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Energy Storage

JRC Opinion

On vibration test procedure and profile for the UNECE Global Technical Regulation No. 20 on Electric Vehicle Safety - Phase 2

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Opinion basis

This document summarises information gathered by JRC on the subject matter “vibration test procedure and profile” following a discussion within an Informal Working Group (IWG) tasked with the development of phase 2 text of the UN ECE’s Global Technical Regulation No. 20 (GTR No. 20) on electric vehicle safety (EVS) and provides the JRC opinion on the subject.

Information from the following sources has been taken into consideration:

- Relevant presentations shared by Contracting Parties (CPs), such as China, OICA (International Organization of Motor Vehicle Manufacturers) and Japan, in the context of the GTR on EVS meetings (see Annex I and references therein)
- Relevant standards and regulations (see Annex I and references therein, Annex II)
- Technical scientific data (open scientific literature) relevant to the subject matter (see Annex I and references therein)

JRC Opinion

The vibration test within the GTR-EVS is an “in-use” test of the rechargeable electric energy storage system (REESS), which is likely to experience vibrations during its operation potentially resulting in a safety hazard.

JRC would agree to keeping a vibration test in GTR, considering it a minimum safety requirement. Nevertheless, this minimum safety requirement could be adjusted by making the vibration profile more representative of what a battery is typically exposed to in an electric vehicle (EV).

JRC would be in favor to allow for manufacturer vibration test profiles to be applied in the context of the GTR, with vibration profile based on vehicle-specific vibration inputs. In that case, manufacturer’s vibration test profiles should be accompanied with the appropriate justification documentation – the corresponding necessary information and guidelines should be discussed and agreed in the GTR-EVS.

Field-testing measurements of vibrations in the vertical, longitudinal and transversal direction (see e.g., China’s and Japan’s measurements (see references 18, 20)) revealed that vibration loads in x- and y-directions are almost 50-70% of the ones in z-direction, but resonance peaks at different frequencies in different directions can be seen, suggesting vibration test in 3 directions makes sense; one could also explicitly suggest that vibration test could be done simultaneously in all 3 directions (if instrumentation allows).

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If a random vibration test profile would be considered as an alternative to the current GTR No.20 sine wave test profile, JRC could agree on the lower and upper frequency values, i.e., 5 Hz and 200 Hz, respectively, as proposed in both China's and OICA's proposals (see reference 16).

Regarding the testing conditions, JRC is in favor of performing the vibration test at the maximum normal operating state of charge (SOC), whereas for the temperature, JRC is in favor of requiring test at room temperature, defined as 22ºC±5ºC for the REESS-level tests in the current GTR No.20.

Based on the data shared by China on the vibration test parameters and profiles, JRC would be in favor of requiring different vibration test parameters for category M1, N1 vehicles as compared to vehicles of other categories. Nevertheless, JRC would welcome more data, also from other stakeholders, to demonstrate the need for such differentiation and to define the vibration test parameters for vehicles of categories other than M1, N1.

Annex I

Analysis

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1. Introduction and background

Vibration is an (external) influence of mechanical nature; it can produce noise, wear and physical distortion by loosening parts or by causing motion between parts in a specimen, which can result in fatigue and failure of mechanical parts. Understanding the mechanical (and vibration) behavior of batteries is critical to improve battery safety since mechanical failure due to e.g. vibrations may directly lead to short-circuits.

Vibration testing (in general) can be conducted to either:

- inform on life performance and verify that the device under test (DUT) will function as designed (or specified) during its expected lifetime (seen as an accelerated stress test)
- find the dynamic properties of the DUT by examining the response to a vibrational force. (this concept is found for instance in determination of the ability to transmit or damp vibrations or in the description of the vibrational modes of a structure at resonances)
- inform on the reliability of the DUT, i.e., the DUT will not constitute a danger to persons during its lifetime (seen as a reliability test)
- ensure that the DUT will not pose a danger during such events as when subjected to short but very high stresses (seen as an abuse or safety test)

Vibration tests have been of importance in the automotive industry for many years, used therein for car components as well as for the whole vehicle, whereas the fatigue failure caused by vibrations is a common problem in electrical power systems.

There is evidence suggesting that the electrical performance and mechanical properties of the lithium-ion cells of an electric vehicle (EV) are affected by road roughness-induced vibrations. Zhang et al. (2017) [1] examined changes in the electrical performance of lithium-ion cells before and after vibration tests using the load profile of the SAE J2380[2] standard. It is also reasonable to suspect that the electrical performance of battery cells would be affected by the structural deformation and cracks inside cells induced by vibration loading[3, 4]. As it was also reported in Li et al. (2019)[5], "*cells operated under vibration stress show a larger ohmic resistance, a higher release of heat, a lower rate of OCV recovery and a higher rate of capacity degradation than the cells under aging and and others. Moreover, the internal impedance of each cell is also changed*

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[1] Zhang, L.; Ning, Z.; Peng, H.; Mu, Z.; Sun, C. Effects of Vibration on the Electrical Performance of Lithium-Ion Cells Based on Mathematical Statistics. *Appl. Sci.* 2017, *7*(8), 802; https://doi.org/10.3390/app7080802

[2] SAE J2380: Vibration Testing of Electric Vehicle Batteries, 2013 (J2380-201312).

[3] Brand, M.; Schuster, S.; Bach, T.; Fleder, E.; Stelz, M.; Glaser, S.; Muller, J.; Sextl, G.; Jossen, A. Effects of vibrations and shocks on lithium-ion cells. J. Power Sources 2015, 288, 62-69.

[4] Wang, D.; Wu, X.; Wang, Z.; Chen, L. Cracking causing cyclic instability of LiFePO4 cathode material. J. Power Sources 2005, 140, 125–128.

[5] W. Li *et al.*, Study on Performance Characterization Considering 6-DOF Vibration Stress and Aging Stress for EV Battery, IEEE Access 7 (2019) 112180-112190; *DOI: 10.1109/ACCESS.2019.2935380.*

because of vibration stress". Hooper and Marco focused their studies[6, 7, 8, 9, 10] on the vibration durability of lithium-ion batteries with different load profiles and in another study[11], the authors defined a process to devise random power spectral density (PSD) profiles utilising vibration measurements from three contemporary EVs for undertaking vibration durability evaluations of underfloor mounted rechargeable energy storage systems (RESS). Hooper and Marco[6] derived test profiles for assessing battery durability over a 100000 miles vehicle life, experimentally assessed the influence of different road types and reported results from commercially available EVs – Leaf, iMiEVand Smart ED.

Although vibration test is not a safety test per se, the effects produced by vibration may alter battery cells in a way that can lead to safety events (see e.g., Hong et al., 2014[12]).

Vibration tests of lithium-ion batteries are important for transportation purposes[13] and a requirement when considering Rechargeable Electrical Energy Storage Systems (REESS) safety under normal operation by the Global Technical Regulation (GTR) No.20 on Electric Vehicle Safety (EVS) of the United Nations Economic Commission for Europe (UNECE) (see Article 6.2.2 of the UNECE GTR on EVS - Phase 1), whereas the vibration profile is one of the main topics being discussed under Phase 2[14] to be delivered in 2021, as also pointed out in the latest contracting parties (CP) meeting (13 November 2020; web meeting). The current vibration test procedure and profile in GTR No.20 (Phase 1) directly follows UNECE's R100.02 requirements.

The purpose of this test is to verify the safety performance of the REESS under a vibration environment that the REESS will likely experience during the normal operation of the vehicle and shall be conducted either with the complete REESS or with REESS subsystem(s). If the manufacturer chooses to test with REESS subsystem(s), the manufacturer shall demonstrate that the test result can reasonably represent the performance of the complete REESS with respect to

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[6] Hooper, J.; Marco, J. Characterising the in-vehicle vibration inputs to the high voltage battery of an electric vehicle. J. Power Sources 2014, 245, 510–519.

[7] Hooper, J.; Marco, J. Experimental modal analysis of lithium-ion pouch cells. J. Power Sources 2015, 285, 247–259.

