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Safety considerations for electric vehicles and regulatory activities

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Abstract

This paper explores some potential hazards associated with electric vehicles and considers how the risks to users are mitigated by European Union and United Nations type-approval regulations. In doing so, it highlights any gaps in the regulations and the international efforts that are currently underway to close them. Vehicle hazards are the main focus for this work, and some consideration is given to the way they are likely to be used by the public. However, hazards relating specifically to infrastructure, such as vehicle charging or battery exchange are generally not included because they are likely to fall under a different regulatory framework.

Keywords: Safety, Regulation, Standardisation

1 Introduction

Electric vehicles have the potential to offer many benefits to society such as improved air quality in towns and cities and reduced carbon dioxide emissions from road transport (depending on the source of the electricity). However, they are very different from conventional vehicles and present some new safety hazards. Clearly, electric vehicles are not inherently unsafe, nor will they necessarily expose the public to greater risks than internal combustion engine vehicles. Nevertheless, there is always the potential for unintended consequences whenever a new technology is introduced. If such consequences are to be minimised, then it is important that vehicle safety regulations keep pace with new technology.

For the purposes of this paper, "electric vehicle" generally includes hybrids as well as purely-electric vehicles. Hybrid vehicles combine electric power from an on-board rechargeable energy storage system (such as a battery) with an internal combustion engine. Different degrees of hybridisation are possible:

- A "mild hybrid" switches the engine off when the vehicle is stationary and then restarts when the accelerator is pressed. Energy from braking is stored and can be used to support the internal combustion engine during acceleration.
- A "full hybrid" is capable of running on battery power alone, although usually for very short distances only.
- A "plug-in hybrid" can be charged directly from the grid and can run on electric power for longer distances
- An "extended-range electric vehicle" uses a small internal combustion engine to charge the battery rather than drive the wheels.

Purely-electric vehicles run on battery power only and do not use an internal combustion engine or liquid fuel.

2 Road vehicle legislation

Most (if not all) regions of the world operate some form of road vehicle legislation. However, this paper focuses primarily on European Union (EU) Directives and Regulations as well as United Nations (UN) Regulations. The activities of the main international standards bodies are also introduced.

2.1 European Union type-approval

European Community Whole Vehicle Type-Approval (ECWVTA) is the main form of vehicle certification in Europe. The EU type-approval system requires independent, third-party approval covering all testing, certification and conformity of production assessments. Each member state of the EU must appoint an approval authority to issue approvals and a technical service to carry out the testing. The key principle of the system is that an approval issued by one authority will be accepted in all member states.

Directive 2007/46/EC (the Framework Directive) applies to powered four-wheel vehicles including passenger cars, goods vehicles and trailers (lightweight, low-powered four-wheeled vehicles referred to as quadricycles are not included; instead, they fall within the type-approval framework for powered two- and three-wheeled vehicles).

The Framework Directive lists more than 40 separate EU Directives that the vehicle must comply with in order to gain type-approval. These specify performance requirements and tests for various aspects of the vehicle ranging from tyres through to exhaust emissions and braking systems. The Framework Directive also lists United Nations (UN) Regulations that are considered to be acceptable alternatives to certain EU directives.

European Union Directives are generally kept up to date, but several EU Directives have started to lag behind their corresponding UN Regulation, particularly on the subject of electric vehicles. However, EU type-approval is undergoing a process of simplification in line with the recommendations contained in the final report of the CARS 21 High Level Group [1]. As part of this process, EU Directives are being repealed and replaced with a smaller number of EU Regulations that apply directly in each member state. These EU Regulations typically follow a "split-level" approach, comprising two-parts:

- Fundamental provisions are set out in an EU Regulation laid down by the European Parliament and Council and adopted through the ordinary legislative procedure;
- Technical specifications that implement the fundamental provisions are laid down in one or more separate EU Regulations adopted by the Commission with the assistance of a regulatory committee (typically comprising representatives of EU member states, the automotive industry, component manufacturers and other stakeholders).

As an example of this split-level approach, in 2014 each of the separate EU Directives on vehicle safety will be repealed by Regulation (EC) No. 661/2009 and replaced, where appropriate, with reference to the corresponding UN Regulation. A series of implementing regulations are also being created where there is no UN Regulation that is equivalent to the old separate EU Directive.

2.2 United Nations Regulations

UN Regulations (previously known as UNECE Regulations) are administered by the World Forum for Harmonisation of Vehicle Regulations (WP.29), which is a subsidiary body of the United Nations Economic Commission for Europe. The regulations are based on the principles of type-approval and of reciprocal recognition of approval among participating countries. The legal framework for the reciprocal recognition of UN Regulations is set out in the "1958 Agreement".

