Available online at www.sciencedirect.com

ScienceDirect

Transportation Research Procedia 33 (2018) 35–42

Transportation Research Procedia

www.elsevier.com/locate/procedia

XIII Conference on Transport Engineering, CIT2018

Design and Validation of a Tool for Prognosis of the Energy Consumption and Performance in Electric Vehicles

Jorge Alonso del Valle[a], Juan Carlos Viera[a], David Anseán[a], Christian Brañas[b], Pablo Luque[c], Daniel Álvarez Mántaras[c], Yoana Fernández Pulido[a]

[a]University of Oviedo, Department of Electric, Electronic, Computers and Systems Engineering, Electronic Technology Area, Ed. Torres Quevedo (Departamental Oeste), bloque 2, Campus Universitario, 33204 Gijón, Spain

[b]University of Cantabria,Electronics Technology,Systems and Automation Engineering Department,Av.de los Castros s/n 39005 Santander,Spain

[c]University of Oviedo, Department of Construction and Manufacturing Engineering, Transport Engineering and Infrastructure Area, Ed. Torres Quevedo (Departamental Oeste), bloque 7, Campus Universitario, 33203 Gijón, Spain

Abstract

This work develops a software tool to calculate and predict the energy consumption of an electric vehicle (EV) for any desired route. The software tool is based on a mathematical model of an electric vehicle, which relates the energy consumption of the vehicle with factors such as the speed and the terrain slope. In addition, factors such as driving style, weather conditions and traffic congestion can be taken into account. The model has been validated with real data from an electric vehicle. On the other hand, this work proposes a methodology to use this tool with any other EV, as long as its basic characteristics are known.

The results obtained in this work are applied in automated testing systems, specific for EV storage systems at laboratory level. The main advantage lies in the use of more realistic power profiles than those commonly used and proposed in the specialized literature (e.g., FUDS). In addition, the proposed methodology can be applied to any EV, in different scenarios of orography, traffic, climatology, etc.

Keywords: Electric Vehicles; Batteries; Energy Consumption; Energy Efficiency; Energy Management

1. Introduction

The importance of the electric vehicle (EV) has notably grown in the last few years. Its development makes possible to reduce fossil fuels dependence and stimulates renewable energies penetration (Kempton, 2005; Chan,

2352-1465 © 2018 The Authors. Published by Elsevier Ltd.

10.1016/j.trpro.2018.10.073

2007). Batteries are, in most cases, the energetic basis for the electric vehicles and its evolution is increasing vehicles autonomy and energy efficiency.

The battery system has an important influence on the vehicle's performance. Because of that, it is important to have a good battery system, and to determine if a battery system has a good performance, it has to be properly tested. There are several test procedures which has been designed to test batteries for electric vehicles, such as the United States Council for Automotive Research (USABC) test procedures. The power cycle used on these procedures is a simplification of the FUDS driving cycle [3]. However, the energy consumption of an electric vehicle is affected by numerous factors, such as the vehicle weight, terrain slope, aerodynamics, and vehicle speed (Guzzella, 2013; Fiori, 2016). This means that an electric vehicle can be usually operated in a more demanding way than the FUDS cycle. For that reason, several organizations developed other driving cycles. Some of them, like the ARTEMIS cycles, are based on real driving cycles, which were measured among several European vehicles (André, 2004).

The problem with driving cycles is that all of them only resemble the specific conditions of the route and the driving style used on the test. Some of them may have higher terrain slopes, like the Vail2NREL cycle, while other may be on almost flat terrains. As well, some of them may have been done with more aggressive driving styles than others, in terms of speed and acceleration (Silvas, 2016). Terrain slope, vehicle speed and acceleration have a big impact on the energy consumption (Ehsani, 1997). However, if the routes that the vehicle is usually going to perform are known, it is possible to develop a specific driving cycle for these specific routes. This would be a way of testing the batteries with similar charge and discharge profiles than the ones which will really have.

