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Consideration of Vibration testing requirements for EVS-GTR

1. Introduction

This paper provides technical analysis of REESS vibration testing requirements for GTR No. 20 on Electric Vehicle Safety (EVS).

Since the inception of the automobile, vehicle manufacturers have incorporated durability testing with an emphasis on examining and mitigating potential component failures due to vibration and other fatigue failure mechanisms. Currently, manufacturers routinely expose preproduction test vehicles to a diverse and rigorous range of operating/road conditions intended to simulate the most demanding circumstances that the vehicle could encounter over its lifetime. As a result of this testing, system deficiencies (if any) are identified and remediated before the vehicle is deemed “production ready”. The high level of robustness of this process is necessary to support the consumer acceptance of these products necessary to compete in the current highly competitive vehicle sales market.

With respect to battery systems covered by this GTR, this paper will provide information detailing why safety implications from potential vibration induced failure modes are sufficiently mitigated by other safety system performance requirements already specified in the GTR.

Even so, a foundational principle governing the development of the performance specifications of this GTR is that conventional ICE powered vehicles currently exhibit an acceptable level of safety and that requirements applied to their electric powered counterparts should not be more severe and thus unnecessarily increase the cost and reduce the market viability of these vehicles.

In addition, now that we have field exposure data for vehicles covered by this GTR, we can see that vibration induced safety events are extremely rare. While examination of thermal events in the field include many cases where the root cause was not able to be specifically determined, vibration induced failures can likely be ruled out for the majority of these cases. Currently, the fact that vibration induced safety events for both electric and ICE powered vehicles are extremely rare, serves as a testament to the robustness of existing durability testing procedures manufacturers currently utilize.

2. Vibration test in Vehicle development

(a) Vibration in vehicle development

For vehicle development, engineers have to satisfy various technical requirements such as safety, handling and stability, ride comfort, NVH, strength and durability, reliability as well as reduction of environmental impact in accordance with the product concept and the market demands. In order to verify the performance, each vehicle manufacturer considers the applicable road and environmental conditions around the world and reproduce such conditions to their own development tools such as test track, simulator, and so on, utilizing its exclusive experiences and knowledge.

Many factors such as road surface, accumulated mileage, driving speed, ambient temperature, etc. affect the vehicle vibration, and in consequence affecting the durability of parts, reliability of equipment, ride comfort, and so on. Vibration is one of the essential and most important characteristics in the vehicle development influencing the cost and mass of the vehicle and its components, and, therefore, one of the basic competitive area among vehicle manufacturers.

In general, the vibration load depends on the harshness of the road conditions and vehicle-accumulated mileage, and causes fatigue or wear of the vehicle and components, that may result in the deterioration of vehicle performance and possibly lead to the failure of certain components.

In order to prevent such failures, the components that are not expected to be replaced during the vehicle's service life, are designed with a sufficient safety factor set for the assumed vibration load. Failure modes analysis highlights the failure modes that are significant to the functionality and safety of the product. Identification of these failure modes can be used to tailor the durability testing to provide a more robust evaluation as well as to improve the development efficiency by optimizing the testing elements.

As such, vibration is one of the essential durability and reliability requirements for vehicle development applied for any vehicles, regardless of its powertrain, in order to make a competitive product containing vehicle specific and proprietary aspects.

(b) Vibration requirements in battery standards

In order to ensure the safety during the transportation of lithium-ion batteries, test requirements are specified in UN Manual of Tests and Criteria, chapter 38.3 in order to ensure the safety of transportation. It is composed of the following tests:

- T1 altitude simulation,
- T2 thermal test,
- T3 vibration,
- T4 impact,
- T5 external short circuit,
- T6 impact/crush,
- T7 overcharge
- T8 forced discharge.

T1 to T5 are performed in series using the same test samples. As the conditions may not always be predicable or kept stable depending on the transporter, a severe test is imposed for transportation.