UN Regulations generally provide for the approval of vehicle systems and components, or for specific aspects of a vehicle, but there is no "whole vehicle" approval mechanism. Several UN Regulations have been amended to include specific provisions for electric vehicles. These include UN Regulation 12 (protective steering), UN Regulation 13 and 13-H (braking), UN Regulation 51 (noise), UN Regulation 83 (emissions), UN Regulation 85 (engine power) and UN Regulation 101 (CO_2 emissions). In addition, proposals to amend UN Regulation 94 (frontal impact), UN Regulation 95 (side impact) have now been adopted. UN Regulation 100 sets out specific provisions for electrical power trains and was recently made mandatory for EU type-approval.

Some of the work of preparing amendments to these UN Regulations, particularly those relating to safety, was carried out by an informal working group on Electric Safety, which was set up in 2008, and by "groups of interested experts" that emerged from this informal working group.

2.3 United Nations 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 generally achieved by following a performance-based approach when preparing the requirements.

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.

The UN Global Technical Regulations that are currently in place do not require special provisions for electric vehicles because they cover topics that are unrelated to the vehicle's powertrain. However, a proposal was made at the 155th Session of WP.29 to set up two informal groups on electric vehicles, under the 1998 Agreement, to create a basis for the possible development of a UN Global Technical Regulation. One group will focus on safety, while the other will focus on environmental aspects of electric vehicles.

The proposal envisages safety provisions for electric vehicles that will cover electrical safety in normal, everyday use as well as following a crash. The "in-use" topics proposed are:

- Occupant protection from electric shock;
- Charging requirements;
- Safety requirements for rechargeable energy storage systems.

The "post-crash" topics proposed are:

- Electrical isolation;
- Battery integrity;
- Best practices or guidelines for manufacturers and/or emergency responders;
- Battery discharge procedures.

The proposal recognises that the work already carried out under the 1958 Agreement to amend and update UN Regulations is a potential input to this work.

2.4 International standards

While vehicle legislation is the main focus for this paper, it is worth noting that a variety of international standards are emerging for electric vehicles, many of which deal with safety topics. However, these are essentially voluntary industry standards, unless a specific reference to the standard is made in an EU Directive or Regulation or a UN Regulation.

International standards work for electric vehicles is largely being undertaken by two bodies: ISO (International Organisation for Standardisation) and the International Electrotechnical Commission (IEC). Traditionally, standards work between these bodies is shared according to the general principle that all matters relating to electrical and electronic equipment are reserved for IEC and all other matters are reserved for ISO.

However, there are aspects of electric vehicles that have the potential to fall under the responsibility of both bodies, which brings the risk of duplication if the work is not coordinated. A general consensus was agreed between the two bodies in the 1990s whereby ISO focussed on work relating to electric vehicles as a whole, while IEC focussed on electric components and supply infrastructure. Further information about the basic division of work and the key technical committees has been described comprehensively elsewhere [2].

More recently, in 2011, a memorandum of understanding on the international standardisation of electrotechnology for road vehicles was signed to ensure ongoing cooperation. The agreement describes two fields of application:

- On-board equipment and performance of road vehicles;
- Interface between externally chargeable vehicles and electricity supply infrastructure.

Briefly, the memorandum states that ISO is responsible for all standardisation issues concerning road vehicles and on-board systems, but any standards should reference existing IEC standards for electrical and electronic components (unless vehicle-specific conditions require otherwise). The memorandum cites existing modes of cooperation in ISO/IEC Directives, Part 1, clause B.4.2.2, for standards relating to all interfaces between externally chargeable road vehicles and the electricity supply infrastructure.

3 Safety considerations and regulatory activities

This section discusses some potential safety considerations for electric vehicles. As noted, it was not the intention to imply that electric vehicles are unsafe or would expose the public to greater risks than conventional vehicles. Instead, the focus was on some general hazards and how they are regulated under EU type-approval and in UN Regulations under the 1958 Agreement.

3.1 Electrical safety in use

The voltages used in electric vehicles are potentially very dangerous. However, a range of safety features are typically used to ensure the safety of occupants or other persons. Crucially, the high voltage circuit is isolated from the vehicle chassis (and any other conductors). This means that a person would need to touch both the positive and the negative sides of the circuit to receive an electric shock. This would require a loss of isolation on both sides of the circuit (i.e. a double-fault). In fact, the ground-fault monitoring system would detect any leakage of current and would disconnect the high voltage system from the rechargeable energy storage system.