In this paper, a model for generating EV battery test schedules for any desired route is proposed. With the developed model, it is possible to evaluate EV batteries in any route, with different traffic and weather conditions and with different driving styles. The developed model is based on data from a real electric vehicle; a Bombardier NV-2000 Sport-E, equipped with a full electric instrumentation in order to measure voltage and current on the batteries, as well as the vehicle speed and position, using a GPS. The developed model was used to design a methodology for evaluating every possible electric vehicle in any possible conditions. Besides that, the power profiles generated by the model were applied to batteries in laboratory conditions, and it was used to select the optimum battery for an electric vehicle, based on several tests that resembled local routes and different driving styles and traffic conditions. The proposed test schedule can be applied to single battery units, instead to a full battery pack, so it can drastically reduce the cost of electric vehicle battery testing, besides the accuracy improvement due to the use of real, specific, power profiles.

2. Methodology

2.1. Model Design

The designed model calculates the energy consumption of an electric vehicle. It is affected by several factors, which can be written as the different forces that the vehicle suffers. The forces are classified in passive and active forces.

a) Passive forces: Include the aerodynamic resistance (1), rolling resistance (2) and slope resistance (3):

$$F_{AER} = \frac{1}{2}\rho C_D A_F v^2 \tag{1}$$

$$F_{ROL} = mgf_R \tag{2}$$

$$F_{SLO} = mg\sin\theta \tag{3}$$

Table 1. Variables used in equations (1) to (9)

Variable	Meaning	Units
ρ	Air density	Kg/m^3
C_D	Drag coefficient	Dimensionless
A_F	Vehicle frontal area	m^2
v	Vehicle speed	m/s
m	Vehicle mass	Kg
g	Gravity acceleration	m/s^2
f_R	Rolling resistance coefficient	Dimensionless
θ	Road slope	Rad
γ	Rotative masses acceleration coefficient	Dimensionless
a	Vehicle acceleration	m/s^2
F_X	Force caused by X on the vehicle	N
P	Power extracted from battery system	W

b) Active forces: Only includes the vehicle acceleration (4):

$$F_{ACC} = \gamma m a \tag{4}$$

The power consumption (5) is calculated as product of the resultant force on the vehicle and its speed. As the resultant force on the vehicle is the sum of equations (1) to (4), the power consumption can be expressed as equation (5):

$$P = F \cdot v = (A + B \cdot v + C \cdot v^2 + D \cdot \sin\theta + E \cdot a) \cdot v \tag{5}$$

As expressed in (5), the electric vehicle's power consumption depends on its speed, acceleration, the terrain slope and five different constant parameters (A, B, C, D and E). These parameters are different for each electric vehicle, so, if they can be measured or identified, energy consumption can be calculated as the derivative of power consumption respecting time.

2.2. Electric Vehicle

The vehicle used for the model is a Bombardier NV-2000 Sport-E, which is shown in Fig. 1. It has a 4 kW electric motor supplied by a six lead-acid battery pack, which has a 72 V voltage. An additional 12 V battery is used for auxiliary systems, such as lights and radio.

The vehicle is equipped with an instrumentation system, which can measure several data from the batteries and the vehicle itself. The measured variables are the vehicle speed, the battery units' voltages, the electric current across them, the temperature of each battery and the vehicle position; this last one measured by a GPS. All the different variables are measured and logged with a Graphtec GL-800 data acquisition system, with a 10 Hz logging frequency.

2.3. Tests design and execution

The model has to be correctly parametrized in order to resemble the electric vehicle under test. This means that the different parameters from equation (5) have to be identified with data from the electric vehicle. In order to do that, several tests were designed; each of them is designed for identifying one or more parameters from equation (5).

Fig. 1. Bombardier NV-2000 Sport-E Electric Vehicle

a) Constant speed test: The vehicle is run at constant speed on a relatively flat surface. This means that slope and acceleration are zero, so equation (5) is reduced to equation (6). As the vehicle has two different speed limiters, one at 25 km/h and other at 40 km/h, several tests are run at both speeds. Power is calculated as product of the battery pack voltage and the current across it.

$$P = (A + B \cdot v + C \cdot v^2) \cdot v \tag{6}$$

b) Acceleration test: The vehicle starts the test stopped on a relatively flat surface. Then, the accelerator pedal is pressed and the vehicle has to accelerate until it reaches its top speed of 40 km/h. As acceleration cannot be maintained constant, this test has to be repeated several times, and the average acceleration is considered as a constant acceleration. Given that the slope is zero, equation (5) is reduced to equation (7). As parameters A, B and C were identified in the constant speed test, the acceleration test is used to identify parameter E.

