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Evolution in electric vehicle safety legislation and global harmonisation activities

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Abstract

Electric vehicles are very different from conventional internal combustion engine vehicles and present some new challenges for safety that must be accommodated in legislation. This paper reviews the latest developments in vehicle safety legislation with respect to electric vehicles. The development of two new United Nations (UN) Global Technical Regulations is the main focus for the paper; namely, UN Global Technical Regulation No. 13 on hydrogen and fuel cell vehicles and a draft UN Global Technical Regulation under development on electric vehicle safety. However, consideration is also given to the key differences between the major legislative jurisdictions and the implications for the development of Global Regulations.

Keywords: EV (electric vehicle), Hydrogen, Policy, Regulation, Safety

1 Introduction

Electric vehicles are entering the market in ever-increasing numbers [1]. Although they remain a very small proportion of the overall fleet, they are expected to achieve a wider market appeal over the next 10 to 15 years [2]. Most consumers expect their car to meet minimum safety requirements regardless of the type of power train [3]. Collisions and other adverse incidents (such as engine fires, for example) happen regularly with conventional vehicles yet consumers balance the risks with the undoubted benefits of personal mobility. Nevertheless, the reaction of consumers to such incidents with electric vehicles is, at present, unknown. There is the potential, therefore, to affect consumer confidence, particularly if incidents are related to the new power train components (a battery fire, for example, could have a damaging effect on consumer confidence if reported widely by the media). If consumer confidence is reduced, the uptake of this important technology could be delayed with implications for the global efforts to reduce carbon dioxide emissions from road transport.

Legislators and their industry stakeholders have long-recognised the need to update vehicle safety legislation to accommodate electric vehicles [4]. It is critical that any new hazards associated with these vehicles and their technologies are mitigated, without placing an undue burden on an emerging market [5]. Global legislative harmonisation has been a long-held objective of the automotive industry, and in the current economic climate, it is even more relevant for its long-term health. Significant progress has been made in this regard in all of the major legislative jurisdictions around the World. For example, several United Nations (UN) Regulations have been amended to include specific provisions for electric vehicles and the same can be said for legislation in China, the European Union, Japan, and the United States.

2 Harmonisation of electric vehicle regulations

The World Forum for Harmonisation of Vehicle Regulations (WP.29), a working party of the Inland Transport Division of the United Nations Economic Commission for Europe (UNECE), is responsible for creating a uniform system of vehicle regulations. Harmonised requirements and test procedures for the type-approval of vehicles and components are set out in UN Regulations (formerly known as UNECE Regulations). However, these are being supplemented with UN Global Technical Regulations, which are intended to extend harmonisation activities to countries that operate self-certification regimes and do not recognise type-approval.

2.1 UN Regulations

UN Regulations are based on the principles of type-approval and the mutual recognition of approvals among participating countries. The legal framework for the reciprocal recognition of UN Regulations is set out in the "1958 Agreement". UN Regulations provide for the approval of vehicle systems and components; however, at present, there is no "whole vehicle" approval mechanism. That is left to national rulemaking processes (or regional processes, such as those of the European Union). An International Whole Vehicle Type-Approval System is under development by WP.29, although it will not include self-certification regimes.

2.2 UN Global Technical Regulations

UN Global Technical Regulations are also administered by WP.29. They are established under the "1998 Agreement", which is open to countries that do not participate in the 1958 Agreement. For example, the United States does not participate in, or recognise, UN Regulation approvals. Vehicle legislation in the United States operates on the principle of self-certification whereby the manufacturer certifies that their product complies with all the applicable federal standards. Nevertheless, the United States is a contracting party to the 1998 Agreement and hence UN Global Technical Regulations are compatible with both type-approval and self-certification systems. This is usually achieved by following a performance-based approach when preparing the requirements. UN Regulations also follow a performance-based approach, but may also include design requirements that are usually considered to be incompatible with self-certification regimes.

