

Experimental Test Campaign on a Battery Electric Vehicle: On-Road Test Results (Part 2)

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ABSTRACT

The experimental measurement of the energy consumption and efficiency of Battery Electric Vehicles (BEVs) are key topics to determine their usability and performance in real-world conditions. This paper aims to present the results of a test campaign carried out on a BEV, representative of the most common technology available today on the market. The vehicle is a 5-seat car, equipped with an 80 kW synchronous electric motor powered by a 24 kWh Li-Ion battery. The description and discussion of the experimental results is split into 2 parts: Part 1 focuses on laboratory tests, whereas Part 2 focuses on the on-road tests.

As far as on-road tests are concerned, the vehicle has been tested over three different on-road routes, ranging from 60 to 90 km each, with a driving time ranging from approximately one and half to two and half hours. The routes have been designed to include different pathways (i.e. city driving, rural roads and highway), different vehicle speeds and road slopes that could be encountered in real-world driving. The influence of the driving modes of the vehicle (i.e. normal versus economic driving mode (ECO) drive) on the energy consumption and range has been also addressed. The results show that the energy consumption of the vehicle ranges from 111 to 148 Wh/km (i.e. equivalent gasoline consumption from 1.2 to 1.7 l/100km) in normal driving mode, depending on the route. The ECO driving mode shows lower energy consumption compared to the normal driving mode, with higher energy recuperation from regenerative braking. The driving range calculated with an abbreviated test approach goes from 139 to 185 km in normal driving mode, and up to 188 km for the ECO mode.

The paper provides the reader with a detailed description of the measurement equipment and setup adopted during the tests, setting the background for future technical analyses and experimental campaigns.

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INTRODUCTION

Determining the energy consumption and efficiency of Battery Electric Vehicles (BEVs) under different driving conditions is a key topic to understand the potential benefits of this technology in replacing conventional fuel vehicles. Although the conventional fuel vehicles have substantially increased their efficiency over the last decade [1], in order to reduce the dependency on oil and as well as pollutants and Greenhouse Gases (GHGs) emissions [2, 3], new low-carbon vehicles technologies (i.e. Hybrid Electric Vehicles, (HEVs), and BEVs) are constantly expanding their market shares.

HEVs technology basically aims to complement the combustion engine technology by means of energy recuperation and boosting and/or an alternative propulsion system based on an electric motor. In

particular, the energy recuperation system recovers part of the kinetic energy which the vehicle dissipates during braking and deceleration driving phases. This energy is typically stored in a battery and then used to boost the vehicle during the accelerations and/or provide a short full-electric driving range to the vehicle. HEVs are typically equipped with a small sized battery and a small-to-medium sized electric motor, designed to support and/or replace combustion engine torque, especially at low rotational speeds, where the combustion engine is characterized by low fuel efficiency. Such technology can be arranged in many different configurations (i.e. micro, mild and full hybrid) according to the battery capacity and costs, the drivetrain architecture (i.e. serial/parallel/through-the-road hybrids) and the relative power of the electric motor with respect to the combustion engine installed (i.e. Degree of Hybridization, DoH). Although HEVs

technology enables to increase the overall efficiency of the vehicle, constituting a valuable technological step forward with respect to conventional fuel vehicles, this increase is not always linked to a decrease of gaseous emissions, as shown by the authors [4].

On the other hand BEVs constitute a paradigm shift compared to conventional fuel vehicles, although their popularity is still limited by their high purchase cost (mainly due to the cost of the battery) and the doubts of the consumers on their effective driving range and usability. Beyond these limitations, previous studies from the authors suggest that the relatively short range of the current generation of BEVs is not a strict limitation, and approximately one-fourth of the urban cars could be shifted from conventional fuel vehicles to BEVs [5] without any negative impact due to the shorter range. This share increases to approximately half of the fleet by accepting a very limited modal-shift [6]. These studies are based on a large-scale activity datasets acquired on conventional fuel vehicles from private citizens, and highlight that the actual potential of BEVs might go far beyond the common expectations. However they rely on the fine-tuning of the numerical models and, therefore, on an accurate experimental estimate of BEVs' energy consumption in real driving conditions.