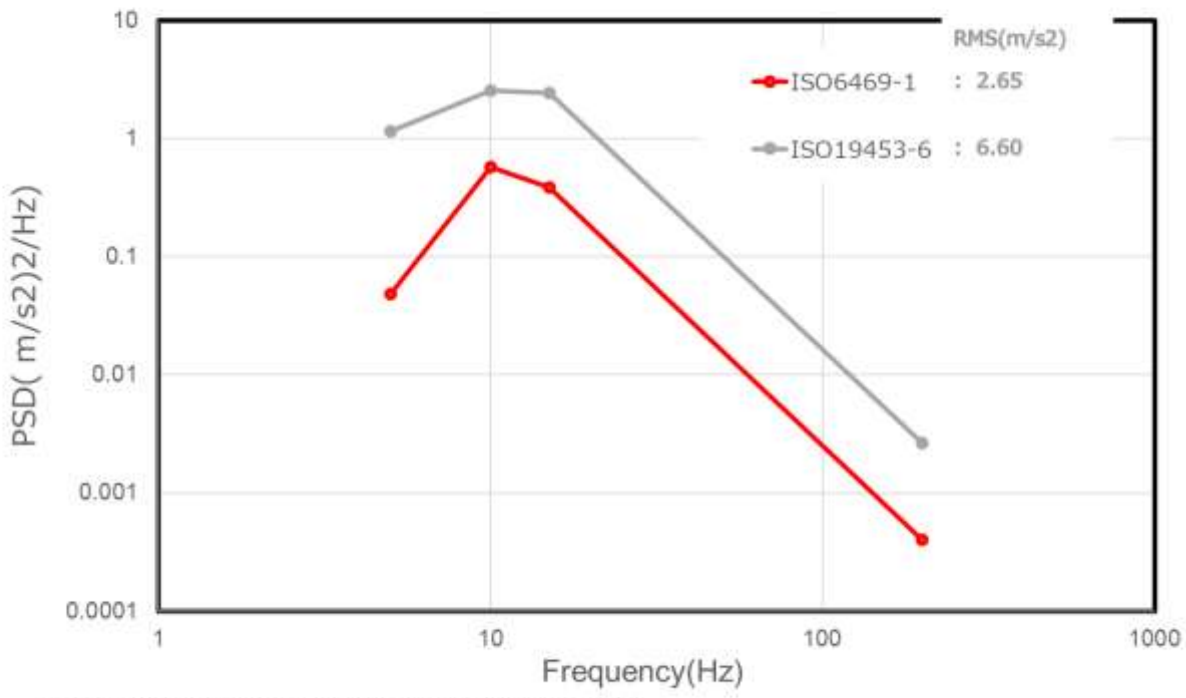
In addition, the traction battery is fixed to the vehicle, and therefore the environmental conditions are equivalent to other components. This means that the traction battery design can be optimized according to the vehicle characteristics without having excessive mass.

As mentioned above, vehicle manufacturers can understand and sufficiently anticipate the driving environment and its load to the vehicle as well as other climatic conditions. In this regards, vehicle regulation is largely different from the transport regulation.

The vibration characteristics of the battery pack are greatly affected by its masses and dimensions, its mounting position, the vehicle structure, suspension, tire, and so on. For example, relatively small battery packs weighing about 10kg can be mounted at various locations in a vehicle. Therefore, it is necessary to withstand a relatively high vibration load. On the other hand, the BEV battery pack with high capacity exceeds several hundred kg and is designed based on the vibration load specific to the vehicle.

Recently, vibration profiles for traction batteries have been established in international standards: ISO 6469-1 published in 2019 with respect to safety and ISO 19453-6 published in 2020 with respect to durability and reliability. The vibration profiles of these standards were generated by measuring acceleration data with the actual vehicles. For the safety requirement in ISO6469-1, the minimum profile from the acquired data was adopted while for durability requirements in ISO19453-6, the median profile was adopted. These standards enabled component manufacturers to develop their own batteries.