[8] Hooper, J.; Marco, J.; Chouchelamane, G.; Lyness, C. Vibration durability testing of nickel manganese cobalt oxide (NMC) lithium-ion 18650 battery cells. Energies 2016, 9, 52.

[9] Bruen, T.; Hooper, J.; Marco, J.; Gama, M.; Chouchelamane, G. Analysis of a battery management system (BMS) control strategy for vibration aged nickel manganese cobalt oxide (NMC) lithium-Iion 18650 battery cells. Energies 2016, 9, 255.

[10] Hooper, J.; Marco, J.; Chouchelamane, G.; Lyness, C.; Taylor, J. Vibration durability testing of nickel cobalt aluminum oxide (NCA) lithium-ion 18650 battery cells. Energies 2016, 9, 281.

[11] Marco, J.M., Hooper, J., Defining a representative vibration durability test for electric vehicle (EV) rechargeable energy storage systems (RESS). In Proceedings of the Electric Vehicle Symposium (EVS 29), Montréal, QC, Canada, 19–21 June 2016.

[12] S-K. Hong, B. I. Epureanu, and M. P. Castanier, Parametric reduced-order models of battery pack vibration including structural variation and prestress effects, *J, Power Sources* 261 (2014) 101-111.

[13] UN 38.3, United Nations (UN) Recommendations on the Transport of Dangerous Goods, Manual of tests and criteria, 7th Revised edition (2019); 38.3.4.3.2 Test procedure; p 436.

[14] For more information on Phase 2: https://wiki.unece.org/pages/viewpage.action?pageId=3178628

its safety performance under the same conditions.

In the 19th EVS-GTR Informal Working Group (IWG) meeting in Berlin (5-9 December 2019) a discussion took place and focused on vibration test and profiles[15]:

- China commented that during phase 1 of the GTR vibration was considered a safety requirement and in Phase 2 aims to improve the profile to be more realistic.
- OICA recalled that its basic position is to drop the vibration test as there are no field issues due to vibration and noted that if CPs still wish to adopt vibration requirement, ISO profile should be considered.
- EC commented that the discussion in Phase 2 aims at addressing durability issues while for GTR phase 1, the profile of UN ECE R100.02 was simply copied.
- Chair advised that CPs should consider whether vibration should be a safety requirement or not and requested OICA to summarise their proposal and the rationale.
- Feedback from CPs on the different vibration profiles under consideration was requested.

Background information

In the 18th IWG -meeting in Tokyo, China, Japan and OICA had an in-depth discussion on vibration test and reached a basic consensus to continue discussion about a possible modification of the present GTR No.20 vibration method and whether it should remain in the GTR No. 20 at all. Currently, there are two proposals on vibration profile: the one proposed by China and the other proposed by OICA. In order to better promote the vibration profile modification, China, Japan and OICA had a web-meeting (October 18, 2019) to clarify each profile's purpose/concept and grounds (referred test data and derivation procedure) [16]. China reported the results of CN-JP-OICA discussion on the vibration profile (EVS19-HACT0400, EVS19-HACT0410) during the 19th IWG meeting (Berlin, December 5-9, 2019).

<u>The main content and views of China were:</u>

- ➢ China introduced the background and procedure of their proposal (more details can be found in "EVS1419-401.pptx" and "EVS1545-402 [CHN] EVS-GTR Vibration load proposal.pdf"), and concluded that they believed vibration effects are closely related to safety and should be retained in GTR regulation.
- ➢ China noted that the current vibration method in GTR No. 20 (Phase 1) regulation is not reasonable and should be modified.

<u>The main content and views of OICA were:</u>

[15] Final version of meeting minutes and action points; "EVS20-A07 [0212]EVS-19 Meeting minutes.docx". In: https://wiki.unece.org/display/trans/EVS+20th+session.

[16] Final version of draft meeting minutes of CN- JP-OICA web-meeting; "EVS19-HACT0400 [CN]Final version of draft meeting minutes of CN-JP-OICA web-meeting.docx"; In: https://wiki.unece.org/display/trans/EVS+19th+session.

- OICA noted that they do not agree vibration is related to safety and that taking a design reliability driving test specification is not the correct starting point for the development of a safety requirement.
- OICA suggested using the same approach as in ISO 6469-1:2019 to modify the current vibration method in GTR regulation, but allow OEM-specific test profiles and include the profile developed by China as an example of an OEM-specific profile.

The main views of Japan were:

- Japan noted that they hold a positive attitude to discuss the vibration profile for modification of GTR No.20 and will accept a revised test method if it is reasonable – they consider there are two candidates for an alternative GTR vibration profile. First, each profile's grounds need to be clarified, next, whatever is considered valid should be specified and adapted for the GTR, and finally it needs to be discussed.
- Japan noted that the relevant supporting materials of ISO 6469-1:2019 should be provided to clarify the referred test data and derivation procedures.

China and OICA presented their materials at the 19th IWG-meeting in Berlin (see also 5.3 REESS vibration profile in "EVS20-A07 [0212]EVS-19 Meeting minutes.docx"), whereas the ISO expert also presented the vibration test profile, which is part of ISO 6469-1 3rd edition of April 2019 (ISO 6469-1:2019[17]).

2. Comparison of vibration test requirements - China's vs. OICA's vs. current GTR No.20

As previously explained, China, Japan and OICA had a web meeting on October 18, 2019 to clarify each profile's purpose/concept and grounds (referred test data and derivation procedure) (see "EVS19-HACT0410 [CN]Report on the discussion of vibration in CN-JP-OICA web-meeting.pdf"). A graphical representation of the two proposals and the GTR No.20 vibration profile was reported and presented below (Figure 1) together with clarifications also reported during the web meeting (Figure 2).

[17] ISO 6469-1: Electrically propelled road vehicles - Safety specifications - Part 1: Rechargeable energy storage system (RESS), 2019.

