batteries

MDPI

Article

Experimental Application of the Global Technical Regulation on In-Vehicle Battery Durability

Gian Luca Patrone * and Elena Paffumi

Joint Research Centre, European Commission, 21027 Ispra, Italy
* Correspondence: gian-luca.patrone@ec.europa.eu

Abstract: Battery aging of electrified vehicles is a key parameter to be controlled in order to ensure sufficient energy efficiency and driving range across the whole vehicle lifespan. The United Nations Economic Commission for Europe has recently adopted a new regulatory framework, the Global Technical Regulation No. 22, prescribing minimum performance requirements for in-vehicle battery durability. With the implementation of this new GTR, monitors of the battery state of certified energy and range 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' correctness is checked, the battery durability performances are controlled in Part B against the defined limit values by a fleet monitoring procedure. This work presents the results of a testing campaign executed at the Joint Research Centre testing facilities on an aged pure electric vehicle to measure its capacity and range fade. The aim is to explore the applicability of GTR No. 22, assessing the in-vehicle battery performance fade of an aged electric vehicle, illustrating the several steps of the developed regulation and experimental methodology.

Keywords: electric vehicles; battery durability; battery aging; state of health; vehicle testing; UN GTR No. 22

check for updates

Citation: Patrone, G.L.; Paffumi, E. Experimental Application of the Global Technical Regulation on In-Vehicle Battery Durability. *Batteries* **2023**, *9*, 454. https://doi.org/10.3390/batteries9090454

Academic Editors: Jie Deng and Chulheung Bae

Received: 29 June 2023
Revised: 9 August 2023
Accepted: 23 August 2023
Published: 5 September 2023

1. Introduction

The transport sector is contributing significantly to greenhouse gas (GHG) emissions and global warming and has the highest dependence on fossil fuels of any sector, globally accounting for 37% of CO2 emissions from end-use sectors [1,2]. Despite being one of the sectors heavily impacted by the COVID-19 pandemic, emissions are on the rise due to growing demands, and the adoption of alternative fuels remains partial. That growth is most prominent in developing and emerging economies. European country policies and vehicle manufacturers need to put concrete measures into practice to respect commitments of the Paris Agreement during COP21 [3] and the European Green Deal [4], targeting a 90% cut in GHG production in the European Union by 2050 [5,6].

The electrification of the powertrain seems to be the most attractive solution, especially if cleaner assortments of energy production are employed in the future, and customer acceptance is growing significantly [7]. In the last decade, huge improvements have been reached, ensuring affordable batteries with higher and higher specific energy and power. Extensive research and development activities are pushing battery cathode, anode, and electrolyte chemistries to increase the specific energy content of batteries [8,9], and the adoption of modern battery generations is contributing to increased electro-mobility, reducing range anxiety, allowing shorter charging times with high power chargers and making battery electric vehicles (BEVs) an economically feasible choice.

An important aspect of BEVs is the topic of aging; in fact, battery performance characteristics are worsening over the battery's lifetime, influenced by the storage and usage conditions and depending on complex physical and chemical processes occurring in the cells. Battery aging is due to several secondary reactions happening in the battery components and manifests mainly in capacity and power fading [10,11]. Battery aging is a complex phenomenon influenced by many operating variables, such as calendar time and Ah throughput during cycling, but also Depth of Discharge (DoD), C-rate and temperature [12,13].

The results of this work contributed to inform the discussion within the United Nations Economic Commission for Europe (UN ECE) Electric Vehicles and Environment Informal Working Group (EVE IWG). This group is among the IWGs of the Working Party on Pollution and Energy (GRPE) [14] subsidiary body of the World Forum for Harmonization of Vehicle Regulations (WP.29) preparing regulatory proposals on vehicle emission and energy consumption. One recent development of the EVE IWG has been the GTR No. 22 [15] regulating in-vehicle battery aging within electrified vehicles. The discussion group addressed both the electric range and energy efficiency decrease during the vehicle lifetime due to battery aging. A loss of driving range might lead to diminished utility, resulting in decreased electric vehicle usage and a corresponding decrease in displaced travel distance that might then be covered with a different means of transport; it can also influence electrification and electric vehicle sales. A decrease in vehicle efficiency could impact the upstream emissions by increasing the amount of energy needed per unit of vehicle distance covered. Both efficiency and range have the potential to influence not only the utility but also the environmental performance of the vehicle. Furthermore, alongside changes in range and energy consumption, hybrid electric vehicles frequently incorporate both a conventional and electric powertrain. In the case of these vehicles, the criteria pollutant emissions from the conventional powertrain could potentially be influenced by the degradation of the battery over time [16].

GTR No. 22 [15] prescribes that modern off-vehicle charging hybrid electric vehicles (OVC-HEVs), i.e., plug-in hybrid vehicles and pure electric vehicles (PEVs), should have vehicle-specific monitors on the actual state of health (SOH) of the battery pack, expressed in terms of state of certified energy (SOCE) and state of certified range (SOCR), available for the customers. These values will then be checked against minimum performance requirements, as set in GTR No. 22 for the SOCE for categories 1–1 and 1–2 [17]. The mentioned limits on energy capacity fading foresee a minimum SOCE of 80% over 5 years or 100,000 km, whichever comes first, and 70% up to 8 years or 160,000 km, whichever comes first, for the light-duty vehicles.

This work is presenting the results of a test campaign carried out in the European Commission Joint Research Centre (JRC) Vehicle Emission Laboratory (VELA) on an aged mid-sized BEV. The vehicle was tested with the applicable test cycle [18] to derive the measured SOH. Comparing it with the SOH indication retrieved from the CAN bus of the vehicle, we are approximating a first application of what would happen in Part A of GTR No. 22.

Details on GTR No. 22 and the results of the test campaign, considerations about the aging of the vehicle, and an application of pass/fail statistics foreseen in Part A of the GTR [15] are reported in the following chapters.

