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Usable battery energy measurement on road on an aged mid-size battery electric vehicle

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Executive Summary

This work presents the results of an on-road test campaign on an aged mid-size battery electric vehicle. After a full charge, the vehicle has been completely discharged by driving on the road, with different routes (combining speeds and road slopes), and payloads, until the vehicle cut off the driving power or a safe low level of state of charge acquired from the CAN bus was reached. The resulting driving range and discharged battery energy were measured. The same vehicle has been tested in the laboratory in previous test campaigns, by driving on a chassis dynamometer at a constant speed or with standardised conditions according to the WLTP test procedure but also discharged with a vehicle-to-grid enabled station. Considerations on the influence of environmental and route conditions on the usable battery energy during the on-road test are made comparing the results of the different test campaign.

1 Introduction

The transport sector is a major contributor to greenhouse gas emissions and global warming, with the highest reliance on fossil fuels of any sector worldwide, accounting for 37% of CO_2 emissions from end-use sectors [1].

The JRC supports the harmonisation of vehicle testing regulations by contributing to the technical discussions within the United Nations Economic Commission for Europe (UNECE) informal working groups (IWG) of the Working Party on Pollution and Energy (GRPE), a subsidiary body of the World Forum for Harmonization of Vehicle Regulations (WP.29) [2].

Among the UNECE IWGs, the Electric Vehicles and the Environment (EVE) IWG in which the JRC has been actively involved for years, has recently developed the new Global Technical Regulation (GTR) No. 22 on battery ageing in electrified vehicles, setting minimum performance requirements for in-vehicle battery durability for electrified light duty vehicles (LDVs) [3]. According to GTR No. 22, monitors of the battery state of certified energy (SOCE) and range (SOCR) will be available in every production vehicle, the accuracy of which will be tested statistically by applying an in-use verification procedure (Part A). Once the monitors' accuracy is checked, the battery durability performances are controlled in Part B against the prescribed minimum performance requirements (MPRs) by a fleet monitoring procedure.

During the Part A of the GTR No. 22 the accuracy of the SOCE monitor is verified for a number of statistically sampled vehicles by comparing the displayed monitor value to the SOCE measured during a test. The SOCE measured is calculated as a ratio between the measured UBE of the sampled aged vehicle and its certified UBE. If the measured SOCE and the SOCE from the monitor are statistically sufficiently close according to the statistical parameters prescribed in GTR No.22, the accuracy of the SOCE monitor is confirmed.

The EVE IWG has been working on the extension of the GTR No. 22 to HDVs, keeping the same concept and structure as described above for the LDVs. The proposal for a new UN GTR was voted in the 92th session of GRPE in March 2025.

Heavy duty vehicles (HDVs) make up a relatively small proportion of vehicle fleets in many countries, but they produce a disproportionate amount of emissions that have a negative impact on the climate and pose risks to human health. The global HDV fleet is projected to contribute more greenhouse gas emissions than the light-duty vehicle (LDV) fleet by 2025. Zero-emission vehicle (ZEV) technology for HDVs has the potential to significantly reduce negative impacts on climate and air quality [4]. In the European Union, Battery Electric Vehicles (BEVs) accounted for a 43% share of city bus sales in 2023, indicating significant progress towards the proposed target of 100% of city bus sales being zero-emission vehicles by 2035 [5]. Electric truck sales are also expected to continue to increase thanks to strong and ambitious policies, such as the European Union's CO_2 standards for HDVs, which target 90% CO_2 emissions reduction by 2040 [6].

Unlike LDVs, the type approval and determination of energy consumption of heavy duty vehicles (HDV) takes place at component level: the engine and the different vehicle components are tested separately on test benches. Depending on the region of regulations, software has been developed, such as “Vehicle Energy Consumption Calculation Tool” (VECTO) [7] in Europe and Greenhouse Gas Emissions Model (GEM) [8] in the USA, to calculate the energy consumption values for of the whole vehicle depending on its configuration.

The main challenges during the development of the GTR for electrified HDVs were related to the lack in international regulations of a clear operational definition and test procedure for determining the UBE for such vehicles to be used in Part A to verify the accuracy of the SOCE monitor. Due to the complexity and vastness of the electrified HDV vehicle fleet, the EVE IWG defined four different test options to fully discharge the vehicle’s battery, after pre-conditioning and recharging to determine the UBE:

- driving on a track
- driving on an open road
- using a bidirectional power supply
- driving a test cycle on a chassis dynamometer.

The EVE IWG extensively analysed the pros and cons of each test methodology, and the boundary conditions to define the UBE value. Regardless of the type of discharge test the vehicle should provide the same measured energy, so all the test procedures should result in the same measured usable energy of the battery. In practice, however, the definition of the UBE is operational, so it is very important to best define the environmental and working condition of the battery prior to the test, the recharge procedure, the fully charged state as well as the fully discharged state at the end of the test, called break-off criterion to guarantee repeatability in the results of the test procedure. In addition, the battery is monitored and protected by the battery management system (BMS) during its entire life.

Applying a discharge cycle on a chassis dynamometer following a driving trace in controlled environmental conditions is the practice for LDV type approval. The HDVs dyno test equipment is rare and expensive, so the laboratory test method was not selected as the only possible testing procedure. Discharging the vehicle and delivering electricity to the grid by means of a bidirectional power supply can be another way to limit the uncertainty factors, despite some errors are introduced by not-driving the vehicle, but not all vehicles are currently technically equipped with this technology that enables to discharge through the plug. Therefore, in the EVE IWG it was defined to also leave the possibility of measuring the UBE of electrified HDV vehicles while driving either on a track or on the road.

To support this specific discussion on the development of a test procedure for the HDV UBE determination with an on-road test measurement, a test campaign was organised on an electric vehicle. It was decided to use a passenger car to rely on previous work of the authors, where the same vehicle has been extensively tested and characterised, also applying the GTR 22 for passenger cars [9].