$$P = (A + B \cdot v + C \cdot v^2 + E \cdot a) \cdot v \tag{7}$$

c) Slope test: The vehicle is run at constant speed through a road section with a notable slope. As acceleration is zero, equation (5) is reduced to equation (8). The test is repeated several times in order to reduce error. Slope is calculated with GPS data, considering the altitude difference between different road points. Therefore, parameter D is identified.

$$P = (A + B \cdot v + C \cdot v^2 + D \cdot \sin\theta) \cdot v \tag{8}$$

d) Braking test: Electric motors can be used as electric generators if an external torque is applied to them. This happens when the electric vehicle is braking. In order to study this phenomenon, a braking test was designed. Starting with the vehicle at a 40 km/h constant speed, the brake pedal is pressed until the vehicle is completely stopped. Analysing the data from the vehicle, it became clear that there was a linear relationship between the regenerative power and the vehicle speed. Therefore, the energetic behaviour under braking is modelled with equation (9) and parameters F and G are identified using data from the braking test.

$$P = F \cdot v + G \tag{9}$$

The proposed tests were carried out in the Viesques University Campus (Gijón), and the obtained results were used for identifying the seven parameters from the model.

3. Model Validation and Application

3.1. Model Validation

In order to validate the obtained model of the electric vehicle, several routes were made with the electric vehicle. Figure 2 shows one of the routes used for model validation. After performing these routes, the power consumption profile was calculated from the battery system data (voltage and current). The same routes were simulated using the model calculated in the previous chapter, which was programmed in a MatLab® script. Therefore, comparing the power consumption data between the real routes and the simulated routes, the model error was calculated.

Several different routes were used for validating the model. The parameters were optimized to minimize the error, resulting in an average error of a 2.59% when comparing the power consumption calculated with the model and the real power consumption from the electric vehicle.

3.2. Application for Electric Vehicle Battery testing

The obtained model for the electric vehicle was applied for generating battery test schedules, with similar power profiles to the real demand on the batteries. A methodology to be able to generate any desired test on any desired route and conditions was designed. The methodology is shown on Figure 3, and it is composed of the following steps:

1. Gather route points: The desired route has to be drawn on Google Earth® or on Google Maps® application, and exported as a KML file.
2. Add elevation data: This is done with the online tool GPS Visualizer
3. Load data into MatLab® application: Once the user has a KML file with elevation data, the designed MatLab® script can load it and calculate the power consumption profile under any driving style and weather conditions.

Fig. 2. Example of one of the routes used for validating the electric vehicle model

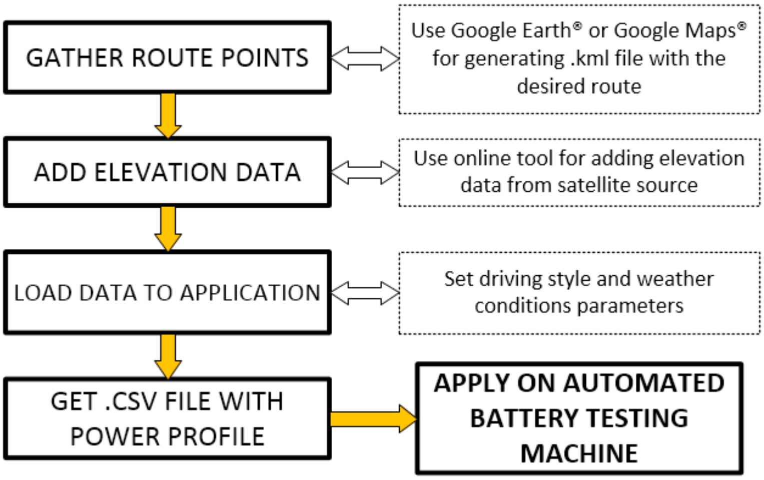

Fig. 3. Methodology for generating real power profiles for electric vehicle battery testing

The designed application generates a .csv file with the calculated power profile for the desired test route, vehicle and conditions. This file can be loaded in an automated battery testing equipment, so the generated power profiles can be applied to any battery in laboratory testing.

