Enhancing the ns-3 simulator by introducing Electric Vehicles features

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***Abstract*—Electric Vehicles (EVs) sales are increasing in the recent years due to several factors such as cost reduction, fuel cost increase, pollution reductions, government incentives, among others. At the same time, Intelligent Transportation Systems (ITS) are continuously improving, and researchers use different simulators in order to test their proposals before implementing them in real devices. However, traditional communications-aimed simulations do not include fuel consumption issues that are a key factor in transportation systems. This paper presents the addition of Electric Vehicles consumption to the ns-3 simulator, which currently is one of the most used network simulators. Our proposal follows all the models, coding style, as well as engineering guidelines of ns-3, coupled with the characteristics of each vehicle, to accurately estimate the energy consumption. We also analyze the performance of our proposal while simulating a part of the E313 highway, located in Antwerp, Belgium. In particular, we compare the ns-3 results obtained in terms of energy consumption to those obtained in SUMO. In addition, we study the impact of our proposal on the overall simulation time.**

***Index Terms*—Electric Vehicles, Vehicular Networks, Simulation, Energy Consumption, ns-3.**

I. Introduction

Automobile factoring has become one of the most important world-wide industries, not only at economic level but also in terms of research and development. The first step in this development has been the proposal of elements designed to enhance people's safety. Another consideration it is the increase in the number of vehicles present in our roads and the effects produced by this situation, such as traffic jams and pollution. In fact, according to a report by the European Union, the transportation sector is responsible for nearly 28% of the total CO_2 emissions, while the road transport is accountable for over 70% of the transport sector emissions [1].

Therefore, several advances in order to mitigate these undesirable situations have been proposed in the recent years [2], [3], [4], and the Electric Vehicle (EV) is foreseen as one of the most important players to reduce polluting emissions. EVs are considered the most promising alternative to internal combustion engine vehicles towards a cleaner transportation sector. Having null tailpipe emissions, EVs contribute to fight localized pollution, which is particularly important in overpopulated urban areas [5].

Research in Intelligent Transportation Systems (ITS), in general, and more specifically, in Vehicular Networks has found in simulation the most useful method to test new challenges and opportunities. This is mainly due to the high cost of deploying such systems in real scenarios and the problems related to scalability. When simulating vehicular environments, different issues must be addressed, such as mobility models, wireless communications, vehicular fuel/energy consumption, among others. Moreover, considering real environments and scenarios, communications elements, and signalling impairments of wireless communications for vehicles, must be taken into account.

According to this, and focusing on the study of Electric Vehicles global deployment, there is a lack of integrated simulation tools that consider ITS key factors such as mobility models, street map layouts, communication network technologies, along with fuel/electric consumption, all together within a holistic approach. We consider that a network simulator should definitely integrate the mapping of such real world considerations into the simulation principles, in order to empower researchers towards comprehensive studies including mobility, connectivity, and consumption aspects.

In the near future, all the vehicles will need to be wirelessly connected among them (V2V communications) and also to the infrastructure (V2I), for different purposes, such as autonomous driving, smart traffic management, accident avoidance, multimedia resources, etc., and hence, the use of accurate and comprehensive simulation environments will be crucial to better test new protocols and approaches prior to make them real.

To address the above mentioned issues, in this paper, we propose the introduction of EVs consumption into the ns-3 simulator. In particular, we provide researchers the possibility to take into account the electricity required by EVs while simulating the communication between vehicles with minimal overhead.

The paper is organized as follows: in Section II we review some of the most relevant existing improvements previously included in the ns-3 simulator, and existing alternatives in the literature to estimate the energy demanded by EVs. Section III presents the main characteristics of the ns-3 simulator and what should take into account in order to introduce new features, and we detail the EV consumption model which has been included in the simulator. In Section IV, we present the both the simulation scenario and the validation results of our proposal. In particular, we present the selected scenario, the characteristics of the vehicles used, and the overhead introduced by our approach. Finally, Section V shows the main conclusions drawn from this work.

II. Related Work

Simulation is a key factor when researchers aim to validate their proposals, especially in vehicular research areas where a real implementation may require considerable amounts of money and resources. Weingartner et al. [6] studied the most important network simulators and presented a performance comparison by implementing the same use case set-up in five different simulators, namely ns-2 [7], OMNet++ [8], ns-3 [9], SimPy [10], and JiST/SWANS [11]. Simulation results revealed large differences in terms of both run-time and memory usage. Similarly, Martinez et al. [12] presented a comprehensive study and comparison of various publicly available simulation environments specifically addressed to Vehicular ad hoc Networks (VANETs) simulation.