The previous work of the authors presented the outcomes of a test campaign conducted in December 2021 at the European Commission Joint Research Centre (JRC) VEhicle Laboratory (VELA) on an aged mid-sized battery electric vehicle (BEV) used at the JRC as service vehicle. This vehicle was tested on a chassis dynamometer test cell, using the Worldwide harmonized Light vehicles Test Procedure (WLTP) [10, 11] applicable test cycle to determine its State of Health (SoH). The Part A of the GTR No. 22 was applied comparing these measured results with the SoH data obtained from the vehicle's Controller Area Network (CAN). The collected data represent a comprehensive characterization of the vehicle and its aging according to standardized procedures.

In August 2023 and May 2024, the test campaign was repeated to characterize the vehicle's aging, and alternative test procedures were also tested to understand if the test procedure has an influence on the determination of the UBE.

The on-road test campaign described in this work was organized specifically referring to the HDV proposed test procedure, to experiment, on a known vehicle, if the total measured energy from the battery from full to empty state of charge is different from the one recorded in lab normed tests, and additionally if it is influenced by the environmental conditions, driving style, road grading or payload encountered from the vehicle while driving on-road. The vehicle and the battery were conditioned and the battery temperature was controlled during the test to avoid extreme events.

The vehicle was tested with full discharges on the road, with three routes of length similar to the vehicle's full driving range. The discharge was finished within the JRC premises until the vehicle’s power was cut and a warning tell-tale appeared on the dashboard or up to when a safe low SoC close to zero was reached. Three different routes were used to investigate the effect of driving power, one predominantly urban and rural, one highway, and one containing a long uphill road. To estimate the effect of a payload, the same routes were repeated with an additional 160 kg of payload in the trunk.

The test results are compared to laboratory tests, where the UBE is measured in a stable and controlled environment in particular for the driving power request. The laboratory tests were performed in 2023 both applying the WLTP and by driving constant speed. In constant speed tests, the vehicle was discharged in a controlled environment at 23°C, by driving on a chassis dynamometer, using the cruise control option and by setting the dyno in “constant force mode”. This allowed to easily set a constant driving power without performing the complex coast-down procedure prescribed by WLTP to derive parameters for simulating resistances encountered by the vehicle on road in the Road Load Simulation (RLS) mode. This test was performed to resemble a constant power discharge by a bidirectional power supply.

Additionally, a CHAdeMO [12] charging station capable of V2G (Vehicle to Grid) operation has been used for the bidirectional discharge test. Some discharge tests were conducted starting with the vehicle fully charged, with the first part of the test discharging at a constant power of 6 kW using the station, and returning energy to the grid. The completion of the discharge was achieved by driving at constant speed in "constant force" mode on the dyno, as described above.

The details of the test procedures will be provided in the following chapter.

2 Material and Methods

2.1 Tested vehicle

The vehicle of the test campaign is a JRC property BEV, registered in April 2015, used for service purposes. This medium sized 5-seater vehicle has an unladen mass of 1520 kg and is powered by an 80 kW/280 Nm synchronous electric motor located on the front axle. The vehicle's main specifications are listed in Table 1 [9].

Table 1: Main characteristics of the tested vehicle.

Powertrain	FWD synchronous EM
EM maximum power	80
EM maximum torque	280
Unladen mass (kg)	1520
Nominal battery energy (kWh)	24 (192 Li-ion cells, 96S-2P)
Wheel size	205/55 R16
Length (mm)	4440
Width (mm)	1770
Height (mm)	1549
Wheelbase (mm)	2700

Table 2 shows the accumulated age and mileage of the vehicle at the start of the 3 test campaigns carried out on chassis dynamometer and on-road.

Table 2: Age of the vehicle at the beginning of the test campaigns.

Test campaign	Date	Age (years months)	Mileage (km)	Lab test	Tests
1	December 2021	6y 8m	9050	x	WLTP CCT and STP
2	August 2023	8y 4m	12300	x	WLTP CCT and STP
				x	Constant force mode discharge
				x	V2G discharge
3	May 2024	9y 1m	13200		On-road discharge

This is a vehicle used only within the JRC premises as service vehicle and the total mileage of the vehicle is very low compared to its age. The vehicle has been used for normal driving in an urban environment and, exceptionally, in rural and motorway conditions. Additionally, it has been used for interoperability tests with charging stations, including high-power ones, and has been parked both outside, exposed to weather conditions, and inside, in temperature-controlled environments. Despite being a service vehicle, its use can be assumed to be similar to that of a very low mileage user.

2.2 Test equipment and measurement points

2.2.1 Chassis dyno test cell

The laboratory experimental tests were conducted at the JRC VELA in Ispra, Italy, specifically in the VeLA-8 test cell, which features a 4x4 independent roller bench chassis dynamometer for accurate road simulations [13]. The dynamometer has a nominal power of 300 kW per axle, allowing for maximum speeds of 260 km/h and acceleration of 10 m/s².

The wheelbase is adjustable from 1800 mm to 4600 mm, making it suitable for testing light-duty and small commercial vehicles, including internal combustion engine ones, fully electric, or hybrid powertrains. Environmental conditions of the test cell can be controlled using a climatic system, ranging from -30°C to 50°C in ambient temperature and 0% to 95% humidity.

The VeLA-8 emission measurement system is optimized for reliable testing of hybrid vehicles during combustion engine shut-off phases. More details can be found in [14].

2.2.2 Current clamps

To measure the high voltage and 12V battery currents, the vehicle was instrumented with high-precision current clamps on both positive and negative electrode battery cables. The signal of the current clamps was acquired by a certified and periodically calibrated power meter. The accuracy of the entire measurement is guaranteed, as the clamps and the power analyser have high precision and frequency, the main technical specifications of the current clamps are reported in Table 3. The clamps used were flux gate type current sensors. The battery voltage value was taken through the CAN bus acquisition.