A UN Global Technical Regulation is not a legal document. However, a contracting party to the 1998 Agreement that voted in favour of establishing a global technical regulation is obliged to begin the process of transposing the global requirements into their local legislation. Contracting parties may adapt or modify the specifications in a UN Global Technical Regulation for their local legislation, but they may not increase the levels of stringency or performance.

3 UN Global Technical Regulation No. 13 on hydrogen and fuel cell vehicles

3.1 The development of the UN Global Technical Regulation

The Executive Committee of the 1998 Agreement (AC.3) adopted a proposal to develop a UN Global Technical Regulation on hydrogen and fuel cell vehicles in 2007. The proposal was submitted jointly by three co-sponsors; Germany, Japan and the United States. Their aim was to develop a Global Technical Regulation that:

- Attains equivalent levels of safety as those for conventional gasoline-powered vehicles;
- Is performance-based and does not restrict future technologies.

Two UN Informal Groups on hydrogen and fuel cell vehicles were formed under the development process set out in the proposal. These comprised: a subgroup on safety reporting to the Working Party on Passive Safety (GRSP) and a subgroup on environmental aspects reporting to the Working Party on Pollution and Energy (GRPE). In addition, two distinct phases of development were proposed: the development of the UN Global Technical Regulation (Phase 1) and the assessment of future technologies and harmonisation of crash tests (Phase 2).

Phase 1 – Development of the UN Global Technical Regulation

For the first phase, it was envisaged that a UN Global Technical Regulation would be prepared by the subgroup on safety (by 2010) based on a combination of component-, subsystem- and vehicle-level requirements. In parallel, the subgroup on environmental aspects would investigate the possibility of harmonising environmental requirements for hydrogen and fuel cell vehicles.

Phase 2 – Assessment of future technologies and harmonisation of crash tests
For the second phase, it was envisaged that the UN Global Technical Regulation would be amended to maintain its relevance with the findings of new research and the state of the technology beyond Phase 1. In addition, discussions would open on the topic of harmonisation of crash test procedures for hydrogen and fuel cell vehicles. Twelve meetings of the subgroup on safety were held between September 2007 and June 2011, along with three meetings of a drafting task force that met to discuss and agree some specific technical issues.

The text of the UN Global Technical Regulation (as prepared during Phase 1) was agreed by GRSP during its 52nd session in December 2012. It was then adopted by WP.29 during its 160th session in June 2013 and now appears in the Global Registry as UN Global Technical Regulation No. 13 on hydrogen and fuel cell vehicles. Further work envisaged for Phase 2, as listed in the Regulation, includes:

- Potential scope revision to address additional vehicle classes;
- Potential harmonisation of crash test specifications;
- Requirements for material compatibility and hydrogen embrittlement;
- Requirements for fuelling receptacle;
- Evaluation of performance-based test for long-term stress rupture in Phase 1;
- Consideration of research results reported after completion of Phase 1 – specifically related to electrical safety, hydrogen storage systems and post-crash safety;
- Consideration of 200 percent nominal working pressure, or lower, as the minimum burst requirement;
- Consider safety guard system for the case of isolation resistance breakdown.

Work is likely to begin in the second half of 2013, and to continue through 2014, although a formal timeline is yet to be published..

3.2 Overview of the main performance tests and requirements

UN Global Technical Regulation No.13 applies to passenger cars, vans, buses and coaches with hydrogen storage systems having a nominal working pressure of 70 MPa or less, and a maximum fuelling pressure of 125 percent of the nominal working pressure. The technical requirements within the Regulation are set out in two main sections: Section 5 specifies performance requirements and Section 6 specifies test conditions and procedures. Each of these sections cover: the compressed hydrogen storage system; the vehicle fuel system; and electrical safety. Optional requirements and test procedures for liquefied hydrogen vehicles are set out in an additional section (Section 7).