2. Materials and Methods

2.1. In-Vehicle Battery Durability GTR Overview

In Part A of GTR No. 22 [15], the accuracy of the monitors on the actual state of health (SOH) of the battery pack, expressed in terms of SOCE and SOCR, is verified for each vehicle family by experimentally measuring the usable battery energy (UBE) and the electric driving range by applying the Worldwide Harmonized Light-duty Test Procedure (WLTP) on some vehicle samples [18]. By dividing the measured UBE and range by the respective values from the certification, it is possible to calculate the measured SOCE/SOCR values to be compared with the onboard metrics read from the monitors of the vehicles to verify that their accuracy falls within a predetermined tolerance range.

A pass-or-fail decision about the correctness of the monitors will be reached through a statistical method on a sample of a minimum of 3 up to a maximum of 16 vehicles, evaluating the deviation of the monitor from the measured value according to a statistical formula reported in the GTR No. 22 [15]. More precisely, the initial foreseen sample size is 3 vehicles. If the average deviation of the read and measured values falls below a defined limit, the monitor is accepted; if it is over the higher boundary limit, it is rejected; if the average deviation falls in between the acceptance and rejection limit, the sample size is increased progressively by 1 vehicle up to a maximum of 16 (see Appendix A for the tabulated parameters of Part A of GTR No. 22 [15]).

In Part B of GTR No. 22 [15], the battery durability is checked against the MPRs: since the accuracy of the monitors has been statistically proofed in the previous phase, it is possible to verify the battery durability of aged vehicles through a remote collection of the onboard SOCE/SOCR values for a statistically adequate sample of vehicles within the same battery durability family, as defined in the same GTR No. 22 [15], together with additional information such as the age of the vehicle, the distance traveled, and eventual V2X applications. A battery durability family shall pass if equal to or more than 90 percent of the monitor values read from the vehicle sample is above the MPR. Figure 1 shows a graphical representation of the GTR No. 22 [15] steps for the case of SOCE.

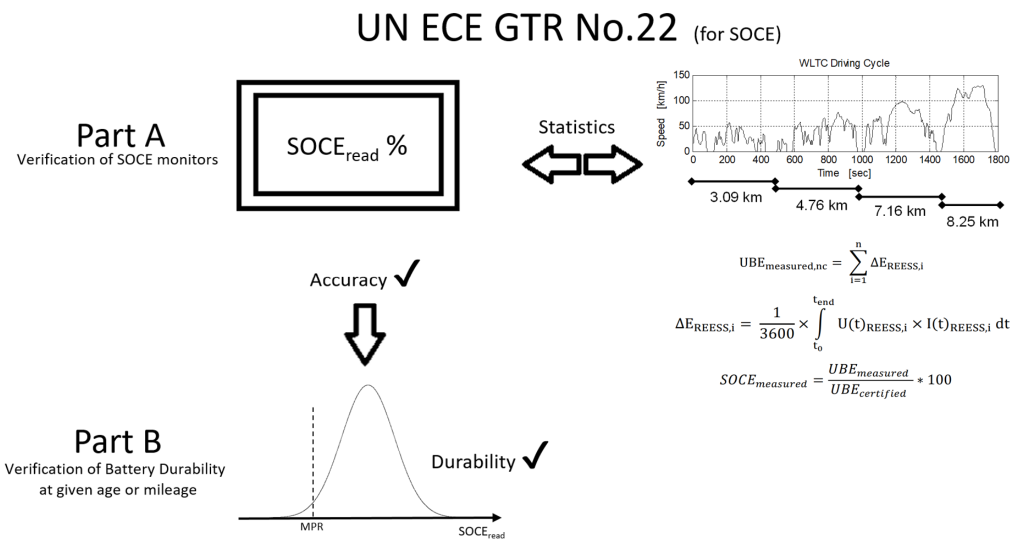

Figure 1. Graphical representation of the GTR No. 22 [15] steps for the case of SOCE.

2.2. Tested Vehicle and the Laboratory

The tested BEV is a JRC property vehicle used for service purposes. It is a mid-size 5-seat vehicle, having an empty mass of 1520 kg and powered with an 80 kW/280 Nm synchronous electric motor at the front axle. The vehicle's main characteristics are reported in Table 1.

Table 1. Main characteristics of the tested vehicle.

Architecture	Battery Electric Vehicle
Propulsion	Synchronous electric motor
Drive Type	FWD
Max. Power (kW)	80
Max. Torque (Nm)	280
Empty mass (kg)	1520
Battery	24 kWh 192 Li-ion cells (96S-2P)
F/R tire and wheel size	205/55 R16
Length (mm)	4440
Width (mm)	1770
Height (mm)	1549
Wheelbase (mm)	2700

The battery is composed of 192 Lithium-Ion cells (96S-2P architecture) for a 24 kWh nominal capacity and circa 360 V nominal voltage.

The tested vehicle was registered on 29 April 2015. The experimental tests reported here were performed in December 2021, with an odometer reading of 9050 km. As evident, this is a special-purpose vehicle, only used inside the JRC premises, and the total distance covered by the vehicle is quite low if compared to its age (6 years and 8 months). The vehicle has been used for normal driving in urban environments and exceptionally in extra urban and highway conditions; it has been used for interoperability tests with charging stations, including high-power ones, and kept parked both externally exposed to weather conditions and internally in temperature-controlled environments. Despite being a company vehicle, its usage seems similar to a low mileage user operation with both cycle and calendar aging effects.

The experimental tests were performed at the JRC VELA in Ispra (Italy) [19,20], precisely in the VeLA-8 test cell, equipped with a 4 × 4 independent roller benches chassis dynamometer that has a nominal power per axle of 300 kW for full-road simulations with a maximum speed and maximum acceleration, respectively, of 260 km/h and 10 m/s^2 and an inertia range of 250–4500 kg. The chassis dyno wheelbase can be adjusted depending on the tested vehicle from 1800 mm up to 4600 mm. The laboratory test cell is designed for testing light-duty and small commercial vehicles with internal combustion engines (ICEs) or full-electric and hybrid vehicles.