One of the most used network simulators is ns-3, that researchers use to validate their proposals. For instance, Kumar et al. [13] used the ns-3 for the implementation of various architectures aimed at Data Center Networks (DCNs) and the study of their performance. The information they provided included the realization of the most popular designs for DCN and the tools available in ns-3 to study their performance. Remy et al. [14] presented LTE4V2X, a novel framework for a centralized vehicular network organization using Long Term Evolution (LTE), specially designed to overcome the extremely dynamic network topology and the large variable number of mobile nodes that face Vehicular Networks. Authors analyze its performance by using the ns-3 simulation environment and a realistic urban mobility model. Other authors, such as Spaho et al. [15] used the ns-3 to investigate the performance of both Optimized Link State Routing and Ad-hoc On Demand Distance Vector routing protocols in a VANET crossroad scenario. Authors also generated the vehicle mobility patters with Cellular Automaton based VEhicular NETwork. In particular, their simulations relied on the IEEE 802.11p standard already implemented in the ns-3.

Those are examples of researchers that use the ns-3 simulator to validate their proposals in several networking areas, however, we can also find numerous works that present the development of new features in this simulator, increasing its capabilities. For instance, Baldo et al. [16] presented a new simulation module, specially designed for the ns-3, aimed at LTE network simulation. This module was designed following a product-oriented perspective in order to allow LTE equipment manufacturers to test Radio Resource Management and Self-Organizing Network algorithms before they are actually deployed. Guidolin et al. [17] presented the implementation of a 2x2 Multiple Input Multiple Output in a LTE module which can be considered as possible extension to the next generation cellular networks. Thanks to the modularity of the ns-3 simulator, the code developed could be merged with any other evaluation at any point of the protocol stack, from the lower to the application layers. Fernandes et al. [18] presented a tool for simulating heterogeneous Vehicular Networks. In particular, they extended DIVERT, an existing microscopic traffic simulator, by adding ns-3 support resulting in a very tightly integrated simulator.

More related to our work, Wu et al. [19] introduced an integrated devices energy consumption module for the ns-3. In particular, it models energy source and energy consumption. It is important to highlight, that unlike our approach, their proposal only addresses the communication devices consumption. Our work addresses the EVs energy consumption instead.

As for energy consumption, Sarker et al. [20] used ns-3, MatLab, and the Simulation for Urban MObility (Simulation for Urban Mobility) to validate a system designed to balance the Battery State of Charge (BSoC) at Wireless Power Transfer (WTP) lanes. In particular, the authors required all those tools because the ns-3 is not able to estimate EVs consumption. Mets et al. [21] designed their own framework to model and simulate both the communication and power networks, and hence validate proposals addressing the future Smart Grid. Anderson et al. [22] proposed GridSpice, a scalable open-source simulation framework for modeling, designing, and planning the Smart Grid. GridSpice seamlessly integrates existing electric power simulation tools to enable modeling of large electric networks that blur the boundaries between generation, transmission, distribution, and markets. However, this simulator does not provide any communication capabilities which are required by ITS. More recently, Torres et al. [23] implemented a simulator able to model and predict the EVs energy demand which relies on Vehicular Networks. However, this approach do not consider realistic mobility and map layouts.

Although the ns-3 is one of the most used communications aimed simulator, in its current version it does not allow to estimate the consumption of vehicles, either EVs or those based on internal combustion engines. Taking into account this, along with the necessity of having an integrated simulation tool able to accurately model vehicles' mobility, realistic maps, communication network technologies, along with electric consumption, in a holistic way, in this paper, we have implemented a ns-3 module which will allow researchers to perform comprehensive studies including transportation, networking, and consumption features.