3.2.1 Compressed hydrogen storage system

The assessment of the hydrogen storage system includes the high-pressure container as well as its primary closure devices. In a typical system, the “closure devices” might include a thermally-activated pressure relief device, a check valve that prevents reverse flow to the fill line and an automatic shut-off valve that can close to prevent the flow of hydrogen from the container. The performance requirements and test procedures for the hydrogen storage system each comprise five main parts. These are summarised in the remainder of this subsection.

Verification tests for baseline metrics
Two metrics are assessed to establish a baseline level of performance; the initial burst pressure and the initial cycle life (before leak) of the hydrogen container. In each case, three new containers are randomly selected from the design qualification batch of at least 10 containers.

The initial burst pressure test verifies the repeatability of the containers presented for design qualification and establishes the midpoint initial burst pressure, which is used during other performance tests. All containers tested must have a burst pressure within ±10% of the midpoint burst pressure and greater than or equal to 225 percent of the nominal working pressure of the container (or 350 percent for glass fibre composites).

The initial pressure cycle life test cycles the container between 2 (±1) MPa and 125 percent of its nominal working pressure 22,000 times, or until a leak occurs. Leakage must not occur within a number of cycles, which is set individually by each contracting party at 5,000, 7,500 or 11,000 cycles for a 15 year service life. This reflects differences in the expected worst-case lifetime vehicle range and the worst-case fuelling frequency among the contracting parties to the Global Technical Regulation, (which are drawn from different regions in the World).

Verification test for performance durability (hydraulic sequential tests)

The durability test focusses on the container's structural resistance to rupture under representative usage conditions that include repeated fuelling, physical damage and environmental extremes. Since the focus is on structural stress and fatigue, the tests are conducted hydraulically, which allows more repetitions of stress exposure in a practical test time. The testing profile and key requirements are shown in Figure 1.

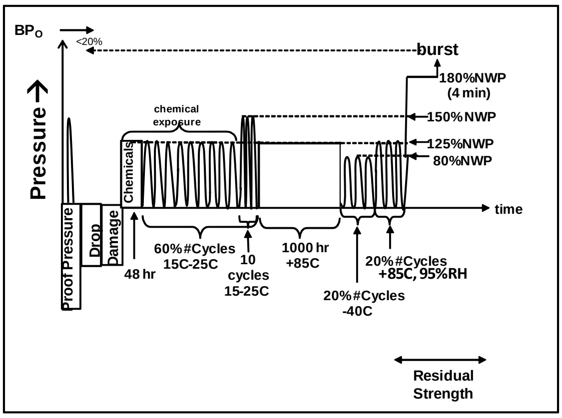
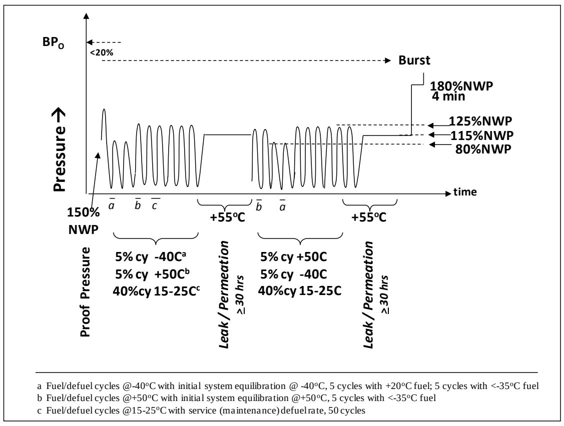


Figure 1: Verification test for performance durability

Figure 1 illustrates that the performance durability tests are conducted in a sequence on the same container. The container must not leak during the sequence or during a residual proof pressure test. The residual burst pressure must be within 20 percent of the baseline initial burst pressure.