Environmental conditions can be established using a robust climatization system, allowing the control of the ambient temperature from −30 °C to 50 °C and humidity. The VeLA-8 emission measurement system is also customized to allow hybrid vehicles to be tested properly during the phases when the combustion engine is switched off. A description of the testing facility is reported in [21,22].

2.3. Driving Cycles

The tests were performed in a chassis dyno test cell conditioned at 23 °C and with controlled humidity, applying the WLTP testing procedures and calculations for PEVs [18,23,24].

In detail, the two following driving cycles were applied [18,23,24] as shown in Figure 2:

- The Worldwide Harmonized Light-duty Test Cycle (WLTC);
- The Worldwide Harmonized Light-duty Shorten Test Procedure (WLTP STP).

The WLTC is the European certification driving cycle for the light-duty vehicles (LDVs) [18,23,24]. It was designed to reproduce the real-world operating conditions of LDVs more closely than the earlier NEDC cycle. The cycle is comprised of four phases, created to reproduce the urban, the rural, the extra-urban and the highway conditions, respectively, with a duration in time and driven distance of (Figure 2a): low speed (589 s and 3.09 km), medium speed (433 s and 4.76 km), high speed (455 s and 7.16 km), and extra high speed (323 s and 8.25 km).

According to the WLTP Consecutive Cycle Test (CCT), the driving range is derived by driving continually during the WLTC starting with a fully charged battery until the break-off criterion is achieved. This occurs when the driver can no longer adhere to the driving trace because of the vehicle power reduction; the vehicle shall be brought to a standstill, and the driving shall be interrupted.

The WLTP STP is foreseen for high energy capacity, pure electric vehicles in order to shorten the testing duration for the driving range determination [18,23,24]. The cycle consists of two dynamic segments (DS1 and DS2) and two constant speed segments selected to be at 100 km/h (CSS_M and CSS_E) (Figure 2b). The dynamic segments DS1 and DS2 are needed to calculate the energy consumption of the specific phase. The duration of the constant speed segments CSS_M and CSS_E are calculated for each specific tested vehicle characteristic and are designed to cut the test duration by discharging the battery quicker than with the CCT test. The calculated length of the 100 km/h sequences depends on the vehicle's available battery capacity.

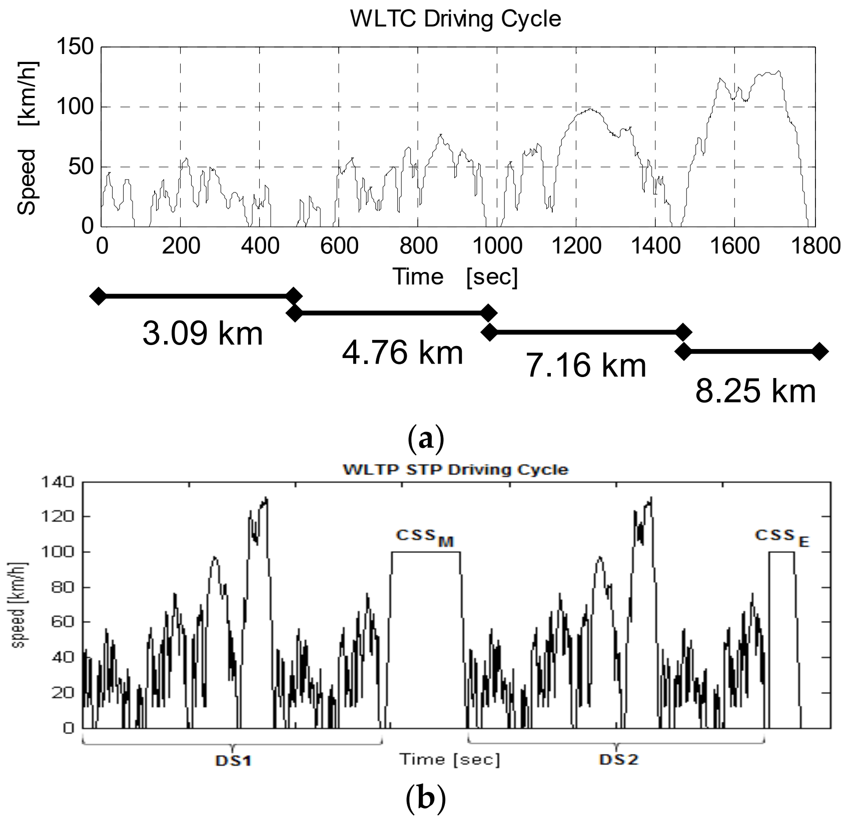

Figure 2. Driving cycles adopted: (**a**) WLTC; (**b**) WLTP STP [18,19,23,24].

After each driving range test, the fully depleted battery is recharged with a 6.6 kW AC charger.

2.4. Measurement Points

During the driving cycle tests, the voltages and the currents were measured at different component levels in the vehicle to calculate the electric power consumption and efficiencies. A complete depiction of the measurement points is presented in Figure 3 and Table 2.

