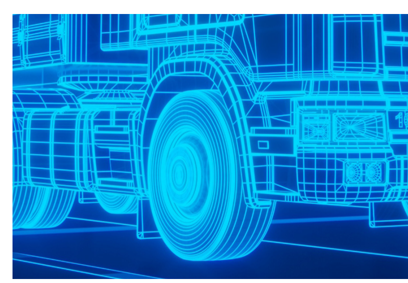
International Transport Forum

Regulations and Standards for Clean Trucks and Buses

On the Right Track?



Decarbonising Transport

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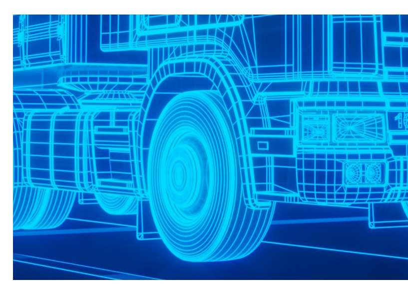

Decarbonising Transport

The International Transport Forum

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Case-Specific Policy Analysis Reports

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The initiative (https://www.itf-oecd.org/decarbonising-transport) brings together a partnership that extends far beyond the ITF's member countries. It includes work streams aiming to:

- track progress to evaluate how current mitigation measures contribute to reaching objectives for reducing greenhouse gas (GHG) emissions from transport

- develop in-depth sectoral and focus studies to identify effective policies in specific modes (e.g. road transport) and thematic areas (e.g. cities)
- bring policies together in a catalogue of effective measures, to support countries to develop their GHG emission mitigation strategy in transport.
- support the policy dialogue, leveraging on extensive engagement with the United Nations Framework Convention on Climate Change (UNFCCC), including the ITF's designation as focal point for transport of the Marrakech Partnership for Global Climate Action (MP-GCA).

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What we did

This report outlines the current status of technical regulations and standards for heavy low- and zero-emission vehicles (LZEVs). These include in particular fuel cell electric vehicles and plug electric vehicles, i.e. battery electric vehicles and plug-in hybrids. The report includes information on regulations and standards on vehicle safety, charging and refuelling infrastructure, environmental and energy-related performance and identifies remaining barriers and opportunities for their future development.

The focus of the report is on the evolution of regulations and standards in developed economies. It also offers insights for policymakers in developing countries interested in working towards a transition to low- and zero-emission technologies.

What we found

Establishing technical regulations and standards is a crucial step when introducing new LZEV technologies. These are important pre-requisites for developing safe and reliable vehicles, for distributing the energy for the vehicles and, ultimately, for their capacity to meet environmental policy objectives. Significant work in this area has already been done in the framework of the United Nations as well as other international and national standardisation organisations.

Electricity and hydrogen will be key energy vectors needed in heavy-duty LZEVs. Like vehicles with internal combustion engines, regulations will need to ensure their safe use. Current international safety standards that apply to electric vehicles and batteries tend to cover cars, light commercial vehicles and heavy vehicles like buses and trucks under a single framework. However, some provisions for heavy vehicles (in particular fuel cell electric vehicles) have gaps. Differences in technical requirements and duty cycles between light and heavy vehicles also require further differentiation in regulations and standards.

Existing regulations for the refuelling of hydrogen vehicles mainly relate to compressed gaseous on-board storage. Most fuel cell busses (but also other heavy duty vehicles) are currently equipped with tanks using a nominal working pressure of 35 MPa. Manufacturers are now considering tanks capable of withstanding a pressure of 70 MPa as a way to increase energy density and vehicle range. Such high-pressure tanks are already in use in passenger cars.

The potential of alternative solutions of storing hydrogen for LZEVs remain uncertain, for instance that of liquid (cryogenic) hydrogen. Systems that use chemical bonding of hydrogen and swappable solutions like exchangeable tanks are unlikely to become commercially viable within the next decade. Due to high purity requirements for hydrogen used in fuel cells, the transition towards hydrogen-propelled heavy vehicles may initially also see increased use of internal combustion engines, despite their comparatively low energy efficiency.

Technical standards for electric vehicle charging aim to cover a broad range of vehicle categories. However, their focus has been mainly on passenger cars. Only recently have they begun to accommodate higher power, requirements for bi-directional power flow control, multiple DC outputs, updates on communication and charging processes and charging with liquid cooling.

DC charging has seen important developments, as it is now looking beyond electric car charging (with up to 450 kW) to DC-charging of 1 Megawatt or more. These developments were supported by organisations such as CHAdeMO, a collaboration platform rooted in the electricity industry, and CharIn, an association with roots in the European automotive industry and the proponent of the Combined Charging System (CCS). The preparation of new norms has also progressed on electric road systems, in particular overhead contact lines for use by heavy vehicles on motorways.

Environmental and energy-related vehicle regulations have primarily focused on tailpipe energy use and emissions. However, these do not account for the full environmental impacts of vehicle use. Recent efforts aim to harmonise international regulations on tailpipe emissions and expand their scope to include emissions from other life-cycle phases. These include vehicle production, especially in the case of vehicles using batteries, and emissions from fuel production and electricity generation.

Technical regulations of air pollutant emissions from heavy vehicles typically apply to engines. These are tested under laboratory conditions over specific drive cycles and via supplementary road tests, using portable emissions measurement systems In contrast, technical regulations and standards looking at tailpipe greenhouse gas (GHG) emissions and final energy use relate to the entire vehicle, which adds greater regulatory complexity. International harmonisation on tailpipe emissions is currently far more developed for air pollutants. Further work is needed to align tailpipe GHG emission regulations and to integrate LZEVs in their frameworks.

Batteries will be a core feature of LZEVs. Unless properly regulated, battery manufacture and end-of-life treatment can have detrimental impacts on the environment, however. Several governments are developing policies to make transparent the environmental and sustainability performance of batteries. The European Union is at the forefront of these initiatives.

Regulating the carbon intensity of fuels and, more broadly, energy vectors is another focus for some governments. Norms include renewable electricity quotas, mandatory blending of fossil fuels with low-carbon alternatives and low-carbon fuel standards. The latter regulate the carbon intensity of energy vectors while providing economic incentives.

The effectiveness of blending mandates and low carbon fuel standards depends on their capacity to accurately account for life-cycle emissions of the energy vectors, in particular their production (“well-to-tank”) and use (“tank-to-wheel”) phases. Integrating life-cycle emissions in suitable ways in international technical regulations and standards is an important requirement for an effective transition towards lower carbon intensity overall.

What we recommend

Ensure that vehicle safety regulations and standards for electric and hydrogen cover all classes of road vehicles and better differentiate between light and heavy vehicles

Safety regulations and standards should fully cover heavy vehicles, accounting for their specific characteristics. For battery electric vehicles, this will require a greater focus on specific components such as batteries, powertrains and charging, possibly combined with the definition of a limited set of representative vehicle designs. For hydrogen buses and trucks, this will require the full inclusion of vehicles with a gross mass exceeding 4.5 tonnes. The UN-led World Forum for the Harmonization of Vehicle Regulations (WP.29) is working on these issues.

Leverage the experience of international regulatory fora to extend the coverage of safety-related requirements to heavy electric vehicles

Regulations and standards need to address the issues of thermal runaway, propagation and electrolyte leakage. This task is complex and highly relevant for heavy vehicles due to the larger size of their components in comparison with light vehicles. It will require a constructive dialogue between stakeholders. The WP.29 activities in this area are important to make progress.

Ensure that the scope of regulations on the safety of hydrogen-powered heavy vehicles addresses aspects that are currently not adequately considered

Regulatory priorities for hydrogen-powered vehicles include the development of safety requirements for heavy vehicle gaseous storage tanks, the need to account for higher lifetime travel of heavy vehicles compared to light vehicles, and the introduction of test procedures and periodic inspections for high-pressure vessels. Crash-related safety provisions are also needed, especially in the cases of rollover crashes that are not currently part of tests. Readying heavy vehicle tanks for gaseous hydrogen at 70 MPa nominal working pressure is another priority. Future regulatory developments will also need to ensure that other forms of on-board hydrogen storage are covered, in particular liquid hydrogen.

Involve diverse transport and energy stakeholders in the development of charging standards for electric heavy vehicles

The technical specificities of heavy vehicles make a differentiation in the types of chargers used for cars and heavy vehicles probable. Some of the charging solutions under development focus on high power of more than 1 Megawatt. The important implications for the electricity system require cooperation between truck manufacturers, components producers, road infrastructure providers and the electricity industry.

Address missing elements in regulations and standards related to electric road systems

Electric road systems (ERS) could help sidestep some challenges that large electric batteries pose for long-haul trucking. International standards for ERS will have to ensure interoperability to enable the technology to be developed by more than a single manufacturer. They should also stipulate the standard for metering electricity consumption. ERS will also need adequate safety specifications. Catenary-based solutions can build on experiences and standards with railway and trolleybus services.

Develop hydrogen refuelling protocols for heavy vehicles using gaseous storage at 70 MPa, new nozzles and instruments guaranteeing compliance with stringent fuel quality requirements

Refuelling protocols for heavy vehicles with 70 MPa on-board hydrogen storage will have to be incorporated into international standards. These should cover pre-cooling of the fuel to avoid risks emanating from the high flow rates required. Future international regulations can build on existing Japanese refuelling protocols for fuel cell buses and benefit from the work ongoing in the EU-funded PRHYDE project. Specific refuelling protocols are also under development in the International Organization for Standardisation (ISO). New nozzles that cope with high flow rates will also be needed; their development is underway in the United States and Japan. Ensuring these new technologies are internationally harmonised internationally is important to ensure economies of scale for technology developments. The durability of hydrogen fuel cell vehicle also requires instruments guaranteeing effective compliance with stringent fuel quality requirements.

Increase the focus of pre-normative research on the safe use of low- and zero emission vehicles with existing vehicle infrastructure, especially for hydrogen-powered options

The safe use by LZEVs of tunnels, garages and other vehicle infrastructure conceived for conventional vehicles needs to be ensured. This concerns notably hydrogen-powered vehicles. Risks associated with fire as well as crash exposure risks of vehicles using batteries and compressed or liquid hydrogen in confined spaces must be assessed. Research on the safe use of low- and zero-emission vehicles with existing and new vehicle infrastructure, especially for heavy vehicles, is limited and deserves greater attention. The European Committee for Standardisation is currently preparing an initiative in this area.

Harmonise regulations on tailpipe GHG emissions and energy consumption of heavy vehicles, also integrating instruments evaluating energy use for low- and zero-emission vehicles

International harmonisation of on tailpipe GHG emissions and energy consumption of heavy vehicles can make product development cheaper. It will also ensure greater opportunities to scale up the application of high standards. Such harmonisation must reflect real-world driving conditions and be applicable to LZEVs. Integrating hybrid powertrain concepts that distribute loads across multiple engines and auxiliary loads is an important challenge in this respect. This requires greater transparency regarding the portion of all-electric driving for plug-in hybrid vehicles. Achieving this necessitates first the acquisition of greater experience on the usage profile of plug-in hybrid vehicles, and then, once better data become available, a refinement of the way all-electric driving shares for plug-in hybrids are integrated in regulations.

Fully integrate electricity and hydrogen into regulatory policies on low-carbon fuels

Accounting for the carbon intensities of electricity and hydrogen in technical regulations and standards on low-carbon fuels should be a priority. Challenges here include the wide variety of possible production pathways for electricity and hydrogen, the variability over time of the carbon intensity of their production and the need for technology-neutral comparisons. Regulations will also have to reflect differences in their transportation, distribution and powertrain efficiency. Hydrogen is especially relevant in this respect, as it has comparatively higher energy losses across its life-cycle with respect to the direct use of electricity.

Address non-regulated pollutants and integrate hydrogen-powered vehicles using internal combustion engines in regulations on tailpipe pollutant emissions

Regulatory priorities should include the development of test procedures for air pollutants that are currently not regulated. These include ammonia, N_2O, methane and formaldehyde. They should also cover the durability of exhaust after-treatment systems. Targeted new regulations on pollutant emissions testing may also be needed for hydrogen-powered internal combustion engines. This could be part of policies to foster the uptake of hydrogen use in heavy vehicles.

Address the environmental performance of vehicle batteries with regulatory innovation targeting their durability, carbon footprint and the sustainability of associated supply chains

Ensuring that the integration of electric heavy vehicles occurs in a sustainable way requires important regulatory innovations. These cover topics or aspects that are not adequately addressed in existing legislation. They comprise battery durability, carbon footprint (including second life and recycling) and the sustainability of associated supply chains. These provisions have particular importance to address criticalities of materials such as cobalt, nickel and lithium. Despite significant developments taking place in Europe and useful resources offered by the OECD Due Diligence Guidance for Responsible Supply Chains of Minerals, more efforts are needed to make progress in this field.

Develop an internationally harmonised regulatory framework for the application of differentiated road charges and access restrictions based on environmental performances of vehicles

There is currently no international framework for a coherent application and differentiation of road charges or access restrictions based on the environmental performance of vehicles. This is the case for both light and heavy vehicles. Its development should be made a priority given the importance of improving air quality, reducing GHG emission and addressing the increasing concerns about the availability of raw materials for battery materials. The enforcement of road charges or access restrictions that differentiate between electric and non-electric driving could also be significantly enhanced by systems that can automatically detect the driving mode. Geofencing offers advantages in this respect, provided that privacy concerns can be addressed, but would require an international regulatory framework that does not yet exist.

Introduction

Mobility and energy are on the verge of important clean transitions. Rapid progress on technological developments, growing policy attention on the need to respond to environmental issues (in particular climate change) and increased commitments to public spending in response to the Covid-19 socio-economic impacts are core to this movement.

Low- and zero-emission vehicles (LZEVs) include battery electric vehicles (BEVs), plug-in hybrid electric vehicles (PHEVs) and fuel cell electric vehicles (FCEVs). They are a key pillar of the clean mobility and energy transitions. This is due to their unique capacity to enable zero or near-zero emissions of greenhouse gases (GHGs) and local pollutants from the tailpipe, a feature that needs to be complemented by low-carbon processes in the vehicle manufacturing and energy supply, transformation and distribution processes.

Key LZEV technologies, especially battery storage, have been experiencing substantial cost reductions in the recent past and are expected to continue doing so in forthcoming years (IEA, 2019a). These cost reductions are paving the way for large scale adoption of LZEVs, triggering the expansion of battery production capacity in new manufacturing plants (and also being reinforced from it).