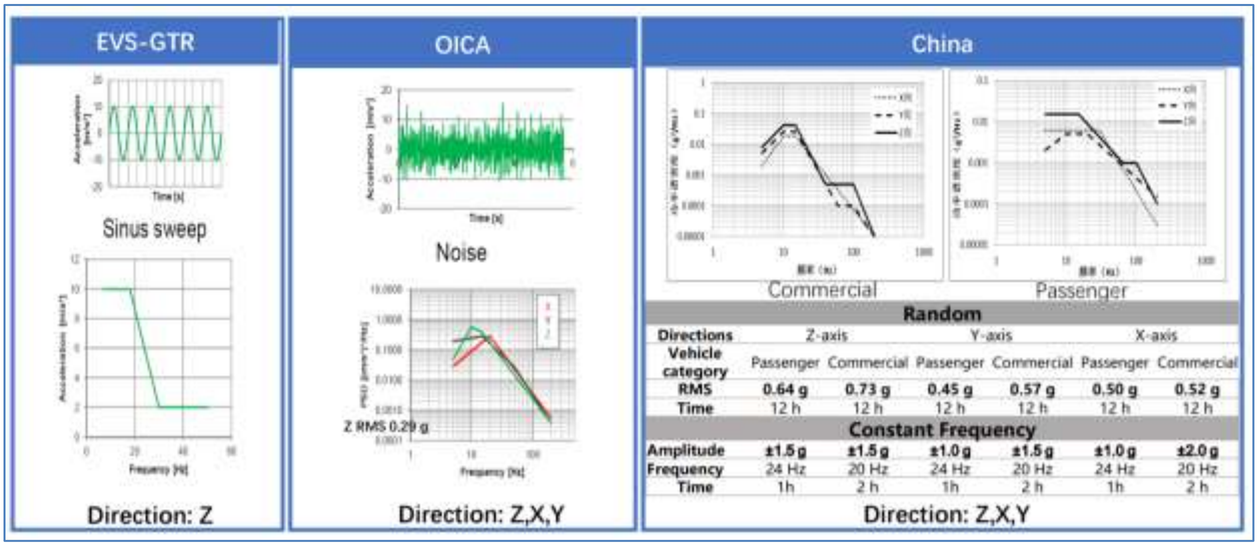


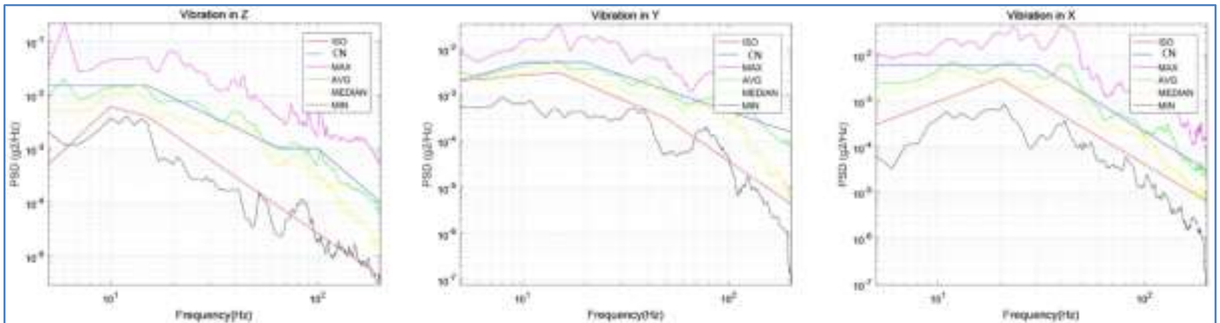
Figure 1. Current proposals of China and OICA as discussed in CN-JP-OICA web meeting GTR No.20 test profile is also depicted (Adopted from the final version of the draft meeting minutes of CN- JP-OICA web-meeting[16]) (1 g = 9.81 m/s^2 ; 1 g^2/Hz = 96.24 (m/s^2)^2/Hz)

Items		China proposal	OICA proposal
Concept of vibration test	Purpose of vibration test	Assurance over life time mileage	Detection of initial failures and design problems
	Assumed load condition	Average vibration input to REESSs in the market vehicles ⇩ Average value of PSD lines of test vehicles	Development of realistic minimum safety profile * LIVs of profiles are calculated and compared
Test vehicle	--	22 types of vehicles	74 measurements on different vehicles of different size and battery and from 5 manufactures
Rough road condition	Rough road types	9 types	Will be supplied later
	Driving condition (speed, time, range)	See the "EVS1419-401.pptx" for details	
	Rational of road conditions for international regulation		
Profile development	G measuring points	At least 4 sensors are fixed distributed at different installation points	
	Data processing	Extraction of max. G data Making PSD profile for each road Calculation of average PSD	
Vibration test time	Test structure	Random_12hr * 3 directions +Sinusoidal_1hr * 3 directions	
	Time acceleration	Applied (Life time rough road driving time is accelerated to 12hrs)	

Figure 2. Current proposals with clarifications on purpose/concepts and grounds as discussed by interested parties during CN-JP-OICA web meeting (Adopted from the final version of the draft meeting minutes of CN- JP-OICA web-meeting[16])

It was also reported (see "EVS19-HACT0410 [CN]Report on the discussion of vibration in CN-JP-OICA web-meeting.pdf") that OICA's proposal follows ISO 6469-1_6.2.2.1_Test option 1, whereas the China's proposal for the passenger vehicle type, is also specified in ISO 6469-1_6.2.2.2_Test option 2 (example of the OEM specific test).

China considers vibration is closely related to the safety of EVs and should be included in GTR: generally vibration causes structural and connection damage to the battery pack (a high voltage energy storage system), which can further cause external short circuits, eventually leading to safety problems. Therefore, China recommended modifying the existing test methods in GTR No.20 based on the road spectrum acquired from actual vehicle test data. Test results from 22 vehicles in operation in 9 different road types supported China's recommendations on vibration test conditions and profile, as presented in EVS19 (Berlin, 2019) [18], and are depicted in figure 3, also in comparison to ISO's (ISO 6469-1).



Direction	MAX	AVG	CN proposal	Median	ISO 6469-1	MIN
Z	1.3468	0.6364	0.6364	0.4821	0.2647	0.2060
Y	0.8922	0.4378	0.4378	0.3539	0.2520	0.1486
X	1.1094	0.4910	0.4910	0.3568	0.2343	0.1253

Figure 3. China proposal - Test results and recommended vibration test conditions (adopted from China's presentation in EVS19 (Berlin, 2019)[18]) (1 g = 9.81 m/s^2 ; 1 g^2/Hz = 96.24 $(m/s^2)^2/Hz$)

Additionally, a graphical comparison of the vibration profiles in Z-axis was presented by the ISO representative. ISO considers the proposed vibration profile, referred to as safety profile in ISO 64697-1 proposal - see Figure 4; hereafter as "option 1"), more realistic for passenger vehicle application over the UN ECE R100.02 (identical to GTR No.20 phase I) vibration profile. Additionally, ISO considers a vibration profile based on vehicle measurements (preferred) as an option 2, but only when it is not below the vibration profile option 1. ISO 6469-1 safety profile (option 1), as explained by the ISO expert, was chosen to be load equivalent to UN ECE R100.02.

[18] Review of the concept, test data and derivation procedures of China proposal. In: EVS19, Berlin, DE, December 2019; "EVS19-E3VP-0100 [CN]Review of the concept, test data and derivation procedures of China proposal.pdf"; https://wiki.unece.org/display/trans/EVS+19th+session.

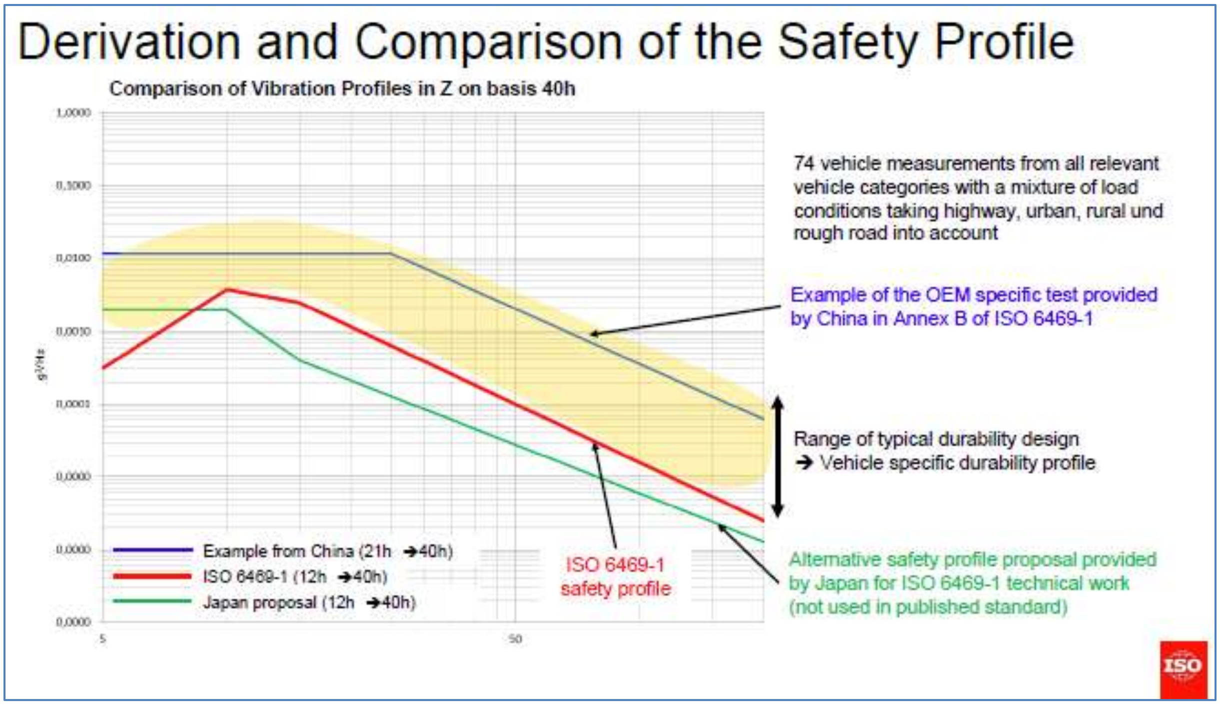


Figure 4. Comparison of China's and ISO 6469-1 vibration profiles in Z-axis including Japan's proposal for ISO 6469-1 (1 g = 9.81 m/s^2 ; 1 g^2/Hz = 96.24 $(m/s^2)^2/Hz$)

OICA supports the ISO 6469-1 vibration profile and test conditions to be considered for the modification of the current GTR No.20.