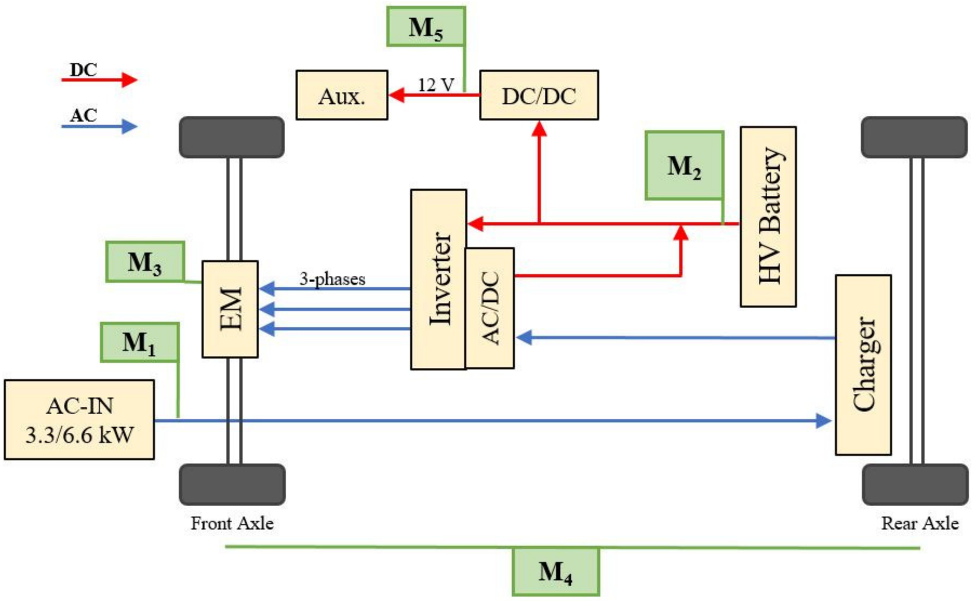

Figure 3. Schematic representation of the vehicle systems and measurement points [19].

Table 2. Detail of measurement locations [21,22] (see Figure 3).

Measurement Point Marker	Explanation
M_1	Electrical energy from the mains to the high-voltage battery (Wh) (acquired directly at the recharging station)
M_2	Current (A) and Voltage (V) from the high-voltage battery to the inverter, the low-voltage auxiliary systems and the HVAC systems; (acquired both by CAN bus and current clamp measurements)
M_3	Rotational speed (rpm) and torque (N·m) of the electric motor; (acquired by CAN bus)
M_4	Mechanical energy at the wheel (Wh); (acquired by the dyno)
M_5	12V battery electrical energy measurement (acquired both by CAN bus and current clamp measurements)

3. Results

The results of the testing campaign on the aged vehicle are discussed in this chapter. Section 3.1. presents the energy and driving range measurement and the derived energy consumption. Section 3.2. compares the aged vehicle performances with the initial figures obtained during certification and an estimate of the SOH is derived. Section 3.3. compares the obtained measured SOH value with the value read from the CAN, and finally, the GTR No. 22 Part A statistics is applied as an example, assuming the tested vehicle to be one of the vehicles sampled for the SOCE/SOCR monitor validation.

3.1. Usable Battery Energy, Driving Range and Energy Consumption

The WLTP CCT and STP procedures [18,23,24] have been applied at 23 °C to determine the aged vehicle UBE, energy consumption, and driving range. During the CCT procedure, the break-off is reached in the fourth phase of the fifth repeated WLTC; instead, during the STP, the break-off occurs during the second CSS, as prescribed, corresponding to approximately the same driven distance and lower test time with respect to the standard CCT procedure.

The UBE measured according to WLTP calculations [18,23,24] is approximately 17,607 Wh for the CCT test and 17,385 Wh for the STP, while the driving range is, respectively, 113.06 km and 114.00 km. The resulting WLTP energy consumption values are 155.74 Wh/km for the CCT test and 152.51 Wh/km for the STP procedure.

Table 3 is reporting the details of the specific energy consumption for each cycle repetition; a higher value is measured in the first cycle both for CCT and STP.

Table 3. Details of specific energy consumption expressed in Wh/km for the different parts of the cycles: CCT procedure on the left and STP procedure on the right.

WLTC Cycle n.	WLTP CCT	°	WLTP STP
1	158.16	WLTC cycle 1	155.58
2	153.66	WLTC cycle 2	151.71
3	152.50	DS1	147.43
4	159.15	DS2	144.06
Tot. up to break-off	158.31	Tot. up to break-off	156.19
WLTP post processed energy consumption	155.74	WLTP post processed energy consumption	152.51

Table 4 below is a further split of the results, reporting energy consumption values for the CCT and STP procedures phase by phase. The energy consumption decreases while driving the cycles, and it is also evident how the specific energy consumption is higher for the fourth phase of each repeated WLTC cycle, reproducing highway driving conditions up to over 130 km/h, with respect to other phases corresponding to a lower speed.

Table 4. Details of specific energy consumption expressed in Wh/km for each phase of the cycles: CCT procedure on the left and STP procedure on the right.

WLTC Cycle n.	Phase n.	WLTP CCT	WLTC Cycle n.	Phase n.	WLTP STP
1	1	145.57	DS1	1	138.16
	2	142.99		2	137.69
	3	145.20		3	143.12
	4	191.06		4	190.22
2	1	138.02		1	126.69
	2	131.58		2	127.80
	3	143.54	CSS1		167.02
	4	190.73	DS2	1	124.61
3	1	136.10		2	129.20
	2	129.69		3	140.85
	3	142.44		4	191.31
	4	190.50		1	123.49
4	1	138.10		2	127.46
	2	129.65	CSS2		210.14
	3	158.12	WLTP post-processed energy consumption		152.51
	4	194.84			
5	1	144.54			
	2	155.82			
	3	152.02			
	4	234.80			
WLTP post-processed energy consumption		155.74			

3.2. Calculate the SOCE/SOCR Monitor

The measured UBE and ranges during the tests have been divided by the values of certification to obtain the measured SOCE and SOCR, an indication of the in-vehicle battery aging at this specific point in its lifetime. The values are reported in Table 5 for both the CCT and the STP procedure.

Table 5. Measured SOCE and SOCR values for the aged vehicle being tested.

	$\mathbf{SOCE_{meas}=\frac{UBE_{meas}}{UBE_{cert}}}$ (%)	$\mathbf{SOCR_{meas}=\frac{Range_{meas}}{Range_{cert}}}$ (%)
CCT	73.4	70.7
STP	72.4	71.2

The aged vehicle (6 years and 8 months), despite the low accumulated mileage, is quite close to the MPR enforced for 8 years or 160,000 km (30%). The company service vehicle has been used for testing fast charging stations and has been kept parked outside the JRC buildings both in summer and in winter conditions, with a significant contribution expected from calendar aging. The battery SOH from the CAN bus is estimated to have a value of 78%, underestimating the aging with respect to the measured value, but it has to be noted that this value does not reflect the new global technical regulation provisions since the vehicle was registered in 2015.