Countries with large stakes in the automotive market are already developing a wide range of policy instruments to advance on economic and industrial competitiveness in this transitional phase. Some examples include: public procurement programmes, fuel-economy standards coupled with incentives for LZEVs, mandates for specific vehicle categories (e.g. buses or cars), economic instruments that help bridge the upfront cost gap between electric and conventional vehicles, minimum requirements and financial support for the deployment of charging infrastructure.

The most significant policy developments have recently taken place in Canada, the People's Republic of China, Europe, India, Japan, Korea and the United States (in particular California) (IEA, 2020b). A growing body of commitments and concrete decisions have also been made by local authorities to improve urban air quality (C40, 2020).

A key component of the policy support targeted specifically automotive batteries. This is due to the strategic importance of the battery technology value chain, which has a major relevance in the spectrum of growth-inducing developments that characterise electric mobility. China has been leading the charge on this front, along with Japan and Korea, since they have all have been involved in the production of batteries for consumer electronics for a number of years. Recent developments in the European Union have also demonstrated a strong willingness to encourage more risk-taking and step up investment in the establishment of a European battery industry; in particular by granting access to public funding that would be compatible with European state aid rules for important, large, highly innovative and transnational battery manufacturing projects with European Interest (IPCEI). The United States also have a long history of funding of battery R&D.

Despite a false start in the early- to mid-2000s, similar developments are now re-emerging in the case of hydrogen and fuel cells, with renewed momentum from stakeholders and growing awareness that heavy vehicles offer better opportunities for increases in market deployment (IEA, 2019c), even if light vehicles will remain important for fuel cell cost reductions from large scale production (Park, 2020). Developments include:

- A recent announcement on the upcoming formulation of a national hydrogen energy industry development strategic plan in China (National Development and Reform Commission, 2020).

- The launch of the European hydrogen strategy in July 2020. This aims to drive demand in a range of sectors, including heavy industry and transport, which are considered more difficult to decarbonise than power generation. In March 2020, the European Commission created a new Industrial Strategy and a Clean Hydrogen Alliance to accelerate the decarbonisation of industry and maintain industrial leadership (European Commission, 2020b). The Netherlands and Germany have also recently launched hydrogen strategies (German Federal Ministry of Education and Research, 2020; Government of the Netherlands, 2020), which add to the European Fuel Cells and Hydrogen Joint Undertaking (FCH JU), established in 2008, and its extension and reinforcement in 2014 (Fuel Cells and Hydrogen Joint Undertaking, 2020).
- A long-lasting engagement on hydrogen and fuel cells in Japan, including the launch of its Basic Hydrogen Strategy in 2017 (Ministry of Economy Trade and Industry, 2017).
- Korea's Hydrogen Economy Roadmap, launched in 2019 (Ministry of Trade, 2019).
- The 2016 launch of the H2@Scale initiative of the United States Department of Energy, the latest step in a long-lasting engagement on hydrogen use in the United States, which pioneered the development of hydrogen and fuel cell technologies globally.[1]
- The launch, in Vancouver (Canada) in 2019, of a new Hydrogen initiative in the context of the Clean Energy Ministerial (Clean Energy Ministerial, 2019).

The private sector accompanied these policy initiatives with a dynamic response. Several announcements from vehicle and automotive component manufacturers confirm the escalating momentum for electrification of transport and the growing interest in the integration of low-carbon hydrogen in the transport fuel mix. While recent industry announcements focused largely on cars, buses and batteries, industry-led initiatives like the Hydrogen Council (established in 2017) are now scaling up efforts to bring forward the case of hydrogen and fuel cells, developing a united vision and long-term ambition to accelerate policy support and mobilise investments in the development of the hydrogen and fuel cells.

The establishment of technical regulations and standards is a crucial pre-requisite for the large-scale deployment of new technologies (see Box 1 for differences and complementarities between them).

Box 1. Regulations and standards: Differences and complementarities

Regulations and standards are important pre-requisites for safe and reliable vehicles, the distribution of the energy they need to travel and their capacity to meet environmental policy objectives.

While they are both related with technical aspects and developed through activities that bring together a range of different stakeholders, including public authorities, industry and non-governmental organisations, regulations and standards are distinguished by a key feature. Unless they are adopted or mandated in legislation, standards are of a voluntary nature and engage only those who are willing to adopt them. In some cases, they are developed to ease exchanges and create a common understanding between different industrial players. In contrast, regulations establish limit values and test procedures that have a legally binding nature in countries where they apply. Like other legal documents, regulations may also rely on technical standards to deal with specific technical aspects.

If internationally harmonised, both regulations and standards have the additional advantage to apply across a broader geographical scope. In such cases, they can become key enablers of trade facilitation, economies of scale and cost reductions, and they are therefore also important promoters of economic and industrial development.

LZEVs are no exception to the need for regulations and standards. Currently, a broad range of safety codes, regulations and standards address the areas of vehicle safety, environmental performance and charging/refuelling infrastructure for LZEVs. These tend to have a comprehensive nature, covering (at least initially) all vehicle categories at once. A key reason for this is that a broad scope helps to minimise the unit costs of developing regulations and standards, while ensuring that benefits (due to market scale) are maximised. A second reason is that new and emerging or rapidly evolving technologies (such as those used on LZEVs) come with greater requirements in terms of time and effort needed to develop or adapt regulations and standards, while the capacity available to do this is limited. This capacity is therefore prioritised first for general aspects, and only later to address more specific issues.[2]

Regulations and standards on LZEVs and their charging or refuelling infrastructure are developed through co-operative processes involving different stakeholders. In particular, work on international harmonisation and development of standards has a long lasting history in both the automotive and the energy sectors. Key reasons for this are:

- the relevance of the automotive sector for the development of internationally-traded products (vehicles and other appliances using energy, and electricity in particular)
- the role international standards can have for the removal of barriers that limit benefits due to scale, consistency and the facilitation of international trade, as well as the interoperability of vehicles and services they need when moving across borders
- the presence of major industrial players in both the automotive and the energy sectors, allowing them to have sufficient capacity to engage in the co-operative processes required for the development of technical regulations and standards.

Heavy vehicles like trucks and buses have an important role to play in this context, since they account for roughly a quarter of transport energy demand and direct GHG emissions (mostly because of trucks) and a third of the value of all new vehicle sales.

This report focuses on the central role that heavy LZEVs will play in the context of the clean energy and clean mobility transitions. It looks at buses, medium and heavy freight trucks in particular[3] and accounts for the relevance they have for the automotive industry, the electricity sector and the development of transportation infrastructure, including the provision of charging and/or refuelling points for vehicles.

The analysis developed in this report details existing technical regulations and standards covering the use of heavy LZEVs and their refuelling/charging infrastructure.

The report is structured in two main chapters, covering:

- safety standards, i.e. regulations and standards for the safe operation and refuelling/charging of heavy LZEVs
- environmental and energy-related performance standards and regulations that are specifically related to heavy LZEVs, some of their key components (in particular batteries) and the forms of energy (known as energy vectors) that they need.

The report informs policymaking by integrating recommendations on regulatory and standardisation issues that still need to be addressed to further advance deployment of heavy LZEVs, helping all stakeholders to identify priorities to address remaining barriers and challenges.

Although the report focuses on regulatory and standardisation developments taking place in developed economies, it can also be an important resource for developing countries interested in the transition to low- and zero-emissions technologies. Highlighted findings could accelerate their capacity to embrace new technologies by accepting/incorporating regulations and standards that have already been or are now being developed.

The report will also serve to inform the ITF in-house modelling work and the broader Decarbonising Transport Initiative on the transition of passenger and freight transport towards clean mobility.

Safety regulations and standards for low- and zero-emissions vehicles

Safety regulations and standards are important to guarantee the safe use of vehicles and infrastructure. Clean mobility and energy technologies, in particular LZEVs, are a crucial response to key challenges of our times. Such challenges include: climate change, improved health and environmental conditions due to lower air pollution and the promotion of economic development through the reduction of risks associated with stranded assets, the growth-enhancing nature of technological innovation and the opportunities they bring to reduce the cost of transporting people and goods. It is therefore important that safety regulations and standards, important pre-requisites for the introduction of new technologies and the development of safe and reliable vehicles, are further developed to ensure a full integration of LZEVs.

Significant progress on international safety regulations and standards for LZEVs (including BEVs, PHEVs and FCEVs) and their charging or refuelling infrastructure has already been made. The core organisations involved in these regulatory activities include the United Nations, through its World Forum for the harmonisation of vehicle regulations (WP.29), along with the main standardisation bodies, including the International Organization for Standardization (ISO), the International Electrotechnical Commission (IEC) and the Society of Automotive Engineers (SAE). All are characterised by active participation from governmental entities, supra-national standardisation bodies, such as the European Committee for Standardisation (CEN), the European Committee for Electrotechnical Standardisation (CENELEC) and national ones, as well as industry and non-governmental organisations.[4]

Committees, working parties and groups in each of these entities have been focusing on different aspects of LZEVs and their charging or refuelling infrastructure safety, according to their constituencies and areas of expertise.

This section reviews this work, focusing on key overarching documents and attempting to identify priorities for future developments by looking at three main areas of interest: vehicles, charging/refuelling and infrastructure. In the case of vehicles and charging/refuelling, the analysis developed here differentiates further cases based on electricity and hydrogen as key energy carriers. The analysis developed here pays specific attention at the case of heavy LZEVs.

Existing standards and regulations for electric vehicles

Table 1 lists the most comprehensive Global Technical regulations and standards related with the safety of electric vehicles (EVs), including vehicles using batteries and fuel cells. Table 2 includes information on nationally applied international and national regulations on EV safety in major automotive markets. Table 3 lists selected international safety standards with specific relevance for heavy electric vehicles and their batteries.

Table 1. Safety-related global technical regulations and main international standards for electric vehicles and their batteries

Name/code	Outline
Global technical regulation	
UN GTR 20	Performance of electrically-propelled road vehicles and their rechargeable electric energy storage systems
International standards	
ISO 6469 1-3	Specifications for batteries and high-voltage systems on electric vehicles
ISO 6469 4	Specifications for batteries and high-voltage systems on electric vehicles following a collision
ISO/DIS 21498	Specifications for high-voltage systems on electric vehicles
ISO 12405	Specifications for lithium-ion battery packs and systems
ISO 21782	Specifications for electric propulsion components (motor, inverter, DC-DC converter) and their combinations (motor system) for electric vehicles
SAE J1766	Recommended practice for electric and hybrid vehicle battery systems integrity in the event of a collision
SAE J2929	Safety standard for electric and hybrid vehicle propulsion battery systems using lithium-based rechargeable cells
SAE J2344	Guidelines for electric vehicle safety
SAE J2464	Recommended practices on electric and hybrid electric vehicle rechargeable energy storage system (RESS) safety and abuse testing
UL 2580	Specifications and stress tests for large electric vehicle batteries aiming to mitigate the risk of fire and electrical hazards

Table 2. Safety-related international or national regulations for electric vehicles and their batteries in selected markets

International or national regulation name/code	Adopting economies	Outline
UN Regulations 12, 94, 95 and 137 and new regulations on rear collision (upcoming)	Albania, Armenia, Australia (12, 94 and 95), Azerbaijan (137), Belarus, Bosnia and Herzegovina (137), Egypt, European Union, Georgia, Japan, Kazakhstan (137), Malaysia, Montenegro (137), New Zealand (12, 94 and 137), Nigeria, North Macedonia (137), Norway (12 and 137), Republic of Korea (137), Republic of Moldova, Russian Federation, San Marino, Serbia (137), South Africa (137), Switzerland (12 and 137), Thailand (137), Tunisia (95 and 137), Turkey, Ukraine and United Kingdom	Performance requirements for electrical powertrains in case of frontal, lateral or rear-end collisions
UN Regulation 100	Albania, Armenia, Azerbaijan, Belarus, Bosnia and Herzegovina, Egypt, European Union, Georgia, Japan, Kazakhstan, Malaysia, Montenegro, Nigeria, North Macedonia, Norway, Republic of Moldova, Russian Federation, San Marino, Serbia, Switzerland, Tunisia, Turkey, and United Kingdom	Performance requirements of electric powertrains and batteries
Motor Vehicle Safety Standard 305	Canada, United States	Performance requirements for battery and high voltage systems in the event of a collision
GB/T 31498	China	Performance requirements of electric vehicle following a collision
Motor Vehicle Safety Standard, Article 91	Korea	Performance requirements for high voltage system of electric vehicles
Motor Vehicle Safety Standard, Article 18	Korea	Performance requirements for electric installations for electric vehicles
GB 38031	China	Performance requirements for batteries of electric vehicles
QC/T 743	China	Specifications for lithium-ion batteries of electric vehicles

Notes: UN Regulations are included in this table because they are nationally applied international regulatory texts. Countries listed in the table regarding UN Regulations include only contracting parties to the 1958 Agreement administered by the World forum for the harmonisation of vehicle regulations (WP.29) of the United Nations. Other countries, including India, can rely on UN Regulations for the definition of their regulatory environment on vehicle safety, without being parties of the 1958 Agreement.

The European Union includes countries in the European Union (Austria, Belgium, Bulgaria, Croatia, Republic of Cyprus, Czech Republic, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Ireland, Italy, Latvia, Lithuania, Luxembourg, Malta, Netherlands, Poland, Portugal, Romania, Slovakia, Slovenia, Spain and Sweden).

Table 3. International safety standards addressing battery requirements for heavy electric vehicles

International safety standard name/code	Outline
SAE J2910	Recommended practice for design and testing hybrid electric or fully-electric trucks and buses for electrical safety
SAE J3004	Standardisation of battery packs for fully electric and hybrid trucks and buses
SAE J3125	Integration of battery pack systems in bus electrification

The United Nations Global Technical Regulation 20 (UN GTR 20) is the most comprehensive vehicle safety regulation for EVs to date. It aims to establish equivalent safety levels for electric vehicles[5] as for conventional vehicles with internal combustion engines. It was established in 2018 to assess the potential safety risks and prevent hazardous events occurring in EVs and their battery systems during normal use (driving, parking, charging) and post-crash stages. Its development is carried out by the Electric Vehicle Safety informal working group (EVS IWG) hosted under the Working Party on Passive Safety (GRSP) of the World Forum for the harmonisation of vehicle regulations (WP.29) of the United Nations.