III. ns-3: Electric Vehicles Module

In this work we have faced two main challenges: (i) including new code into the ns-3 network simulator, while

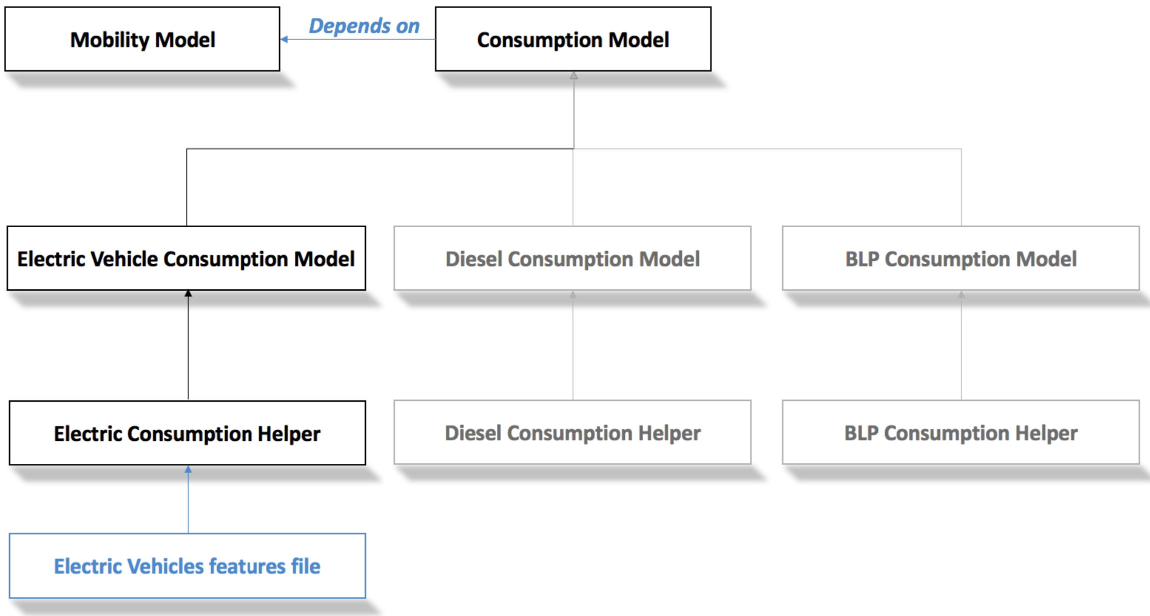


Fig. 1. Software structure of the proposal according to the ns-3 code guidelines and module dependencies.

maintaining its original design and structure, as well as its coding style guides, and (ii) introducing and validating an EV consumption model. In this section we present the modifications implemented in the ns-3, as well as the consumption model added to enable the joint simulation of both vehicular communications and EV energy consumption.

A. Modifying the ns-3 simulator

The ns-3 is a discrete-event simulator for communication networks mainly used for educational and research purposes [9]. The ns-3 is used to establish topologies defined by interrelated nodes to which communication models (UDP, IPv4, etc.) and mobility models are added.

The last release of simulator is the ns-3.29, which has more than 38 modules developed in C++ addressing different simulation scenarios. The development is constant and has an activity community of developers, mainly composed of researchers from several universities. In fact, a consortium of different organizations around the maintenance and development of the simulator was established [24]. The initial agreement establishing and specifying the operation of the ns-3 consortium was made between the University of Washington and the INRIA.

The ns-3 is composed by standard modules, and each module integrates the following components: (i) a model class responsible for the calculations, (ii) a helper class that implements the necessary methods to carry out a simulation (read data from a file, create the model, etc.), and (iii) an example script of one simulation using the module that serves as a reference for users who want to use it.

In our work, we have implemented a new ns-3 module designed for including the simulation of the energy consumption of EVs. The class design of the module implemented is depicted in Figure 1. As shown, the ElectricConsumptionHelper class is in charge of creating the electric consumption model for each node (ElectricVehicleConsumptionModel), which in turn inherits from the abstract class of consumption model (ConsumptionModel). This design allows adding new consumption models, and thus enabling the simulation of different types of vehicles in a simple manner. Notice that we have carefully designed the model to enable the addition of new consumption models for different vehicle engines (diesel, gasoline, gas).

With regard to the internal dependencies of the module with other modules of the simulator, our module has only a dependence that cannot be avoided. In particular, our consumption module uses the mobility module. This is logical, since the calculation of a vehicle's consumption will always depend on its mobility and speed. It can not be considered a critical dependence, since it is a very consolidated module in the ns-3 code, and that hardly changes in new versions.

The functionality of the implemented module could be summarized as follows. The user will execute the simulation script, passing as parameters: (i) a file with the mobility trace of each vehicle, (ii) a XML file with the specific attributes of each EV, (iii) the number of vehicles involved in the simulation, (iv) the simulation duration, and (v) the update time (i.e., how often the vehicle's energy is updated in the simulation).