Japan, during the 19th IWG meeting in Berlin (December, 2019), provided their feedback on remaining questions to be answered by OICA[19], having already provided an analysis of China's proposal during the 18th IWG meeting in Tokyo (June, 2019)[20], as well as their position on the current GTR No. 20 vibration profile and test conditions and proposals on the option of using the manufacturer's vibration profile. Japan in their feedback pointed out the concerns on GTR No.20 sinusoidal vibration profile, such as no evaluation on X-/Y-direction and low maximum frequency of 50Hz, given that:

- There are still vibration loads above 50 Hz (see figure 5), which should not be ignored.
- Vibration loads in X- and Y-directions are almost 50-70% of the ones in Z-direction, which should not be ignored.

As shown in figures 5 and 6, China's data reveal higher PSD values than Japan's data and some peaks at several frequencies are observed (see figure 6). Further analysis is however needed to identify the cause of these differences.

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[19] Japan's Response to EVS19-E3VP-0200. In: EVS19, Berlin, DE, December 2019; "EVS19-E3VP-0201 [JP]Short Presentation – Response to EVS19-E3VP-0200.pptx"; https://wiki.unece.org/display/trans/EVS+18th+session.

[20] Japan comments on REESS Vibration Test. In: EVS18, Tokyo, JP, June 2019; "EVS18-E2VP-0100 [JP]Japan comments on REESS Vibration Test.pdf"; https://wiki.unece.org/display/trans/EVS+18th+session.

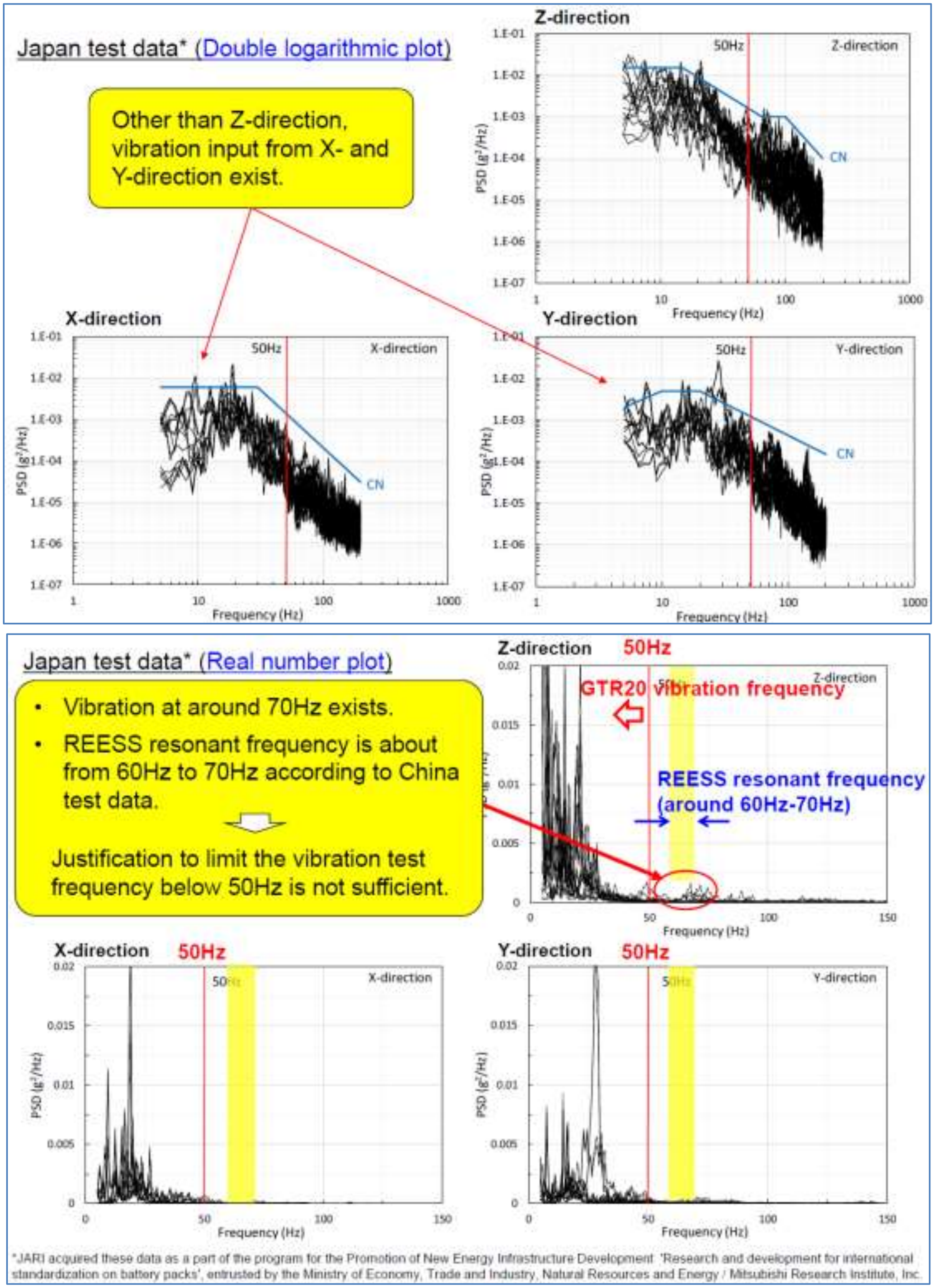
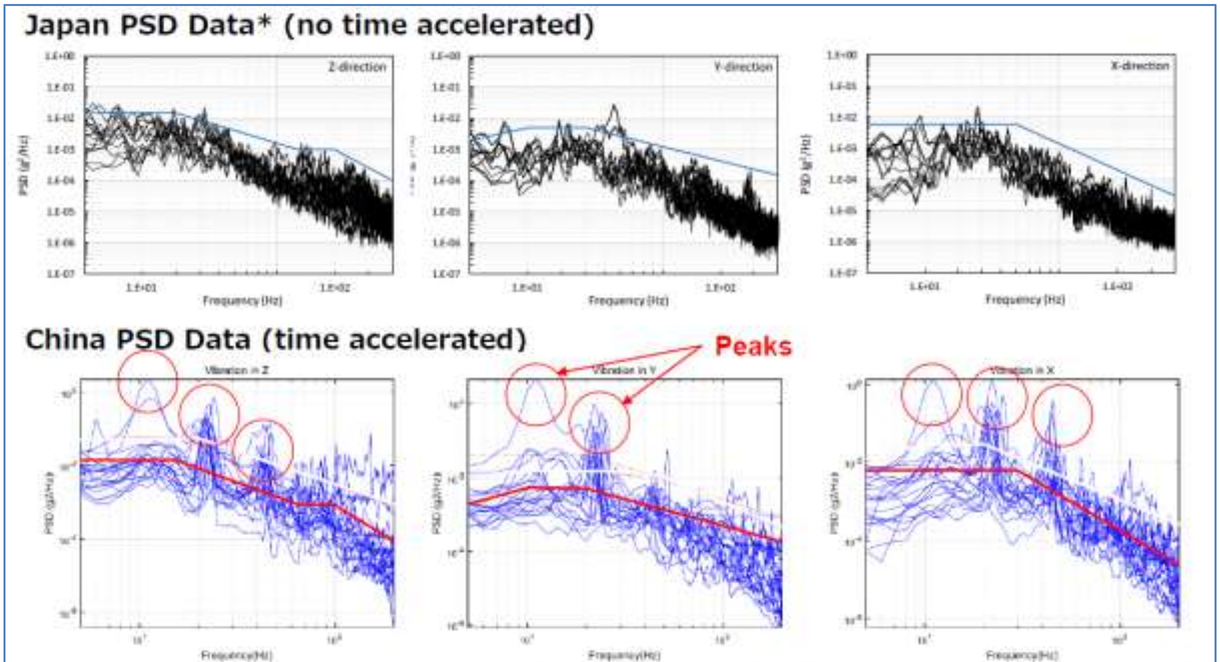


Figure 5. Japan test data: PSD vs. frequency plots (adopted from Japan's presentation in EVS18, (Tokyo, June 2019)[20]) (1 g = 9.81 m/s^2 ; 1 g^2/Hz = 96.24 $(m/s^2)^2/Hz$)



*JARI acquired these data as a part of the program for the Promotion of New Energy Infrastructure Development 'Research and development for international standardization on battery packs', entrusted by the Ministry of Economy, Trade and Industry, Natural Resources and Energy / Mitsubishi Research Institute, Inc.