The objective of this study is to provide the scientific community with the results of a test campaign carried out on a BEV. This vehicle is representative of the most common BEVs technology available on the market today. The tests have been carried out in the laboratories of the Joint Research Centre of the European Commission (JRC), in collaboration with the Italian National Agency for new Technologies, Energy and Sustainable Economic Development (ENEA). The test campaign is carried out in the frame of the pre-normative research activities of the JRC in support of the development of the type approval regulation, and consists of two parts: Laboratory Tests (i.e. Part 1) and On-road Tests (i.e. Part 2).

The laboratory tests are targeted to determine the energy consumption, energy efficiency and driving range over different driving cycles (i.e. NEDC [7, 8, 9, 10], WLTC, WMTC [11] and MAC [12]) and ambient conditions. Ambient temperatures of +25 °C and -7 °C are considered, as prescribed by the current type approval test procedures for passenger cars, and the tests are carried out with and without the Heating, Ventilation and Air-Conditioning (HVAC) system in operation (in cooling and heating mode), [13].

The on-road tests have the objective of determining the same parameters (i.e. energy consumption and range) over three different real-driving routes, ranging from 60 to 90 km each, with a driving time ranging approximately from one and half to two and half hours. The routes have been designed to include different pathways (i.e. city driving, rural driving and highway), and are partially based on the criteria established for the on-road emissions tests for conventional fuel vehicles with Portable Emissions Measurement System (PEMS), [14]. These include the full range of driving speeds which might be encountered in real-world driving, the effect of road slope and altitude variation, as well as the effect of the different driving modes (i.e. normal drive and ECO drive). The shares of the driving time during which the acceleration pedal position is above or equal to 40%, and of the share of driving distance during which the vehicle

speed is above or equal 50 km/h, have been used to monitor the driving style aggressiveness, as per [15] and [16], setting the basis for future studies to define eco-driving rules and eco-indices, or correlating HEVs gaseous emissions to the driving style, [17, 18].

In order to measure the energy consumption, the vehicle has been instrumented with a data logger capable to monitor in real-time the energy flows from and to the different vehicle's sub-systems. A detailed description of this measurement system and its configuration layout is also provided.

These two parts of the test campaign allow a direct comparison of the results, in order to obtain a comprehensive overview of the energy consumption and driving range in type approval and real-driving test conditions for the tested vehicle. This will contribute to the correlation between type approval duty cycles and real-world driving cycles as well as to the evaluation of the impact of auxiliary systems on the driving energy consumption not prescribed by the current regulation.

EXPERIMENTAL SET-UP

Test Vehicle and Measurement Points

The BEV adopted for this study is a 5-seat car, with an empty weight of 1520 kg and powered with a 80 kW / 280 N·m synchronous electric motor in front-wheel driving configuration. The vehicle is equipped with a 96-cells Lithium-Ion battery, accounting for a 24 kWh nominal capacity and approximately 360 V nominal voltage. The vehicle's main characteristics are summarized in Table 1, while its schematic representation is provided in Figure 1. With reference to this figure the vehicle's main sub-systems are:

- Charger unit and AC/DC converter: it converts the 3.3/6.6 kW Alternating Current (AC) from the grid to Direct Current (DC) for the high-voltage battery. The current from the DC charging flows directly into the high-voltage battery;
- High-voltage battery: it is the main energy storage device of the vehicle;
- Inverter unit: it converts DC from the high-voltage battery to 3-phases AC for the Electric Motor (i.e. EM);
- DC/DC converter: it converts the DC from the high-voltage battery to low-voltage DC for the auxiliary systems (i.e. air-conditioning and cabin ventilation system, lights, wipers, etc.);
- Heater: a 5 kW DC resistance to heat-up the cabin, directly connected to the high-voltage battery.

Table 1. Test vehicle characteristics.