Table 3: Current clamp specifications.

Rated current	500 A AC/DC
Diameter of measurable conductors	Max. φ 20 mm
Frequency band (±3 dB)	DC to 200 kHz
Amplitude accuracy DC ±(% of reading + % of full scale)	±0.3% ±0.02%
Amplitude accuracy DC < f ≤ 100 Hz ±(% of reading + % of full scale)	±0.3% ±0.01%
Output noise	5 mV pp or less
Common-Mode Rejection Ratio (CMRR)	0.05% f.s. or less

2.2.3 Measurement points

During both charging and discharging tests, voltage and current measurements were taken at various points within the vehicle to determine electric power consumption and efficiency. A detailed breakdown of these measurement points is illustrated in Figure 1 and Table 4.

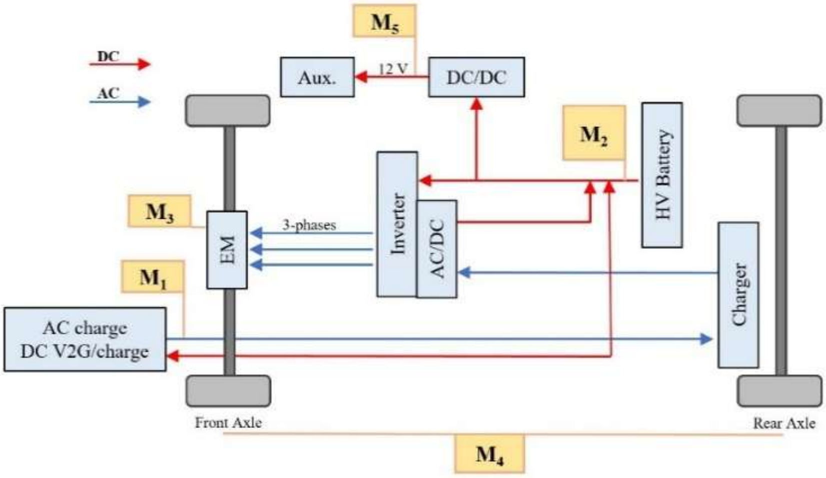


Figure 1: Main BEV components and measurement points

Table 4: Breakdown of current and voltage measurement points.

Measurement point label	Description
M_1	Energy from the grid to the high-voltage battery [Wh] AC charge – DC V2G discharge or charge
M_2	Current [A] and Voltage [V], from the high-voltage battery feeding the inverter, the DC/DC converter; (acquired both by CANbus and current clamp measurements)
M_3	Rotational speed [rpm] and torque [N·m] of the electric motor; (acquired by CANbus)
M_4	Energy at the wheel [Wh]; (measured in dyno tests)
M_5	12V battery energy measurement (acquired both by CANbus and current clamp measurements)

3 Results and Discussion

3.1 Chassis dynamometer tests

The tests according to the WLTP type approval procedure carried out in December 2021 [9] were repeated in August 2023. Both the Consecutive Cycle Test (CCT) and Shortened Test Procedure (STP) were carried out [10, 11]. In the CCT, the WLTC cycle is repeated consecutively, in the STP, two constant speed segments are inserted between the WLTCs, one in the middle and one at the end of the cycle, to shorten the test procedure [10, 11]. The test is terminated when the break-off criterion is met, i.e. when the driver on the chassis dynamometer experiences a power cut and the vehicle can no longer follow the driving trace for four consecutive seconds. At that moment, the vehicle is slowed down and brought at stand still and the test is terminated. Interesting to note that, during the 2021 tests, the break-off criterion was met at the acceleration of the fourth phase (Extra-High) of the fifth WLTC, while in the 2023 test campaign at the acceleration of the third phase (High) of the fifth repetition, approximately 10 km earlier. A lower UBE of 16571 Wh and a lower driving range of 103.89 km were measured, and rather higher electric energy consumption was calculated. The lower measured values of the 2023 test campaign may be due to the battery ageing that occurred in the two years between test campaigns, but also to the vehicle performance, the estimation and calculation of the SoH and SoC by the vehicle's BMS and the operating conditions of the test. Table 5 shows the results in detail, also for the STP.

Figure 2 shows the parameters measured during the CCT test of the 2023 campaign. From plot a it can be noticed that the break-off criterion occurred during the acceleration of the third phase of the last WLTC cycle.

Plot b shows the cumulative discharged energy with higher discharge rates in correspondence of the third and fourth phases of the WLTC cycles at higher power demand, in the order of 20 and 40 kW respectively, as shown in plot c.

Plot d shows the battery voltage, with a highly spiking signal due to the dynamic nature of the transient driving test. Additionally, a rapid drop at the end of the test is evident, with a cut off of the power. This is also confirmed from the SoC data acquired from the CAN of the vehicle, in particular in plot e where both the SoC readable from the dashboard to the driver and the ECU battery SoC are visualised.

The UBE is operationally defined, and in a dynamic test the break-off criterion can be triggered by a particular power demand encountered during any particular cycle phase. Presumably at a lower speed or in a less aggressive driving cycle the vehicle would have continued to deliver energy without cutting the power.

Table 5: Results of the 2021 and 2023 test campaigns for the type approval procedures CCT and STP.