Figure 6. Japan vs. China test data: PSD vs. frequency plots (adopted from Japan's presentation in EVS18, (Tokyo, June 2019)[20]) (1 g = 9.81 m/s^2 ; 1 g^2/Hz = 96.24 $(m/s^2)^2/Hz$)

Another point made by Japan in EVS18, (Tokyo, June 2019)[20] was that durability evaluation should not be the purpose of the GTR's vibration test and that REESS may break during vibration testing with time accelerated conditions (accelerated stress tests), as traction battery packs are commonly designed with little margin for mechanical stress.

3. Overview of vibration profiles and test conditions in existing regulations and standards

Ruiz et al. (2018)[21] presented recently an extensive survey of existing international and national testing standards and regulations for battery systems in electric and hybrid electric vehicles, where vibration profiles designed specifically for electric and hybrid electric vehicles were also reported: vibration test profiles in standards are adapted in most cases from IEC 60068-2-64:1993[22], SAE J2380:2013[2] and UN 38.3:2019 [13].

IEC 60068-2-64:1993 has been taken as the basis for IEC 62660-2(3):2018[23] (2016[24]), and UL 2580:2020[25]. It was also taken as the basis for ISO 12405-1(2):2011(2012), with both standards

[21] Ruiz V., A. Pfrang, A. Kriston, N. Omar, P. Van den Bossch, L. Boon-Brett, A review of international abuse testing standards and regulationsfor lithium ion batteries in electric and hybrid electric vehicles. Renewable and Sustainable Energy Reviews 81 (2018) 1427-1452.

[22] IEC 60068-2-64: Environmental testing Part 2: Test methods - Test Fh: Vibration, broad-band random (digital control) and guidance, 1993.

[23] IEC 62660-2: Secondary lithium-ion cells for the propulsion of electric road vehicles – Part 2: Reliability and abuse testing. Edition 2.0, 2018-12; ISBN 978-2-8322-6289-4.

[24] IEC 62660-3: Secondary lithium-ion cells for the propulsion of electric road vehicles – Part 3: Safety

however, now withdrawn. The general safety relevant tests and requirements, including vibration, are now given in ISO 6469-1:2019 instead. ISO 12405-3:2014 (withdrawn too) has been revised by ISO 6469-1:2019. The vibration with thermal cycling draft Society of Automotive Engineers (SAE) sequential test procedure (Shock/Vibration/Thermal Cycling) developed on behalf of the National Highway Traffic Safety Administration (NHTSA)[26, 27] (hereafter US proposal) took IEC 60068-2-64:1993 and ISO 16750-3:2003[28] as the basis for the vibration profile and sine sweep test parameters and conditions rationale. Additionally, for the random vibration of the US proposal profile and test conditions, guidance was solicited from ISO 16750-3, GMW 3172[29] and ISO 12405-1 in order to simulate what would reasonably be considered long term degradation. The US proposal[26, 27]), as is the case for ISO 12405-1(2) (now withdrawn) both required temperature cycling "*It shall be assumed that the battery pack or system design is especially affected by temperatures over its lifetime; therefore, the vibration testing (test time for each spatial direction) of the battery pack or system shall be superimposed by a temperature profile*".

SAE J2380:2013 is also widely used to define random vibration profiles and has been taken as the basis for SAE J2929:2013[30], UL 2580:2020 (module and pack level only), USABC:1999[31] and related FreedomCAR:2005[32] standards. SAE J2380:2013 reflects rough-road measurements at locations where traction batteries are likely to be installed in EVs/HEVs, equivalent to 100000 miles usage. As mentioned in Kjell and Lang (2013)[33], Hooper et al. (2014)[6], (2016)[8, 10], "*SAE J2380 is the only specification that is defined as a durability test*".

The vibration test profiles vary quite considerably over a wide range of frequencies and amplitudes (see Ruiz et al. (2018)[21]). Test conditions for the vibration test at cell (C), module

requirements. Edition 1.0, 2016-08; ISBN 978-2-8322-3576-8.

[25] UL 2580: UL Standard for Safety for Batteries for Use In Electric Vehicles, ANSI/CAN/UL/ULC 2580 Third Edition, March 11, 2020.

[26] Draft Society of Automotive Engineers (SAE) test procedure "(NHTSA) Vibration with Thermal Cycling - Version 6". In: GTR-EVS 6th session, Seoul, 18-20 November 2014. (EVS-06-37e.pdf); https://wiki.unece.org/display/trans/EVS+6th+session.

[27] Nguyen Nha, Shock/Vibration/Thermal Cycling, National Highway Traffic Safety Administration (NHTSA). In: GTR-EVS 8th session, Washington D.C., 3-5 June 2015. (EVS-08-15e.pdf); https://wiki.unece.org/display/trans/EVS+8th+session.

[28] ISO 16750-3:2003 - This specification describes the mechanical loads that can affect electric and electronic systems and components in respect of their mounting directly on or in road vehicles.

[29] GMW 3172 - This specification provides rationale for test methods common to the automotive industry and to devices used in Automobiles.

[30] SAE J2929: Safety standards for electric and hybrid vehicle propulsion battery systems utilizing lithium-based rechargeable cells. 2013.

[31] Unkelhaeuser T, Smallwood D. SAND99-0497-USABC: United States Advanced Battery Consortium Electrochemical Storage System Abuse Test Procedure Manual. 1999.

[32] Doughty DH, Crafts CC. SAND 2005-3123: FreeDomCAR electrical energy storage systems abuse test manual for electric and hybrid electric vehicle applications. 2005.

[33] Kjell, G. and Lang, J.F. Comparing different vibration tests proposed for Li-ion batteries with vibration measurement in an electric vehicle. In Proceedings of the World Electric Vehicle Symposium and Exhibition (EVS27), Barcelona, Spain, 17-20 November 2013; pp. 1-11.

(M), pack (P) and vehicle (V) level, adapted from Ruiz et al. (2018) (see Table 9 in Ruiz et al. (2018)[21]) and updated to reflect the current landscape are summarised in Table 1. In the same table, the ISO 6469-1 international standard and the national Chinese standard GB 38031:2020[34], as introduced in May 2020, are also included.

An important consideration is that a Li-ion traction battery (pack) contains several electrically connected modules (and multiple cells within each module) that in total can weigh up to several hundreds of kilograms depending on the pack design and EV needs. A battery pack not only has a significant weight and large dimensions but also contains small-size electronic components, thus resulting in a complex system, where vibrations can be found at a wide frequency range and may cause fatigue damages of different kinds. Large structures, as a full battery pack, exhibit low resonance frequencies, thus, a low-frequency excitation is suitable to testing them. On the other hand, small-size electronics exhibit high critical frequencies, thus, a high-frequency test will show if there is an associated risk related to the electronics in contact to the modules/cells. Assembling of battery cells within the pack is sensitive to high frequencies as vibration-induced displacement can cause the cells to burst and expose chemicals (Hong et al., 2014)[12] and in a worst-case scenario, a mechanical component failure caused by vibration can lead to a hard short circuit.

[34] GB 38031-2020: National Standard of the People's Republic of China. Electric vehicles traction battery safety requirements, May 2020.

Table 1. Test conditions for the vibration test at cell (C), module (M), pack (P) and vehicle (V) level (Adapted from Ruiz et al. (2018)[21]) and updated to reflect the current landscape).