Verification test for expected on-road system performance (pneumatic sequential tests)

The on-road system performance test reproduces the "expected" worst-case conditions for a typical vehicle including the fuel (i.e. hydrogen). These include environmental conditions (such as typical temperature extremes) as well as normal usage conditions over the expected lifetime of the vehicle. Pneumatic testing with hydrogen gas provides stress factors associated with rapid and simultaneous interior pressure and temperature oscillations and infusion of hydrogen into materials. The testing profile and key requirements are shown in Figure 2.



a Fuel/defuel cycles @-40ºC with initial system equilibration @ -40ºC, 5 cycles with +20ºC fuel; 5 cycles with <-35ºC fuel
b Fuel/defuel cycles @+50ºC with initial system equilibration @+50ºC, 5 cycles with <-35ºC fuel
c Fuel/defuel cycles @15-25ºC with service (maintenance) defuel rate, 50 cycles

Figure 2: Verification test for expected on-road performance (pneumatic/hydraulic)

Once again, the tests are conducted in a sequence that compounds the stresses on the hydrogen storage system, which must not leak during the sequence or during a residual proof pressure test. The residual burst pressure must be within 20 percent of the baseline initial burst pressure.

Verification test for service terminating performance in fire

This test assesses the capacity of the storage system to prevent rupture during a fire (i.e. under conditions so severe that hydrogen containment cannot reasonably be maintained). Hydrogen is specified as the test gas (in the most realistic manner); however, contracting parties can use compressed air as an alternative for certification of containers for use within their own country. The temperature profile of the fire test is shown in Figure 3. During the test, a temperature-activated pressure relief device must release the gas in a controlled manner without rupture.

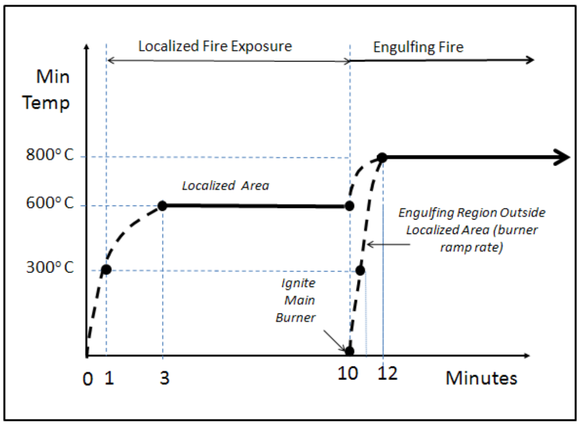


Figure 3: Temperature profile of the fire test

Verification test for performance durability of primary closures
The Global Technical Regulation specifies a range of performance tests for the primary closures of the hydrogen storage system. These are the key components that isolate the hydrogen container from the rest of the vehicle. No tests are specified or required for the wide range of other components that might come into contact with the hydrogen, such as sensors, fuel lines, connectors, refuelling connections or receptacles, etc. These were not deemed to be "safety-critical" components during the development of the Global Regulation. The tests are shown in Table 1.

Table 1: Applicable test procedures for primary closures of the hydrogen storage system

Tests for thermally-activated pressure relief devices	Tests for check valves and automatic shut-off valves
• Pressure cycling test • Accelerated life test • Temperature cycling test • Salt corrosion resistance test • Vehicle environment test • Stress corrosion cracking test • Drop and vibration test • Leak test • Bench top activation test • Flow rate test	• Hydrostatic strength test • Leak test • Extreme temperature pressure cycling test • Salt corrosion resistance test • Vehicle environment test • Atmospheric exposure test • Electrical tests • Vibration test • Stress corrosion cracking test • Pre-cooled hydrogen exposure test

3.2.2 Vehicle fuel system

The Global Technical Regulation specifies requirements for the integrity of the hydrogen fuel delivery system, which includes the hydrogen storage system, piping, joints, and components in which hydrogen is present. The integrity of the system is assessed in-use and post-crash.

In-use fuel system safety
The in-use safety of the hydrogen system is assessed by a package of requirements and tests that specify:

- The characteristics, labelling and location of the fuelling receptacle;
- The provision of over-pressure protection of the low pressure system (downstream of the pressure regulator);
- The characteristics of hydrogen discharge systems, including pressure relief systems as well as the vehicle exhaust system;
- The protection against flammable conditions such as hydrogen leakage or permeation into vehicle compartments;
- The detection of leakage and its signalling to the driver.