The mobility traces will be in Tcl format which is compatible with the ns-3 mobility module. Furthermore, each time that the vehicles' energy consumed is updated during the simulation, an event to access to all the variables of the consumption model is generated, and thus enabling the

```
:~$ ./waf --run "electric-mobility
    --traceFile=mobilityFile.tcl
    --vehicleAttributes=EVsFile.xml
    --nodeNum=500 --duration=120"
```

Fig. 2. Execution Example

statistics compilation either using the standard output or a file.

Figure 2 shows an example of the command line required to launch the simulation. As can be observed, both mobility and EV files are required, as well as the number of vehicles (nodeNum) and the simulation duration. In this example, the update time is not determined, and so the default value (1 second) is set.

B. EV consumption model

The model implemented has been based on that specified by Tamás Kurczveil, Pablo Álvarez López, and Eckehard Schnieder [25] which is included in the SUMO traffic simulator [26].

The first thing to calculate the consumption of a vehicle is to obtain its energy. This can be obtained by adding its kinetic energy, its potential energy, and its rotational energy to then subtract the energy lost due to the resistance of various components of the vehicle. Therefore, the energy of a vehicle at an instant k can be calculated with the following equation:

$$\begin{aligned} E_{veh}[k] &= E_{kin}[k] + E_{pot}[k] + E_{rot}[k] \\ &= \frac{m}{2} \cdot v^2[k] + mgh[k] + \frac{J_{int}}{2} \cdot v^2[k] \end{aligned} \quad (1)$$

where m is the mass of vehicle, v its velocity, g the gravity acceleration, h the altitude, and J_{int} the moment of inertia of internal rotating elements.

Once the energy of the vehicle is calculated, we can obtain the energy consumed (or gained) between an instant k and $k+1$, by adding the energy lost:

$$\Delta E_{cons}[k+1] = E_{veh}[k] - E_{veh}[k+1] + \Delta E_{loss}[k] \quad (2)$$

To calculate the total energy lost, we must add the energy lost by the following four components: (i) the friction of the air, (ii) the friction with the ground, (iii) the friction of curve, and (iv) the constant energy consumed by the vehicle (see Equation 3).

$$\begin{aligned} \Delta E_{loss}[k] &= \Delta E_{air}[k] + \Delta E_{roll}[k] \\ &+ \Delta E_{curve}[k] + \Delta E_{const}[k] \end{aligned} \quad (3)$$

where $\Delta E_{air}[k]$, $\Delta E_{roll}[k]$, $\Delta E_{curve}[k]$, and $\Delta E_{const}[k]$ are defined by the following expressions:

$$\begin{aligned} \Delta E_{air}[k] &= \frac{1}{2}\rho_{air} \cdot A_{veh} \cdot C_w \cdot v^2[k] \cdot |\Delta s[k]| \\ \Delta E_{roll}[k] &= c_{roll} \cdot m \cdot g \cdot |\Delta s[k]| \\ \Delta E_{curve}[k] &= c_{rad} \cdot \frac{mv^2[k]}{r[k]} \cdot |\Delta s[k]| \\ \Delta E_{const}[k] &= P_{const} \cdot \Delta t \end{aligned} \quad (4)$$

where ρ_{air} is the air density, A_{veh} the vehicle's front surface area, C_w air drag coefficient, $s[k]$ the covered distance, c_{roll} the rolling distance, c_{rad} the curve resistance coefficient, and P_{const} the average power of constant consumers.

Depending on whether the vehicle's energy difference between instants k and $k+1$ is positive or negative, it will be necessary to multiply it by a factor of propulsion or recovery, which will be determined by how the vehicle uses the energy to discharge or charge the battery. The equation to estimate the level of vehicle's battery at an instant $k+1$ is then as follows:

$$E_{bat}[k+1] = \begin{Bmatrix} E_{bat}[k] - \Delta E_{cons}[k] \cdot n_{prop} & if\ \Delta E_{bat} < 1 \\ E_{bat}[k] - \Delta E_{cons}[k] \cdot n_{recov} & if\ \Delta E_{bat} > 1 \end{Bmatrix} \quad (5)$$

where n_{prop} is the propulsion factor, and n_{recov} is the constant recovery factor.

IV. Performance

In this section, we show the performance of our proposal. In particular, we firstly detail the scenario used in our simulations, and secondly, we analyze the results obtained in terms of accuracy and overhead.