The multilateral nature of the work carried out at the United Nations allows all regions of the world to contribute to the development and the update of global technical regulations regarding wheeled vehicles, equipment and parts (UNECE, 1998). This comprehensive regulation considers vehicles using batteries, including hybrid, plug-in hybrid, battery electric and fuel cell vehicles. Parties to the 1998 Agreement include all major automotive producing countries and associations of countries. When voting in favour of amendments, parties commit themselves to transpose the UN GTR 20 into their national legislation. Importantly, this means that many of the national regulations included in Table 2 are aligned with the UN GTR 20. The process also benefits from the contribution of industry and non-governmental actors.

The UN GTR 20 specifies safety-related performance requirements of both heavy and light EVs and their rechargeable electric energy storage systems (REESS). These essentially consist of batteries, today mostly lithium-ion, composed of battery bank, battery management system and power distribution buses/channels. The regulation text is technology neutral to avoid specific requirements that might prevent the development of future technologies. It includes test procedures and performance requirements, in particular due to electrical shocks associated with the high voltage circuits of EVs and potential hazards associated with lithium-ion batteries and/or the broader REESS concept.[6]

Both UN GTR 20 and other international regulations and standards applicable to EVs and batteries (including those listed in Table 1) tend to place cars, light commercial vehicles (LCVs) and heavy vehicles like buses and trucks under a single framework. Nevertheless, heavy vehicles contain aspects related with the size and technology of the battery storage, the integration of electric vehicle systems and charging solutions that differ significantly from passenger cars or LCVs. These are:

- The likely need for larger and more durable batteries for medium and heavy trucks. This is due to difference in gross vehicle weight, higher frequency of mission profiles requiring long distance travel and/or high mileage and higher mission profile variability, with direct consequences on the diversity of battery duty cycles.

- Differences in vehicle configurations and a greater reliance on the integration of multiple components by different parties. Manufacturers therefore limit the scope of their work to the development of the chassis, leaving the finalisation of the body structure to other parties.
- Evolutions of vehicle configurations over the course of the service life, due to changes in mission profiles and application area.
- A likely higher power requirement during charging and traction in order to allow intensive/heavy duty vehicle use.
- The relevance of charging-while-driving solutions (that present options other than socket and plug connection) and automation with high power charging. This last trend is already starting to show in technologies like pantographs, inductive charging and electrified roads.

These determinants have already led to the development of international regulations and standards that specifically apply to heavy vehicles (Table 3) and are also helpful to identify the axes of future development of technical regulations and standards.

Priorities for regulatory developments on electric vehicles

Some of the technical standards dealing with heavy vehicles may need to be specifically developed. This is despite the fact that fundamentals for protecting against an electrical shock and the technical justification for the requirements are the same for both light vehicles, heavy vehicles and some components (motors, cables, their integration in the vehicles and integrity following a collision). Two aspects of regulatory development, in particular, deserve future attention:

- The need for flexibility where vehicles are subject to a high degree of customisation. In the case of trucks for example, this requires a focus on different components for safety-related regulations, possibly combined with the definition of a limited set of representative vehicle designs and the standardisation of interfaces, similar to the case of power-take-off components.[7]
- The need to address significant differences in technologies, power requirements and usage profiles.

Due to the rapid trend towards electrification of buses and the prospects for increased electrification of trucks, regulatory developments taking place on separated tracks are likely to be especially important in the case of the integration of the battery and other EV components.

Providing support to manufacturers to understand the full scope of engineering protocols in designing these sophisticated electrified systems is important and the stated intention of the SAE Bus and Trucks Battery Committees. They are currently developing the SAE J3125 and SAE J3004 standards (among those listed in Table 3) on the integration of battery pack systems for electric buses.

Major technical regulations and standards, in particular the UN GTR 20, have also already handled separately battery safety specifications for light and heavy vehicles. Given the significant differences in battery technologies and pack capacity (or size) between light and heavy vehicles, this will likely continue to be the case in the future.

Thermal runaway is a failure in EV battery cells and is a major concern for consumers, manufacturers and regulators. Thermal runaway can occur during charging or due to mechanical damage to the batteries and can cause the emission of gases (which may be toxic and/or corrosive), fire and, in very rare circumstances, explosion (ITA-COSUF, 2019). Factory defects, improper control management and aging and wear can also result in thermal runaway conditions. Furthermore, thermal runaway in one battery cell can also cause failure in adjacent cells, in an effect known as thermal propagation. Both thermal runaway and propagation are especially important for heavy vehicles given the large size of their battery packs.

The development of a representative performance test to stem thermal runaway is challenged by the complexity of the internal short-circuit mechanism at its origin, which requires additional research (UNECE, 2018). For these reasons, thermal runaway is one of the focal areas of future regulatory and standardisation developments identified by the EVS IWG of the UN and the ISO Technical Committee on Electrically Propelled Vehicles (ISO/TC 22/SC 37).[8, 9]

Risk-minimising technologies like internal short circuit detection and intervention are one solution to prevent thermal runaway and propagation, including the event of a collision between vehicles. Indirectly, these also address hazards due to fire and gas venting. A prequalification test, in particular, may offer the possibility to demonstrate immunity to thermal propagation. Other strategies that make cells inherently more resistant to thermal runaway include thermally stable chemistries (e.g. non-flammable electrolytes, ionic liquids) and improvements in cell design (improved anode and cathode materials). Physical safeguards (such as heat resistant and puncture-proof separators) can also prevent propagation, complementing early detection of thermal runaway, but they could lead to significant losses of energy density. This is also the case for the integration of cooling systems based on the circulation of a fluid, as they require heat exchangers. This has important implications on the limitation of the performance of battery electric heavy vehicles. Another possible limitation of physical safeguards is the possibility to suppress thermal runaways and propagation through cooling of the cells in the event of an emergency/accident, facing greater challenges if the cells are difficult to access.

Safety- and environment-related risks for batteries affected by thermal runaway and propagation include the leakage of electrolytes and their toxicity. This is expected to lead to the development of standards on battery sustainability in Europe by the CEN/CENELEC and the topic is also being discussed in the context of UN GTR 20 developments.

The topics of thermal runaway and fire hazard (including vehicles involved in a fire of an external cause) are also closely related with challenges on the safe integration of hydrogen and electric heavy vehicles in existing infrastructure. These are beyond the scope of technical regulations and standards on vehicles and electrical components, and they are briefly discussed in Box 2, at the end of the next section.

Existing standards and regulations for fuel cell electric vehicles

Tables 4 and 5 contain the main international and national safety-related technical regulations and standards with specific relevance for the safe operation of fuel cell electric vehicles (FCEVs). These standards and regulations cover fuel cells, compressed hydrogen storage tanks and other components of the hydrogen fuel system and tend to focus (due to greater need to handle risks) on hydrogen storage systems. FCEVs also use electrical components, including batteries, meaning many of the vehicle safety regulations and standards related with EVs and batteries listed in Table 1 and Table 2 also apply. Similarly to EVs, FCEV regulations and standards have a scope covering both heavy and light vehicles.

Table 4. Safety-related global technical regulations and main international standards for fuel cell electric vehicles

Name/code	Outline
Global technical regulation	
UN GTR 13	Requirements and tests for the approval of hydrogen-fuelled vehicles and their components
International standards	
ISO 23273	Specifications for fuel cell vehicles and against hydrogen-related hazards for all vehicles fuelled with compressed hydrogen
ISO 13985	Construction and safety requirements related with fire and explosion for refillable fuel tanks for liquid hydrogen used in land vehicles
ISO/TR 15916	Basic considerations for the safety of hydrogen systems
SAE J2578	Recommended practice for general fuel cell vehicle safety
SAE J2579	Requirements for design, construction, operation, maintenance, verification of design prototype and production of hydrogen fuel systems in fuel cell vehicles

Notes: Standards reported in Table 1 also apply for the electric part of FCEVs. Additional international standards related with material specification include ISO 7866 for aluminium alloys, ISO 12862 for welded aluminium alloys, ISO 11114-1 and ISO 11114-4 for metallic materials. ISO 19881 covers gaseous hydrogen in land vehicle fuel containers, IEC 62282-2-100 covers the safety of modules for fuel cell technologies and IEC 62282-3-100 the safety of stationary fuel cell power systems.

Table 5. Safety-related international or national regulations for fuel cell electric vehicles in selected markets

International or national regulation or standard name/code	Adopting economies	Outline
UN Regulation 134	Albania, Armenia, Australia, Azerbaijan, Belarus, Bosnia and Herzegovina, Egypt, European Union, Georgia, Japan, Kazakhstan, Malaysia, Montenegro, New Zealand, Nigeria, North Macedonia, Norway, Republic of Korea, Republic of Moldova, Russian Federation, San Marino, Serbia, South Africa, Switzerland, Thailand, Tunisia, Turkey, Ukraine and United Kingdom	Requirements and tests for the approval of hydrogen-fuelled vehicles and hydrogen storage systems
Regulations 79/2009 and 406/2010	European Union	Type-approval of hydrogen-powered motor vehicles
Technical Standard – Attachment 101	Japan	Performance requirements for high voltage system of fuel cell electric vehicles

Motor Vehicle Safety Standard 301	Canada	Requirements on the integrity of the fuel system
Motor Vehicle Safety Standards 301, 303 and 304	United States	Requirements on the integrity of the fuel system
Motor Vehicle Safety Standard, Article 91	Korea	Requirements on the integrity of the fuel system
GB/T 24548, 24549 and 24554	China	Requirements on fuel cell electric vehicles
JARI S001 and S002	Japan	Specifications for containers of compressed hydrogen vehicle fuel devices
KHK 0128	Japan	Specifications for compressed hydrogen fuel containers with maximum filling pressure up to 70 MPa
High Pressure Gas Safety Control Law	Korea	High pressure gas safety control
CSA B51	Canada	Specifications for high-pressure cylinders for the on-board storage of natural gas and hydrogen for automotive vehicles
CSA ANSI HPRD 1	Canada	Specifications for thermally activated pressure relief devices (TPRD) for compressed hydrogen vehicle fuel containers
ANSI/CSA HGV 3.1	Canada	Specifications for compressed hydrogen gas fuel system components, intended for use on hydrogen gas powered vehicles

Notes: UN Regulations are included in this table because they are nationally applied international regulatory texts. Standards reported in Table 2 also apply for the electric part of FCEVs. Additional European standards related with material specification include EN 9809-1 for steel, EN 1964-3 for stainless steel and EN 13322-2 for welded stainless steels.

Countries listed in the table regarding UN Regulations include only contracting parties to the 1958 Agreement administered by the World forum for the harmonisation of vehicle regulations (WP.29) of the United Nations. Other countries, including India, can rely on UN Regulations for the definition of their regulatory environment on vehicle safety, without being parties of the 1958 Agreement.

The European Union includes countries in the European Union (Austria, Belgium, Bulgaria, Croatia, Republic of Cyprus, Czech Republic, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Ireland, Italy, Latvia, Lithuania, Luxembourg, Malta, Netherlands, Poland, Portugal, Romania, Slovakia, Slovenia, Spain and Sweden).

UN GTR 13 is a regulation established in 2013 for hydrogen and fuel cell vehicles. Its safety provisions focus on hydrogen fuel tanks, the fuel system, high voltage systems for hydrogen-fuelled vehicles and integrity in vehicle crash conditions. Like all other UN GTRs, it was jointly developed by a broad range of contracting parties, including all major automotive producing countries (in particular China, the European Union, Japan, the Republic of Korea, and the United States) and was subsequently adopted and transposed into national regulations such as those included in Table 5.

UN GTR 13 applies to gaseous hydrogen storage systems with a nominal working pressure up to 70 MPa. It also includes optional requirements for liquid hydrogen storage systems, which are also covered by the

ISO 13985 standard but to date have received less attention than compressed gas storage systems. Possible hydrogen storage systems of the future that use chemical bonding of hydrogen and swappable solutions are not currently included.

UN GTR 13 includes a range of test and performance requirements for compressed hydrogen storage systems to assure robust qualification for vehicle service, in particular:

- safe performance of basic functions of fuelling, de-fuelling and parking under extreme on-road conditions without leak or rupture throughout the specified service life
- safe performance in fires without compromising the containment of the hydrogen within the storage system.

Priorities for regulatory developments on fuel cell electric vehicles

UN GTR 13 (and UN Regulation 134, having a similar scope and content) is currently well suited for vehicles used for passenger transport that have a gross vehicle mass below 4.5 t.[10] However, it will require updates, now underway, to ensure that technical specifications will be able to effectively support the use of hydrogen on heavy vehicles (especially in long distance applications to freight transport). Major developments to the UN GTR 13 have occurred since 2017. Key reasons for this include the update/clarification of existing requirements, the introduction of additional safety and durability provisions, ensuring improved coherence with UN GTR 20 (established in 2018, i.e. five years after UN GTR 13) and, indeed, a desire to include other vehicle classes within its scope of application (UNECE, 2017).

Future agenda items for the UN GTR 13 that have been specifically flagged for buses (Kim, 2019, 2020), but also have broader relevance for trucks, include:

- changes in size and volumes of compressed hydrogen storage systems, as heavy applications rely on larger storage tanks with cylindrical shape, requiring the adaptation of safety requirements
- the adjustment of service life (i.e. the maximum time period for which service usage is qualified and/or authorised, set to 15 years for light vehicles and likely to be set to 25 years for heavy vehicles
- the need for detailed test procedures and periodic inspection requirements for high-pressure hydrogen storage tanks of heavy FCEVs, given they are currently not being inspected
- crash-related safety provisions, especially in the cases of rollover (for buses with storage tanks on the roof) and side impacts (sled tests) (i.e. cases that are not currently subjects to tests, also requiring the collection of accident data).

These, along with the proposal to reduce the minimum burst requirement to 200% of the nominal working pressure for certain types of hydrogen fuel containers (so to reduce material requirements and weight, and hence costs), of the hydrogen tank and aspects related with material compatibility and hydrogen embrittlement, are the main axes of regulatory developments currently under discussion.

Additional areas for areas of development include:

- the rationalisation of the specifications for thermally activated pressure relief devices (TPRD) for compressed hydrogen vehicle fuel containers, opening up the possibility to equip storage systems composed of multiple/repeating components (e.g. cylinders) with a single TPRD, rather than one per cylinder

- the introduction of specific test procedures for modifications of the hydrogen storage system.