The model was applied for the evaluation of lead-acid batteries for the electric vehicle under testing. There were three potential battery models, which had to be evaluated to identify the model with the best performance for the electric vehicle application. In order to test the batteries, two different test schedules were generated with the designed application. One of the tests resembles an urban route across the streets of Gijón, with several stops and a low average speed. The other test resembles a rural route with high elevation changes and an aggressive driving style.

The designed test schedule consists on an initial full charge of the battery, followed by a rest period and the driving cycle itself. The routes are continuously repeated in a loop until the battery voltage drops below the limit determined by the manufacturer. Therefore, the indicator for the battery performance is the number of full laps completed by each battery model until they are completely discharged.

All the tests were carried out in a PEC SBT10050 battery testing machine, which is shown in Figure 4 (left), among the different battery models evaluated with the designed test schedule. The testing machine has 12 channels for secondary battery testing, with a limit of 100 V and 50 A per channel. In this application, four channels were used in parallel, which resulted in a limit of 200 A, as the results from the electric vehicle testing showed maximum current peaks between 150 and 200 A.

4. Results and Discussion

An example of the test schedule application is shown on Figure 4 (right). The battery voltage is represented in the blue line, and the battery power consumption is represented in the orange line. In this example, the battery completed nine laps to the urban circuit until it became fully discharged.

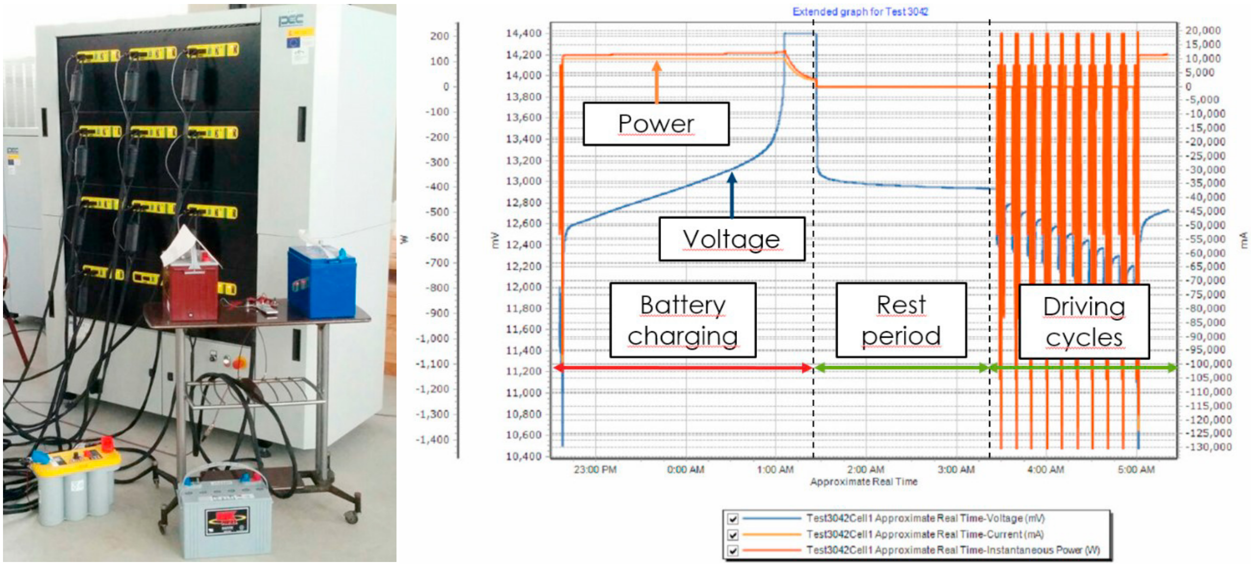

Fig. 4: On the left, PEC SBT10050 Battery testing machine on the left. On the right, Example of the test schedule application. The battery is initially charged, and then the model-generated power profile is applied until the battery voltage drops below the minimum allowed voltage; in this case, 10.4V

The test schedule was applied several times to each battery. Table 2 shows the average completed laps on each battery model on each route. It is important to remark that the different tested batteries have different capacities, so in theory the highest capacity battery should be able to complete the most amount of laps to each circuit. In practice, each battery model behaves differently on different applications.