Post-crash fuel system integrity
UN Global Technical Regulation No.13 does not attempt to harmonise existing crash tests in each jurisdiction (i.e. in terms of the impact configuration). Instead, it sets out a series of harmonised performance requirements:

- Fuel leakage limit - volumetric flow of 118 NL per minute for 60 minutes after the crash;
- Concentration limit in enclosed spaces - 3±1 percent by volume in the passenger, luggage or cargo compartments;
- Container displacement – container to remain attached to the vehicle at a minimum of one attachment point.

As noted earlier, the potential harmonisation of crash test specifications for hydrogen and fuel cell vehicles will be discussed during Phase 2 of the development of the UN Global Technical Regulation.

3.2.3 Electrical safety

The Global Technical Regulation specifies electrical safety requirements for fuel cell vehicles in-use and post-crash. The requirements were developed in close cooperation with the UN Informal Group on Electric Safety (ELSA) and are consistent with the requirements specified for electric vehicles in UN Regulations (under the 1958 Agreement).

Electrical safety requirements in-use
The in-use requirements are derived from those in UN Regulation 100 (Electric power trains). Principally, they require that protection against direct contact inside the passenger compartment is verified using a standardised test wire (i.e. in line with protection degree IPXXD) and outside the compartment with a test finger (in line with IPXXB).

Exposed conductive parts (i.e. parts that can become energised under isolation failure) must be protected against indirect contact. This is provided by a requirement for exposed conductive parts, such as barriers and enclosures, to be connected to the chassis to prevent dangerous potentials being produced. In addition limits are specified for the resistance between all exposed conductive parts and the chassis of 0.1 ohm when there is a current flow of at least 0.2 ohm.

Finally, detailed specifications and test procedures are included for isolation resistance. The specifications depend on whether the power train comprises separate or combined DC and AC buses and their connections.

Electrical safety requirements post-crash
The post-crash electrical safety requirements are derived from those in UN Regulations 94 (front impact) and 95 (side impact). Three performance criteria are specified (a fourth criterion in the UN Regulations was not adopted for the Global Technical Regulation – Low electrical energy, limited to 2.0 Joules):

- Physical protection - against direct and indirect contact, assessed in the same manner as the in-use requirements;
- Electrical isolation - minimum resistances are specified depending on whether the DC and AC buses are separate or combined;
- Absence of high voltage (≤ 30 VAC or 60 VDC within 60 seconds after the impact).

At least one of these three criteria must be met following the impact test. However, the isolation resistance criterion does not apply if more than one part of the high voltage bus is unprotected (i.e. the conditions of IPXXB are not met). Further requirements are specified for electrolyte spillage (none in the passenger compartment and up to 7 percent elsewhere) and retention of the rechargeable energy storage system.

4 UN Global Technical Regulation on electric vehicles

4.1 The development of the Global Technical Regulation

A proposal to establish two new UN Informal Groups on electric vehicles was submitted and adopted at the 155th session of WP.29 in March 2012. The co-sponsors of the proposal were China, the European Union, Japan and the United States. They proposed that one group would focus on safety and report to GRSP, while the other group would work on the environmental aspects of electric vehicles and report to GRPE. This follows the same structure as that deployed during the development of UN Global Technical Regulation No. 13 on hydrogen and fuel cell vehicles. The specific objectives of the co-sponsors, as set out in their proposal are:

- Exchange information on current and future regulatory requirements for electric vehicles in different markets;
- Identify and seek to minimise the differences between regulatory requirements, with a view toward facilitation of the development of vehicles to comply with such requirements;
- Where possible, develop common requirements in the form of one or more UN global technical regulations

The first meeting of the UN Informal Group on electric vehicle safety took place in April 2012. Their aim is to prepare a global technical regulation for electric vehicles that covers high-voltage electrical safety, the safety of electrical components and rechargeable energy storage systems. Their estimated time of completion is the end of 2014. At the time of writing, two further meetings had taken place with a (fourth) meeting scheduled for October 2013.