Architecture	BEV
Propulsion	Synchronous electric motor
Max. Power [kW]	80
Max. Torque [N·m]	280
Mass [kg]	1520
Battery	24 kWh – 96 Li-Ion cells 360 V (nominal voltage)



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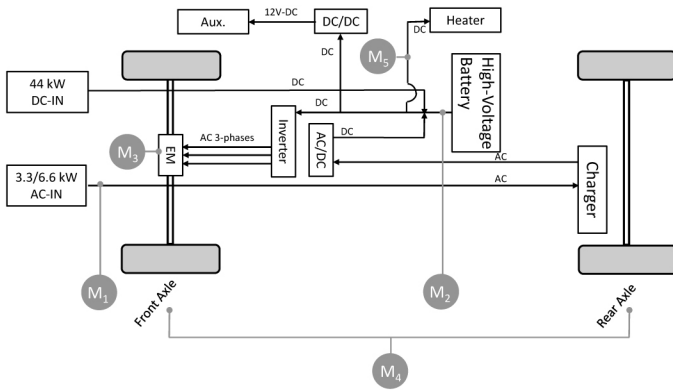


Figure 1. BEV schematic representation and measurement points (see Table 2).

Please note that the cooling system of the cabin is loaded on the low-voltage auxiliaries (i.e. downstream with respect to the DC/DC), whereas the heating system is directly loaded on the high-voltage battery.

All the sub-systems are inter-connected by several power lines. The schematic representation of Figure 1 reports the main power-line, each depicted with an arrow; single arrows refer to the mono-phase AC power lines (AC label), the low-voltage DC power lines (DC-12V label), and the high-voltage DC power lines (DC label). The three parallel arrows refer instead to the 3-phases AC power line (AC 3-phases label). The vehicle is also equipped with a 44 kW DC fast charging line. Gray circles in Figure 1 represent the measurement points on the vehicle used to monitor the energy flows, and used for the analyses reported in this article. A detailed description of these measurement points is provided in Table 2.

Table 2. Measurement points summary (see Figure 1).

Measurement point label	Description
M ₁	Energy from the grid to the high-voltage battery [Wh]; (acquired directly on the recharging station)
M ₂	Current [A] and Voltage [V], from the high-voltage battery feeding the inverter, the low-voltage auxiliary systems and the heating system → energy outflow from the battery to all subsystems [Wh]; (acquired both by CANbus and current clamp. Note that it can be also calculated by SOC scaling)
M ₃	Rotational speed [rpm] and torque [N·m] of the electric motor → mechanical energy of the electric motor [Wh]; (acquired by CANbus)
M ₄	Energy at the wheel [Wh]; (calculated by (1)).
M ₅	Current [A] and Voltage [V], from the high-voltage battery to the heater → energy from the battery to the cabin heating system [Wh]; (acquired by current clamp)

The measurement at the stage M₁ is acquired directly on the 3.3/6.6 kW AC recharging station, by monitoring the electric energy required to recharge the battery. The measurement at the stages M₂ is acquired in double mode, i.e. via the vehicle CANbus and via a current clamp directly mounted on the battery output power-line. Additionally the energy outflow from the battery (i.e. M₂) can be also calculated by considering the SOC variation, scaled on the nominal capacity of the battery. The measurement at the stage M₃ is acquired only via

CANbus, whereas the measurement at the stage M₅ is acquired only via current clamp. The energy at the wheel (i.e. stage M₄) is calculated by (1), according to the parameters reported in Table 3.

Table 3. Parameters to calculate the energy consumption at the wheel (i.e. measurement point M₄), according to (1).

Parameters	Description	Value
m _v	Vehicle mass:	
	- Laboratory tests: = curb weight + driver (75 kg).	1595 [kg]
	- On-road tests: = curb weight + driver (75 kg) + one passenger (70 kg) + equipment (5 kg).	1670 [kg]
g	Gravity acceleration.	9.81 [m/sec ²]
μ	Road friction coefficient.	0.0127 (non-dim.)
ρ	Air density.	1.18 [kg/m ³]
c _x	Vehicle drag coefficient.	0.28 (non-dim.)
A	Vehicle front surface area.	2.27 [m ²]
α	Road slope angle.	Variable, [rad]
v _{wind}	Wind speed velocity	[m/sec]
sign	Sign function, it determines the sign of the algebraic sum (v + v _{wind})	(non-dim.)

$$E_{wheel} = \int_{t_{in}}^{t_{fin}} m_v a t + m_v \cdot g \cdot \sin \alpha t + \mu \cdot m_v \cdot g \cdot \cos \alpha t + \text{sign}(v(t) + v_{wind}(t)) \frac{\rho}{2} c_x A (v(t) + v_{wind}(t))^2 \cdot v(t) dt \quad (1)$$

These parameters have been kept constant, regardless the change of the environmental conditions, such as ambient temperature, humidity and atmospheric pressure (e.g. variations due to the altitude during the on-road tests).