Safety requirements for electrical power trains are set out in UN Regulation 100. It comprises specifications and test procedures in four main areas: protection against electric shock; rechargeable energy storage systems; functional safety; and determination of hydrogen emissions. With regards to protection against electric shock, the requirements generally apply to high voltage buses when they are not connected to external high voltage supplies. There are three main aspects: protection against direct contact; protection against indirect contact with exposed conductive parts; and isolation resistance.

Vehicles may employ various means to prevent direct contact with live parts, such as insulating materials or physical barriers. UN Regulation 100 ensures that the conventional electrical protection degrees (IPXXB or IPXXD) are enforced. For example, the regulation specifies that live parts in the passenger or luggage compartments must be protected to a degree of at least IPXXD. Enclosures in other areas must have a protection degree of at least IPXXB. In each case, an access probe is pushed against any openings of the enclosure with a specified test force and must not touch live parts. In the case of IPXXD, the probe is a test wire, 1 mm in diameter and 100 mm long, and in the case of IPXXB, the probe is a jointed test finger, 12 mm in diameter and 80 mm long.

Protection against indirect contact with live parts is closely related to the prevention of electrical faults. The regulation requires that any exposed conductive parts, such as barriers or enclosures, are connected to the chassis to prevent dangerous potentials being produced. The regulation also specifies a limit 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 amperes.

Finally, detailed specifications are included for isolation resistance. The specifications depend on whether the power train comprises separate or combined DC and AC buses. Limits are specified according to the type of buses and their connections, and test procedures are provided in an annex.

UN Regulation 100 was updated and amended in 2010. The work was carried out by the UN informal group on electric safety, which comprises representatives from national governments, the automotive industry, their suppliers and test institutes. The new version covers electrical safety requirements for all types of electric vehicles including purely electric vehicles, hybrids and hydrogen fuel cell vehicles. It covers both passenger and commercial vehicles, provided their speed exceeds 25 km/h. The regulation was officially made mandatory for EU type-approval during 2010 and any vehicles that meet its requirements should not pose an electrical safety hazard during the normal operation of the vehicle.

3.2 Electrical safety post-crash

A collision could compromise the electrical safety measures described in the previous section and could increase the risk of electric shock. For example, electrical isolation might be lost such that both the positive and negative sides of the circuit come into contact with the vehicle bodywork. If any of the occupants touched the bodywork they would become part of the high voltage circuit and would receive an electric shock. However, it is likely that most electric vehicles will be fitted with a device that disconnects the rechargeable energy storage system from the high voltage circuit in the event of a crash. This is generally achieved by linking the system to crash detection sensors used to activate pre-tensioners and air bags. For example, Justen and Schöneburg [3] describe the current philosophy implemented by Daimler in Mercedes-Benz hybrid and electric vehicles. Two different switch-off strategies have been implemented by Daimler: a reversible cut-off for minor collisions and an irreversible cut-off for more severe collisions. Another example is provided by Uwai *et al.* [4], in a description of a shutdown system developed by Nissan.

Disconnecting the rechargeable energy storage system from the rest of the high voltage circuit will reduce the risk of electric shock during and following a crash, but it will also be important to ensure that the rechargeable energy storage system is not damaged in such a way that can lead to a fire or an explosion. Furthermore, discharging the rechargeable energy storage system will be important for the safe handling and recovery of the vehicle. This was illustrated in the United States where an electric vehicle caught fire three weeks after a pole impact test [5]. The battery was damaged during the impact and coolant leaked onto the electronic components during the post-impact static roll of the vehicle. The battery was not discharged before the vehicle was placed in storage and the ensuing fire destroyed the vehicle and several others parked nearby.

Directive 96/79/EC and UN Regulation 94 set the minimum requirements for the frontal impact performance of cars. They both specify a frontal impact test in which the car is propelled into an offset, deformable barrier at 56 km/h. Similarly, Directive 96/27/EC and UN Regulation 95 set the minimum requirements for side impact performance. They specify an impact test in which a mobile deformable barrier is propelled into the side of the car at 50 km/h.

There are no specific provisions for electric vehicles in the EU Directives for frontal and side impact. The test procedures and occupant safety requirements could be applied to any vehicle, regardless of power train type; however, there are no specifications for the preparation of an electrical power train or for the electrical safety of the occupants during and following the impact. In 2009, a group of interested experts on post-crash provisions for electric vehicles was formed. The aim of the group was to derive amendments to UN Regulations 94 and 95 so that they are appropriate for the assessment of electric vehicles. The group was formed mainly of experts in electrical safety from the UN informal working group on electrical safety and experts in crash safety from the UN informal working group on frontal impact.