Region of applicability	**International**				**EU and further countries** (see Ruiz et al. 2018)	**USA**				**India**	**China**
S&R / **Vibration parameters**	**SAE J2929*** **		**ISO 6469-1*** **	**IEC 62660-2(3)**	**UN ECE R100.02**	**UL 2580**		**USABC**	**Freedom CAR**	**AIS-048**[35]	**GB 38031:2020**
Level (C, M, P)	C M P		RESS/RESS subsystem	C	C M P	C	M$^{\#\#}$ P	C M P		M	P or System
Type of profile	Random	Sine wave	Random	Random	Sine wave logarithmic sweep	Random		$^{\#\#\#}$ or Sine wave or Random		Sine wave	Random + (Sinusoidal at fixed frequency)
Frequency range (Hz)	10-190*	7-200^{+}	5-200	10-2,000^{++}	7-50**	10-2,000^{++}	10-190*	10-190*		30-150	5-200 (24)
PSD wave random (m s^{-2})^2/Hz	0.4-11*		0.0004-0.5774	0.14-20^{++}		0.14-20^{++}	0.4-11*	0.4-11*			
Loading range sine wave (m s^{-2})		9.81-19.6 (>12 kg)$^{+}$ 9.81-78.5 (<12 kg)$^{+}$			2-10**			7-49		30	z-/x-/y-axis 14.72/9.81/9.81

[35] AIS-048: Battery Operated Vehicles - Safety Requirements of Traction Batteries. 2009.

Axis	Vertical, longitudinal, lateral	Three mutually perpendicular mounting positions of the cell	Vertical, longitudinal, transversal		Vertical		Vertical, longitudinal, lateral			Vertical axis and horizontal	Recommended loading sequence^, ^^: z-axis random and z-axis fixed, y-axis random and y-axis fixed, x-axis random and x-axis fixed frequency
SOC (% rated capacity)	95-100% max. normal vehicle operation		Max. normal operation SoC	80 (HEV) 100 (BEV)	>50 % normal operating range	80 (HEV) 100 (BEV)	100 & 20 (Z-sine, random) 60 (X & Y-sine, random)	100 & 20 (Z-sine, random) 60 (X & Y-sine, random)		100	>=50 % of normal working range specified by the manufacturer
Vehicle level (V)	SOC at normal vehicle operation										

PSD: Power spectral density, * based on SAE J2380. **Higher can be requested by manufacturer. *** A profile 'which reflects the application' may be used as alternative. [+]based on UN 38.3, [++]based on IEC 60068-2-64. [##] At the module level for those electric energy storage assemblies intended for use in applications larger than passenger vehicles. The module level testing shall be representative of the electric energy storage assembly. [###] Vibration endurance test in accordance with the anticipated end application vehicle vibration profile. ^ The testing bodies can also choose their own sequence to shorten the conversion time. ^^ The vehicle running direction is x-axis direction and other horizontal direction perpendicular to the running direction is Y-axis direction.

4. Comparison of vibration tests profiles using Sine sweep vibration profile

A sine sweep test is the common method used in automotive testing to quickly determine resonances within a DUT[36], which could cause failure under normal operating vibration conditions. As found in IEC 60068 2-64:2008, it is determined that a resonance point is any excitation of the DUT over two times the input excitation from the vibration stand.

Comparing the current GTR No.20 (and UNECE R100.02) to other standards, the loading value (peak acceleration of 10 m/s^2) is comparable to the one required by NHTSA (US proposal and lower than those required in SAE J2929, USABC and FreedomCAR (please refer to figure 7, notice that the level of testing is also included in the graph: C: cell, M: Module, P: Pack). Also lower than AIS-048 and QC/T 743[37] (Indian and Chinese standards with 30 g loading at M and P level, respectively). Typically, a sine profile with a constant acceleration value between 0.5 g to 2 g (typically 1 g) within the frequency range of the vibration test is used to determine the resonant frequencies of components[38]. This is the case for the fixed frequency sinusoidal vibration load part of the sequence of the of the GB 38031-2020 Chinese standard (see figure A2.5-1) and China's proposal under discussion for the GTR (see figure 1) too that should be applied in each direction sequentially (see figure A2.5-1), with a constant acceleration of 1.5 g (z-axis), 1 g (y-axis) and 1 g (x-axis) for M1 and N1 vehicles.

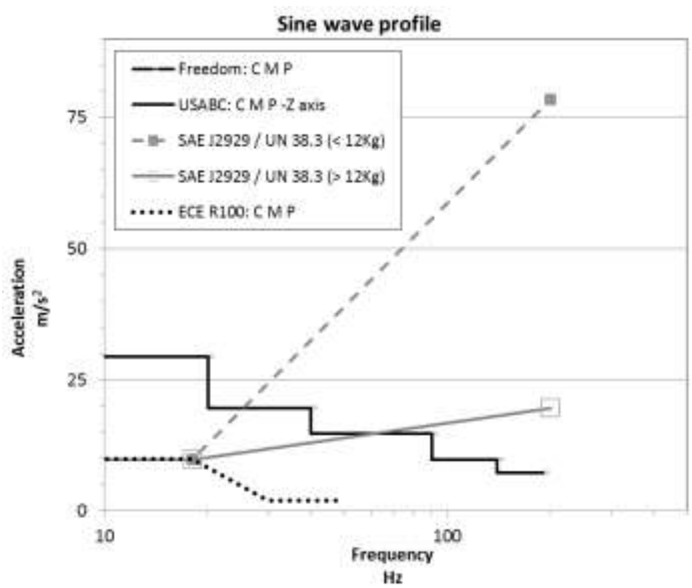


Figure 7. Comparison of sine wave testing profiles for various standards and regulations (adapted from Ruiz et al. (2018)[21])

[36] Mechanical resonances are the tendency of a mechanical system to absorb more energy when the frequency of its oscillations matches the system's natural frequency of vibration than it does at other frequencies. It may cause violent swaying motions and even catastrophic failure in improperly constructed RESS resulting in very dangerous and life threatening situations.

[37] QC/T 743: Lithium – ion batteries for electric vehicles Chinese voluntary standards for automobiles. 2006.

[38] Harrison, T., Resonance. Vibration Testing. Vol. 5. 2014, Naerum, Denmark: Bruel and Kjaer.

Regarding frequency range, the UNECE R100.02 (and the GTR No. 20) requires testing from 7 Hz up to 50 Hz, whereas the Chinese standard (GB 38031-2020) and proposal under discussion for the GTR both require testing in 3 directions for the fixed frequency sinusoidal vibration load part of the sequential test procedure at 24 Hz (for 1 h) and 20 Hz (for 2 h) for passenger and commercial vehicles respectively. NHTSA (US proposal)[26, 27] proposed to test from 10 Hz up to 1000 Hz for the Sine sweep part of their sequential test procedure. Looking into other standards, it can be seen that in most of the cases, testing reaches around 200 Hz for the non-random vibration profiles (this is the case of SAE J2929 = UL 2580 (M, P), USABC, FreedomCAR, AIS-048 and QC/T 743). As specified in UN 38.3 (similar to SAE J2929), aiming at simulating vibration during transport and ensuring their safe transport, for batteries with a gross mass of more than 12kg, from 7 Hz to a peak acceleration of 1 g is maintained until 18 Hz is reached. The amplitude is then maintained at 0.8 mm and the frequency increased until a peak acceleration of 2 g occurs (approximately 25 Hz). A peak acceleration of 2 g is then maintained until the frequency is increased to 200 Hz.

Based on this comparison, the value set in the GTR No.20 for the upper frequency limit is smaller compared to the other standards' upper frequency depicted in Figure 7 (i.e., 200 Hz). On the lower frequency side, Hooper et al. (2014)[6] suggested the need for testing in the 0-7 Hz range (range that it is not assessed by recognised standards and regulations).

Although sinusoidal vibration profiles have been specified by many vibration test standards and the existing regulations for the evaluation of RESS and RESS subassemblies, they do not represent accurately in-service vibrations experienced by chassis-mounted automotive components – they are better suited to the assessment of automotive components mounted onto e.g. internal combustion engines (see e.g. Hooper et al. (2016)[10] and references therein).

