *Proceedings of the 4th International ICST Conference on Simulation Tools and Techniques*, pp.222–230.

Wu, X., Freese, D., Cabrera, A. and Kitch, W.A. (2015) 'Electric vehicles' energy consumption measurement and estimation', *Transportation Research Part D: Transport and Environment*, Vol. 34, pp.52–67.

Xiao, P., Lou, J., Niu, L.M. and Gao, H. (2016) 'Modeling and simulation of regenerative braking performance of electric vehicles based on decoupling strategy', in *Key Engineering Materials*, Vol. 693, pp.1667–1675, Trans Tech Publ.

Yanan, G. (2016) 'Research on electric vehicle regenerative braking system and energy recovery', *International Journal of Hybrid Information Technology*, Vol. 9, No. 1, pp.81–90.

Ye, M., Bai, Z.F. and Cao, B.G. (2008) 'Energy recovery for battery electric vehicles', *Proceedings of the Institution of Mechanical Engineers, Part D: Journal of Automobile Engineering*, Vol. 222, No. 10, pp.1827–1839.

Ye, X., Wen, F., Ang, S.P. and Salam, M.A. (2014) 'OPNet-based performance analysis of the communication network in a charging station of electric vehicles', in *2014 IEEE PES Asia-Pacific Power and Energy Engineering Conference (APPEEC)*, IEEE, pp.1–6.

Yi, Z. and Bauer, P.H. (2014) 'Energy consumption model and charging station placement for electric vehicles', in *Smartgreens*, pp.150–156.

Zhang, Q-Y. and Huang, J. (2018) 'Research on regenerative braking energy recovery system of electric vehicles', *Journal of Interdisciplinary Mathematics*, Vol. 21, No. 5, pp.1321–1326.

Zhang, R. and Yao, E. (2015) 'Electric vehicles' energy consumption estimation with real driving condition data', *Transportation Research Part D: Transport and Environment*, Vol. 41, pp.177–187.

Zou, Z., Cao, J., Cao, B. and Chen, W. (2015) 'Evaluation strategy of regenerative braking energy for supercapacitor vehicle', *ISA Transactions*, Vol. 55, pp.234–240.