Vehicle manufacturers may determine the vibration profile applied for their development and final verification of traction batteries either by referring to the vibration profile specific to the vehicle or to those of aforementioned international standards.



The profile of ISO19453-6 is converted to 12hr of testing duration
.Data of ISO19453-6 is from category 2, whose mass is typically more than 20kg.

3. History of vibration requirement in EVS-GTR (GTR No. 20) phase1

The vibration requirement in GTR No. 20 is based on the test procedure described in the UN Regulation No. 100-02, which entered into force as of 15 July 2013. The test procedure for UN-R 100-02 was developed by the group of interested experts on Rechargeable Energy Storage System (REESS IWG) led by Germany joined by the experts from Europe and Japan, from 2010 to 2012. Around that period, relatively limited experiences on the high energy traction batteries of EV were available within the automotive industry and the industry standards with respect to the safety of the automotive traction battery system were being developed at ISO or SAE in parallel. However, the safety regulation for REESS had to be prepared in order to wipe away the anxiety in the market and to support the growth of the EV market.

For the development of the vibration test procedure, the group recognized the difficulty in determining a common vibration profile applicable to various types of vehicles and REESS, and therefore decided to use the profile of "UN Manual of Tests and Criteria", paragraph 38.3.4.3. (Test T3: Vibration) as the basis. This vibration profile is not intended to simulate and reproduce the vibration of an actual vehicle, but to apply reasonable levels of mechanical stress in order to eliminate the poorly designed batteries from the market.

For GTR No. 20 phase 1, it has been agreed to maintain the test procedure of UN-R100-02 for the time being and to resume the discussion for phase 2. The rationale provided in the Part 1 of GTR No. 20 (paragraph 130 – 138), as reproduced in the Appendix, are correct and valid, but does not sufficiently describe how REESS will behave in case that a certain failure occurs due to the vibration while operating the vehicle.

4. Summary of field information

So far, no real-world cases of fire or explosion of the traction battery have been identified where vibration was identified as the causal factor.

5. Effect of vibration on safety

An FMEA analysis for the potential failures caused by vibration on the traction batteries is conducted as shown in Table 1.

Table 1: Possible failures in REESS due to vibration and their effect on safety

Possible failures		Effect	Assessment
Area	Failure		
Cell	Disconnection of electrode tab lead welding	Loss of cell voltage (or loss of a part of jelly roll connections)	Detected by BMS either by capacity loss in case of partial disconnection of the jelly roll, or cell voltage drop if the jelly roll is totally disconnected. At worst, a thermal runaway may occur due to the joule heat but safety will be ensured by the thermal propagation requirement.
	Electrode stack / jelly roll movement and damage	Internal short circuit between the electrodes	Detected by BMS by cell voltage drop. At worst, a thermal runaway may occur but safety will be ensured by the thermal propagation requirement.
		Damage of cell sealing and electrolyte leakage	Detected by BMS, either by reduced capacity or insulation resistance fault.
	Physical contact of electrodes and cell envelope (can, pouch…)	Internal short circuit	Detected by BMS by cell voltage drop. At worst, a thermal runaway may occur but safety will be ensured by the thermal propagation requirement.
Cell connections	Cell connection welding broken	Increase of electrical resistance Loss of cell voltage	Detected by BMS by cell voltage drop At worst, a thermal runaway may occur due to the joule heat but safety will be ensured by the thermal propagation requirement.
Cell restraint in battery pack	Cell movement damages the cell insulation materials	Loss of electrical insulation	Detected by BMS as isolation failure.
		Short circuit between cells through conductive structure parts	Harmonized design & production quality standards established within the vehicle manufacturing industry (e.g. IATF 16949) ensure that such cases caused by faulty design practice are very unlikely to occur.
Power wiring in battery pack	Disconnection of power wiring due to mechanical failure	Loss of propulsion	No safety issue for the battery
	Contact between a power wiring (of isolated system) and ground	Loss of propulsion Loss of electrical isolation of power wiring	Isolation failure is not a safety risk by itself. To become a safety risk at least one other problem/risk needs to occur at the same time. Detected by BMS as isolation failure.
	Contact between a power wiring (of chassis connected system) and ground	Short-circuit	External short-circuit protection takes effect.