Accident data tracking and analysis is also a topic with strong relevance for the safe integration of heavy vehicles using compressed hydrogen storage tanks in existing infrastructure (especially in confined spaces such as garages and tunnels, due to risk factors for fire hazards). This is an aspect that was already flagged for heavy EVs using batteries and is further discussed in Box 2. Issues related with fire development and propagation involving these vehicles and guidelines and recommendations on safety management and fire-fighting are the subject of a new work item proposal under development in the technical committee on hydrogen in energy systems of the European Committee for Standardisation (CEN/JTC 6).[11]

Box 2. The safe integration of hydrogen and electric heavy vehicles in road transport infrastructure

The safe integration of heavy electric vehicles in existing and new infrastructure deserves particular attention, especially since existing infrastructures have in most cases been initially conceived to host conventional vehicles (Van den Berg, 2020).

Tunnels and garages are especially important. The introduction of electric vehicle and hydrogen-based technologies (including fuel cell range extenders) may require structural changes in depots and logistical centres related with fire hazards, and operational changes to underground facilities like tunnels with the establishment of new procedures for incident management.

Safety is also important for first responders handling an LZEV accident. This is a subject covered by the ISO 17840 standard (which is not specific to EVs) and, in North America and for electric vehicles, by the SAE J3108, SAE and SAE J2990 standards.

In the Netherlands, a study on the operation of zero-emission enabling buses at the Schiphol airport concluded that buses with a fuel cell and hydrogen tanks have higher risk profiles during tunnel operation than battery electric alternatives (ITA-COSUF, 2019). This suggests that hydrogen-powered vehicles are currently subject to greater challenges than electric vehicles using batteries.

Key priority areas for the safe integration of hydrogen and electric heavy vehicles in existing infrastructure include:

- the assessment of risks associated with fire and/or crash exposure of vehicles using batteries and compressed hydrogen in confined and semi-confined (e.g. underpasses) spaces, including the need to collect information on accidents
- additional research on fire development/propagation involving these vehicles
- to review and update guides and recommendations on safety management and fire-fighting (even in cases where responses have already been developed, since they do not necessarily include consideration on confined spaces), requiring the integration of new energy vehicles
- the development of additional measures related with risk minimisation solutions (e.g. thanks to early detection, clear markings) and related technical requirements in existing or new norms
- the integration of new energy vehicles in incident management procedures.

Fire risks associated with accidents involving electric-powered passenger cars have been found to be similar to those involving fossil-fuel powered passenger cars. Nevertheless batteries can remain on fire for a long time, they can reignite after being extinguished and they can release toxic and flammable gases (van Straalen, 2020). Recent efforts in Germany, New Zealand and Norway have considered adapting fire safety requirements for parking garages, additional requirements in these areas have already been imposed in Australia and the United States.

Hydrogen-powered passenger cars have different risks to conventional cars both in the way a fire starts and the appropriate responses to restrain it (e.g. whether or not to intervene, and how). Safely accommodating hydrogen-powered passenger cars in parking garages and reducing the risks of fires may require the use of ventilation systems and automatic fire extinguishers (van Straalen, 2020). Austrian regulations for fire safety in parking garages already account for the possible presence of hydrogen-powered passenger cars, by not allowing them in underground parking.

There is a growing consensus among major manufacturers on 70 MPa as the nominal working pressure for compressed hydrogen storage on heavy vehicles, starting from buses, followed by medium trucks.

The option of liquid (cryogenic) hydrogen could also remain open for heavy transport, but considered that the technology readiness of this solution for road transport is lower than for compressed storage. This suggests that the development of international technical regulations and standards on liquid (cryogenic) hydrogen storage is currently subject to a lower urgency than in the case of gaseous storage. Similar considerations emerged on the subject of alternative on-board hydrogen storage methods, including systems that use chemical bonding of hydrogen and swappable solutions, unlikely to be viable for commercial development in the next decade. Swappable solutions could also be relevant for battery storage.

Existing standards and regulations for electric vehicle charging

International standards on electric vehicle charging are largely defined by activities carried out by the International Electrotechnical Commission (IEC), the International Organization for Standardization (ISO) and (especially for North America and Japan) the Society of Automotive Engineers (SAE). At the IEC, the Technical Committee 69 (IEC/TC 69) focuses specifically on electrical power/energy transfer systems for electrically propelled road vehicles and industrial trucks.

Table 6 gives a summary of the main international standards for electric vehicle charging, including documents related with conductive and wireless charging (physical hardware and communications between vehicles and chargers) and battery swapping. Table 7 includes standards specifically related with heavy road vehicles. Communications between the vehicle or the charger and the rest of the electricity system are discussed in Box 3.

Table 6. Main international standards for electric vehicle charging

Standard name/code	Outline
Conductive charging	
IEC 62196	Series of standards for conductive charge connectors (plugs, socket-outlets, vehicle connectors and vehicle inlets) for electric vehicles
IEC 61851	Series of standards covering safety-related specifications on the charging station, the electromagnetic compatibility and the communication between vehicle and charger (including vehicle to grid functionality)
ISO 17409	Specifications for the connection of electric vehicles with an external electric power supply
ISO 15118	Series of standards for vehicle-to-grid communication interfaces, protocols and data requirements
SAE J1772	Specifications for conductive charge connectors (plugs, socket-outlets, vehicle connectors and vehicle inlets) for electric vehicles (most relevant for North America and Japan)
SAE J2953	Requirements and specification by which a specific electric vehicle and charger can be considered interoperable
SAE J3068	Electric vehicle power transfer system using an AC three-phase capable coupler
Inductive charging	
IEC 61980	Series of standards and specifications for the equipment needed for the wireless transfer of electric power from the supply network to electric road vehicles
ISO 19363	Safety and interoperability requirements for the on-board equipment that enables magnetic field wireless power transfer for electric vehicle charging
SAE J1773	Recommended practices on electric vehicle inductively-coupled charging
SAE J2954	Specifications on safety, interoperability and electromagnetic compatibility of wireless power transfer for light plug-in electric vehicles
Battery swapping	
IEC 62840	Series of standards for electric vehicle battery swap systems

Table 7. The main international standard specific to heavy electric vehicle charging

Standard name/code	Outline
SAE J3105	Electric vehicle power transfer system using conductive automated connection devices (including overhead pantographs)

The IEC 61851-1 is the foundational standard for conductive charging of electric road vehicles with a rated supply voltage up to 1 000 V AC or 1500 V DC. It contains safety-related specifications of the connection between the EV and charger, defines the characteristics and operating conditions of the charger and includes requirements needed for its electrical safety. The IEC 61851 series of standards specifies charging *Modes* and connection *Cases* for AC charging, as well as modes and *Systems* for DC charging.

Modes define the connection between vehicle and the electricity supply and can be summarised as follows:

- Mode 1 (now obsolete) refers to AC charging from a standard household socket.
- Mode 2 refers to AC charging from a standard household socket through a cable equipped with a control and a protection device capable of communicating with the vehicle to control the charging process.
- Mode 3 refers to AC charging via a dedicated EV connector, socket and circuit, using a standardised communication protocol. In Case A, this occurs with a cable that is permanently connected to the vehicle and plugged to the charger. In Case B, the charging cable has a connector at both ends. In Case C, the cable in this case is permanently connected to the charging station and plugged to the vehicle.
- Mode 4 is about with DC charging. The latter is differentiated in three Systems (A, B and C), detailing requirements related with the communication between vehicles and chargers to control it, corresponding to different inlets and connectors.

The IEC 62196 series of standard complements IEC 61851 with specification of EV-specific connectors for AC and DC charging. For AC charging, these include:

- Type 1 for AC charging, first described in SAE J1772 and most relevant for Japan, North America and countries with 110 V household electricity.
- Type 2, most relevant in countries with 220 V electricity in households, namely in Europe, and also similar to the Chinese standard GB/T 20234.
- Type 3, now used only for some light vehicles, such as scooters and microcars.

For DC charging, these encompass configurations of connectors and inlets that relate with the systems defined in the IEC 61851 series of standards, commonly known as CHAdeMO (system A, configuration AA), the Chinese connector described in the standard GB/T 20234 (system B, configuration BB) and the CCS Combo 1 (North America) and 2 (Europe) connectors (system C, configurations EE and FF). The latter is the system mandated, in Europe, by the Alternative Fuels Infrastructure Directive (AFID) (European Commission, 2014), but other systems (namely CHAdeMO) are also allowed and widely deployed in Europe.

SAE J1772 is the core standard of reference for conductive charging in North America and uses the concept of *Methods* to distinguish charging *Levels*, for AC and DC charging (each divided in levels 1 and 2, based on voltage and power), including specifications on connectors and inlets, as well as communication protocols and performance requirements.

General safety concepts and specifications for the connection of electric vehicles with an external electric power supply (including in the case of pantographs) are addressed in the ISO 17409 standard.[12]

The ISO 15118, developed as a cooperative activity between the ISO/TC 22/SC 31 and IEC/TC 69, is another foundational series of standards governing charging (both conductive and wireless) of electric road vehicles. It contains specifications on an EV-charger digital communication protocol that governs the EV charging process and includes both wired (AC and DC) and wireless charging applications and pantographs. The ISO 15118 is applicable to AC, automated/wireless and DC charging, and covers the Plug & Charge technology; making it possible to identify and automatically charge vehicles once they plug at a charging station. It is mirrored by the SAE J2953 standard in North America.

For wireless charging, the ISO 15118 is complemented by the IEC 61980 and ISO 19363 standards, which contain specifications on the characteristics and the interoperability of the equipment and the magnetic field requirements for inductive power transfer (and are mirrored by the SAE J1773 and SAE J2954 in North America). The IEC 62840 standard covers battery swapping.

The IEC 61851 and IEC 62196 series of standards on conductive charging cover high power up to 350 kW. Recent developments of the IEC 61851-23 will accommodate higher charging power and will be subject to additional requirements on the bi-directional power flow control, multiple DC outputs, updates on communication and charging processes and charging with thermal management system; liquid cooling in particular (Delaballe, 2020).[13] In addition to IEC 61851-24 (CHAdeMO), which covers vehicle-to-grid and bi-directional DC charging, the ISO 15118 series of standards is also relevant for bi-directional charging, as it includes specifications for vehicle-to-grid communication interfaces, protocols and data requirements for the high-level communication between EVs and chargers.[14]

DC charging is also an area subject to important developments, involving both the CHAdeMO collaboration platform (rooted in the electricity industry) and the CharIn association (an aggregator of European industry's view with its roots in the automotive industry). CHAdeMO has been developing the CHAdeMO DC charging protocol, associated with a specific DC connector and inlet, and CharIn has been promoting the CCS Combo configurations to develop single (but macro-regional, i.e. applicable across North America or across Europe) connectors and inlets for AC and DC charging.

CHAdeMO's approach is focused on power transfer and minimum communication requirements (e.g. authentication, verification and payment). It leaves aspects related with the broader vehicle-charger interoperability framework to the market (e.g. though the use of 4G/5G/WiFi as well as the smartphone apps of charging point operators). It places also a greater emphasis on the charger, which plays the role of the gateway between the EV and the back-end systems. The latter is effectively the master for any additional (and more complex) communication. For example, those that govern smart charging practices and require communication with the power supplier. In contrast, CharIn has opted for a tighter integration (and control) of power transfer and advanced communications, with the use of a more complex protocol in the CCS standard. This places a greater emphasis on the role of the vehicle, considering it the master (i.e. the main device in charge of) for more complex communications.

Both organisations are working on high-power charging (from 50 kW up to 450/500 kW). In particular, CHAdeMO and the China Electricity Council (CEC) just released the first publication of ChaoJi, a high-power charging standard (500 kW, capable up to 900 kW) using a harmonised new plug ensuring backward compatibility with both existing CHAdeMO and China's GB/T standards via simple adapters (Ni and Imazu, 2020). The ChaoJi research and development group hopes to also make backward compatibility with existing CCS chargers.

Box 3. International standards for communications beyond the charger

The Open Charge Point Protocol (OCPP) covers the communication between EV chargers and a central system managing them. It was developed in 2009 as an open, patent and royalty free protocol with no cost or licensing barriers by Elaad, a non-profit centre founded by the Dutch electricity distribution and transmission system operators.

The OCPP aims to facilitate EVSE-cloud interoperability (i.e. standardised communication between charging stations and the central control systems that supports them, such as a charging network provider or a utility) while also ensuring that charger manufacturers and charger network providers can compete on price, service, product features, and innovation. It increases flexibility and resilience by allowing charging infrastructure to be sold to multiple network providers. It is compatible with all existing communication protocols between vehicles and chargers, including those included in the ISO 15118 series of standards and the IEC 61851-24 (CHAdeMO).

The OCPP is continuously updated (the current version the OCPP 2.0, was released in 2018, and version 1.6 is the most widely used) and currently governed by the Open Charge Alliance, a Foundation created in 2014, counting 160 members and open to interested participants.

Since 2019, the OCPP 2.0 has a central role in the development (currently ongoing) of the IEC 63110 standard defining a protocol for the management of electric vehicle charging and discharging infrastructures. Expectations that emerged at the Workshop suggest that the OCPP will indeed evolve into the finalised version of the IEC 63110 before 2022 (Driessen, 2020).

Priorities for regulatory developments on plug-in electric vehicle charging

While technical standards for EV charging aim to cover a broad range of vehicle categories, the focus to date has been on passenger cars. Looking forward, economic drivers,[15] policy developments and a number of technical characteristics (e.g. with respect to battery size, capacity, power, durability and charging time) that are unique to heavy vehicles suggest that there will be a growing need for differentiation.

One of the aspects that is prominently emerging as a crucial area for differentiation is charging power. Historically, electric buses have relied on much higher charging power than passenger cars and other light vehicles, needing 50 kW for depot charging and up to 600 kW for opportunity chargers like pantographs.

As bus electrification is taking off and truck electrification is in sight, CharIn established a task force for High Power Charging for Commercial Vehicles (HPCCV). Its aim is to define a new commercial vehicle high-power charging standard to maximise customer flexibility (Bracklo, 2020), with a specific focus on the vehicle side. This work goes beyond the scope of CharIn activities on electric car charging (up to 450 kW), clearly considering charging of 1 MW or even more (up to 4.5 MW: 1 500 V and 3 000 A). The CharIn expectation is to have a technical standard ready in 2023 and technology on the market in late 2023 or early 2024, as the standardisation activities in the IEC framework have started.

Though charging standards for power ratings above 1 MW are not currently within the scope of the work being developed for the ChaoJi protocol, charging power exceeding this amount is technically possible. This signals the possibility of a single global standard through the harmonisation of CCS and ChaoJi for heavy truck charging at very high power still open (although not likely).