The proposals to amend UN Regulations 94 and 95 were completed in 2010 and adopted by WP.29. With regards to the protection against electric shock following the impact test, the amendments specify four performance criteria:

- Physical protection (IPXXB and resistance between exposed conductive parts and electrical chassis < 0.1 ohm);
- Electrical isolation (minimum resistance specified depending whether DC and AC buses are separate or combined);
- Absence of high voltage (≤ 30 VAC or 60 VDC);
- Low electrical energy (< 2 Joules).

At least one of these four 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). This requirement was added to prevent vehicles meeting the isolation resistance criterion and hence gaining approval while presenting a risk of electric shock (because more than one part of the high voltage bus is accessible).

If the vehicle is equipped with an automatic device that separates the rechargeable energy storage system from the rest of the high voltage circuit in the event of a crash, or a device that divides the power train circuit, (one of) the criteria must be met by the disconnected circuit, or by each divided circuit individually after the disconnect function is activated. However, although the amendments include provisions for vehicles with an automatic disconnect device, there is no requirement to fit one. Two of the four criteria to assess the projection against electric shock can be met with no automatic disconnect device: physical protection and isolation resistance.

UN Regulations 94 and 95 will also now specify requirements for the retention of the rechargeable energy storage system and electrolyte spillage. The requirements for the retention of the rechargeable energy storage system depend on its location. If it is located within the passenger compartment, it must remain in the location in which it was installed and all its components must remain within its boundaries. No part of a rechargeable energy storage system located outside the passenger compartment can enter the passenger compartment during the test. The assessment is made by visual inspection only and no guidance or tolerances are provided.

Electrolyte spillage within the passenger compartment is not allowed in the amendments to UN Regulations 94 and 95. Outside the passenger compartment, it is limited to 7%; except where open-type traction batteries are fitted. For these batteries, spillage outside the passenger compartment is limited to 7% up to a maximum of 5 litres. These requirements are valid over a 30 minute period, starting from the point of impact. Batteries have traditionally featured liquid electrolytes; however, solid electrolytes have started to emerge. The amendments do not distinguish between liquid and solid electrolytes and hence the 7% limit should apply in either case (if the requirement is applied strictly).

The amendments to UN Regulations 94 and 95 will ensure that the electrical safety measures in an electric vehicle are capable of functioning in a collision (at least up to the severity of the regulatory crash tests). Nevertheless, some residual risks could remain. These are summarised below:

- Validation of amendments

Although the amendments have been prepared by experts, they have not been validated experimentally. Performing a series of crash tests (and/or obtaining data from manufacturers) would help to confirm that the amendments are appropriate and consider all the hazards.

- Side impact – taller vehicles

The side impact legislation does not apply to a vehicle if the reference point of the lowest seat is more than 700 mm from the ground. This recognises that taller vehicles tend to perform very well in side impact tests. While this could apply to an electric vehicle too, the electrical components might be damaged resulting in an electrical safety hazard even when there is a low risk of collision injury. Amending the legislation to require taller electric vehicles to undergo a side impact test (i.e. to assess only the post-impact electrical safety) could potentially avoid this hazard.

- Fuel leakage – hybrid vehicles

The frontal and side impact legislation permits fuel (or a substitute) to leak from the fuel system following the impact test, but limits the leakage rate to 5x10-4 kg/s (i.e. 30 grams/min). However, hybrid electric vehicles could present a new hazard due to their high voltage components, which can generate enough energy to create a spark. Adopting more stringent requirements for fuel leakage with hybrid vehicles might reduce the risk of fuel leaking from a hybrid vehicle following a collision and coming into contact with high voltage components.

- Automatic disconnection of the electrical energy source

An automatic disconnection device can be used to provide protection, but it is not mandatory, and other means of protection can be provided that do not require an automatic disconnection device to be fitted. The current performance metrics are less design prescriptive, but there is a risk that they may not perform in collision scenarios that differ from the regulatory impact tests. A mandatory requirement to fit an automatic disconnection device could allow the protection against electric shock to be controlled in a broader set of circumstances.

- Structural integrity of the rechargeable energy storage system

The amendments specify requirements to control the movement of a rechargeable energy storage system during the frontal and side impact tests, but there are no requirements for its structural integrity. Mechanical loading of a rechargeable energy storage system can lead to shorting and possibly rupture, with the risk of sparks, fire and explosion. Amending the frontal and side impact legislation to include post-impact structural integrity requirements for the rechargeable energy storage system would reduce the risk of this potential safety problem.