Please note that application of the formula (1) is particularly difficult for on-road tests, because of the inaccuracies in the real time measurement of the road slope angle α, the wind speed and the wind direction during the test. In particular the road slope angle has been derived from the altitude maps of the on-road routes, given the vehicle instantaneous position by GPS records, according to [19]. These values have been also integrated with GPS altitude measurements appropriately smoothed and processed, and a sensitivity technique analysis has been carried out to assess the effect of this smoothing on the derived road slope angle. The wind speed and direction during the on-road driving have been instead measured by an ultrasonic sensor (see *Measurement Equipment* section) and the recorded values have been submitted to a smoothing process too. Also the of the road friction coefficient was particularly difficult to quantify for the on-road tests, due to the changes in the road surface (i.e. inhomogeneous asphalt) and tire dynamic. Equations from the literature related to the wheel dynamic have been applied to perform a sensitivity study of these effects; however this represents only a simplified attempt to address these issues and dedicated future study are needed to improve the results to derive on-road efficiency.

The tested vehicle is three years old (i.e. registered in 2011 and tested in 2014), with a total mileage of approximately 5,000 kilometres. Therefore it is likely that its battery performance is slightly degraded by aging compared to a brand new vehicle. For example we noticed during our tests that the State-of-Charge (SOC) indicator at a CANbus level did not allow recharging above a variable threshold between 86% and 90% (upper bound) and discharging below 3% (lower bound). This has been also confirmed by battery energy-in measurements in M_2 (i.e. via vehicle CANbus) during overnight full recharge tests, which allowed an average value of recharge energy equal to 20.5 kWh (i.e. 85% of the nominal energy capacity). For this reason we have decided to use this value to scale the driving range test results, later referred as battery usable SOC.

Measurement Equipment

The measurement equipment installed on the vehicle consists of a data logger based on a modular chassis with 8 configurable slots (Figure 2, from label 4 to 11). Its operative temperature ranges from -40 to $+70$ °C, it is dust-proof and shock resistant, designed to be powered with 9-30 volts DC (i.e. Power-in label 1 in Figure 2) to be mounted on-board of the tested vehicle. It embeds a dual-core CPU plus a configurable FPGA chip. The data can be either stored on the embedded 1 GB non-volatile flash memory (expandable via USB-port) or downloaded via the Ethernet port (i.e. Output-port, label 2 in Figure 2). This port can be also used to configure the modules for live telemetry.

The structure of the data logger is:

- GPS, label 3 in Figure 2: serial port for GPS-receiver, it works with NMEA standard sentences, providing the system with: dynamic update of absolute UTM timestamp, absolute geographical position, vehicle speed related to ground, vehicle course related to North, signal quality and number of satellites.
- Power (V-in), labels 4 and 6 in Figure 2: two groups of 3 channels each with voltage input for single or three-phases power measurements. Voltage input up to 300 V rms, 24 bits, differential, simultaneous sampling, integrated anti-alias filters, 50 k-samples/second per channel, (i.e. bandwidth at 24.6 kHz).
- Power (I-in), labels 5 and 7 in Figure 2: two groups of 4 channels each with current input for single or three-phases power measurements. Current input up to 1600 A rms (with 1600:5 transformer), 24 bits, differential, simultaneous sampling, integrated anti-alias filters, 50 k-samples/second per channel, (i.e. bandwidth at 24.6 kHz).
- Analog-in, label 8 in Figure 2: 16 channels for analogic inputs at the voltage of ± 10 V, 16 bits, differential, 250 k-samples/second multiplexed.
- Thermocouples, label 9 in Figure 2: 16 channels, 24 bits, integrated with a Cold Junction Compensation (CJC), supporting thermocouples of types J, K, T, E, N, B, R, S.