The high power rating of these chargers has important implications for impacts on the electricity system. At a minimum, they would require that the location of charging hubs is developed coherently with the capacity of the electricity transport and distribution system. Clustering high power charging in specific locations is likely to require sizable investments for grid reinforcement and/or grid-based storage as a buffer. This highlights a clear need for cooperation between truck and component manufacturers, and road and electricity infrastructure providers, including electricity generators, operators of transmission and distribution systems and charge points. Concentrating power demand requirements at specific times (e.g. overnight, when transport activity is lower) is also likely to be detrimental for the flexibility of the electricity system, an important requirement at a time when electricity supply is progressively developing towards variable forms of renewable energy.

The high voltages needed for high power charging are increasing needs for safety protections and automated charging, two of the subjects being addressed in the work of the IEC/T 69.[16, 17] Automation for EV charging is also confirmed as a priority area for standardisation developments over the next years identified by the roadmap of the ISO/TC 22/SC 37.[18]

Electric road systems (ERS) are another area of interest for electrified heavy vehicles. ERS could enable a shift away from using fossil diesel in long-haul trucking while offering far better energy efficiency than hydrogen and helping address the challenges of battery electrification of long distance heavy trucks in terms of battery size, cost and charging power. ERS are also compatible with a range of electrified drive trains (including BEVs, PHEVs and FCEVs, provided that they can connect to the electricity distribution system), as well as other technical developments that may influence trucking going forward, such as high-capacity vehicles and hub-to-hub autonomous highway trucking. From an economic perspective, ERS makes most sense for long-distance HDVs (trucks and coaches) and when installed on high capacity roads, e.g. motorways.

ERS inevitably raise a number of regulatory challenges, not limited to technical regulations and standards, due to the novelty of the electric road concept and its technical characteristics (Box 4). On the economic side, an important barrier is the dependency of their economic viability on the achievement of high frequencies of use. This increases the risk profile of investments aimed to deploy road electrification infrastructures before there are enough vehicles having the capability to use it.

Box 4. Electric road systems

Electric road systems (ERS) enable a transfer of electricity between vehicles in-motion and the road transport infrastructure. They include wireless or conductive systems. The latter include roadside, in-road and overhead catenary arrangements. A number of demonstrative projects for wireless systems have been developed in France, Korea, Italy, Germany, Spain, Sweden and the United States.

Sweden has been the country that developed the most consistent set of demonstration projects on conductive systems, along with Germany and Japan for some of them (Bateman et al., 2018). These efforts resulted in positive conclusions on the capacity of these technologies to operate effectively. Overhead catenary technologies have been the most frequently considered and extensively tested ERS projects at highway speed or on high capacity roads and developed in partnership with major truck manufacturers. Large-scale shuttle pilots for the overhead contact line solutionwere opened in Germany at a first test track in 2019 (BMU, 2019).

Some of the core challenges for the development of technical standards to date include the need to ensure interoperability. This would enable ERS to be developed by more than a single manufacturer. In addition, metering systems will be important to enable payments that account for the electricity consumed. ERS will also need adequate safety specifications.

The interoperability and safety of dynamic wireless power transfer for EVs is currently being addressed by the IEC/TC 69, with the development of the IEC 63243 standard. Communication interfaces between the vehicle and the infrastructure and magnetic field requirements for inductive power transfer will fall within the scope of other standards (ISO 15118 and ISO 19363, respectively) (Bateman et al., 2018).

The situation is different for conductive systems, which are not yet the subject of targeted work from international standardisation bodies, except for overhead catenary based solutions, which have the advantage of the possibility to build on the experience and standards already developed for other similar cases (e.g. in railways and for trolleybuses, covered by the European EN 50119 standard). The latter applies to electric traction overhead contact line systems in heavy railways, light railways, trolley buses and industrial railways of public and private operators). In particular, a technical specification for the use of overhead contact lines on motorways by heavy vehicles was included as an Annex (C) to the EN 50119 standard. Having a single legal entity in charge of building the systems on the vehicle and infrastructure side is also an issue that has implications for fair competition and the risk of creating monopolies (Bateman et al., 2018). This is less relevant for catenaries, as overhead contact lines are already competitively supplied for rail and trolleybuses, enabling industry competition to also extend into motorway applications (still leaving open questions on the vehicle to overhead catenary connection).

ERS faces challenges regarding billing users, but may take advantage of existing regulations for road tolling, using road tolling components, processes and structures (billing and metering on a kilometre basis would fit in the existing road tolling system), enhancing it by an energy premium once a metering system is developed.

Additional important areas for research are whether ERS should be assimilated to a power grid, a road infrastructure, or both. This has implications for the need to meet existing regulatory standards, or require standards to be adapted to allow for the implementation of these novel technologies. In some jurisdictions, this also has implications for the legal position of land owners, traditionally falling within duties and powers of administrations charged of the provision of safe travel and the maintenance of road infrastructure, requiring the extension of their mandate to include electrical equipment and capital recovery through charging operations (Bateman et al., 2018).

Existing standards and regulations for hydrogen refuelling

As in the case of hydrogen-powered vehicles, the focus of standards for hydrogen refuelling (Table 8 contains a summary of the main ones) are gaseous systems (with nominal working pressures of 35 MPa and 70 MPa) and light fuel cell vehicles.

Requirements for fuelling stations or the fuelling station/vehicle interfaces are covered by the ISO 19880 series of standards and the ISO 17268 standard. These are developed by the ISO technical committee 197 on hydrogen technologies (ISO/TC 197). The ISO 19880-1, in particular, includes the main safety requirements/operative limits for hydrogen refuelling stations for light road vehicles. This also falls within the scope of the SAE J2600 in North America, developed by the SAE Fuel Cell Standards Committee.

These requirements are compatible with existing fuelling protocols included in the EN 17127 standard in Europe and the SAE J2601 standard in North America. They are also adopted in other global areas and aligned with the JPEC-S0003 fuelling protocol standard in Japan. The ISO 14687 (production specifications) and ISO 19880-8 (fuel quality control) and SAE J2719 (hydrogen fuel quality) standards are also crucially important for hydrogen refuelling, as they deal with the quality of the hydrogen used in the proton exchange membrane (PEM) of fuel cell road vehicles.

Table 8. Main international and national standards for hydrogen refuelling

Standard name/code	Outline
International	
ISO 17268	Specifications on gaseous hydrogen land vehicle refuelling connection devices (receptacle and protective cap, mounted on vehicle; nozzle; communication hardware)
ISO 19880	Series of standards on the requirements on the design, installation, commissioning, operation, inspection and maintenance of gaseous hydrogen refuelling stations for light road vehicles
ISO 14687	Minimum quality characteristics of hydrogen fuel as distributed for use in proton exchange membrane fuel cells
ISO 21087	Validation protocol of analytical methods used for ensuring the quality of the gaseous hydrogen used by vehicles with proton exchange membrane fuel cells
North America	
SAE J2600	Specifications for hydrogen refuelling connectors, nozzles, and receptacles for fuel cell and other vehicles using compressed hydrogen
SAE J2601	Protocol for hydrogen refuelling of light vehicles
SAE J2799	Communications hardware and software requirements for hydrogen light vehicles and buses
SAE J2719	Hydrogen fuel quality for fuel cell vehicles
Europe	
EN 17127	Outdoor hydrogen refuelling points dispensing gaseous hydrogen and incorporating filling protocols
EN 17124	Product specification and quality assurance of hydrogen fuel for proton exchange membrane (PEM) fuel cell applications for road vehicles
EN 17268	Design, safety and operation characteristics of gaseous hydrogen land vehicle refuelling connectors with nominal working pressures up to 70 MPa
Japan	
JPEC-S0003	Protocol for hydrogen refuelling of light vehicles

In Europe, significant progress on pre-normative research and standardisation for hydrogen-fuelled vehicles was triggered by the introduction of the Alternative Fuels Infrastructure Directive (AFID). This was based on the consideration that the lack of harmonised development of alternative fuels infrastructure across the Union prevented the development of economies of scale on the supply side and Union-wide mobility on the demand side (European Commission, 2014). Technical specifications for hydrogen refuelling points for motor vehicles resulting from this process include the European standards EN 17127 (on gaseous hydrogen dispensers)[19], EN 17124 (product specification and quality assurance) and EN 17268 (gaseous hydrogen land vehicle refuelling connection devices).

For hydrogen heavy-vehicle refuelling, the historical focus has been on tanks using nominal working pressure of 35 MPa, without pre-cooling (and therefore taking place over longer times) because these were sufficient requirements to allow overnight charging of urban buses while allowing enough fuel storage to operate the vehicles throughout the day.

Priorities for regulatory developments on hydrogen refuelling

A core priority is the development of refuelling protocols for medium and heavy vehicles (70 MPa compressed hydrogen storage systems and more than 10 kg of storage capacity and 35 MPa and more than 6 kg) in international standards, as recently highlighted by a report of the CEN/CENELEC (2019) and in the ISO TC 197 plenary meeting in December 2019 (Fuel Cell & Hydrogen Energy Association, 2020). Currently, a protocol for refuelling fuel cell bus using compressed hydrogen storage tanks at 70 MPa exists in JPEC-S0003 standard. This includes pre-cooling, a key requirement for high flows needed in hydrogen-powered trucks to avoid surges in temperature and overpressures in the fuel tank and enable higher rates of refilling.

Other important remaining challenges include safety risks related with failures of pre-cooling (e.g. for failures in the gas temperature sensor), protocol algorithms for high mass flows and the certification of dispensers and the need to address uncertainties in metering.[20] The design of refuelling protocols and connections between vehicle and refuelling station as the basis for a heavy duty specific protocol (to be developed in parallel) is under development in the Technical committee on Hydrogen Technologies of the International Standardisation Organisation (ISO/TC 97).[21]

Another priority is the development of a hydrogen-refuelling nozzle for 70 MPa and high refuelling flows, which are considered crucial for heavy hydrogen trucks (Mattelaer, 2020). Work has started in the United States and Japan.[22] It will be important to harmonise this worldwide.

In Europe, these aspects are the subject of the protocol for heavy hydrogen refuelling (PRHYDE) project. This project was established by the Fuel Cells and Hydrogen Joint Undertaking (FCH JU) of the European Commission, the fuel cell and hydrogen industries (Hydrogen Europe) and the research community (Hydrogen Europe Research). The PRHYDE project aims to determine relevant requirements for heavy-vehicle fuelling, limitations and gaps of current fuelling hardware (nozzle and receptacle to achieve the flows needed in heavy trucks, communication hardware between vehicle and refuelling station) and formulate recommendations for heavy-fuelling protocols (European Commission, 2019a; Mattelaer, 2020).

The need to ensure hydrogen quality (ISO 14687 Grade D) for use in PEM fuel cells is also an area where further developments are necessary. A first challenge is the need for a reference laboratory capable to perform and certify the required gas analyses. A second challenge is the frequency of quality checks (performed by producers based on sampling and lab testing), as it is currently not regulated. A third challenge is the absence of official guidelines for sampling hydrogen.[23]

The subject of hydrogen fuel quality also raised the question of whether hydrogen internal combustion engines (ICEs), which are able to operate with less stringent purity requirements, could be better starting point than FCEVs for the transition towards hydrogen of heavy vehicles.

Finally, additional regulatory developments on the safe transport of hydrogen to refuelling stations (see the case of Europe, Box 5) may also require further consideration. This could be especially relevant if hydrogen deliveries will grow without the parallel development of hydrogen backbone pipelines and/or local generation of hydrogen.

Box 5. European regulations for the safety of hydrogen transport

At ambient temperature and pressure, hydrogen is a highly volatile gas that can ignite easily. Hydrogen liquefies at 20 K (-252°C), close to absolute zero, requiring significant amount of energy to reach and maintain such low temperatures. Making sure that transporting hydrogen is safe therefore requires strict guidelines. These fall within the scope of the Agreement concerning the international carriage of dangerous goods by road (ADR) (UNECE, 2020a), developed by the Working Party on the Transport of Dangerous Goods (WP.15) of the Economic Commission for Europe of the United Nations.

The second article of the Agreement indicates that dangerous goods may be carried internationally in road vehicles subject to compliance with defined conditions regarding their packaging, labelling and the construction, equipment and operation of the vehicle carrying the goods in question.

Receptacles aimed at the transport of flammable gas (including hydrogen) are subject to provisions detailed in Chapter 6.2 of the ADR. These largely refer to ISO standards, accompanied by transitional provisions. The scope of the ADR is limited to goods that are being transported and excludes the fuel used to propel the vehicle, as long as the energy contained in the tanks aimed at propelling the vehicles does not exceed 54 000 MJ. Special provision 392 of the ADR also specifies the requirements to transport tanks aimed at propelling vehicles (for example when delivering new vehicles to a dealership on a truck). Special Provision 392 refers to UN GTR 13, amongst others, for the transport of hydrogen-fuelled vehicles.

In addition to the ADR, some governments have also developed systems that aim to guarantee safety along the transport routes for dangerous goods, while also enabling their transport over major roads and rail and shipping routes. One example is the Dutch Basisnet, which includes the designation of specific transport routes on the basis of a risk assessment, but does not yet account for hydrogen tube trailers. Such risk assessment accounts for the importance of a given route for the transport of dangerous goods, the space along that transport route for building developments, the safety of local residents and includes provisions allowing the Ministry of Infrastructure and the Environment to implement measures to limit the risks of transport on the route concerned (Rijkswaterstaat, 2015). As hydrogen deliveries grow, systems that aim to guarantee safety along the transport routes for dangerous goods like the Dutch Basisnet are likely to have a growing relevance, unless trucking activity for hydrogen deliveries is replaced by pipelines, and will need to be updated to account for hydrogen.

Environment and energy-related regulations and standards for low- and zero emissions vehicles

International regulations and industry standards regarding transport vehicles also cover aspects related with environmental and energy-related performance and the test procedures necessary for their assessment. Their existence is rooted in the need to:

- manage impacts of transport vehicles on local air quality, given their negative implications for health
- ensure that vehicles contribute to energy efficiency improvements, given that cost-effective energy savings have positive implications for economic development
- enable the transportation sector, currently largely reliant on fossil oil, to effectively contribute to the reduction of GHG emissions and the mitigation of climate change.