WLTP Test	UBE (Wh)	Driving range (km)	Energy Consumption WLTP weighted (Wh/km)
CCT 2021	17607	113.06	155.7
STP 2021	17385	114.00	152.5
CCT 2023	16571	103.89	159.5
STP 2023	16704	98.01	170.4

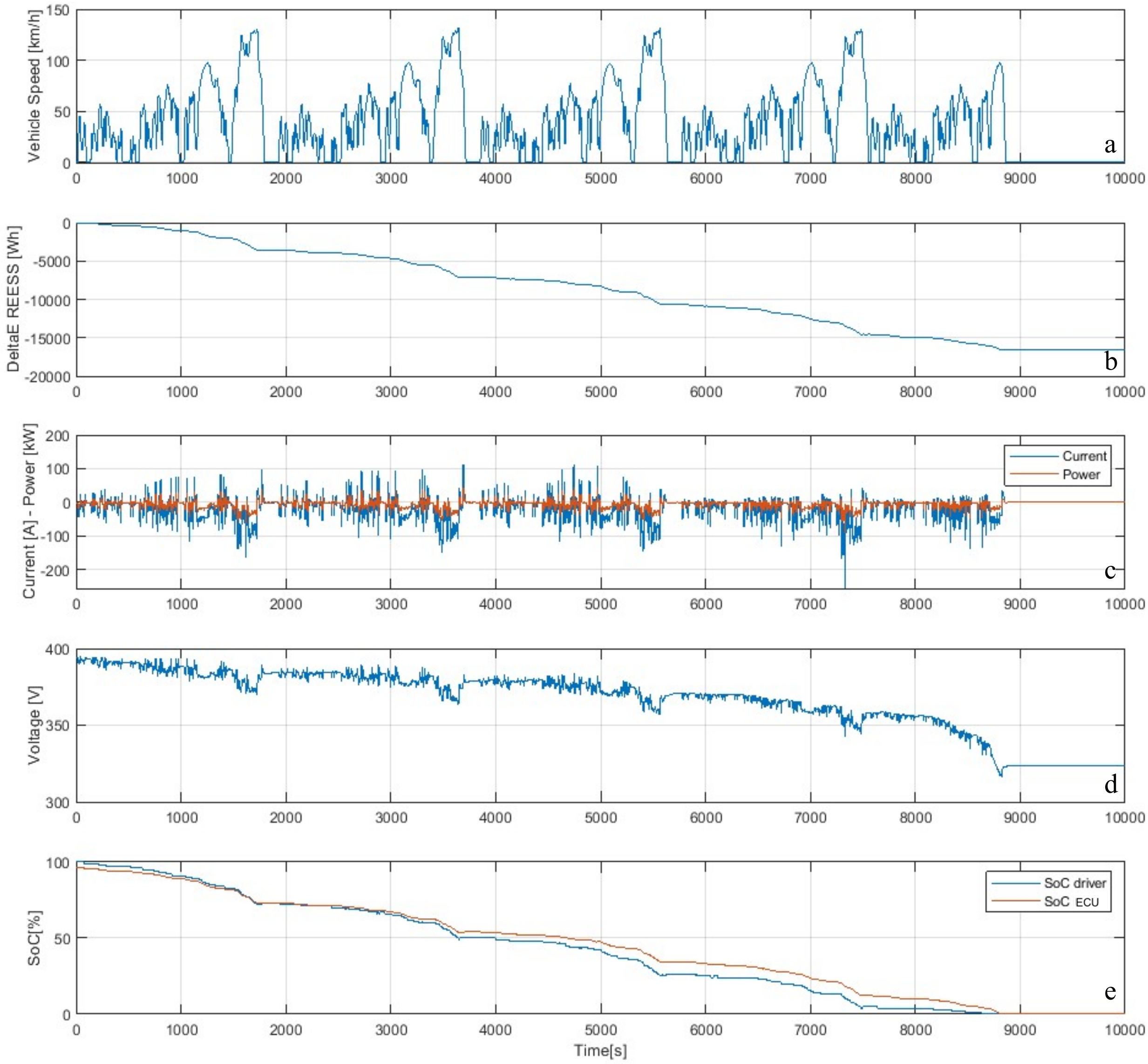


Figure 2: Time plot of the test parameters of the WLTP CCT procedure for the 2023 campaign.

3.2 Constant power discharge tests

Other interesting results were gathered during laboratory tests in the 2023 campaign. At that time, the UNECE EVE IWG was already in the process of discussing testing procedures to determine the UBE for HDVs. Due to the complexity and variety of such vehicles, an attempt was made to simplify the testing and discharging of the battery, while maintaining the repeatability and accuracy required for a battery energy measurement. Therefore, alternative procedures, simpler than discharging the electric vehicle in the laboratory according to WLTP type approval procedures, were tested:

- using the chassis dynamometer constant force mode, maintaining a constant vehicle speed via the cruise control to deliver a constant power;
- using a V2G-enabled charging station, which discharges the vehicle battery and feeds energy back into the grid via the vehicle's CHAdeMO standard plug.

In order to discharge the vehicle at a C-rate corresponding approximately to a normal charging power, 1/4 C was selected (considering the nominal battery energy of 24 kWh) setting a force on the chassis dyno of 480N and maintaining a speed of 35 km/h through the cruise control. This setting corresponds to a constant driving power of approximately 4.7 kW. The resulting driving range was 94 km, with basically no energy recovery encountered during the cycle, and 17290 Wh of energy discharged.
The higher discharged energy during this test may be due to the constant speed, the absence of regenerative braking and also a lower power demand at low SoC, which leads to a slower voltage drop.
For convenience reasons two short pauses were made during the discharge, to allow for a driver change.
Figure 3 shows the parameters measured during the discharge; a much more constant discharge power, the absence of energy recovery during the test, and the more constant decreasing rate of the SoC can be noticed.