Table 2. Tested battery models and completed laps on each route

Battery model	Capacity	Urban Circuit Laps	Rural Circuit Laps
Fullriver DCG79	79 Ah	19.5	<1
MK 8G27	88 Ah	20.5	3.5
Trojan 27-Gel	91 Ah	17.5	2.5

The results show some interesting facts, as the lowest-capacity battery, the Fullriver DCG79, completed more laps to the urban circuit than the highest-capacity battery. However, the Fullriver battery model could not complete a single lap on the more demanding rural circuit without having its voltage drop under the minimum allowable value. The highest capacity model, the Trojan 27-Gel, showed a poor behavior on the urban circuit, as it completed the least amount of laps among the tested models, although it was able to complete more than two laps on the rural circuit. It becomes clear that the MK 8G27 battery model had the best performance, as it completed the highest amount of laps both in the slow paced urban circuit and in the high demanding rural circuit.

5. Conclusion and Future works

A methodology for modelling the power consumption for an electric vehicle was proposed. The generated model is based on the identification of the parameters that relate energy consumption from the electric vehicle with its speed, acceleration and road slope. A real electric vehicle was modelled with the proposed methodology in order to validate it, resulting in an average error of less than 3% when comparing the real power profile with the one obtained with the vehicle model. The model was used for generating several power profiles that resemble specific routes and driving styles, and it was applied in laboratory testing for selecting the optimal battery for the electric vehicle. A test schedule was designed, based on the generated power profiles, in order to choose the best performing battery between three models, using two different routes with different energy demands. The results showed that the theorically best battery, based on capacity, had a poorer performance compared with the other models under test. The proposed methodology allowed the evaluation of electric vehicle batteries in laboratory conditions with power profiles that resembled real road testing, without the need of performing real routes and without the need of buying full battery systems, as the power profiles were scaled for testing single battery units.

Future works and improvements will include the application of the proposed methodology to lithium-ion batteries and the comparison between different battery technologies. The model will be improved with the inclusion of pedal sensors in the vehicle, in order to improve the fidelity of driving styles to real drivers. As the electric vehicle had a low top speed, cornering was not taken into account, so further improvement will be made with the consideration of maximum corner speeds for faster electric vehicles.

6. Acknowledgements

This work was supported by the Science of Innovation Spanish Ministry and FEDER funds under the Project TEC2016-80700-R (AEI/FEDER, UE), by the Principality of Asturias Government under project FC-15-GRUPIN14-073 and the University Institute of Industrial Technology of Asturias (IUTA) under project SV-15-GIJON-1.13.

7. References

[1] C.C.CHAN; *The State of the Art of Electric, Hybrid and Fuel Cell Vehicles; Proceedings of the IEEE*, vol. 95, no. 4, pp. 704-718, April 2007

[2] KEMPTON, W.; TOMIC, J.; *Vehicle-to-grid power implementation: From stabilizing the grid to supporting large-scale renewable energy; Journal of Power Sources*, vol. 144, pp. 280-294, June 2005

[3] United States Council for Automotive Research Manuals for Battery testing; Online, Available: http://www.uscar.org/guest/article_view.php?articles_id=86

[4] GUZZELLA, L.; SCIARRETTA, A.; *Vehicle Propulsion Systems: Introduction to Modelling and Optimization*, pp. 21-23

[5] FIORI, C.; AHN, K.; RAKHA, H.; *Power-based electric vehicle energy consumption model: Model development and validation; Applied Energy*, vol. 168, pp. 257-268, April 2016

[6] ANDRÉ. M.; *Real-world driving cycles for measuring cars pollutant emissions – Part A: The ARTEMIS European Driving Cycles, Report INRETS-LTE 0411*, June 2004

[7] SILVAS, E. et. Al.; *Synthesis of Realistic Driving Cycles With High Accuracy and Computational Speed, Including Slope Information, IEEE Transactions on Vehicular Technology*, vol. 65, pp. 4118-4128, June 2016

[8] EHSANI, M.; RAHMAN, K.; TOLIYAT, H.; *Propulsion System Design of Electric and Hybrid Vehicles; IEEE Transactions on Industrial Electronics*, vol. 44, pp. 19-27, February 1997