5. **Comparison of vibration test profiles using a random vibration profile**

For a more realistic simulation of automotive chassis-mounted components, which are excited by road-induced vibrations, a random vibration profile can be applied. Random vibration excites a defined band of frequencies, as such, resonant frequencies within the DUT are excited regularly and together, subsequently causing interactions, which typically would not occur within a sine vibration test (see e.g. Hooper et al. (2016) [10] and references therein).

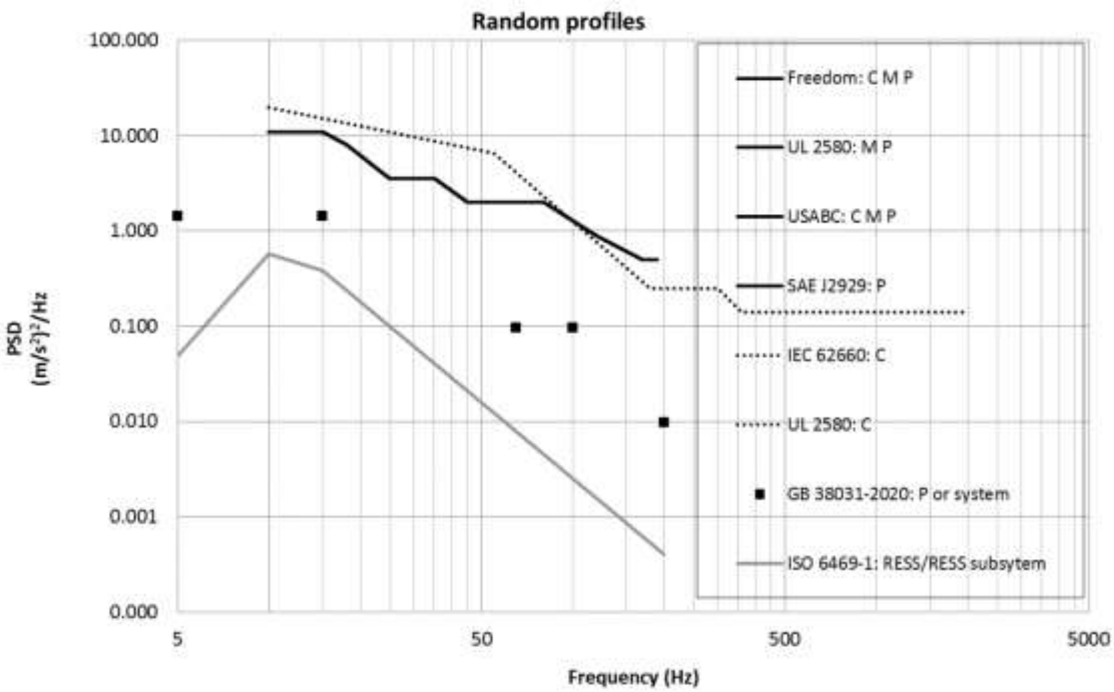


Figure 8. Comparison of random vibration profiles PSD vs. Frequency – logarithmic plot) for various standards and regulations

By a closer look at the frequency range, the test of battery cells according to IEC62660-2 calls for random vibration in the frequency range 10-2000 Hz, which is by far the widest range among the standards; UL 2580 specifies the same frequency range for cells too. Other standards, requiring testing at frequencies up to 200 Hz, are applied to battery packs (see Table 1).

According to Kjell and Lang (2013)[33], regulations and standards specify vibration tests and associated profiles not consistent with results from field vibration testing. For instance, UNECE R100.02 (and the current GTR No. 20) prescribes testing only in the vertical direction and the upper frequency is 50 Hz. GTR sets however minimum safety requirements. Manufacturers can use own vibration profiles. SAE J2380, SAE J2929, UL 2580 and USABC require testing from 10 Hz up to 190 Hz. As these standards are applicable to testing packs and modules, which can have low resonance frequencies, 10 Hz is a rather high lower frequency; both the ISO 6469-1:2019 and GB 38031:2020 start at 5 Hz. On the other hand, according to Kjell and Lang (2013)[33], 200 Hz is a rather low upper frequency as packs and modules can contain a substantial bill of small electronic components.

Annex II

Existing regulations and selected standards

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A1. Existing regulations

A1.1 UNECE R100.02 (and GTR No.20 Phase 1)

A vibration test for the complete pack or subsystems is required by this regulation, where a sine sweep test in the vertical direction between 7 Hz and 50 Hz is specified. Up to 18 Hz, the acceleration should be 1 g and then decreasing and between 30 Hz and 50 Hz the acceleration should be 0.2 g. UNECE R100.02 requires only testing in the vertical direction up to 50 Hz, at a rather low excitation level. Pass/fail criteria include no evidence of rupture (applicable to high voltage REESS (s) only), electrolyte leakage, fire and explosion.

A1.2 UN 38.3 (7th edition, 2019)

The focus of this regulation lays on the safe transportation (not usage) of lithium-ion and lithium metal batteries, including altitude, temperature, vibration, shock, and impact/crash testing.

The vibration shall be a sinusoidal acceleration waveform with a logarithmic sweep between 7 Hz and 200 Hz and back to 7 Hz traversed in 15 minutes. This cycle shall be repeated 12 times for a total of 3-hours in all three orthogonal directions.

The logarithmic frequency sweep shall differ for cells and batteries with a gross mass of not more than 12 kg and for batteries with a gross mass of more than 12 kg. For cells and small batteries (<12 kg) – from 7 Hz a peak acceleration of 1 g_a (10 m/s^2) is maintained until 18 Hz is reached. The amplitude is then maintained at 0.8 mm (1.6 mm total excursion) and the frequency increased until a peak acceleration of 8 g_a occurs (approximately 50 Hz). A peak acceleration of 8 g_a is then maintained until frequency is increased to 200 Hz. For large batteries (>12 kg) – from 7 Hz a peak acceleration of 1 g_a is maintained until 18 Hz is reached. The amplitude is then maintained at 0.8 mm (1.6 mm total excursion) and the frequency increased until a peak acceleration of 2 g_a occurs (approximately 25 Hz). A peak acceleration of 2 g_a is then maintained until frequency is increased to 200 Hz.

Cells and batteries meet this requirement if there is no leakage, no venting, no disassembly, no rupture and no fire during the test and after the test and if the open circuit voltage of each cell or battery directly after testing in its third perpendicular mounting position is not less than 90% of its voltage immediately prior to this procedure (voltage requirement not applicable to test cells and batteries at fully discharged states).

A2. Existing standards (selected)

A2.1 International Standardisation Organisation - ISO 6469-1 3rd edition (April 2019)

This standard specifies safety requirements for rechargeable energy storage systems (RESS) of electrically propelled road vehicles for the protection of persons. The 3rd edition includes vibration testing requirements (under 5.1 Mechanical requirements), where it is specified that the RESS shall provide the safety performance under mechanical loads due to vibration and mechanical shock, which a RESS will likely experience during the normal operation of a vehicle over its lifetime. Compliance shall be tested in accordance with 6.2. The test of the battery pack/system is done as three single-axis tests with random excitation 5-200 Hz and the safety profile, derived from a broad range of experimental data, was chosen to be load equivalent to UN ECE R100.02

A2.2 International Electrotechnical Commission - IEC 62660-2 standard (2018)

This is a reliability and abuse test for automotive traction lithium-ion battery cells. It includes high-temperature endurance, temperature cycling, vibration, shock, crush, electrical short circuit, and forced discharge testing. The vibration test presented in this standard is obtained from ISO 16750-3:2007 (old revision) (ISO16750-3, 2012), which is a general standard for testing electrical and electronic equipment in road vehicles. For batteries in electric vehicles, the severity for sprung mass in a passenger car is most relevant and three uniaxial random vibration tests 10–2000 Hz are suggested. The vibration portion of the test consists of a random vibration profile executed over an 8-hour time span for all three axes.