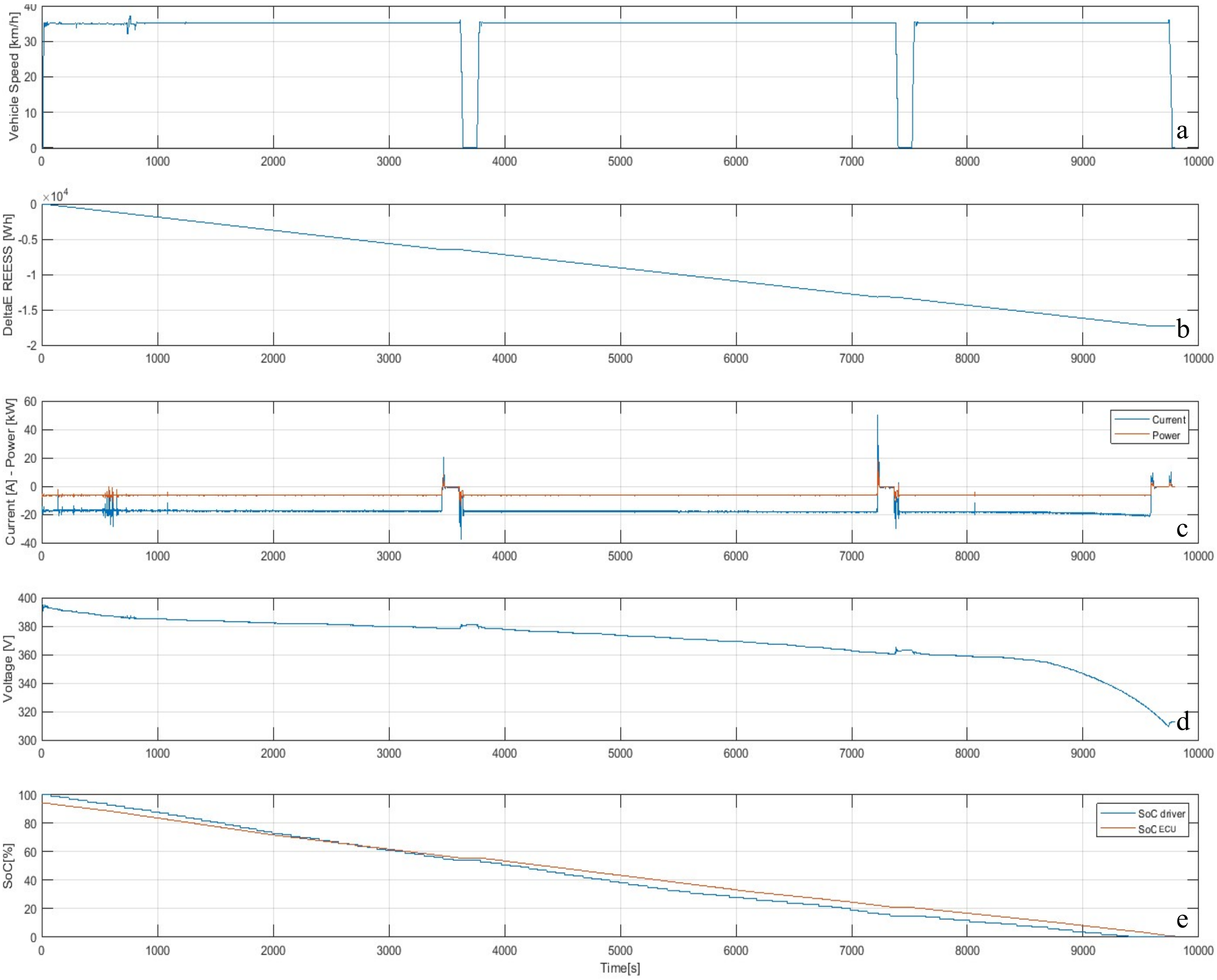


Figure 3: Time plot of the test parameters during the constant speed and power discharge test for the 2023 campaign.

A CHAdeMO standard V2G-enabled column, which is capable of discharging the vehicle from the charging plug and sending the energy back to the grid has been used to replicate this methodology and discharge the vehicle at a constant power of 6kW.

During the test campaign, the vehicle disconnected at a SoC close to 50% even though a complete discharge at 6 kW was set on the station interface. It was therefore decided to complete the discharge following the previous methodology, driving on the chassis dyno at 35 km/h.

Figure 4 shows the parameters measured during the discharge and the drive on the cassis dynamometer immediately after the discharge in V2G mode. The quantities acquired from the CAN line are only available while driving, being the vehicle in “key off” mode during V2G discharge.

It can be seen that the drive on the chassis dynamometer started at a SoC of 50%, and the end of the discharge has a very similar behaviour of that in the previous test. A constant discharge power of 6 kW was maintained in both discharge modalities, as shown in Figure 4. The total energy discharged was 17275 Wh, respectively 7013 Wh in V2G and 10262 Wh driving on the dyno.