- Frequency-in, label 10 in Figure 2: 8 channels for frequency-dependent digital acquisition plus 32 channels for logical states. Switching speed at 7 μ -seconds, inputs voltage up to 24 V.
- CANbus-in label 11 in Figure 2: 2 independent CAN High Speed ports at 11 bits and 29 bits messages IDs, baud rate up to 1 Mbps, interfaced with the Electronic Control Unit (ECU) for both standard (i.e. DBC, OBD, FMS) and non-standard (i.e. editable) protocols.

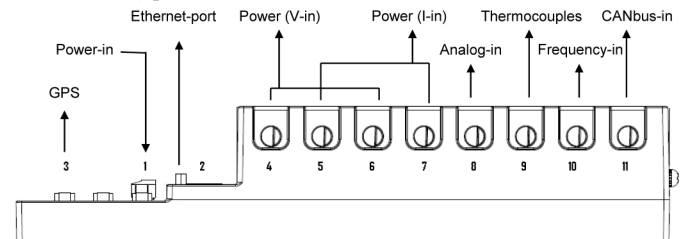


Figure 2. Schematic representation of the measurement system.

The data logger modules are based on standard components from [20] and assembled with a customized software interface from [21]. This interface is capable to perform live-data visualization, data synchronisation and remote storage as well as control the configuration of the system. The system has been configured for the present test campaign according to the measurement points described in Table 2.

The modules 4 to 7 have been used for the inverter acquisition, (i.e. 3-phases voltages and currents acquired by means of current transformer); the module 6 for the recording of the AC recharging pilot signal [22,23]; the module 8 has been used for DC acquisition, (i.e. from and to the high-voltage battery and heater system acquired by means of current clamps based on Hall effect) plus ambient data acquisition from a sensors array mounted on the vehicle's roof. This array implements ambient temperature, pressure and relative humidity sensors, plus wind speed and wind direction ultrasonic sensors. Module 9 has been used for cabin thermal acquisition, according to the specifications described in the European MAC draft test procedure [12], while module 11 has been used for CANbus acquisition, integrated with a GPS antenna mounted on port 3. Please note that 3-phases voltages and currents measured at the inverter have not been used for deriving the results presented in this work.

On-Road Routes

Three on-road driving routes have been used in this study. They have been designed to include different pathways (i.e. city driving, extra-urban driving and highway), the full range of vehicle speeds which might be encountered in real-world driving, and different road conditions (i.e. uphill, downhill, flat terrain). The selected routes are partially based on the criteria established for on-road emissions tests for conventional fuel vehicles with Portable Emissions Measurement System (PEMS) [14].

The routes have been labeled Route 1, Route 2 and Route 3 and their details are reported in [Appendix](#), in [Figure 5-\(a\)](#), [\(b\)](#) and [\(c\)](#) respectively. All routes begin and end at the Vehicle Emission Laboratories (VELA) of the Joint Research Centre of the European CoMission in Ispra (Italy), at the GPS latitude of 45.809870 deg north and GPS longitude of 8.628956 deg east from Greenwich (i.e. checkered flag in the GPS-traces figures). Each route has been repeated three times: twice in the normal driving mode and once in the ECO driving mode.

[Route 1](#) is representative of an uphill and downhill extra-urban driving, characterized by a significant altitude variation (i.e. from approximately 220 to approximately 1150 meters above the sea level), and low driving speed (i.e. approximately 50 km/h). The route has been split into two phases: phase 1 (30.32 km, lasting for approximately 50 minutes) representative of the uphill part, and phase 2 (31.46 km, lasting for approximately 50 minutes) representative of the downhill part. These two phases are very different, and they have been designed to identify the different working modes of the electric motor, i.e. driving mode uphill and regenerative mode downhill.