4.2 Overview of the main performance tests and requirements

A first draft of the UN Global Technical Regulation on electric vehicle safety was prepared by the international organisation of motor vehicle manufacturers (OICA). The main technical provisions appear to be taken *verbatim* from those already in force in UN Regulations under the 1958 Agreement, such as UN Regulation 100 (on electrical power trains) and UN Regulations 94 (front impact) and 95 (side impact). However, it seems likely that the draft Global Technical Regulation will develop further; for example, to take input from the full range of contracting parties such as those that do not operate or recognise UN Regulations. Nevertheless, the remainder of this subsection summarises the key provisions, as they currently stand.

The draft Global Technical Regulation applies to passenger cars and buses up to a gross vehicle weight of 4,536 kg. The technical provisions are set out in two sections: Section 5 specifies performance requirements; Section 6 specifies test procedures. Within each section, the draft Regulation covers electrical safety in-use; electrical safety post-crash; the safety of the rechargeable energy storage system.

4.2.1 Electrical safety in-use

The requirements for electrical safety in-use are derived from UN Regulation 100 (electric power trains) and UN Global Technical Regulation No.13 (hydrogen fuel cell vehicles). They were summarised briefly in subsection 3.2.3 and it appears that, at present, no significant changes have been made for the draft Global Technical Regulation on electric vehicle safety.

4.2.2 Electrical safety post-crash

The post-crash electrical safety requirements are derived from those in UN Regulations 94 (front impact) and 95 (side impact) and in UN Global Technical Regulation No.13 (hydrogen fuel cell vehicles). As discussed in subsection 3.2.3, UN Global Technical Regulation No.13 specifies three performance criteria: absence of high voltage, physical protection and isolation resistance. A fourth criterion, low electrical energy, which is specified in UN Regulations 94 and 95, was not included in UN Global Technical Regulation No.13. However, it has been included in the draft Global Regulation on electric vehicle safety, albeit with a limit of 0.2 Joules (rather than 2 Joules).

4.2.3 Safety of the rechargeable energy storage system

The rechargeable energy storage system requirements are derived from UN Regulation 100 and specifically the 02 series of amendments, which came into force on 15th July 2013. This latest update to Regulation 100 sets out detailed requirements and test procedures for the safety of rechargeable energy storage systems. The tests can be performed on a complete rechargeable energy storage system, or on “a related subsystem including the cells and their electrical connections”.

Vibration
This test applies a sinusoidal waveform with a logarithmic sweep between 7 Hz and 50 Hz and back to 7 Hz in 15 minutes, up to a maximum acceleration of 10 m/s^2. The cycle is repeated 12 times for 3 hours in the vertical direction of the mounting orientation of the rechargeable energy storage system.

Thermal shock and cycling
This test comprises thermal cycling between -40°C and 60°C, repeated for five cycles. The rechargeable energy storage system (or related subsystem) must be stored for 6 hours at each temperature extreme, with a maximum interval of 30 minutes between each temperature.

Mechanical shock
This test comprises an acceleration/deceleration pulse that peaks between 20 g and 28 g for passenger cars and 10 g and 17 g for buses (up to 4,536 kg, in line with the Scope).

Mechanical integrity
This test applies a force of 100 kN to the rechargeable energy storage system (or related subsystem) with a defined “crush plate”. The force is maintained for at least 100 ms, but not greater than 10 s.

Fire resistance
This test exposes the rechargeable energy storage system (or related subsystem) to fire with detailed specifications for the distance to the source, exposure to the flame and timings. These specifications differ from those for hydrogen containers and were defined specifically for rechargeable energy storage systems.

External short circuit protection
The positive and negative terminals of the rechargeable energy storage system (or related subsystem) are connected to produce a short circuit. The test continues until a protection function interrupts or limits the short circuit, or for at least one hour after the temperature measured on the casing has stabilised.