Clean mobility and clean energy technologies are crucial to respond to these challenges. This is particularly the case in the development of LZEVs. Developing technical regulations and standards on the environmental performance of clean vehicles, and not just on their safety, is therefore important to enable the large scale industrial deployment of these technologies while guaranteeing that this is effectively delivering net benefits in terms of better air quality, grater energy efficiency and lower GHG emissions.

Given the integrated nature of transport services, the assessment of their environmental and energy-related performance is best developed using a life cycle approach, to account for the combined contribution of vehicles, fuel and infrastructure required to perform services. Regulations for these assessments are currently developed independently for each of these components. In more advanced cases, they are also framed into a set of policies that are indeed intended to address the whole life cycle perspective.

The analysis developed here focuses on the vehicle and fuel components of the life cycle, with particular attention given to the strongest differences between LZEVs and conventional vehicles. This section is structured in three main parts. The first looks at environmental and energy-related performance regulations and standards for plug-in and fuel cell electric vehicles, specifically focusing on their use phase. The second part focuses on the main vehicle components that differentiate between the powertrains of LZEVs and conventional vehicles. Specific attention is given to batteries, which are at the centre of significant debates and policy focus, and highlighting lessons that could also be applicable to fuel cells. The third part zooms in on regulatory aspects specifically related with low-carbon fuels, analysing the energy vectors needed by LZEVs in this context.

Since the focus of this section is on energy vectors, and these can be used across different transport vehicle classes, the key link with heavy LZEV (the focus of this report) comes primarily through the specific attention paid to electricity and hydrogen, i.e. the key vectors that heavy LZEVs would require to operate. In addition, the analysis includes targeted considerations in the cases that have specific relevance for heavy vehicles (such as the peculiar nature of driving profiles for heavy PHEVs).

Existing environmental- and energy-related standards and regulations for plug-in and fuel cell electric vehicles

The work already developed on regulations for the environmental and energy-related performance of road vehicles is extensive and wide-ranging. It can be categorised as follows:

- A distinction needs to be made between technical and policy-setting regulations. Technical regulations focus on aspects such as the measurement procedures and tests for tailpipe pollutant and GHG emissions/energy consumption. Policy-setting regulations define overall limit values for technical parameters and timelines for their development.
- A classification relates to the regulated subject. Two main subjects can be identified: tailpipe local air pollutants and tailpipe GHG emissions (strictly related with energy efficiency).
- Categorisation can be developed on the basis of the vehicles that are targeted, since test procedures and regulated parameters are not the same for all vehicle classes. Two main sub-groups can be identified: light and heavy vehicles.
- Regulations can be grouped according to their geographical scope of application: global (e.g. UN), supra-national (e.g. European), national (e.g. China, Japan, Korea or the United States), sub-national level (e.g. California) and city-level (Zero-, low-emission zones).
- An identification system of texts that differentiates between regulations that have broad relevance (e.g. covering all vehicle types) and other that have a specific focus (e.g. on plug-in and fuel cell electric vehicles only).

In addition to the multiple categorisations, there are several overlaps between regulations. For example, some regulatory texts can include provisions that are both related with test procedures (technical) and limit values (policy setting). Others focus exclusively on tests. Some can have a scope covering several different powertrains, while others have a narrower focus only on specific types. Some can apply only to light or heavy vehicles, others to both.

Tables 9 to 15 provide a comprehensive overview of international and national regulations on the environmental performance of road vehicles, focusing on light vehicles (cars and light commercial vehicles) and heavy road vehicles (buses and trucks), using some of the categorisation approaches identified above.

UN global technical regulations (Table 9) and UN Regulations (included in Table 10 to Table 12 and Table 14) have a prominence in energy and environmentally-related regulations. Similar to the case of safety-related regulations, these texts are developed in the framework of the Working Party on Pollution and Energy (GRPE) of the World Forum for the harmonisation of the vehicle regulations (WP.29) of the United Nations, and its informal working groups. Supra-national and national authorities are heavily involved in these global activities.[24] In many cases, they are also the main governmental actors involved in the development of these international texts, their transposition in their own jurisdictions and/or the development of complementary, independent or alternative national requirements, a case that is most relevant for policy-setting regulations.

Table 16 focuses on standards specific to heavy vehicles using electric and hydrogen-powered powertrains. Central bodies in charge of their developments include the ISO Technical Committee on Electrically Propelled Vehicles (ISO/TC 22/SC 37) and the SAE Committees on i) Light Vehicle Performance and Economy Measure, ii) Hybrid – EV and iii) Truck and Bus Powertrain.

Table 9. UN global technical regulations on the environmental performance of road vehicles

Global technical regulation name/code	Scope	Outline
	Light and heavy vehicles	
UN GTR 5	Vehicles: performance (pollutants, fuel system) ICEs, HEVs	Technical requirements for on-board diagnostic systems (OBD) for road vehicles (first developed for heavy vehicles)
	Light vehicles	
UN GTR 15	Vehicles: performance (pollutants, GHGs) ICEs, HEVs, PHEVs, BEVs and FCEVs	The world harmonized light-duty vehicles test procedure (WLTP) to determine tailpipe emissions of pollutants and CO_2, fuel (including hydrogen) or electric energy consumption and electric range for cars and other light vehicles
UN GTR 19	Vehicles: performance (fuel reservoir) ICEs, HEVs and PHEVs	Worldwide harmonized method to determine the levels of evaporative emissions from light vehicles fuelled with petrol or gas
New UN GTR on RDE (upcoming)	Vehicles: performance (pollutants) ICEs, HEVs and PHEVs	Real Driving Emissions (RDE) of gaseous compounds and particles from light vehicles on the road
	Heavy vehicles	
UN GTR 4	Vehicles: performance (pollutants) ICEs, HEVs	The Worldwide harmonized Heavy-Duty Certification procedure (WHDC) for the measurement of the tailpipe emission of pollutants from internal combustion and hybrid engines of heavy vehicles
UN GTR 10	Vehicles: performance (pollutants) ICEs, HEVs	World-harmonized Not-to-Exceed (WNTE) requirements for off-cycle tailpipe emission of pollutants from internal combustion and hybrid engines of heavy vehicles

Notes: ICE = internal combustion engine; HEV = hybrid electric vehicle; PHEV = plug-in hybrid electric vehicle; BEV = battery electric vehicle; FCEV = fuel cell electric vehicle.

Table 10. Selected environmental performance regulations addressing pollutant levels, greenhouse gas emissions and energy efficiency of light vehicles

Regulation name/code	Scope and adopting economies	Outline
	International	
New WLTP UN Regulation 154	To be defined. Expected: European Union and other countries in Europe, Japan, India, Korea and others	Emissions of pollutants and CO_2, fuel or electricity consumption and electric range according to the world harmonized light-duty vehicles test procedure (WLTP)
	Supra national	
European Regulation 715/2007 and the implementing European Regulations 692/2008 - on Euro 5 and Euro 6*****	European Union	Requirements on measurement of fuel (including hydrogen) and/or electricity consumption and pollutant and CO_2 emissions of light vehicles and other technical requirements for pollution control devices and access to vehicle repair and maintenance information (on-board diagnostics [OBD]) (Euro 5 and 6, including RDE)
	Sub national	
CARB ZEV Regulation (California code of regulations 1962.2)	California	Zero-emission vehicle standards for passenger cars, light trucks, and medium vehicles, 2018-2025

Notes: ***** Amended by 630/2012 for motor vehicles fuelled by hydrogen and mixtures of hydrogen and natural gas, by 2016/427 and 2016/646 on real driving emissions (RDE), and by 2017/1151 (amended by 2017/1154, 2017/1347, 2018/1832 and 2018/1832, further enhancing RDE).

UN Regulations are included in this table because they are nationally applied international regulatory texts. Countries listed in the table regarding UN Regulations include only contracting parties to the 1958 Agreement administered by the World forum for the harmonisation of vehicle regulations (WP.29) of the United Nations. Other countries, including India, can rely on UN Regulations for the definition of their regulatory environment on vehicle safety, without being parties of the 1958 Agreement.

The European Union includes countries in the European Union (Austria, Belgium, Bulgaria, Croatia, Republic of Cyprus, Czech Republic, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Ireland, Italy, Latvia, Lithuania, Luxembourg, Malta, Netherlands, Poland, Portugal, Romania, Slovakia, Slovenia, Spain and Sweden).

Table 11. Selected environmental performance regulations addressing pollutant emissions of light vehicles

Regulation name/code	Adopting economies	Outline
	International	
UN Regulation 83	Albania, Armenia, Belarus, Bosnia and Herzegovina, Egypt, European Union, Georgia, Malaysia, Montenegro, Nigeria, North Macedonia, Norway, Republic of Moldova, Russian Federation, San Marino, Serbia, Switzerland, Turkey, Ukraine and United Kingdom	Emission of gaseous and particulate pollutants from internal combustion engines for cars and light vehicles (the most recent series of amendments – 7 – is based on the New European Driving Cycle (NEDC) and aligned with Euro 5)
New RDE UN Regulation (upcoming))	Expected those listed for UN Regulation 83	Worldwide harmonized method to determine the levels of Real Driving Emissions (RDE) of gaseous compounds and particles from light vehicles
	National	
EPA Tier 3 standard	United States	Motor vehicle emission and fuel standards to control air pollution
Post New Long-Term Emissions Standards	Japan	Pollutant emissions for light vehicles (equivalent in stringency to Euro 6), measured based on the world harmonized light-duty vehicles test procedure (WLTP)
GB 18352	China	Limits and measurement methods for pollutant emissions from light vehicles (China 6, aligned with Euro 6, upcoming in 2021 and already applied in selected cities; China 5 currently set as nationwide standard), including RDE and on-board diagnostics
Clean air conservation act, enforcement decree and rules	Korea	Equivalent to California's Low Emission Vehicle (LEV) standards for gasoline and Euro 6 for diesel light vehicles
	Sub national	
CARB LEV III (California code of regulations 1961.2)	California	Motor vehicle emission and fuel standards to control air pollution

Notes: UN Regulations are included in this table because they are nationally applied international regulatory texts. Countries listed in the table regarding UN Regulations include only contracting parties to the 1958 Agreement administered by the World forum for the harmonisation of vehicle regulations (WP.29) of the United Nations. Other countries, including India, can rely on UN Regulations for the definition of their regulatory environment on vehicle safety, without being parties of the 1958 Agreement.

The European Union includes countries in the European Union (Austria, Belgium, Bulgaria, Croatia, Republic of Cyprus, Czech Republic, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Ireland, Italy, Latvia, Lithuania, Luxembourg, Malta, Netherlands, Poland, Portugal, Romania, Slovakia, Slovenia, Spain and Sweden).

Table 12. Selected environmental performance regulations addressing greenhouse gas emissions and energy efficiency of light vehicles

Regulation name/code	Adopting economies	Outline
	International	
UN Regulation 101	Albania, Armenia, Azerbaijan, Belarus, Bosnia and Herzegovina, Egypt, European Union, Georgia, Kazakhstan, Malaysia, Montenegro, Nigeria, North Macedonia, Norway, Republic of Moldova, Russian Federation, San Marino, Serbia, Switzerland, Tunisia, Turkey, Ukraine and United Kingdom	Measurement of the tailpipe emissions of CO_2 and fuel (excluding hydrogen) or electric energy consumption and electric range for cars and light vehicles based on the New European Driving Cycle (NEDC)
	Supra national	
European Regulation 2019/631	European Union	Tailpipe CO_2 emission performance standards for new passenger cars and for new vans, setting new targets that apply from 2025 (15% improvement in g CO_2/km from 2021 levels) and 2030 (37.5% for cars and 31% for LCVs from 2021 levels) and including a mechanism to support the uptake of LZEVs
	National	
EPA safer affordable fuel efficient (SAFE) vehicles	United States	2020 update of the earlier version of the Corporate Average Fuel Economy (CAFE) and greenhouse gas emissions standards for passenger cars and light trucks, establishing new standards that require a reductions of CO_2 emissions/km by 1.5% each year through model year 2026 (less than the 5% annual improvement required of previous CO_2 standards, issued in 2012)
Updated top-runner fuel economy standards based on the Energy Conservation Law	Japan	Fuel efficiency standards for light vehicles with a target year of 2030, expanded to cover battery electric vehicles (BEVs) and plug-in hybrid electric vehicles (PHEVs), including a well-to-wheel accounting and measured based on the world harmonized light-duty vehicles test procedure (WLTP)
GB 27999	China	Corporate-average fuel consumption (CAFC) standard: fleet average fuel economy standard for new cars: 5 L/100 km (NEDC) in phase 4 for 2020 and 4 L/100 km (NEDC, to be converted to WLTP) for 2025 in phase 5 (upcoming), counting zero emissions for new energy vehicles (NEV) and using multipliers for vehicles consuming less than 3.2 L/100 km

Notification No. 2014-235	Korea	Fuel economy and GHG standards for light vehicles (including light commercial vehicles), to be fully phased-in by 2020, requiring a 30.7% reduction in the fleet average GHG emission for passenger vehicles from 2015
Sub national		
CARB LEV III GHG (California code of regulations 1961.3)	California	Tailpipe GHG emission standards and test procedures for passenger cars, light trucks and medium passenger vehicles.

Notes: UN Regulations are included in this table because they are nationally applied international regulatory texts. Countries listed in the table regarding UN Regulations include only contracting parties to the 1958 Agreement administered by the World forum for the harmonisation of vehicle regulations (WP.29) of the United Nations. Other countries, including India, can rely on UN Regulations for the definition of their regulatory environment on vehicle safety, without being parties of the 1958 Agreement.

The European Union includes countries in the European Union (Austria, Belgium, Bulgaria, Croatia, Republic of Cyprus, Czech Republic, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Ireland, Italy, Latvia, Lithuania, Luxembourg, Malta, Netherlands, Poland, Portugal, Romania, Slovakia, Slovenia, Spain and Sweden).

Table 13. Selected environmental performance regulations addressing pollutant, greenhouse gas emissions and energy efficiency of heavy vehicles

Regulation name/code	Scope and country	Topic/Subject
Supra national		
European Regulation 595/2009 and the implementing European Regulations 582/2011 – on Euro VI***** and 2017/2400 - on CO_2 emission and fuel consumption******	European Union	Requirements on measurement of fuel (including hydrogen) and/or electricity consumption and pollutant and CO_2 emissions of heavy vehicles and other technical requirements for pollution control devices and access to vehicle repair and maintenance information (on-board diagnostics) (Euro VI, including on-road PEMS testing).
Sub national		
Advanced Clean Truck Regulation	California	Regulation phasing in heavy-duty electric trucks and vans starting in 2024 and requiring a progressive development to a full transition by 2045.