[Route 2](#) is representative of a mixed extra-urban and city driving. It has been split in two phases too, i.e. phase 1 (31.15 km, lasting for approximately 40 minutes) and phase 2 (32.91 km, lasting for approximately 60 minutes). Phase 1 is characterized by extra-urban driving (i.e. non congested roads with a driving speed between 50 and 70 km/h), whereas phase 2 is characterized by a short high-speed extra-urban road (i.e. driving speed peaked at 90 km/h), followed by approximately 15 minutes of city driving (i.e. driving speed below 50 km/h) and 40 minutes of extra-urban driving (i.e. driving speed between 50 and 70 km/h). Altitude varies between 220 meters (starting point) and 450 meters (city driving) above the sea level.

[Route 3](#) is instead representative of mixed conditions: extra-urban driving, city driving and highway, split into 4 phases. The route has been designed to have approximately 1/3 of urban, 1/3 of extra-urban and 1/3 of highway path. Phase 1 (21.71 km, lasting for approximately 30 minutes) is characterized by extra-urban driving (i.e. non congested roads with a driving speed between 50 and 70 km/h). Phase 2 is characterized by three repetitions of an 8.40 km urban driving cycle, accounting for 25.2 km and approximately 80 minutes. This part takes place over congested city roads, with several traffic lights and a driving speed below 50 km/h. Phase 3 is characterized by a highway path, lasting for 34.21 km and 20 minutes, with a driving speed between 80 and 130 km/h, while phase 4 is again an extra-urban driving as per phase 1 (7.89 km lasting for approximately 15 minutes). As per [route 2](#), the altitude varies between 220 meters (starting point) and 400 meters (city driving) above the sea level.

RESULTS

Energy Consumption Results

[Table 4](#), [Table 5](#) and [Table 6](#) presents the results of the road tests, for [Route 1](#), [Route 2](#) and [Route 3](#) respectively. Three tests have been performed for each route: two repetitions in normal driving mode (i.e. Normal 1st and 2nd, first two lines in each cell) and one repetition in ECO driving mode (ECO, third line in each cell, italic). According to the technical specification of the tested vehicle, the ECO mode imposes a partial cut-off of the power of the electric motor, in order to save energy.

All the on-road tests have been performed with the HVAC system switched-off, whereas the auxiliary systems imposed by law to drive on public roads (i.e. front lights and turn signals) have been used during the driving.

The tables report for each test a summary of the ambient conditions (i.e. ambient temperature and weather at the route starting point), while the time-dependent atmospheric pressure, ambient temperature and humidity and the battery 96-cells temperature range (acquired by the vehicle CANbus) are reported in [appendix](#), from [Figure 6](#), [7](#), [Figure 8](#). It can be noticed that the battery cells temperature during these tests never goes higher than +36 °C. However, it depends on ambient temperature and driving load (e.g. it increases during the uphill part of [Route 1](#) and highway part of [Route 3](#)).

The tables also summarize the length in km of the driving route and the main characteristic of its phases speed profile (i.e. uphill, downhill, urban, extra-urban, highway driving), as given above, together with the overall altitude variation, to evaluate its effect on the energy consumption.

For each route the table reports the energy consumption results calculated at the battery level (i.e. without considering the efficiency loss of the recharge) by the current and voltage at the battery outlet from the CANbus (i.e. M_2 according to [Table 2](#)), as per the laboratory tests. These values are given in Wh/km per route phase, as defined above, and combined for the entire route, per each test condition, i.e., normal driving 1st and 2nd, and ECO mode.

The distance specific energy consumption values have been converted to equivalent liters of gasoline per 100 km (i.e. liters/100km, see values in parenthesis), by applying the conversion suggested by the Environmental Protection Agency (EPA, [24]) as per (2). The energy content of the gasoline fuel has been assumed equal to 8.90 kWh/liter (i.e. 115 kbtu/gallon).

$$\text{Consumption} \frac{l}{100km} = \text{Consumption} \frac{Wh}{km} \cdot \frac{0.1123}{10} \quad (2)$$

The results show that the distance specific energy consumption significantly depends on the characteristics of the driving route (i.e. driving speed and slope profile). The values range from 111-130 Wh/km for [Route 1](#) and [2](#) (combined results in normal driving mode), characterized by uphill/downhill phases and extra-urban driving, up to 148 Wh/km for [Route 3](#), characterized by highway driving.