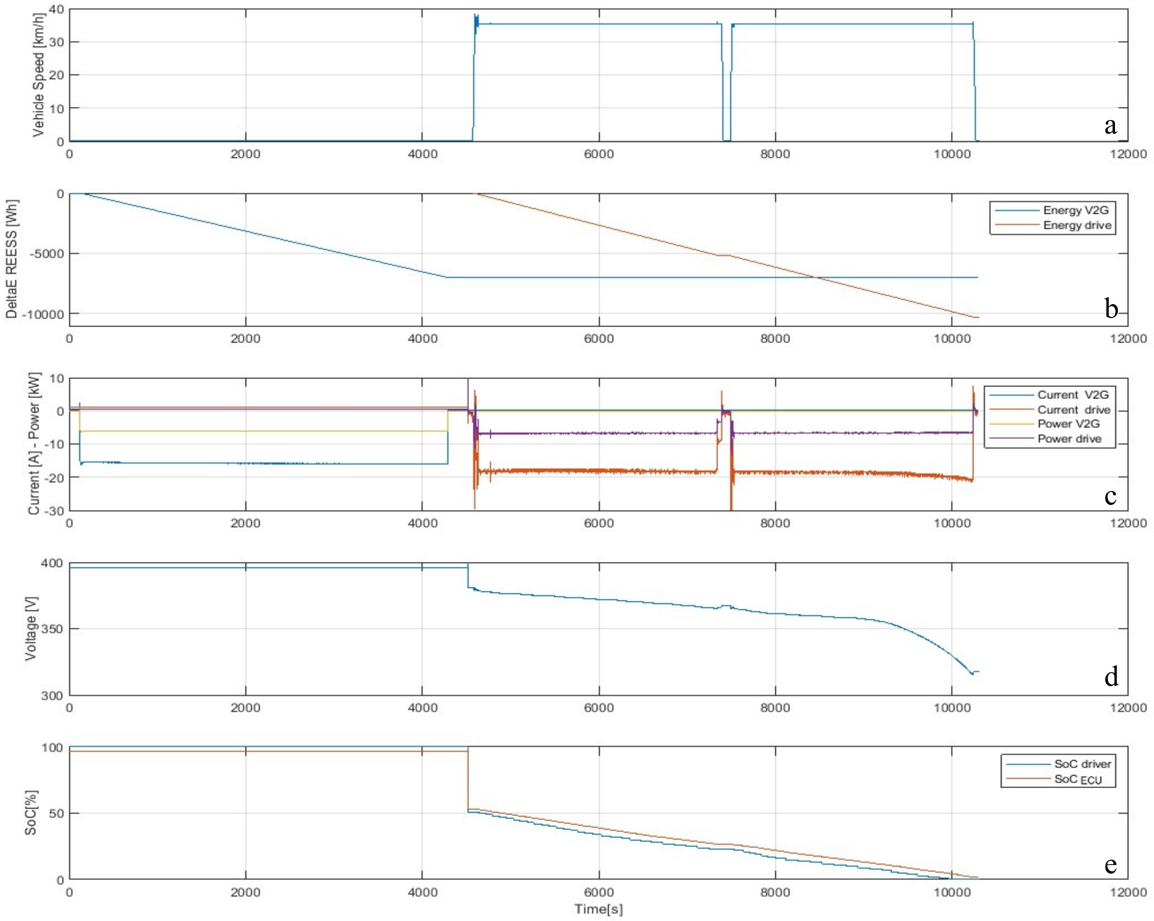


Figure 4: Time plot of the test parameters of the V2G constant power and constant speed and power discharge test for the 2023 campaign.

3.3 On-road discharge tests

The possibility of measuring the energy during a full discharge of the battery by driving a vehicle either on a dedicated track or on open roads is the other option considered by the UNECE EVE IWG to measure the UBE of HDVs. To support the EVE IWG discussion around the definition of the boundary conditions of these tests, in May 2024, a test campaign on the same vehicle was organised on the road. Three different routes were driven, the first mainly rural, one containing a long ascent to an altitude of over 1000 m a.s.l. and one with a highway section. Details on the course driven and the altimetry can be found in Figure 5. The route was designed to complete the discharge within the JRC premises, for safety reason. The JRC consists of a private campus with an external ring road of approximately 3.5 km, which was repeated until the break-off condition was reached, as shown in the last portion of the altimetry in Figure 5. Immediately after a power cut was reached or in the presence of a very low SoC, the vehicle was driven to the VELA laboratories and the battery recharged.

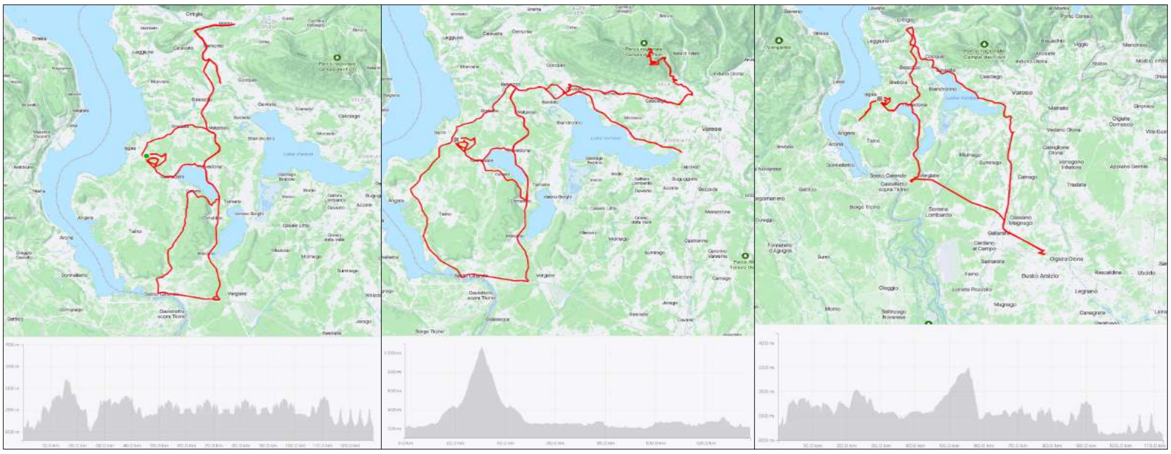


Figure 5: Test routes details and altimetry (Rural, Mountain, Highway)

The mountain and motorway tests were repeated by loading an additional 160 kg payload on board to study its effect on the UBE measurement. The weather during the test campaign was either sunny or cloudy, and mild temperatures of 15 to 25 degrees were encountered; the tests were avoided in the event of rain due to the installation of the measurement equipment underneath the vehicle. Table 6 shows the main results calculated up to the occurrence of the break-off criterion; for all tests the cumulative discharged energy does not change significantly regardless of the route and payload. This means that neither the dynamicity of the routes nor the power required by the road slope or the payload influences the UBE measurement of the tested mid-sized vehicle. The effect of these variables are small and the driving power request from the vehicle still remains within normal driving power range.

During the test in urban and rural conditions there was no power cut until a very low SoC of 3.6 per cent. In order not to put the vehicle in alarm, it was decided to terminate the test. Analysing the data, it was noted that the SoC value was very low, but the battery voltage was about ten volts higher than at the end of the other tests. In order to have accurate and repeatable road driving tests of the cumulative discharged energy, it is very important to define a uniform cut-off condition.