Notes: ***** Amended by 2016/1718 - on enhancing on-road portable emission measurement system (PEMS) testing and 2019/1939 - further enhancing on-road PEMS testing including cold engine start provisions and PN measurements - Step E.

****** Amended by 2019/318 - integrating hybrids.

Table 14. Selected environmental performance regulations addressing pollutant emissions of heavy vehicles

Regulation name/code	Adopting economies	Outline
	International	
UN Regulation 49 – Series 5	Albania, Armenia, Belarus, Bosnia and Herzegovina, Egypt, European Union, Georgia, Malaysia, Montenegro, Nigeria, North Macedonia, Norway, Republic of Moldova, Russian Federation, San Marino, Serbia, Switzerland, Turkey, Ukraine and United Kingdom	Emission of gaseous and particulate pollutants from internal combustion engines for heavy vehicles (up to Euro V)
UN Regulation 49 – Series 6	Albania, Armenia, Belarus, Bosnia and Herzegovina, Egypt, European Union, Georgia, Malaysia, Montenegro, Nigeria, North Macedonia, Norway, Republic of Moldova, Russian Federation, San Marino, Serbia, Switzerland, Turkey, Ukraine and United Kingdom	Emission of gaseous and particulate pollutants from internal combustion engines for heavy vehicles (aligned with Euro VI, up to step D)
	Supra national	
Moving average window (MAW) protocol	European Union	Moving average window (MAW) protocol for off-cycle emissions, included in Regulation 582/2011 and UN Regulation 49
	National	
EPA emissions standards for heavy highway engines	United States	Emission standards from model year 2007 diesel heavy engines and vehicles - Included in the Code of Federal Regulations (CFR) 40, part 86.007-11
Not-to-exceed (NTE) protocol	United States	Not-to-exceed (NTE) emission limits and testing requirements for heavy engines - Included in CFR 40, part 86
Post New Long-Term Emissions Standards	Japan	Pollutant emissions for new diesel engines used in heavy commercial vehicles (equivalent in stringency to Euro VI and United States EPA for heavy highway engines), measured based on the WHDC
GB 17691	China	Limits and measurement methods for emissions from heavy vehicle engines (China VI, aligned with Euro VI, upcoming in 2021 and already applied in selected cities; China V currently set as nationwide standard)
Clean air conservation act, enforcement decree and rules	Korea	Euro VI emissions standards for heavy vehicles since 2014

Notes: UN Regulations are included in this table because they are nationally applied international regulatory texts. Countries listed in the table regarding UN Regulations include only contracting parties to the 1958 Agreement administered by the World forum for the harmonisation of vehicle regulations (WP.29) of the United Nations. Other countries, including India, can rely on UN Regulations for the definition of their regulatory environment on vehicle safety, without being parties of the 1958 Agreement.

The European Union includes countries in the European Union (Austria, Belgium, Bulgaria, Croatia, Republic of Cyprus, Czech Republic, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Ireland, Italy, Latvia, Lithuania, Luxembourg, Malta, Netherlands, Poland, Portugal, Romania, Slovakia, Slovenia, Spain and Sweden).

Table 15. Selected environmental performance regulations addressing greenhouse gas emissions and energy efficiency of heavy vehicles

Regulation name/code	Adopting economies	Outline
International		
European Regulation 2019/1242	European Union	Setting new targets for tailpipe CO_2 emission standards for heavy vehicles that apply from 2025 (15% improvement in g CO_2/km vs. 2019/2020) and 2030 (30%) and including a mechanism to support the uptake of LZEVs
European Regulation 2017/2400	European Union	Laying down the rules for issuing licenses to operate a simulation Vehicle Energy Consumption calculation Tool (VECTO) with a view to determining CO_2 emissions and fuel consumption of new vehicles
National		
EPA phase 2 greenhouse GHG and fuel efficiency standards	United States	Standards to reduce greenhouse gas emissions and improve fuel efficiency of medium- and heavy vehicles – included in CFR 40, part 1036 and CFR 40, part 1037
Heavy top-runner fuel economy standards based on the Energy Conservation Law	Japan	Fuel efficiency standards for heavy vehicles (trucks, buses with a gross vehicle weight above 3.5.t): phase 2, with a target year of 2025
GB 30510	China	Fuel consumption limits for heavy commercial vehicles (based on GB/T 27840 for base models and a computer simulation model for variants), currently at stage 3 (stage 4 under consideration) and sect according to vehicle weight and configurations classes
GB/T 27840	China	Fuel consumption test methods for heavy commercial vehicles powered by ICEs (modified version of the WHDC to be run on a chassis dynamometer)

Table 16. Selected international environmental performance standards addressing electric and hydrogen-powered vehicles

International standard name/code	Outline
ISO 8714	Specifications for the calculation of energy consumption and range of electric cars and LCVs
ISO 8715	Specifications for the calculation of speed, acceleration and hill climbing ability of electric cars and LCVs
ISO 23274	Chassis dynamometer test procedure to determine the electric energy during charge-depleting use of light PHEVs and exhaust emissions and the electric energy and fuel consumption for light HEVs or PHEVs in charge-sustaining mode
ISO 23828	Procedures for energy consumption measurement for light vehicles fuelled with compressed hydrogen
SAE J1634	Test procedure for light battery electric vehicle energy consumption and range

SAE J1711	Recommended practice for measuring the exhaust emissions and fuel economy of hybrid-electric light vehicles, including plug-in hybrid vehicles
SAE J2572	Recommended practice for measuring fuel consumption and range of fuel cell and hybrid fuel cell vehicles fueled by compressed gaseous hydrogen
SAE J2711	Recommended practice for measuring fuel economy and emissions of electric, hybrid-electric and conventional heavy vehicles
SAE J2841	Utility factor definitions for plug-in hybrid electric vehicles using travel survey data
SAE J2594	Recommended practices to design for recycling proton exchange membrane (PEM) fuel cell systems

The information included in Table 9 to Table 16 is expanded on in the following sections for light and heavy vehicles, followed by a discussion on priorities for future developments.

Environmental- and energy-related standards and regulations for light vehicles

Both technical and policy-setting regulations for light vehicles are comprehensive in terms of scope, covering all powertrain configurations (including ICEs, HEVs, PHEVs, BEVs and FCEVs).

Technical regulations define measurement procedures and tests for tailpipe pollutant and GHG emissions, as well as energy consumption. They also integrate provisions of on-board diagnostics (OBD) and, since OBD has not proven to be an efficient tool for limiting tampering of vehicles, real-world emission tests. The latter require portable emissions measurement systems (PEMS). Pollutant emission testing is also carried out in the case of evaporative emission from fuel tanks.

Key regulatory texts on this subject (Table 9) include UN GTR 15 on the worldwide harmonized light vehicles test procedure (WLTP), UN GTR 19 on evaporative emissions, which may be extended to heavy vehicles and an upcoming UN GTR on real driving emissions (RDE). They contain procedures that are typically applied to the whole vehicle, tested on a dynamometer (e.g. according to the WLTP or the FTP) and in real driving conditions, using portable emissions measurement systems (PEMS).

UN GTRs tend to focus on tests. For countries that apply the WLTP, these test procedures are also reflected in supra-national/national/sub-national technical regulations. Key examples include China, Europe and Japan. In North America, light vehicle testing is based on alternative (and roughly equivalent, in terms of function) test procedures, also representing a range of different vehicle operations and conditions. These include the Federal Test Procedure (FTP) and the Supplemental Federal Test Procedure (SFTP), integrated in the Code of Federal Regulations of the United States (United States Environmental Protection Agency, 2014).

Regulations that promote limit values and timelines on environmental performance of vehicles are strong policy-setting instruments. This is not only for environmental aspects, but also for considerations related with industrial development and trade facilitation, which have been key drivers of the early development of internationally harmonised regulations on vehicles and mutually recognised type approval and continue to remain relevant today. These regulatory texts tend to be developed first by a subset of supra-national, national or sub-national authorities with strong engagement in the automotive industry. They are then integrated into international regulatory frameworks, UN Regulations in particular, and finally adopted more broadly at the global scale.

Tailpipe pollutant emission standards, commonly known as Tier 1, Tier 2, Tier 3 or Euro I-VI are one example of regulations that historically were first developed in the sub-national/national (e.g. in California and the United States) or supra-national (e.g. in the European Union) context, and then (in the case of the European regulations) transposed into UN Regulations. Following this, regulatory texts that originally applied in Europe have then been adopted internationally – by parties that are signatories of the 1958 Agreement administered by the World forum for the harmonisation of vehicle regulations (WP.29) (UNECE, 2020c) – with different timelines and stringencies. The last step of this process is well represented by the case of real driving emissions (RDE) and PEMS testing, first developed in European Regulations (Table 10) and now being integrated in UN global technical regulations and UN Regulations.

In the case of tailpipe GHG emissions and energy consumption, technical regulations (e.g. the UN GTR 15 and the UN Regulations 101 and 154) provide a common basis for test procedures. Supra-national/national/sub-national policy-setting regulations (such as all those listed in Table 12, except for UN Regulation 101) set relevant limit values and timelines. The latter have been increasingly paired with mandates or incentives for the deployment of LZEV powertrain technologies. Examples include: California's Zero Emission Vehicle mandate, China's New Energy Vehicle (NEV) credit mandate and the European integration of incentives in Regulation 2019/631. These are leading the way for LZEVs to be included in corporate average emission calculations. Other supportive policies for energy efficiency and low and zero-tailpipe emission vehicles also include economic incentives such as the modulation of vehicle registration taxes to the performance of vehicles in terms of CO_2 emissions per km or the use of feebates, consisting in a combination of taxes and rebates (International Energy Agency, 2020b).

Environmental and energy-related standards and regulations for heavy vehicles

In the case of heavy vehicles, technical regulations on tailpipe emissions of pollutants apply to their engines, rather than the whole vehicle. Engines are tested under laboratory conditions over specific test cycles. With the exception of the United States, which applies different cycles and procedures, the test cycles are based on the worldwide harmonized heavy-duty certification (WHDC) procedure, described in UN GTR 4 and UN Regulation 49. Engine tests are then complemented by on-road vehicle tests requiring portable emission measurement systems (PEMS) that address off-cycle engine emissions. On-road PEMS tests are evaluated with the moving average window (MAW) or the not-to-exceed (NTE) protocols in Europe and the United States, respectively (European Commission, 2020e). All these tests typically only cover ICEs, as BEVs do not have tailpipe emissions and FCEVs emissions are limited to water.

Other regulatory texts concerning heavy vehicle engine testing include: UN GTR 4 (and UN Regulation 49) for the WHDC, UN GTR 5 for on-board diagnostic systems (OBD) – first developed for heavy vehicles engines; and UN GTR 10 on the World-harmonized Not-to-Exceed (WNTE) requirements for off-cycle tailpipe emission of pollutants (Table 9).

Similar to light vehicles, policy-setting regulations that include limit values and timelines on pollutant emissions tend to be developed first by a subset of supra-national, national or sub-national authorities. This involves strong engagement in the automotive industry, and then integration into harmonised international regulatory frameworks. The Euro I-VI, first developed in Europe Table 13) and then transposed in international and other national regulations (Table 14), are also a relevant example for heavy vehicles, notwithstanding the independent and parallel development of North American standards.

Regulations related with tailpipe GHG emissions and/or energy consumption of heavy vehicles are not internationally harmonised (Table 15). The most advanced existing regulatory frameworks in this field rely on simulations developed with dedicated software tools and have a policy-setting nature, including limit values (Table 15). Key software tools include in particular the Vehicle Energy Consumption calculation Tool (VECTO) in Europe and the Greenhouse Gas Emissions Model (GEM) in North America. Japan also uses a simulation tool. The Chinese regulation on heavy vehicle GHG emissions relies mostly on a dynamometer test.[25] India has also developed regulations on the fuel economy of heavy vehicles. These are based on meeting minimum performance requirements during constant speed fuel consumption (CSFC) testing, but Indian regulators are working toward an India-specific version of the European Commission's Vehicle Energy Consumption Calculation Tool (VECTO) (Sharpe et al., 2019; Sharpe and Sathiamoorthy, 2019). In Europe, Regulation 2019/1242 also includes a mechanism to support the uptake of LZEVs.

Regulations defining test cycles for tailpipe GHG emissions and/or energy consumption of heavy vehicles are also different across jurisdictions. The main European regulation (VECTO software, licensed according to the European Regulation 2017/2400) uses five test cycles (mostly three: long haul, regional delivery, and urban delivery) representative for different vehicle categories. Japan uses the combination of the JE05 cycle (based on Tokyo driving conditions) and a motorway cycle. The regulation in the United States relies on different cycles depending on the engine family's service class[26] and China uses a modified version of the WHVC (AVL, 2018; United States Environmental Protection Agency, 2020b).

Finally, a recent major policy-setting regulatory development that is relevant for both NOx and GHG emissions from heavy duty vehicles is California's Advanced Clean Truck regulation (listed in Table 13), requiring manufacturers to transition from diesel to electric trucks and vans beginning in 2024 and requiring a full transformation by 2045 (California Air Resources Board, 2020a).

Priorities for environmental- and energy-related regulatory developments

Current priorities considered in the European evaluation roadmap for the development of post-Euro 6/VI emission standards for cars, vans, buses and trucks for the development of technical regulations include (European Commission, 2020e):

- the reduction of the complexity and compliance costs
- the development of test procedures for currently non-regulated air pollutants (ammonia, N_2O, methane and formaldehyde) and powertrains (in particular hybrids for on-road PEMS testing)
- the durability of systems that control the tailpipe emissions of pollutants.

The latter is due to the fact that real-world emissions are still not measured under all conditions of use in Euro 6/VI and that air pollutant emissions are not monitored throughout the entire lifetime of vehicles on the road.

The impact on developments for LZEVs is mostly indirect, and primarily due to the expected increase in stringency of regulatory requirements for ICE vehicles.

Priorities for regulation include the definition and/or the revision of limit values for:

- existing and upcoming regulations on tailpipe pollutants
- existing and upcoming regulations on GHG emissions/energy consumption.

These include complementary incentives for LZEVs in cases like the revision of the European Regulation 2019/1242.