- Electrolyte spillage - limits

The limit of 7% specified for electrolyte spillage outside the passenger compartment was derived from other (national) legislation already in force. However, it is unclear how much electrolyte would be dangerous and whether the risk depends on the type of battery chemistry and electrolyte used. Prohibiting electrolyte spillage outside the passenger compartment (as well as inside) would avoid this potential safety problem. Alternatively, further research would enable appropriate limits to be created for different battery types.

- Electrolyte spillage - static roll

The amount of electrolyte that leaks might increase if an electric vehicle rolls over following a collision. Performing a static roll test following the impact test would assess the potential for electrolyte spillage in a broader set of circumstances.

3.3 Crash compatibility of electric vehicles

Electric vehicles are typically heavier than equivalent internal combustion engine vehicles. The rechargeable energy storage system (i.e. batteries, capacitors, electromechanical flywheels, etc) is the principal source of the additional weight. A vehicle may also require certain structural features to accommodate the weight of the rechargeable energy storage system and these features may add further weight themselves. In the longer term, efforts will be made to reduce weight elsewhere in the vehicle, through better design and by incorporating new technologies and alternative materials. However, since there is also significant interest in reducing the weight of conventional vehicles (to improve their fuel economy), electric vehicles could remain heavier in comparison.

There are numerous publications that discuss the potential effects of vehicle weight on safety. The basic physics is relatively straightforward: if two vehicles of different mass collide, the heavier vehicle will experience less deceleration than the lighter vehicle. On that basis, occupants of heavier vehicles are thought to face lower risks in collisions than occupants of lighter vehicles [6]. The reality is more complex and various factors can affect the secondary safety performance of a vehicle in a collision, such as the structural integrity of the passenger compartment, the "crush space" available to absorb energy, the performance of the restraint systems and the age and other characteristics of the occupants. Nevertheless, Talouei and Titheridge [7] found that a 100 kg increase in mass decreases the risk of injury to the driver in a two-car injury accident by 3 %. It could be argued, therefore, that an electric vehicle will offer secondary safety benefits to its occupants (in certain circumstances). However, a heavier vehicle will also be more "aggressive" and hence increasing the mass of a particular vehicle could increase the risks to occupants of other vehicles. Preliminary research carried out by the Highway Loss Data Institute in the United States found that the odds of being injured in a crash are 25 percent lower for people in hybrids than people travelling in non-hybrid models [8]. However, while the analysis included more than 25 hybrid and conventional pairs, it was unclear how many vehicles and collisions the finding was based on.

The relationship between vehicle mass and occupant injury outcome is important; however, some of the benefits associated with mass may actually be related to size [9]. Clearly, mass and size are closely linked (at least in current vehicles), but they can have different effects. The size of a vehicle, especially its front end, is key to its performance in a frontal impact. A larger vehicle is more likely to have a longer crush space to absorb the collision. Broughton [10] found that the mean risk of death for the driver of the smallest type of cars (minis and superminis) is four times the risk for the largest type (4x4s and people carriers).

Many of the first generation of purely-electric vehicles are smaller, lighter vehicles (minis and superminis). Some manufacturers have publicised their electric vehicle development programmes for larger vehicles, but it seems likely that this will remain the case in the short to medium term (unless there is a significant energy storage breakthrough). The composition of the car fleet has already changed over the last 10 years. New car registrations data published by the Society of Motor Manufacturers and Traders (SMMT) shows that the market shares of smaller cars (minis and superminis) and larger cars (4x4 and multi-purpose) have increased relative to medium-sized cars [11]. However, Broughton and Buckle [12] found that changes in the fleet (between 1997 and 2003) appear to have had only a minor contribution to the severity of car accidents. Nevertheless, if purely-electric vehicles penetrate the fleet in significant numbers, the market share of small cars may increase further relative to other vehicles. This may have an effect on casualty statistics, unless improvements in the "compatibility" of vehicles can be achieved, potentially through better self and partner protection requirements in the legislative and/or consumer crash tests.

Another important aspect of vehicle compatibility in a collision is the structural interaction between the two vehicles. Proper structural alignment over a common interaction zone is essential to ensure that energy is absorbed in the most effective way. Current electric vehicles typically display a structural layout that is comparable to that in conventional vehicles. However, electric vehicles also present an opportunity for innovation in vehicle design and styling, particularly in purely electric vehicles or range-extended electric vehicles (where there is no need to mount a large, heavy engine in the frontal compartment). Other developments such as in-wheel motors could further reduce the need for a conventional structural layout at the front of the vehicle and hence in the longer term, there could be greater diversity in the fleet.