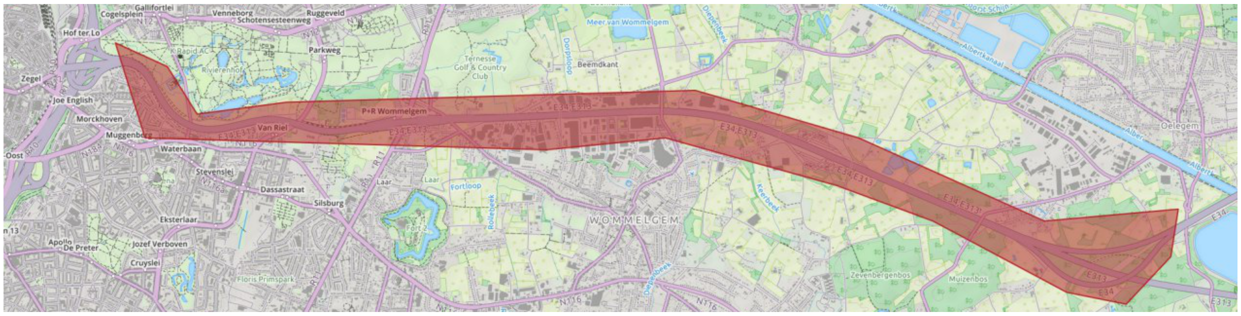
A. Simulation Scenario

To validate our proposal, we selected the Antwerp E313 highway, since the SmartHighway testbed [27] is deployed in such highway. This recently built testbed is one of kind, since it provides Cellular vehicle-to-everything (CV2X) communications in such relevant real scenario (see Figure 3). We used SUMO to extract the primary structure of the highway, while ignoring the rest of segments/roads close to the highway. More specifically, we selected a 12-kilometer-long highway segment with 4 lanes per direction in most of the scenario. As for the vehicles, we introduced different flows from East to West and from West to East, respectively.

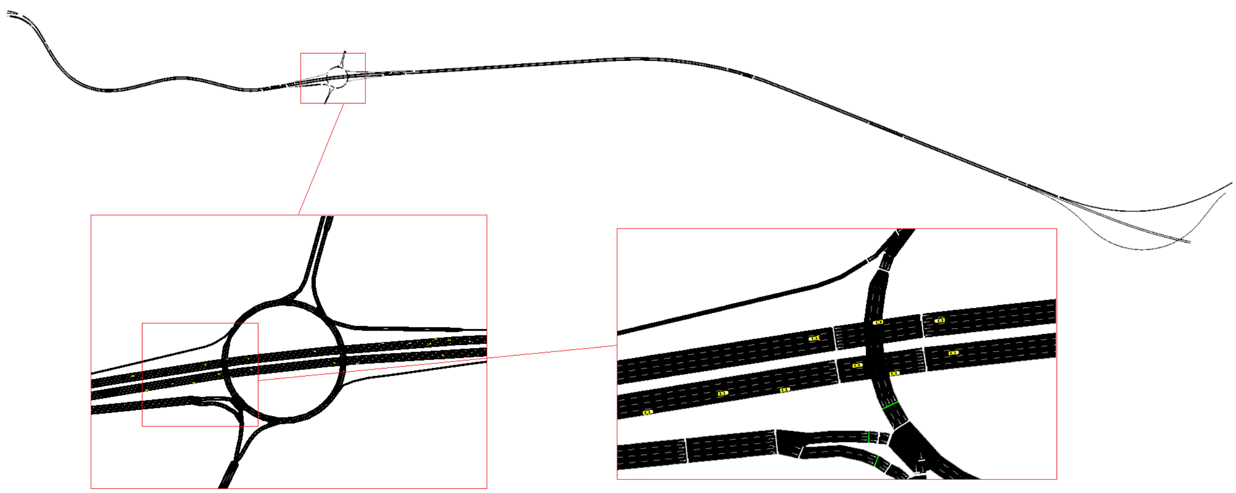
Table I shows the main features of the vehicles used in our simulations. In particular, it presents the percentage of sales

TABLE I
Features of the Electric Vehicles used in our simulations

Make	Model	Sales (%)	MBC (kWh)	Mass (Kg)	FSA (m^2)	C_d
Nissan	Leaf 2018	28.01	40.0	1,557	2.30	0.28
Renault	Zoe	27.01	41.0	1,468	0.75	0.29
BMW	i3	17.60	33.0	1,195	2.38	0.29
VW	e-Golf	15.23	35.8	1,540	1.97	0.31
Tesla	Model S	11.97	72.5	2,250	2.34	0.24