A2.3 International Electrotechnical Commission - IEC 60068-2-64:2008+AMD1:2019 CSV (Consolidated version) standard

Environmental testing - Part 2-64: Tests - Test Fh: Vibration, broadband random and guidance

It demonstrates the adequacy of specimens to resist dynamic loads without unacceptable degradation of its functional and/or structural integrity when subjected to the specified random vibration test requirements. Broadband random vibration may be used to identify accumulated stress effects and the resulting mechanical weakness and degradation in the specified performance. This information, in conjunction with the relevant specification, may be used to assess the acceptability of specimens. This standard is applicable to specimens that may be subjected to vibration of a stochastic nature resulting from transportation or operational environments, for example in aircraft, space vehicles and land vehicles. It is primarily intended for unpackaged specimens and for items in their transportation container when the latter may be considered as part of the specimen itself. However, if the item is packaged, then the item itself is referred to as a product and the item and its packaging together are referred to as a test specimen. This standard may be used in conjunction with IEC 60068-2-47:2005 (Environmental testing - Part 2-47: Test - Mounting of specimens for vibration, impact and similar dynamic tests), for testing packaged products. If the specimens are subjected to vibration of a combination of random and deterministic nature resulting from transportation or real life environments, for example in aircraft, space vehicles and for items in their transportation container, testing with pure random may not be sufficient. See IEC 60068-3-8:2003 (Environmental testing - Part 3-8:

Supporting documentation and guidance - Selecting amongst vibration tests) for estimating the dynamic vibration environment of the specimen and based on that, selecting the appropriate test method. The major changes with regard to the previous edition concern the removal of Method 1 and Method 2, replaced by a single method, and replacement of Annex A with suggested test spectra and removal of Annex C.

A2.4 International Society of Automotive Engineers - SAE J2380 standard (J2380-201312)

This SAE recommended practice describes the vibration durability testing of a single battery (test unit) consisting of either an EV battery module or an EV battery pack – multiple samples would normally be subjected to such testing for statistical purposes. It provides a test procedure for characterising the effect of long-term, road-induced vibration on the performance and service life of electric vehicle batteries. It contains also shock tests for EV batteries; packs or modules. A number of subtests with different spectra are combined in each of the three directions to simulate different types of driving. The random vibration test profiles are executed in all three axes for a duration ranging from 9 minutes to 38 hours. During the tests the battery depth-of-discharge (DoD) is varied. The test unit is instrumented to detect not just resonances but also loss of electrical isolation, abnormal battery voltages, and abnormal temperature conditions. The random vibration test outlined in SAE J2380 is also proposed by UL 2580 to be used if the actual life cycle profile is not known. SAE J2380 is the same as the random vibration defined in ([22] procedure 10). Additionally, some test units may be subjected to life cycle testing (either after or during vibration testing) to determine the effects of vibration on battery life (SAE J2288 may be used for the life cycle testing as applicable).

A2.5 National Standard of the People's Republic of China - GB 38031-2020 (May 2020)

A vibration test is outlined in that standard (section 8.2.1), where the device under test (DUT) is a battery pack or system. The requirements of GB/T 2423.43 for positioning the DUT on the vibration table should be followed, whereas for the test process one should refer to GB/T2423.56. A random and fixed frequency vibration load should be applied in each direction, with the recommended loading sequence being: z-axis random and z-axis fixed frequency, y-axis random and y-axis fixed frequency, x-axis random and x-axis fixed frequency. Here, the vehicle running direction is considered as the x-axis direction and the other horizontal direction perpendicular to the running direction is the y-axis direction. The testing bodies can also choose its own sequence to shorten the conversion time. Voltage and temperature are being monitored during the test and after the test sequence completion (see figure x) for an additional 2 hours. For battery packs or systems mounted on vehicles of categories M1 and N1, the vibration test parameters are given in figure A2.5-1 and the random vibration test curve in figure A2.5-2.

Random vibration			
Frequency Hz	z-axis power spectral density (PSD) g²/Hz	y-axis power spectral density (PSD) g²/Hz	x-axis power spectral density (PSD) g²/Hz
5	0.015	0.002	0.006
10	/	0.005	/
15	0.015	/	/
20	/	0.005	/
30	/	/	0.006
65	0.001	/	/
100	0.001	/	/
200	0.0001	0.00015	0.00003
RMS	Axle z	Axle y	Axle x
	0.64g	0.45g	0.50g
Sinusoidal vibration at fixed frequency y(test time for each direction is 2h)			
Frequency Hz	Fixed frequency amplitude of Axle z	Fixed frequency amplitude of Axle y	Fixed frequency amplitude of Axle x
24	±1.5g	±1.0g	±1.0g

Figure A2.5-1 - Vibration test conditions for battery packs or systems of categories M1 and N1 vehicles (Adopted from [34])

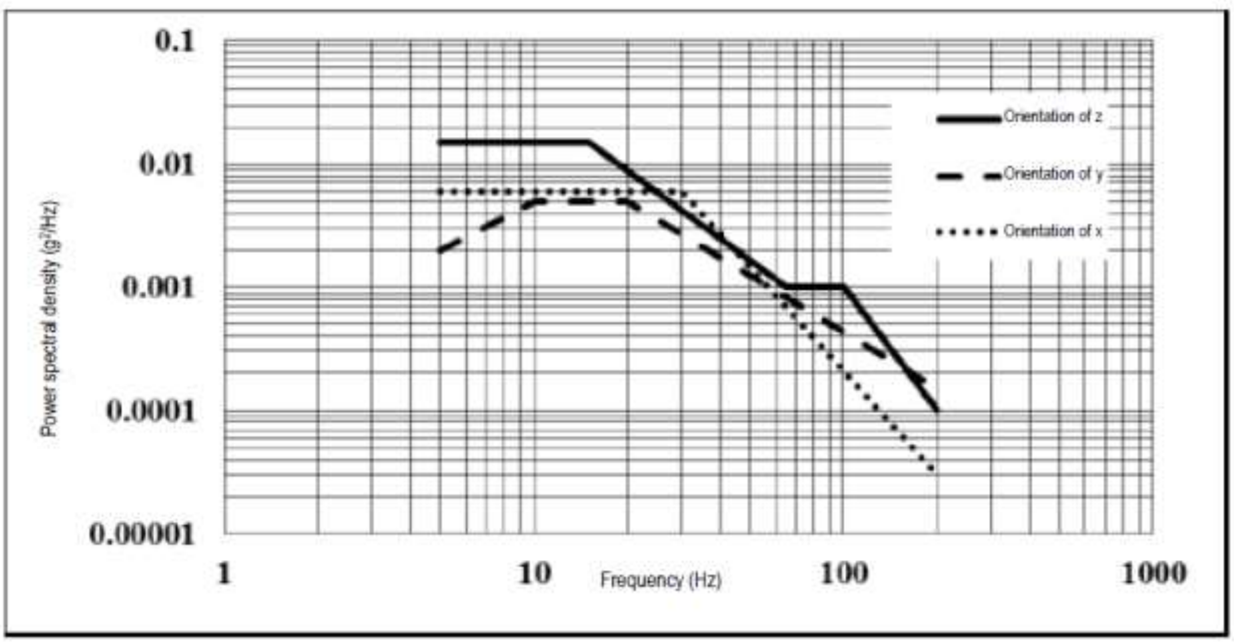

Figure A2.5-2 - Random vibration test curve for battery packs or systems of categories M1 and N1 vehicles (Adopted from [34])

List of acronyms

CPs	Contracting Parties
DG GROW	The Commission's Directorate-General for Internal Market, Industry, Entrepreneurship and SMEs
DoD	Depth of Discharge
DUT	Device Under Test
EVS	Electric Vehicle Safety
GTR	Global Technical Regulation
IEC	International Electrotechnical Commission
ISO	International Standardisation Organisation
IWG	Informal Working Group
OCV	Open Circuit Voltage
OICA	Organisation Internationale des Constructeurs d'Automobiles (International Organization of Motor Vehicle Manufacturers)
PSD	Power Spectral Density
REESS	Rechargeable Electric Energy Storage System
RESS	Rechargeable Energy Storage System
SAE	Society of Automotive Engineers
SMEs	Small and Medium-sized Enterprises
SOC	State of Charge
UN	United Nations
UNECE	United Nations Economic Commission for Europe