The European 7th Framework Project, FIMCAR (Frontal Impact and Compatibility Assessment Research) is developing test procedures that will encourage a common structural interaction zone (www.fimcar.eu). The objective of the researchers is for the measures developed to be suitable for implementation in legislation. While these procedures would reduce the risks associated with poor structural alignment between vehicles, they would not mitigate the more fundamental risks associated with smaller, lighter vehicles when they are in collision with larger, heavier vehicles.

3.4 Rechargeable energy storage systems

The rechargeable energy storage system is arguably the key component of an electric vehicle. Batteries are the most common type, but electric double-layer capacitors and electro-mechanical flywheels may also be used. Any type of rechargeable energy storage system has the potential to be hazardous if it is not designed carefully, although concerns have been raised in the literature about batteries in particular [13]. Hazards can emerge during the normal operation of the battery or during conditions or events outside its normal operating range. These include electrolyte/material spillage if individual cell casings are damaged, the battery's reaction to high external temperatures and fire, and its electrical properties, for example, under short circuit, over-voltage and voltage reversal conditions.

UN Regulation 100 deals with the safety of electric vehicles 'in-use' and includes specifications that relate mainly to the protection of users against electric shock. There are some rudimentary specifications for rechargeable energy storage systems, which cover the protection against excessive current and accumulation of gas. The main requirement concerning excessive current is simply that the rechargeable energy storage system "shall not overheat". However, if it is subject to overheating, it must be equipped with a protective device such as fuses, circuit breakers or main contactors. Accumulation of gas is controlled by a requirement to provide a ventilation fan or duct in places containing an "open-type battery" that may produce hydrogen gas.

UN Regulations 94 and 95 (frontal and side impact respectively) are being amended to include post-impact electrical safety requirements for electric vehicles that will cover protection against electric shock, retention of the rechargeable energy storage system and electrolyte spillage following the impact test. As noted in Section 3.2, the requirements for the rechargeable energy storage system consider only its movement during the impact test.

There are no further safety requirements for the rechargeable energy storage systems in electric vehicles in EU type-approval. In contrast, the energy storage system in conventional vehicles, the fuel tank, must meet the requirements of a specific EU Directive or corresponding UN Regulation. These specify a series of component-level tests and requirements for liquid fuel tanks. Similar legislation is in place for hydrogen storage systems. Developing type-approval requirements for rechargeable energy storage systems would harmonise the safety performance of this key electric vehicle component and would be consistent with the approach for other vehicles.

A group of interested experts on rechargeable energy storage systems was formed in 2010. The group has prepared a proposal for a series of amendments to UN Regulation 100 to specify safety requirements and tests for rechargeable energy storage systems. The proposals have been submitted to the Working Party on Passive Safety (GRSP) of WP.29 and will be discussed during the 51st Session in Geneva on 21-25 May 2012.

The main topics covered by the performance tests include:

- Vibration;
- Thermal shock and cycling;
- Mechanical shock;
- Mechanical integrity;
- Fire resistance;
- External short circuit protection;
- Overcharge protection;
- Over-discharge protection;
- Over-temperature protection.

In general, there must be no evidence of electrolyte leakage, rupture, fire or explosion during each test. 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. UN Regulation 100 already specifies requirements to control the accumulation of gas, but this is currently limited to “open-type” batteries.

The test procedures in the proposed amendments were derived mainly from ISO 12405 on lithium-ion traction battery packs and systems (Part 1: high-power applications, published in 2011, and Part 2: high energy applications, in draft), with due consideration also given to the lithium battery tests in Section 38.3 of the UN Manual of Tests and Criteria. It is unclear, therefore, to what extent the procedures (and particularly the requirements) are relevant for other battery chemistries. Furthermore, it seems likely that additional procedures and requirements will be needed to accommodate other types of rechargeable energy storage systems (i.e. capacitors and flywheels).

3.5 Acoustic perception

The acoustic emissions from a vehicle in motion comprise three main elements: noise from the engine and powertrain; noise from the interaction between the tyres and the road; and finally, noise made by air as it flows around the vehicle. At low speeds (i.e. below 15 – 20 mile/h) the contributions of tyre/road noise and aerodynamic noise are relatively low and hence the powertrain noise is responsible for most of the acoustic emissions from the vehicle. Modern vehicles are quieter than ever, due largely to ever more stringent legislative requirements. Nevertheless, electric vehicles typically generate less powertrain noise than internal combustion engine vehicles.