3.3. Applying the GTR No. 22 Part A Statistics

The accuracy of the SOCE monitors will be verified by GTR No. 22 Part A, according to which the acceptance or rejection of the monitor value will be checked with a statistical analysis based on confidence intervals. An initial sample of three aged vehicles will be taken from the market and tested with the same procedure applied in this work; the difference between the value read from the SOCE/SOCR monitor and the one measured during tests will be evaluated, and the average and standard deviation will be calculated for the sample together with the limit values, as tabulated in GTR No. 22, to verify the correctness of the monitors even if statistically dispersed. If the average value of the difference between the read value and the measured value is sufficiently low, the monitor is accepted. If the value is too high, the monitor value is rejected. If the difference is in the middle, an additional vehicle should be tested. Limit values are set to certainly obtain a pass-or-fail decision with a maximum sample size of 16 values. Details about the calculation and limit values tabulated in GTR No. 22 are reported in Appendix A.

For simplification, it is assumed that the three sampled vehicles are identical to the vehicles tested at the JRC. We are assuming as reference the measured state of certified energy over the CCT procedure, $SOCE_{measured}$ = 73.4%, and the read value from the CAN variable $SOCE_{read}$ = 78%. By applying the formulas in GTR No. 22 [15] (see Appendix A), the difference x_i between the read and measured values is 4.6%, and in this particular case, the standard deviation becomes zero. According to the statistical criterion prescribed in the GTR No. 22, this would result in a pass decision, and the monitor reading would be considered correct and within the tolerance defined in the GTR No. 22. (A = 5%). Table 6 resumes the calculation steps and the obtained result.

Table 6. GTO No. 22 calculation steps and the obtained result.

Vehicle Tested	$SOCE_{read}$ (%)	$SOCE_{meas}$ (%)	x_i (%)	Pass Boundary (%)	Fail Boundary (%)	X_{test} (%)	Decision
1	78	73.4	4.6			4.6	
2	78	73.4	4.6			4.6	
3	78	73.4	4.6	5	5	4.6	PASS

This is just an example case that oversimplifies the situation since the vehicles sampled from the field that will be encountered during the verification of the SOCE/SOCR monitor will be statistically dispersed. In order to also take into consideration this aspect, another example is reported here where two normal distributions are created around the $SOCE_{meas}$ and $SOCE_{read}$ values with a standard deviation of sd = 1.56. Figure 4 shows the normalized probability histograms of the generated distributions, where it is noted that they are only partially overlapping (shaded area) and the average of the $SOCE_{meas}$ distribution is below the $SOCE_{read}$ one. In Table 7, additional information on the distribution quantiles is reported. Iterations of a random sampling over the two distributions are then performed to obtain $SOCE_{meas}$ and $SOCE_{read}$ couples. The GTR statistic was applied for each iteration, and the pass-or-fail decision was recorded for each given sample size.

Table 7. Additional information on generated $SOCE_{meas}$ and $SOCE_{read}$ distributions.

	Minimum (%)	1st Quarter (%)	Median (%)	Mean (%)	3rd Quarter (%)	Maximum (%)	Std. Deviation (%)
$SOCE_{meas}$	67.086	72.356	73.428	73.415	74.488	79.005	1.56
$SOCE_{read}$	72.061	76.937	77.992	77.986	79.048	83.448	1.56

In Figure 5, the cumulative pass curve obtained as a function of the sample size is plotted for this sampling. Table 8 shows the corresponding numerical values for completeness. About 5% of the samples reached a pass decision with an accepted monitor value with a sample size of three. The cumulative percentage of acceptance grew to about 65%, which is the acceptance probability with a sample size of up to 16 vehicles. Since the two generated distributions are not completely overlapping, not all the iterations gave a pass decision; this is due to the characteristic of the developed method aiming at avoiding false passes.