Overcharge protection
The rechargeable energy storage system (or related subsystem) is charged at a rate of at least 1/3C until a protective device interrupts or limits the charging. If no such device is fitted, the charging is continued until it has reached twice the rated capacity of the rechargeable energy storage system.

Over-discharge protection
The rechargeable energy storage system (or related subsystem) is discharged at a rate of at least 1/3C until a protective device interrupts or limits the discharging. If no such device is fitted, the discharging is continued until the rechargeable energy storage system has reached 25 percent of its nominal voltage level.

Over-temperature protection
The rechargeable energy storage system (or related subsystem) is heated in an oven or climatic chamber. The temperature is increased until it reaches the level defined by the manufacturer as being the operating threshold for protective devices against internal overheating. If the rechargeable energy storage system is not equipped with such devices, the temperature is increased to the maximum operational temperature specified by the manufacturer.

In general, there must be no evidence of electrolyte leakage, rupture, fire or explosion during each of the rechargeable energy storage system tests specified in the draft UN Global Technical Regulation on electric vehicle safety. However, electrolyte leakage is assessed by "visual inspection without disassembling any part of the Tested-Device". Since a "Tested-Device" means a complete rechargeable energy storage system or a subsystem, including enclosures, it is possible that electrolyte leakage from cells may not be detected by this approach (i.e. if the leakage remains within the main enclosure). This assumes, therefore, that the principal hazards relating to electrolyte result from leakage outside the battery system and its enclosures.

Venting of gas would be permitted by these requirements and is one means of reducing the risk of explosion; however, at present, there are no controls over the type of substances that may vent, the quantity, and the areas of the vehicle they may vent into.

The test procedures for rechargeable energy storage systems in the draft UN Global Technical Regulation (and in UN Regulation 100) are similar to those specified in voluntary industry standards, such as ISO 12405:2011 (Test specification for lithium-ion traction battery packs). However, there are some differences in the test conditions. For example, the UN Global Technical Regulation (and UN Regulation 100) specifies a frequency range of 7 – 50 Hz for the vibration test, whereas the ISO 12405 specifies a higher level of stringency of 5 - 200 Hz.

5 Conclusions

Efforts to harmonise vehicle legislation can be hampered by diverging requirements and test procedures in different legislative jurisdictions. However, the development of UN Global Technical Regulation No.13 (on hydrogen and fuel cell vehicles), and the early work on the draft UN Global Technical Regulation on electric vehicle safety, are exemplar of the international cooperation that can be achieved. This was illustrated by the comments made by David Strickland, Administrator of the United States National Highway Traffic Safety Administration, when he applauded the adoption of the UN Global Technical Regulation No.13: *"The hard work and cooperative spirit among contracting parties and industry have produced a GTR that is performance- and science-based, well-supported by excellent research, and grounded in credible scientific data".*

Although (Phase 1) of UN Global Technical Regulation No.13 on hydrogen and fuel cell vehicles was completed successfully, with significant progress being made with the draft Global Technical Regulation on electric vehicle safety, harmonisation challenges remain. For instance, only 13 UN Global Technical Regulations have been developed in 15 years of the 1998 Agreement. Furthermore, there must be a political will to transpose the requirements into local legislation since a contracting party is obliged to begin the process only; they are not formally obliged to complete the process. One of the main difficulties lies in developing requirements and tests that are compatible with self-certification as well as type-approval regimes. UN Global Technical Regulation No.13, and the draft Global Technical Regulation, achieve this by following a strict performance-based approach. Nevertheless, the process of aligning requirements and tests can be time-consuming.

Discussions between the United States and the European Union on the proposed Transatlantic Trade and Investment Partnership could yield another solution. For instance, in a joint submission on the proposed partnership, the American Automotive Policy Council (AAPC) and the European Association of Automobile Manufactures (ACEA) proposed a "mutual recognition" system for the US and the EU whereby existing regulations are accepted, based on data-driven analyses, without the need for new regulations. Nevertheless, it seems likely that WP.29 will remain the principal forum for global harmonisation in vehicle legislation.

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