Table 6: Results of the on-road discharge 2024 test campaign.

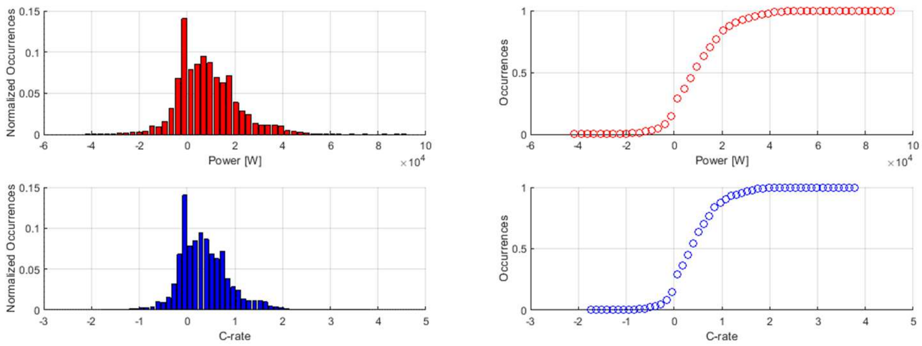
	Rural	Mountain	Mountain payload	Highway	Highway payload
UBE clamp1 (Wh)	17323	17743	17436	17247	17261
UBE clamp2 (Wh)	16161	16290	16136	16400	16427
UBE CAN (Wh)	16853	16217	17143	17172	17158
SoC real break-off (%)	3.6	6.3	4.4	4.6	4.3
Voltage CAN final (V)	321	296	310	316	314
Average moving speed(km/h)	53.8	45.9	44.2	61.5	61.2
Distance break-off (km)	128.1	136.0	125.2	113.4	110.6
Power cut	No	Yes	Yes	Yes	Yes
Break-off / end of test distance (km)	-	1.3	0.4	0.4	1.2
Average energy consumption (clamp1) (Wh/km)	135.2	130.1	138.8	152.1	155.3

3.4 Discussion

In order to check that the range of the driving power demand and energy recovery is similar in the cycles on the roller and in the different driving conditions tested on the road, a histogram of the normalized occurrences of powers and C-rates encountered during discharges is presented in Figure 6. The plots are considering discharge power as positive and energy recovery phases as negative and a nominal battery energy of 24 kWh to calculate C-rates. The cumulative data are also plotted, to better highlight the very low frequency of high power requests. The power data has been filtered by eliminating all values when the power demand is zero, i.e. during vehicle stops.

Table 7 also shows the quantiles, average and maximum values of the not zero power curve encountered in the different tests. The maximum value of the peak discharging electric power has been recorded in the rural test, immediately followed by WLTP CCT and highway payload tests; as the electric motor maximum power is 80 kW, it is most certainly due to short power requests with the accelerator pedal fully pressed. In both the tests with payload, a shift in the distributions towards higher discharge power and higher recovery power can be observed. From the first quartile, it can be seen that reasonably the tests with a higher occurrence of energy recovery are the urban and the mountain tests. It is important to note that there are no significant differences in the power demand for both discharge and energy recovery between the chassis dynamometer and on-road driving, neither for mountain driving nor for high payloads, as expected for a mid-sized passenger car. The range and frequency of the C-rates encountered show that the driving power required for a light duty vehicle is limited, under these conditions of use, including dynamic driving ones.