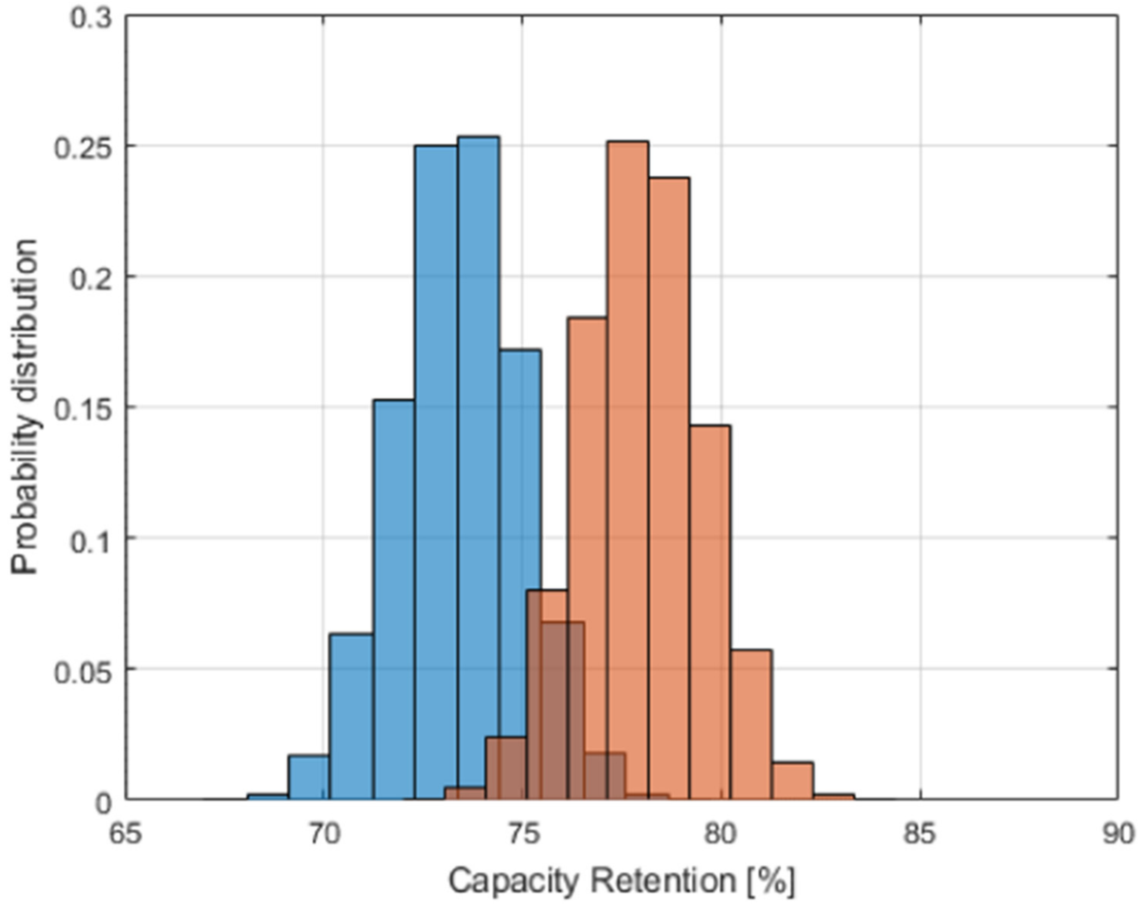

Figure 4. Normalized probability histograms of the generated $SOCE_{meas}$ (blue) and $SOCE_{read}$ (orange) normal distributions.

μ(SOCEmeas) = 73.4; μ(SOCEread) = 78; σ = 1.56

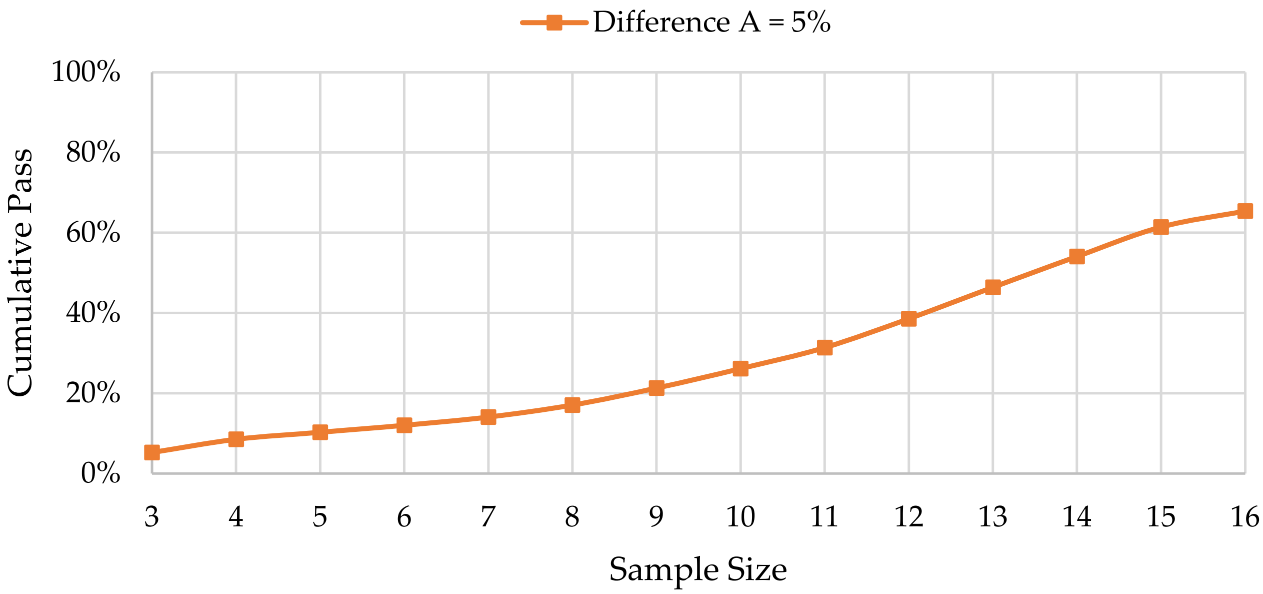

Figure 5. Cumulative pass curve as a function of sample size after iterative sampling $SOCE_{read}$ and $dSOCE_{meas}$ from generated normal distributions and applying the GTR No. 22 Part A statistics.

Table 8. Cumulative pass values.

Sample Size	3	4	5	6	7	8	9	10	11	12	13	14	15	16
Pass rate (%)	5.25	3.30	1.75	1.75	2.05	3.00	4.20	4.85	5.25	7.20	7.80	7.70	7.35	3.95
Cumulative Pass rate (%)	5.25	8.55	10.30	12.05	14.10	17.10	21.30	26.15	31.40	38.60	46.40	54.10	61.45	65.40

4. Discussion and Conclusions

The present work introduces the testing procedures for the in-vehicle battery durability assessment outlined in the new UN ECE GTR No. 22., aiming to verify its applicability on an electric vehicle and illustrating the results obtained with a testing campaign on a JRC property aged battery electric vehicle.

According to GTR No. 22, future off-vehicle charging hybrid electric vehicles and pure electric vehicles will have monitors indicating the actual state of health of the battery pack to the customers, expressed in terms of state of certified energy and state of certified range. The accuracy of these monitors will be confirmed by testing up to 16 vehicles for each vehicle family and applying a statistical procedure (Part A of the GTR 22), while the battery aging at specific years and kilometers will be controlled against minimum performance requirements by remotely collecting the available monitor values from a large number of vehicles within a family (Part B of the GTR No. 22).