The lower levels of powertrain noise from electric vehicles might have implications for the safety of other road users. For example, cyclists might use auditory cues to the presence of a vehicle when executing certain manoeuvres and pedestrians might use auditory cues when crossing the road. Visually-impaired pedestrians in particular may rely on auditory cues. In certain environments (i.e. where vehicles tend to travel at lower speeds), the rates of cyclist and pedestrian casualties might increase if electric vehicles become more widespread. A study from the United States found that hybrid electric vehicles engaged in certain low speed manoeuvres were more likely to be involved in collisions with cyclists and pedestrians than internal combustion engine vehicles [14]. However, it was impossible to identify whether each collision was a result of the cyclist or pedestrian not seeing/hearing the car or vice versa.

More recently, a study from the UK found that relative to the number of registered vehicles, electric (including hybrid) vehicles were less likely to be involved in a collision (of any kind) than an internal combustion engine vehicle, but were equally likely to be involved in a pedestrian collision [15]. The authors concluded that while this potentially supported the perceived increase in pedestrian risk for electric vehicles, the accident rates may reflect the usage patterns of such vehicles.

It seems that the evidence for increased risks to cyclists and pedestrians from electric vehicles is, at present, not particularly strong. However, this may change as more vehicles join the fleet (particularly if they are used in urban environments). In the meantime, various external warning devices are starting to emerge for electric vehicles [16]. A range of sounds, including personalised sounds, have been put forward, although sounds with similar noise characteristics as conventional engines seem to be the most favourable countermeasures [17].

The World Forum for Harmonisation of Vehicle Regulations (WP.29) has determined that electric vehicles present a danger to pedestrians and has directed the Working Party on Noise (GRB) to assess what steps, if any, might be taken to mitigate pedestrian hazards (through acoustic means or other means of communication). In response, GRB has established an informal working group on quiet road transport vehicles to determine the viability of "quiet vehicle" audible acoustic signalling techniques and the potential need for global harmonisation. The use of "quiet vehicle" recognises that many internal combustion engine vehicles are "quiet" at low speeds and may need to be included in any future measures. The activities of the informal group are ongoing and include a draft proposal for a UN Global Technical Regulation on audible vehicle alerting systems for quiet road transport vehicles.

3.6 Electromagnetic fields

There is some public concern about the effects of electromagnetic fields on human health, particularly with respect to fields from mobile phones and power lines. Some of the research has produced contradictory results, but in general, scientific evidence for any effect at the intensity levels typically found in these situations remains rather weak [18]. Nevertheless, the International Commission for Non-ionising Radiation Protection (ICNIRP) has published exposure guidelines, based on the avoidance of established biological effects of electromagnetic fields.

Concerns have also been raised in the media about the exposure of electric vehicle occupants to electromagnetic fields [19, 20]. Electric and hybrid vehicles give rise to particular concerns because they use currents and voltages that are much higher than those used in conventional vehicles, and which can therefore potentially generate much higher intensity fields. There is, however, very little publically-available research on this topic. One comparison of electromagnetic fields from different modes of transport concluded that there was no major difference in fields between electric vehicles and conventional vehicles [21]. Another, more recent, study measured electromagnetic fields in hybrid cars, but found the levels to be much lower than the ICNIRP guidelines [22]. An ongoing European 7th Framework Project, called EM-Safety, is also investigating this issue with the aim of increasing public confidence in the safety of fully electric vehicles with regards to their electromagnetic fields (www.sintef.no).

At present, there are no type-approval requirements for vehicles to address the potential health effects of electromagnetic fields, arguably reflecting the lack of any evidence of harm. The type-approval EU Directive (and corresponding UN Regulation) for radio interference is intended to prevent problems with radio reception and with the functioning of safety equipment on the vehicle. Vehicle emissions are measured outside the vehicle. The lowest frequency measured is 30 MHz, well in excess of the frequencies expected from electric vehicle propulsion components.

3.7 Functional safety

Functional safety relates to the overall safety of a system and is particularly important for complex software-based systems. Electric vehicles typically require greater use of distributed control systems than conventional vehicles, which can be highly integrated. However, the focus here is not on these complex electrical and electronic systems. Instead, consideration is given to the potential for unexpected vehicle movements caused by drivers (or others) being unaware that the vehicle is in an active mode.

Electric vehicles could present some potential functional safety hazards, particularly around the safe operation of the powertrain by drivers. For example, if the vehicle is stationary for a period of time, say in a car park or similar situation, a driver may 'forget' that the vehicle is capable of motion. They may leave the vehicle in this condition, or they may unintentionally activate the power train.