Possible failures		Effect	Assessment
Area	Failure		
	Simultaneous contact between positive power wiring to ground and negative power wiring to ground	Short-circuit	Harmonized design & production quality standards established within the vehicle manufacturing industry (e.g. IATF 16949) ensure that such cases caused by faulty design practice are very unlikely to occur. External short circuit protection may also take effect.
	Intermittent contact/disconnection of power wiring due to damaged welding or screw joint	Electric failure increases resistance, potentially generating thermal energy.	Detected by the BMS.
	Increased contact resistance due to mechanical breakage or loss of pressure in contact points	Electric failure increases resistance, potentially generating thermal energy.	Detected by the BMS.
	Increased resistance due to reduced cross section area in power wiring	Electric failure increases resistance, potentially generating thermal energy.	Detected by the BMS.
Signal wiring	Disconnection of signal wiring due to mechanical failure	Loss of detection of voltage, current or temperature of battery cells	Detected by BMS as sensor failure Limitation or shutdown of traction battery usage either by BMS or by vehicle ECU
	Short-circuit of sensor wiring due to mechanical failure	Activation of fuse or disconnection of cell voltage sensing wiring	Detected by BMS as sensor failure Limitation or shutdown of traction battery usage either by BMS or by vehicle ECU
BMS	Mechanical breakage of sensor systems due to fatigue	Loss of detection of voltage, current or temperature of battery cells	Detected by BMS as sensor failure Limitation or shutdown of traction battery usage either by BMS or by vehicle ECU
	Mechanical breakage of electronic circuit due to fatigue	Loss of communication between battery information and vehicle ECU Loss of detection on voltages, current or temperature of battery cells	Detected by BMS. Limitation or shutdown of traction battery usage either by BMS or by vehicle ECU

Possible failures		Effect	Assessment
Area	Failure		
Enclosure (incl. sealing)	Breakage of enclosure due to fatigue	Loss of water tightness	High voltage parts and cells are not affected by the failure. In case that water intrudes into battery pack, detected by BMS as isolation failure.
	Breakage of sealing of enclosure due to friction	Loss of water tightness	High voltage parts and cells are not affected by the failure. In case of water intrusion into battery pack, detected by BMS as isolation failure.
Mounting	Breakage of fixation between the battery pack and the vehicle due to fatigue	Loss of fixation of battery pack onto the vehicle structure	High voltage parts and cells are not affected by the failure.

6. Conclusion

The maintenance of vibration requirements will not significantly increase the safety of production electric vehicles and thus should be removed from future versions of GTR No. 20. As previously detailed, for battery systems covered by this GTR, potential safety implications from vibration induced failure modes are sufficiently mitigated by other safety system performance requirements already specified in the GTR. In addition, the comprehensive functional and durability testing conducted by vehicle manufacturers during their development processes (e.g. by following IATF 16949 or ISO9001) that is necessary to compete in the highly competitive vehicle market are sufficient to identify and remedy any significant system safety deficiencies before the vehicle is deemed “production ready” and released into the market. These conclusions are supported by the lack of known field incidents attributable to vibration induced safety events.

Appendix

Rationale of vibration requirement in GTR 20 Phase 1

(a)Vibration (paragraphs 5.4.2. and 6.2.2. of this UN GTR):

130. The purpose of this test is to verify the safety performance of the REESS under a vibration environment which the REESS would likely experience during the normal operation of the vehicle.

131. A vibration load spectrum for lithium cells and batteries including lithium ion cells/batteries and lithium polymer cells/batteries is already defined as a type approval test procedure of dangerous goods of class 9 in the Recommendations on the Transport of Dangerous Goods, Manual of Tests and Criteria, paragraph 38.3.4.3. (Test T3: Vibration), with an amplitude sweep ranging from 7 Hz to 200 Hz.