To measure the remaining usable battery energy and driving range of the tested vehicle, the WLTP procedure has been applied. The measured SOCE and SOCR values have been calculated, and the results were compared with certification values. In Section 3.3, an exercise was performed to apply the GTR No. 22 Part A statistics, used to validate the accuracy of the SOCE/SOCR monitor values. Since the vehicle was registered in 2015, and the new GTR No. 22 is still not enforced, the value of the monitor has been approximated with a SOH channel retrieved from the vehicle CAN bus.

Moreover, it was possible to test only one aged vehicle.

Despite the assumptions, the test campaign proved the applicability of the testing method and statistical analysis, as described in Part A of GTR No. 22.

The study can be extended in the future by collecting experimental data points for more aging steps of the same vehicle over the course of many years or for different aged vehicles.

For what concerns the UN GTR, future developments will foresee the extension of the in-vehicle battery durability regulation to other classes of vehicles, such as heavy-duty electrified vehicles, guaranteeing that battery performance will be controlled over time and usage for this important market share of vehicles as well. Making sure each vehicle battery lasts longer would also help ease the pressure on in-demand critical raw materials needed for their production and reduce waste from used batteries [25].

Author Contributions: Conceptualization, methodology, formal analysis, data curation, E.P.; writing—original draft preparation, G.L.P.; writing—review and editing, E.P.; review and editing, G.L.P. and E.P. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Data Availability Statement: The data presented in this study are available upon request from the corresponding author.

Acknowledgments: The authors would like to acknowledge the essential contribution of the JRC VELA laboratory staff.

Conflicts of Interest: The authors declare no conflict of interest.

Disclaimer: The opinions expressed in this manuscript are those of the authors and should in no way be considered to represent an official opinion of the European Commission.

Abbreviations

BEV	Battery electric vehicle
CAN	Controller area network
CCT	Consecutive Cycle Test
CSS	Constant speed segment
EVE	Electric Vehicles and Environment
GTR	Global Technical Regulation
HVAC	Heating, Venting, and Air Conditioning
ICE	Internal combustion engine
IWG	Informal Working Group
JRC	Joint Research Centre
MPR	Minimum performance requirement
NEDC	New European Driving Cycle
OVC-HEV	Off-vehicle charging hybrid electric vehicle
SOH	State of health
SOCE	State of certified energy
SOCR	State of certified range
STP	Shortened test procedure
UBE	Usable battery energy
UN ECE	United Nations Economic Commission for Europe
V2X	Vehicle to Everything
VELA	Vehicle emission laboratories
WLTP	Worldwide Harmonized Light-duty Test Procedure

Appendix A

The calculations and tabulated parameters of GTR No. 22 [15] used in Part A to make a decision on the accuracy of SOCE/SOCR monitor values based on confidence intervals are reported in this Appendix. Distinct statistics shall be considered for the SOCR and the SOCE monitor, here named indefinitely as SOC. A sufficient number of vehicles (at least 3 and not more than 16) shall be sampled from the same monitor family for testing, following a vehicle survey containing information designed to ensure that the vehicle has been correctly used and maintained according to the manufacturer's specifications [15]. For evaluating the SOCE/SOCR monitors, normalized values shall be calculated for each sample:

$$x_i = SOC_{read,i} - SOC_{measured,i}$$

where $SOC_{read,i}$ is the onboard SOCE/SOCR read, and $SOC_{measured,i}$ is the measured SOCE/SOCR of the vehicle i.

For the total number of N tests and the normalized values of the tested vehicles, x_1, x_2, $\ldots x_N$, the average X_{tests} and the standard deviation s shall be determined:

$$X_{tests} = \frac{(x_1 + x_2 + x_3 + \ldots + x_N)}{N}$$

$$s = \sqrt{\frac{(x_1 - X_{tests})^2 + (x_2 - X_{tests})^2 + \ldots + (x_N - X_{tests})^2}{N-1}}$$

For each N tests $3 \leq N \leq 16$, one of the three following decisions can be reached, where the factor A shall be set at 5 percent:

(a) Pass the family if $X_{tests} \leq A - (t_{P1,N} + t_{P2,N}) \cdot s$;
(b) Fail the family if $X_{tests} > A + (t_{F1,N} - t_{F2}) \cdot s$;
(c) Take another measurement if:

$$A - (t_{P1,N} + t_{P2,N}) \cdot s < X_{tests} \leq A + (t_{F1,N} - t_{F2}) \cdot s$$

where the parameters $t_{P1,N}$, $t_{P2,N}$, $t_{F1,N}$, and t_{F2} are taken from Table A1 [15].

Table A1. Pass/fail decision criteria for the sample size [15].

Tests (N)	PASS		FAIL	
	$t_{P1,N}$	$t_{P2,N}$	$t_{F1,N}$	t_{F2}
3	1.686	0.438	1.686	0.438
4	1.125	0.425	1.177	0.438
5	0.850	0.401	0.953	0.438
6	0.673	0.370	0.823	0.438
7	0.544	0.335	0.734	0.438
8	0.443	0.299	0.670	0.438
9	0.361	0.263	0.620	0.438
10	0.292	0.226	0.580	0.438
11	0.232	0.190	0.546	0.438
12	0.178	0.153	0.518	0.438
13	0.129	0.116	0.494	0.438
14	0.083	0.078	0.473	0.438
15	0.040	0.038	0.455	0.438
16	0.000	0.000	0.438	0.438