UN Regulation 100 includes basic functional safety requirements that deal with the safety of occupants, but also those outside the vehicle by preventing (as far as possible) unintentional vehicle movements. For instance, the regulation requires that:

- At least a momentary indication is given to the driver when the vehicle is in "active driving mode";
- When leaving the vehicle the driver must be informed by a signal if the vehicle is still in the active driving mode;
- Vehicle movement by its own propulsion system is prevented during charging as long as the connector of the external power supply is physically connected to the vehicle inlet;
- The state of the drive direction control unit is identified to the driver.

Several other functional safety requirements were removed during the most recent amendment of UN Regulation 100, possibly because corresponding specifications for conventional vehicles were not legislated.

As noted in Section 3.1, UN Regulation 100 applies only to passenger and commercial vehicles (M and N category respectively). Powered two- and three-wheelers and quadricycles (L category vehicles) are not included in the scope. However, the functional safety hazards discussed above are relevant for L category vehicles too. For example, a rider might be sitting on an electric moped or motorcycle in an "active driving mode" when another person inadvertently (or intentionally) operates the throttle. Some form of interlock would be needed to prevent such an action.

4 Conclusions

1. It was not the intention of this paper to imply that electric vehicles are inherently unsafe, or would expose the public to greater risks than conventional vehicles. Instead, the focus was on some general hazards and how they are regulated, particularly under EU type-approval.

2. The main regulatory acts for EU type-approval (i.e. EU Directives) tend to lag behind the corresponding UN Regulations (which are sometimes recognised as alternatives). This "lag" is most noticeable when it comes to provisions for electric vehicles in the safety legislation.

3. The current approach in the framework directive is to permit either the EU Directive or the UN Regulation to be used. In 2014, Regulation (EC) No. 661/2009 (the general safety regulation) will come into effect. It will repeal certain safety directives and will include references to the appropriate UN Regulation.

4. A proposal has been made to develop a UN Global Technical Regulation on electric vehicles. The proposal envisages safety provisions for electric vehicles that will cover electrical safety in everyday use as well as following a crash. Adopting the proposal will help to improve global harmonisation on the safety of electric vehicles.

5. The voltages used in electric vehicles are potentially very dangerous. However, a range of safety features are typically used to ensure the safety of occupants or other persons. In addition, this aspect of the vehicle is regulated under UN Regulation 100, which specifies performance requirements and tests for protection against direct contact, protection against indirect contact and isolation resistance.

6. A collision could compromise the electrical safety measures in an electric vehicle, increasing the risk of electric shock for the occupants (or for the emergency services). Proposals to amend UN Regulation 94 (frontal impact) and UN Regulation 95 (side impact) have been adopted that specify performance criteria and measurement methods for protection against electric shock post-impact.

7. Good compatibility is important in a collision, regardless of the type of power train. However, while electric vehicles are usually heavier than equivalent conventional vehicles,

purely electric vehicles tend to be small cars and hence there may be implications for our casualty statistics if the public are encouraged to downsize to these vehicles in significant numbers. Furthermore, in the future, electric vehicles may not require a conventional structural layout, particularly if there is a move towards in-wheel motors. Although compatibility is not currently considered in vehicle legislation, research is underway to develop test procedures that are suitable for legislation and will encourage a common structural interaction zone.

8. There are a range of potential hazards associated with rechargeable energy storage systems. There are currently no safety requirements for rechargeable energy storage systems in EU type-approval. However, a group of interested experts on rechargeable energy storage systems has prepared proposals for amendments to UN Regulation 100 to specify safety requirements and performance tests.

9. The lower levels of powertrain noise from electric vehicles might have implications for the safety of other road users, such as cyclists and pedestrians. Various warning systems are starting to emerge and a UN informal working group has been formed to determine the feasibility of acoustic signalling techniques and the need for global harmonisation.

10. There is some public concern about the effects of electromagnetic fields on human health, particularly with respect to fields from mobile phones and power lines. Electric vehicles have the potential to generate much higher fields than conventional vehicles. However, limited research has been carried out to measure electromagnetic fields in the passenger compartment of electric vehicles. In the meantime, there are no EU or UN type-approval requirements to deal with the potential health effects of electromagnetic fields in electric vehicles.

11. Electric vehicles could present some potential functional safety hazards, particularly around the unintended operation of the powertrain by drivers. However, UN Regulation 100 includes basic functional safety requirements that should reduce the likelihood (as far as possible) of unintentional vehicle movements.

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[1] Visvikis, C., Morgan, P., Boulter, P., Hardy, B., Robinson, B., Edwards, M., Dodd, M. and Pitcher, M. (2010). *Electric vehicles: review of type-approval legislation and potential risks* (Client Project Report 810). Retrieved May 9, 2011 from http://ec.europa.eu/enterprise/sectors/automotive/files/projects/report_electric_vehicles_en.pdf.

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