(a)



(b)

Fig. 3. Antwerp E313 highway segment used in our simulations: (a) OpenStreetMap view, and (b) detail of the SUMO simulation.

of each model, along with the Maximum Battery Capacity (MBC), the vehicle mass, the front surface area (FSA), and the Air Drag Coefficent (C_d). We used genuine EV sales data for 2018 provided from EVVolumes.com [28] to increase the level of realism of the simulation. More specifically, if we would simulate 1,000 vehicles, 280 of them would be Nissan Leaf, 270 would be Renault Zoe, 176 would be BMW i3, and so on. This is not trivial since there are significant differences between the different models used (for example, the Tesla Model S mass nearly doubles the BMW i3), and these differences greatly affect to the energy consumption of each vehicle. Another important consideration is that vehicles follow realistic mobility models including relevant features, such as car following issues, lane changing rules, overtaking restrictions, and speed limit rules.

B. Validation of the results

Our main goal is adding consumption estimation features for EVs in the ns-3 simulator, offering a new useful and accurate functionality with a minimum overhead. In this section, we present a comparison of the consumption values obtained in ns-3 using our module with those results obtained by SUMO. In addition, we measure the overhead introduced when using our contribution.

1) Consumption model: To validate the implementation of the new ns-3 built-in consumption model, we perform a comparison between the results obtained, for the same scenario, by the SUMO traffic simulator with those returned by our ns-3 module.

Table II shows the simulation results for the highway scenario presented in the previous subsection. As shown, the differences between SUMO and our ns-3 module are quite low, ranging from 7 to 119 Wh per vehicle. Although these differences are not significant, considering that one EV typically consumes around 12-15 kWh in 100 km, and 3 Wh in only a second travelling at 30 kilometers per hour, we made a thorough review to find the origin of these differences.

To make a fair comparison, we used the same mobility traces in the two simulation environments. More specifically, those traces were previously generated using SUMO, and were used to feed both the SUMO consumption model and our ns-3 module. However, we realized that while SUMO handles vehicle's speed as accurately as possible (i.e., using the double data type), it surprisingly generates output traces where the vehicles' speeds are represented only using two decimals. In addition, we found out that the mobility traces generated by SUMO do not represent the same time instants as those