References

1. International Energy Agency IEA. Global EV Outlook 2023. 2023. Available online: https://www.iea.org/reports/global-ev-outlook-2023 (accessed on 3 August 2023).
2. European Environment Agency. Greenhouse Gas Emissions from Transport in Europe. Available online: https://www.eea.europa.eu/ims/greenhouse-gas-emissions-from-transport (accessed on 3 August 2023).
3. European Commission. Paris Agreement COP21. 2015. Available online: https://climate.ec.europa.eu/eu-action/international-action-climate-change/climate-negotiations/paris-agreement_en (accessed on 3 August 2023).
4. European Commission. European Green Deal. Available online: https://ec.europa.eu/commission/presscorner/detail/en/ip_19_6691 (accessed on 3 August 2023).
5. European Commission. Sustainable and Smart Mobility Strategy—Putting European Transport on Track for the Future. 9 December 2020. Available online: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:52020DC0789 (accessed on 3 August 2023).
6. European Commission. Sustainable Mobility the European Green Deal. December 2021. Available online: https://ec.europa.eu/commission/presscorner/detail/en/fs_19_6726 (accessed on 3 August 2023).
7. Bloomberg NEF. Electric Vehicle Outlook 2022. 2022. Available online: https://about.bnef.com/electric-vehicle-outlook/ (accessed on 3 August 2023).
8. Miao, Y.; Hynan, P.; von Jouanne, A.; Yokochi, A. Current Li-Ion Battery Technologies in Electric Vehicles and Opportunities for Advancements. *Energies* **2019**, *12*, 1074. [CrossRef]
9. Dechent, P.; Epp, A.; Jöst, D.; Preger, Y.; Attia, P.M.; Li, W.; Sauer, D.U. ENPOLITE: Comparing Lithium-Ion Cells across Energy, Power, Lifetime, and Temperature. *ACS Energy Lett.* **2021**, *6*, 2351–2355. [CrossRef]
10. Thomas Merichko (FEV North America Inc.). Battery Durability in Electrified Vehicle Applications: A Review of Degradation Mechanisms and Durability Testing. 2016. Available online: https://wiki.unece.org/download/attachments/29884985/EVE-18-04e.pdf?api=v2 (accessed on 3 August 2023).
11. Broussely, M.; Biensan, P.; Bonhommeb, F.; Blanchard, P.; Herreyre, S.; Nechev, K.; Staniewicz, R. Main aging mechanisms in Li ion batteries. *J. Power Sources* **2005**, *146*, 90–96. [CrossRef]
12. Keil, P.; Jossen, A.; Kowal, J. *Aging of Lithium-Ion Batteries in Electric Vehicles*; Technische Universität München—Fakultät für Elektrotechnik und Informationstechnik: München, Germany, 2017.
13. Preger, Y.; Barkholtz, H.M.; Fresquez, A.; Campbell, D.L.; Juba, B.W.; Romàn-Kustas, J.; Ferreira, S.R.; Chalamala, B. Degradation of Commercial Lithium-Ion Cells as a Function of Chemistry and Cycling Conditions. *J. Electrochem. Soc.* **2020**, *167*, 120532. [CrossRef]
14. UNECE; GRPE. Working Party on Pollution and Energy. 2023. Available online: http://www.unece.org/trans/main/wp29/meeting_docs_grpe.html (accessed on 3 August 2023).
15. UN GTR No. 22. In-Vehicle Battery Durability for Electrified Vehicles. 2023. Available online: https://unece.org/transport/documents/2022/04/standards/un-gtr-no22-vehicle-battery-durability-electrified-vehicles (accessed on 3 August 2023).
16. GRPE. *Proposal for a Final Status Report on the Development of a New UN Global Technical Regulation on In-Vehicle Battery Durability for Electrified Vehicles*; UNECE: Geneva, Switzerland, 2021.
17. UNECE. *Special Resolution No. 1 Concerning the Common Definitions of Vehicle Categories, Masses and Dimensions*; TRANS/WP.29/1045; UNECE: Geneva, Switzerland, 2005.
18. UNECE. Global Technical Regulation No. 15 Worldwide Harmonized Light Vehicles Test Procedure. 2014. Available online: https://unece.org/sites/default/files/2022-06/ECE-TRANS-180a15am6e.pdf (accessed on 3 August 2023).

19. Patrone, G.L.; Paffumi, E.; Otura, M.; Centurelli, M.; Ferrarese, C.; Jahn, S.; Brenner, A.; Thieringer, B.; Braum, D.; Hoffmann, T. Assessing the Energy Consumption and Driving Range of the QUIET Project Demonstrator Vehicle. *Energies* **2022**, *10*, 1290. [CrossRef]
20. European Commission. Vehicle Emissions Laboratories. Available online: https://ec.europa.eu/jrc/en/research-facility/vehicle-emissions-laboratory-vela (accessed on 3 August 2023).
21. De Gennaro, M.; Paffumi, E.; Martini, G.; Manfredi, U.; Vianelli, S.; Ortenzi, F.; Genovese, A. Experimental Test Campaign on a Battery Electric Vehicle: Laboratory Test Results (Part 1). *SAE Int. J. Altern. Powertrains* **2015**, *4*, 100–114. [CrossRef]
22. Paffumi, E.; De Gennaro, M.; Martini, G.; Manfredi, U.; Vianelli, S.; Ortenzi, F.; Genovese, A. Experimental Test Campaign on a Battery Electric Vehicle: On-Road Test Results (Part 2). *SAE Int. J. Altern. Powertrains* **2015**, *4*, 277–292. [CrossRef]
23. European Commission. Commission Regulation (EU) 2017/1151 of 1 June 2017 Supplementing Regulation (EC) No 715/2007 of the European Parliament and of the Council on Type-Approval of Motor Vehicles with Respect to Emissions from Light Passenger and Commercial Vehicles (Euro 5 and Euro 6) and on Access to Vehicle Repair and Maintenance Information, Amending Directive 2007/46/EC of the European Parliament and of the Council, Commission Regulation (EC) No 692/2008 and Commission Regulation (EU) No 1230/2012 and Repealing Commission Regulation (EC) No 692/2008. *Off. J. Eur. Union* **2017**, L175. Available online: https://eur-lex.europa.eu/eli/reg/2017/1151/oj (accessed on 3 August 2023).
24. UN Regulation No 154. Available online: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A42021X2039 (accessed on 3 August 2023).
25. UNECE. Major Auto Markets Join Forces for Draft UN Legislation on Electric Vehicle Battery Durability. Press Release. Available online: https://unece.org/circular-economy/press/major-auto-markets-join-forces-draft-un-legislation-electric-vehicle-battery (accessed on 3 August 2023).