CCT



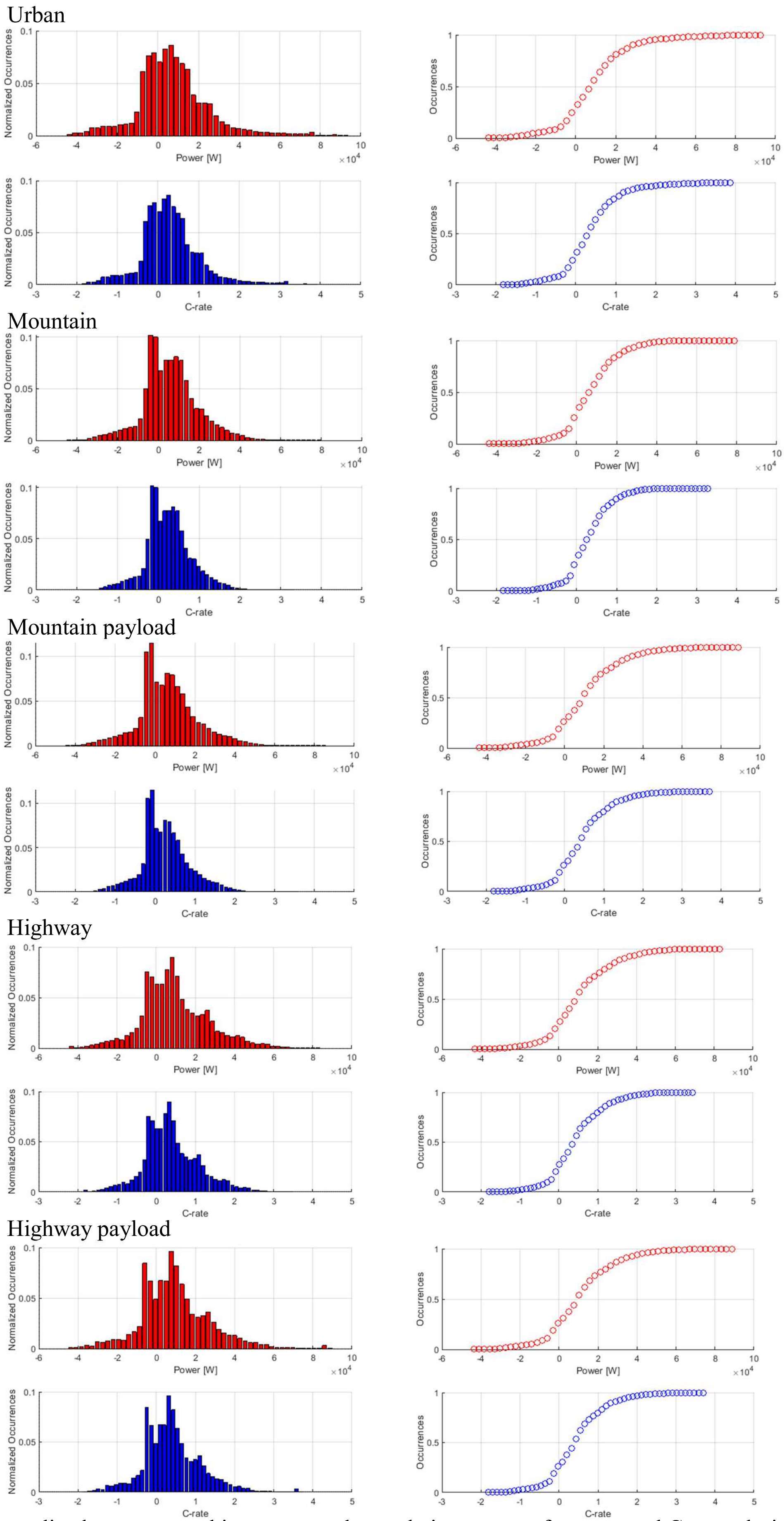


Figure 6: Normalized occurrences histograms and cumulative curves of powers and C-rates during discharges

Table 7: Quantiles, average and maximum values of the not zero power curves for the several discharge tests

	Power [W]				
	25%	Median	75%	AVG	Max. disch
WLTP CCT	-554	7058	15737	8405	90211
Urban	-3108	5775	15152	7275	92914
Mountain	-2544	5082	13188	5971	79216
Mountain payload	-2852	5004	14015	6194	85484
Highway	-1672	7503	18999	9316	82479
Highway payload	-2190	7970	18441	9395	89099

Table 8 shows the SoH CAN indicator during the May 2024 on-road tests. From 75% the SoH value rose to 78% throughout the test campaign, the value encountered during the December 2021 tests [9]. Following consecutive charges and discharges, the BMS probably recalibrated the estimated SoH value. A check of the SOH indicator should be performed at later stage in time after a typical daily vehicle usage.

Table 8: SoH values estimated by the CAN of the vehicle during the May 2024 test campaign progression

Test Number	1	2	3	4	5	6	7	8
SoH CAN [%]	75	76	77	77	77	78	79	78

4 Conclusion

The results obtained show that there is no big influence on the usable battery energy delivered during the discharge from full to empty state of charge with different testing conditions. The measured UBE was similar for all the procedures: the standard WLTP testing, the dyno tests at constant speed, the V2G charging station test and the on-road tests, regardless of the road grading, the dynamic performances of the route and the driving conditions encountered.

The test refers to a mid-size passenger vehicle and no big variation in the driving power request was observed due to the road slope and vehicle payload, as expected. The results presented are only an example of application. The conclusions may be valid for similar vehicles, but cannot be generalised, especially with regard to HDVs, where the powers, the payloads and therefore the C-rates involved are much higher and the battery packs installed are higher in capacity.

In the WLTP and dynamic cycles performed on chassis dyno test cells, the cut-off criterion is defined as the moment when the vehicle experiences a power cut and cannot follow the driving trace for four consecutive seconds. The occurrence of this state depends on the power demand of the cycle at low SoC of the battery, as shown in the WLTP CCT data of 2021 and 2023 test campaigns: the break-off occurred respectively in the acceleration of the fourth and third phase of the fifth WLTC. It depends on several parameters such as the SoH and SoC of the individual battery cells, the dynamicity of the discharge cycle and the environmental conditions.

As mentioned, in the on-road tests, in some cases a power cut was experienced with a SoC of 6.3% and a very low battery pack voltage (295 V), while in another test with a SoC of 3.6%, but a still high voltage of 330 V, the vehicle showed no power cut. In this case, being the SoC very low, even though a power cut was not experienced the test was interrupted stopping the vehicle to avoid a deep discharge. Each manufacturer develops strategies to safeguard the battery health, preserving over discharge and complying with safety regulation such as UNECE Regulation No. 100 [15]. This is to say that the break-off criterion is definitely triggered by some electronic control of the vehicle, and not by a physical event, like the empty tank of an ICE vehicle.

Another factor that led to a discrepancy in the results is the different current measurements at the high voltage battery. For safety reasons, the vehicle was not instrumented with a voltage measurement so only the CAN bus value was used in the calculations. Instead the current entering and exiting the HV battery was measured with high accuracy current clamps, and also the CAN bus value was available. These three current values were quite different, and led to slightly different results from the UBE, however with a range of about 5%. This may be due, especially in on-road driving tests, to the dynamic nature of the test, and the measurement of current clamps on shielded cables. The current clamps being used have a very high measurement accuracy, so the discrepancy is not only a matter of instrument precision or dynamic performances, but rather related to the installation on the cable. We have no details available on the on-board battery instrumentation to measure the current, but the HV battery current value from the CAN bus proved to be sufficiently stable, accurate, and comparable with that of current clamps.

To have repeatable UBE results, the most important factors to take into account are a correct preconditioning of the vehicle and the battery, to ensure a complete charge of the battery, but above all to set repeatable and clear end of discharge conditions, defining a precise break-off criterion for all the applied test methods.

Acknowledgments

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He currently works at the European Commission Joint Research Centre, in the Sustainable, Smart and Safe Mobility unit, providing technical support for the development of new European regulations through experimental tests in vehicle laboratories, desktop research and simulations. His activities include the participation in the UNECE Informal Working Groups Electric Vehicles and the Environment and Automotive - Life Cycle Assessment.