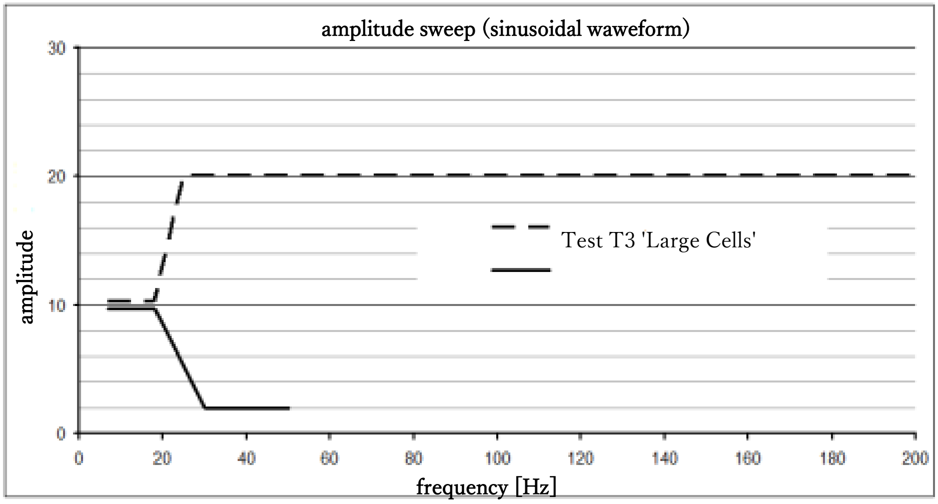
132. As Recommendations on the Transport of Dangerous Goods, Manual of Tests and Criteria sign-off may often also be mandatory for types of REESS (such as lithium metal batteries, lithium ion batteries and lithium polymer batteries) subject to this regulation, having the opportunity to cover this test with test T3, is seen as an efficient approach.

133. However the load curve per Test T3 is assessed as too severe for automotive applications. Despite the recent lowering of the high frequency amplitude in Test T3 from 8g to 2g for "large batteries" with masses more than 12 kg, even this amplitude is still not considered representative for the typical sizes of REESS in vehicles, with a mass of 200 kg or more. Particularly the height of the amplitudes above 18 Hz is seen as unrealistic and does not correlate to the loads seen in road vehicles (except for hypothetical cases of REESS mounted close to or onto a combustion engine). Due to the stiffness of vehicle bodies in relation to the module weight frequencies, frequencies higher than 18Hz cannot be transmitted at significant energy levels.

134. This UN GTR, therefore, uses the same frequency vertices as Test T3, albeit those for smaller cells, but lowers the load curve above 18Hz and truncates it at 50Hz.

Figure 13

Comparison of proposed with Test T3 load curve



135. The test duration is also aligned with Test T3, requiring 12 transitions from the minimum to the maximum frequency and back within 15 min., resulting in a total test duration of 3 hours.

136. While Test T3 requires the test to be performed in all three spatial directions, in vehicle applications this load occurs in the vertical direction only, while the longitudinal and lateral vehicle dynamic loads are significantly lower. The vibration test therefore needs to be performed in the vertical installation direction only. When utilizing this option, the orientation of the REESS in the vehicle must be restricted accordingly; this information shall be communicated to the regulating entity by the vehicle manufacturer. The administrative procedures to ensure such a communication will be specified by the regulating Contracting Party.

137. In many cases, the vehicle manufacturer assesses the vehicle's durability with full vehicle simulation, either by running a rough road test track or by simulating the lifetime fatigue on a 4-poster vibration rig. These methods provide a vehicle specific assessment of the durability of all vehicle components and should be accepted in this context.

138. To finalize the certification of the REESS, a standard cycle has to be performed, to verify that the mechanical loads have not had any negative effect on the electrical function.