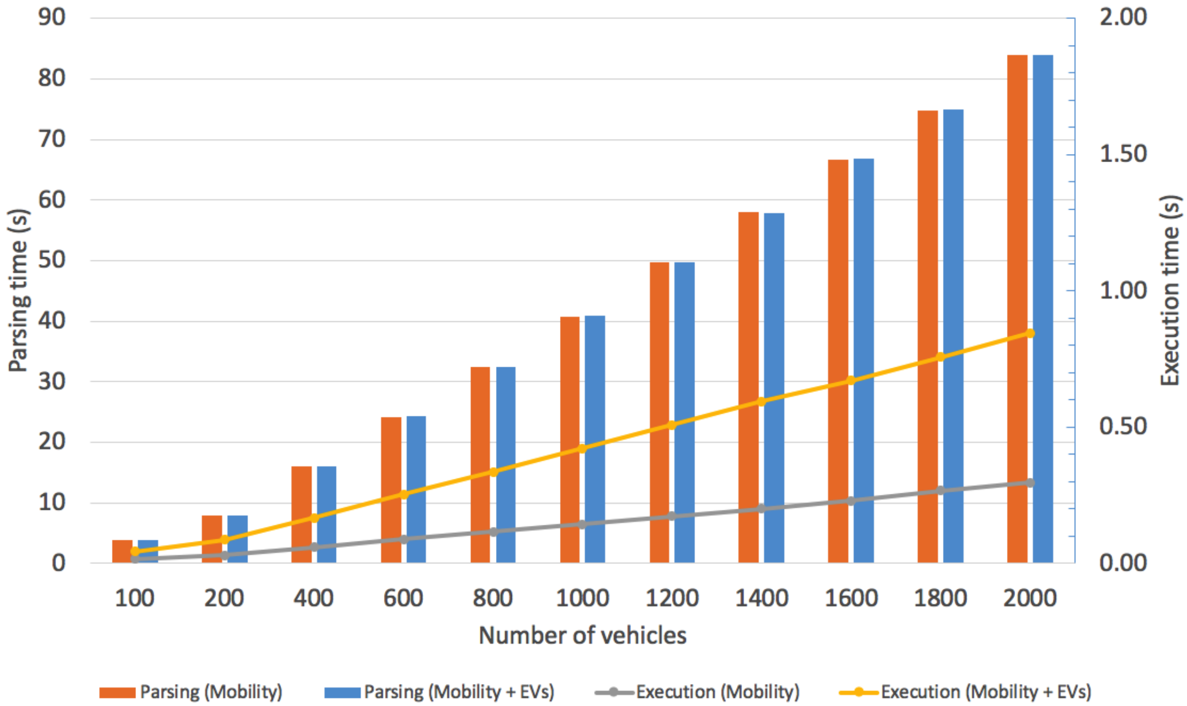


Fig. 4. Execution time depending on the number of vehicles and the modules used on the simulation.

TABLE II
ENERGY CONSUMPTION PER VEHICLE ESTIMATION WHEN SIMULATING IN SUMO AND NS-3 INCLUDING OUR MODULE DURING 240S

Simulation Time	Vehicles	Consumption SUMO (kWh)	Consumption ns-3 (kWh)	Diff. per vehicle
30s	24	0.145	0.137	0.007
60s	46	0.203	0.181	0.022
90s	66	0.273	0.236	0.036
120s	85	0.342	0.288	0.054
150s	104	0.404	0.334	0.070
180s	126	0.461	0.374	0.086
210s	144	0.530	0.425	0.104
240s	166	0.587	0.467	0.119

TABLE III
OVERHEAD OF THE NS-3 EV CONSUMPTION MODULE

	Mobility	Mobility + EVs	Difference
Number of vehicles	2,000		-
Parsing time (s.)	83.99	84.89	0.90
Execution time (s.)	0.30	0.84	0.55
Simulation time (s.)	84.28	85.74	1.45
% of parsing	99.65%	99.02%	-0.63%
% of execution	0.35%	0.98%	0.63%

used internally by SUMO for the calculation of consumption, resulting in different speeds which clearly affect the results obtained in terms of energy consumption. This is the cause of the slight differences between the results of the two simulation environments.

2) Performance Overhead: One key aspect to assess our consumption module is to calculate the impact of the new module on the overall performance of the ns-3 simulator in terms of both overhead and scalabity. To perform this, we measured the simulation execution time when varying the number of vehicles.

Note that we consider *simulation time* as the sum of the *parsing time* (i.e., the initial time required to read mobility and any other files needed) and the *execution time* (i.e., the time required to already run the simulation).

Table III presents the results obtained in terms of overhead when simulating 2,000 EVs. In particular, it shows that parsing input data is the most critical part in our simulations (i.e., using only the mobility aspects). By contrast, we observe that using both the mobility and our consumption module the overall simulation time only increases 1.45 seconds (+1,02%).

Finally, Figure 4 shows both parsing and execution times when varying the number of EVs (ranging from 100 to 2,000 vehicles). In addition, it also presents simulation times when our consumption module is used. Similarly to the data previously presented in Table III, it is observed that parsing times, when using only mobility or mobility + EVs module, are practically the same. Moreover, the differences in terms of execution time are also negligible (less than 0.6 seconds when simulating 2,000 vehicles). The figure also depicts how the simulator scales when highly increasing the number of vehicles simulated. More specifically, the ns-3 simulator provides a good scalability potential since it correctly handles the growing amount of vehicles simulated.

V. Conclusions

Transportation systems are constantly improving, and so simulation emerges as a suitable solution to allow researchers a quick and easy validation of their proposals, while reducing the amount of time and funds required, especially compared to the implementation of real testbeds. Moreover, EVs constitute a valuable alternative to traditional combustion-based vehicles since they offer many advantages, especially in terms of energy cost, pollutant emissions, maintenance, and efficiency.

In this work, we have enhanced the ns-3 simulator by adding the possibility of estimating the amount of energy that any EV would require according to its mobility and specific features (i.e., mass, battery capacity, etc.) with a significant reduced overhead, almost negligible. As future work, we plan to perform a comprehensive analysis which combines vehicular communications and EVs' mobility patterns using our ns-3 enhanced version. We consider that new approaches regarding the reduction of EVs' energy required will be possible by exploiting vehicular communications.

Acknowledgments

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