Targeted incentives based on pollutant emission performance for heavy LZEVs may also be considered in the framework of the Cleaner Trucks Initiative in the United States. The Initiative has a focus on the control of air pollution and is considering how LZEV incentives may be appropriate, given the substantial tailpipe emission reduction potential of these technologies (United States Environmental Protection Agency, 2020a).

Considering differentiated mechanisms to incentivise heavy LZEVs, including the use of larger credit multipliers for the heaviest vehicles, is seen as especially relevant by industry stakeholders.

The global harmonisation of regulations related with tailpipe GHG emissions and/or energy consumption is also an important area of policy development for heavy LZEVs. This is demonstrated by the recent initiative of the International Organization of Motor Vehicle Manufacturers (OICA) to hold a workshop on the topic involving industry stakeholders and governments. To date, this initiative has not yet lead to the creation of a new informal working group of the Working Party on Pollution and Energy of the United Nations World Forum for the Harmonisation of Vehicle Regulations (WP.29). However, it did lead to the creation of an ad-hoc group, set up by OICA, open to all interested parties to work on the subject (International Organization of Motor Vehicle Manufacturers, 2020; UNECE, 2020b).

In addition to the lack of international harmonisation on technical regulations on heavy vehicle fuel economy tailpipe GHG emissions/energy consumption, it is also important to flag that the simulation tools developed for the most advanced regulatory frameworks (including VECTO, in particular) currently do not cover PHEVs, BEVs nor FCEVs (Steininger, 2020; United States Environmental Protection Agency, 2016).[27] Currently, recommended practices on the determination of electricity consumption and range for heavy vehicles have only been developed in the case of the SAE 2711 standard (Table 16), but Europe has also started to work on the subject. This aims to fulfil the requirement of the Regulation 2019/1242, indicating that the Commission plans to adopt a methodology for the calculation of energy use and range for heavy vehicles by the end of 2021 (European Commission, 2019b).

An important challenge is the coverage of different EV configurations (including PHEVs, BEVs and FCEVs) as well as other flexible powertrain concepts that distribute loads across different motors or engines. In the case of hybrids, this also includes the need to differentiate between charge sustaining and charge depleting modes. Japan is also developing a measurement method for the energy use of electric heavy vehicles and will explore the possibility of creating efficiency standards for these electric trucks and buses (Rodriguez, 2020). In China, the current standard for the measurement of energy consumption and range for electric vehicles (GB/T 18386) also applies to heavy vehicles, but a specific standard is in preparation (Rodriguez, 2020).

In the case of PHEVs, these regulatory developments also necessitate utility factors outlining the share of electric driving, which can vary significantly depending on vehicle types and mission profiles. Transparency on utility factors for PHEVs first requires the acquisition of greater experience on the use of PHEV trucks (and therefore policies supporting their initial deployment). Given the evolution of technologies and markets, policies relying on such factors shall also include clear mechanism for their regular re-evaluation and amendment.

Hydrogen-powered vehicles using internal combustion engines may also require targeted developments in technical regulations governing pollutant emission testing. Such vehicles may be part of policy strategies aiming to favour the uptake of hydrogen use in heavy transport, given lower vehicle costs with respect to fuel cell vehicles, especially in the absence of clear prospects for increased scale in fuel cell deployment. The key rationale for this relates with the formation of pollutants such as CO and NOx during fuel combustion due to the temperature increase, even if the fuel does not contain carbon nor nitrogen. In Europe, targeted developments in technical regulations governing pollutant emission testing of hydrogen-powered heavy vehicles using internal combustion engines is being considered, at the time of writing, in the Heavy Duty Portable Emissions Measurement Systems Expert Group of the European Commission.

Policy-setting regulations on urban access and road charges are also a subject that has gained significant attention in recent years. This has largely been driven by the desire of local authorities to mitigate local pollution. Many cities have committed to bring significant portions of their urban environments to zero emission by 2030, especially in Europe, and many have already started to take action (C40, 2019; Sadler, 2020a, 2020b).

Some governments proposed legislation on road charges that depend on the conditions of traffic congestion (and/or the time of the day) and the environmental performance of vehicles, and not only in urban areas. Key examples include the case of the Netherlands, with a 2010 proposal on a basic rate per kilometre, differentiated according to environmental characteristics and a peak rate for busy times and places (Geurs & Meus, 2011; Meurs, 2017).

Public authorities need technical instruments that can better co-ordinate the development of access regulations and road charges for both light and heavy vehicles. Some examples are the development of country-specific labels on LZEVs (namely in France) or differentiated number plates (e.g. in Germany, Norway and recently the United Kingdom) (Sadler, 2020a, 2020b; UK Department for Transport, 2020). Technology is evolving rapidly and cost developments are enabling zero emission vehicles to be the least cost option (on a total cost of ownership basis). However, it is also important that these instruments can differentiate between low (PHEVs in particular) and zero (BEVs and FCEVs) tailpipe emission vehicles (Sadler, 2020a, 2020b). Amongst the country examples cited earlier, Germany opted for using the differentiated plate for PHEVs and zero tailpipe emission vehicles, while Norway and the United Kingdom only included zero tailpipe emission vehicles.

Location-specific time-dependent road charges or access restrictions are important for the management of road congestion. Differentiating these charges based on the environmental performance of vehicles (e.g. distinguishing between zero tailpipe emission driving or not) adds significant opportunities to address local air quality and GHG emission reduction policies, especially in cities. Other advantages could be generated from the optimisation of battery capacity characteristics and travel needs such as minimising material requirements needed for batteries, this is especially relevant for battery electric heavy LZEVs.

Currently, an internationally harmonised framework facilitating a coherent application of differentiated road charges or access restrictions for LZEVs is not available. Its development should be seen as a priority given the importance of improved air quality, GHG emission reduction and emerging concerns about the criticality of battery materials.

Crucial parameters that have been considered in existing schemes include tailpipe GHG emissions and regulatory limits on pollutant emissions. These parameters shall be the focus of future efforts for international harmonisation.

The enforcement of location-specific road charges or access restrictions that differentiate between electric and non-electric driving could be significantly enhanced by systems capable to detect automatically the driving mode. This raises privacy related concerns if the exact location is permanently tracked, but there are other solutions to address this, in a similar way to how digital tachographs are used in trucks to ensure that drivers take enough breaks. Geofencing offers interesting advantages for the enforcement of access restrictions that account for differences between electric and non-electric driving, provided that privacy and other issues (e.g. cybersecurity) can be properly addressed. Privacy issues may again be overcome by systems that do not permanently record locations, instead simply detect whether a vehicle is in or out of a geofenced zone and then record non-compliance within legally tracked zones. Another option may be to review technological solutions that have been recently developed for some of the Covid-19 tracking applications.

In Europe, some of these considerations have direct relevance for heavy vehicles. In particular, the revision of the Eurovignette Directive (1999/62/EC), whose scope of application has a focus on heavy vehicles, and of the European Electronic Tolling Service (EETS) Directive (2004/52/EC), which enables road users (including in particular frequent motorway users, like trucks) to pay tolls electronically throughout the European Union with a single subscription contract, service provider and on-board unit.. (Debyser, 2019; European Parliament, 2020).

Environmental and energy-related standards and regulations for batteries and fuel cells

Batteries are a central technology pillar of all types of LZEVs. They are essential in BEVs, instrumental for PHEVs, and critical to ensure that the energy efficiency of FCEVs is optimised. Batteries and fuel cells are also the core components that differentiate LZEVs from conventional vehicles. Demand for heavy duty LZEVs is set to grow in the coming decades, starting from buses and trucks operated on daily distances below 300 km (IEA, 2020b). This, coupled with their large size, power and energy storage requirements means that LZEVs are set to have important effects on future battery and fuel cell production and demand.

Like other clean-energy technologies needed to generate renewable electricity, batteries and fuel cells are also likely to significantly change material requirements with respect to fossil fuel technologies (European Commission, 2018a; IRIS, 2020; IEA, 2020a; International Renewable Energy Agency, 2019).

The largest material requirements for batteries include graphite, aluminium, nickel, cobalt and manganese. Graphite accounts for roughly half (in terms of mass) of the total mineral requirements for commonly produced in NMC (nickel manganese cobalt oxide) and NCA (nickel cobalt aluminium oxide) battery chemistries. Other high-demand materials include nickel, needed for cathode production and accounting for 15-20% of the total mineral requirements, manganese and cobalt, also needed for the cathode (and accounting for roughly 6% each), plus lithium, estimated at 4% of the total weight requirements (Hund et al., 2020). Graphite, aluminium and lithium are also needed in lithium iron phosphate (LFP) battery chemistries, not requiring nickel or cobalt.

Proton exchange membrane fuel cells, the most commonly used in transport, generally need a catalyst usually requiring platinum. This technology also utilises chromium steel, containing 18% chromium and 8% nickel (Hund et al., 2020). Electrified vehicles also need greater quantities of copper compared with ICE technologies, as well as rare earth elements such as neodymium in magnets for electric motors.

Similar to oil dependency for ICEs, the structural changes in material demand accompanying the transition of ICE vehicles to LZEVs can induce a number of supply risks of raw or refined material. These include limitations in availability, demand/supply unbalances, issues related with the geographical concentration of extraction and/or refining and social and environmental impacts. Together, these risks define the criticality of a material and, especially in cases where specific technologies are responsible for large shares of the demand of the materials, the risk profile associated these same technologies.

One additional challenge characterising batteries are the GHG emissions that are embedded in the materials they need to be produced, their manufacturing processes and end-of-life treatment (their carbon footprint). This is largest for battery packs that have high capacity (as those needed in heavy-duty LZEVs) and for supply chains of battery materials (in particular aluminium production) that are heavily reliant on carbon-intensive sources of electricity generation (Kelly, Dai and Wang, 2019).

Priorities for battery and fuel cell development

Material availability and the social and environmental impacts of the supply chain of battery materials are core drivers of a growing body of policy initiatives that anticipate and mitigate risks, especially in Europe.

European policy developments got started by the establishment of the European Battery Alliance in 2017 and the following adoption of a Strategic Action Plan for Batteries in 2018, aiming to make Europe a global leader in sustainable battery production and use, in the context of the circular economy (European Commission, 2018b). Policy action is gaining increasing relevance following the announcement of the European Green Deal. This growth strategy promotes the transition to a climate-neutral, resource-efficient and competitive economy and the move towards zero-pollution (European Commission, 2019c).

European policy developments on batteries have direct relevance for LZEV regulations. They provide helpful indications of upcoming global priorities. Key pillars of the European policy action include:

- Aspects related with the useful life of batteries used by LZEVs, linked with regulatory developments taking place in the UN framework, in particular on the topic of battery durability.
- Aspects related with battery design, second life and end-of-life of batteries, linked with the revisions of the battery directive (2006/66/EC) and the end-of-life vehicles (ELV) vehicle Directive (2000/53/EC).
- Requirements aiming to bring greater transparency on the carbon footprint of batteries and clear rules for product differentiation.[28]

The main short-term objective for the regulatory work on in-vehicle battery durability (e.g. calendar life and cyclic ageing), is the definition of minimum performance criteria and in-service verification methodology in a UN GTR. This intends to maximise driving range and prevent substandard products from entering the market. Other developments also include further modelling and assessment of data collected from real vehicles, allowing room for continued development of the regulation as the technologies evolve(UNECE, 2020b).

Important developments for battery design and recycling are pack design and construction requirements that focus on reversible assembly techniques and the use of standardised tools and configurations for modular design. It will be important that battery design requirements incorporate strict safety-related aspects given the challenges discussed for EV safety with respect to thermal runaway management, which may have implications on pack and modules arrangements, as well as sealing.

Repair, reuse and repurposing requirements need solutions that enable access to the battery management system to facilitate diagnostics/determination of the state of health of the battery. Open data diagnostics connectors are an option under consideration. Safety protocols for cell/modules are also important to facilitate dismantling and reuse/repurposing (Santos Gil, 2020).

A clear distinction between the end-of-life requirements of vehicles and those of batteries can improve end-of-life management practices and facilitate material recycling. This can be further strengthened, in the case of batteries, by the availability of information on the critical materials (such as cobalt, nickel and lithium) that they contain. This can be achieved via a labelling system linked with a battery information database. Other important aspects that help to assess the life cycle performance of battery manufacturing are transparency on the content of recycled materials and minimum requirements on recycled material content (Santos Gil, 2020). These involve a need for clear definitions of both the recycled content (e.g. the raw materials obtained from waste, different from the waste that originates it) and the overall reference weight (changing significantly if it refers to packs, modules or cells). The question of recycling oxygen (not relevant for circular economy, but part of the weight of active materials) is also a technical detail that deserves proper consideration (Tytgat, 2020).

Another important challenge is the need to balance material recycling from a circular economy perspective (including risks of exporting critical materials through second hand vehicle trade), the interest of manufacturers for low costs of raw materials and the challenges of recyclers due to net costs currently associated with recycling of batteries. Regarding this last point, it is important to clearly attribute responsibility for the end-of-life management of the battery and its components, along with a recommendation to ensure that refurbished batteries, out of the control of the first producer, are under the extended producer responsibility of the refurbisher (Tytgat, 2020).

The carbon footprint of batteries is a major point of discussion in the LZEV deployment and debate. Product environmental footprint category rules (PEFCR) for rechargeable batteries for mobile applications already exist and are based on the ISO 14040 standard, dealing with life cycle assessments (Santos Gil, 2020). The European plan is to rely on these rules and reach consensus on the lithium-ion chemistries to consider, e.g. lithium cobalt oxide (LCO), NCA, NMC, lithium-manganese dioxide (LiMn) and LFP and one of the challenges is the need to ensure the availability of rules for all battery chemistries in the market. The aim of this work is to ensure greater transparency on the carbon footprint per battery model and per battery plant through the introduction of clear rules for product differentiation. The latter may include other environmental impacts, in addition to carbon footprint (Santos Gil, 2020). This work is being considered in the framework of the European Green Deal and may have relevance for policy developments on carbon border adjustments (European Commission, 2020d).

European policy developments on batteries will also address supply chain sustainability issues with a broader scope than solely environmental aspects and build on the OECD due diligence guidance for responsible mineral supply chains (Box 6). The European Commission is considering the introduction of binding requirements. These include the adoption and communication of a supply chain policy in line with the OECD framework, the identification and management of social/environmental risks in supply chains, the development of third-party audits of supply chain partners and the disclosure of information to Member States authorities and other stakeholders (Santos Gil, 2020).

Box 6. The OECD due diligence guidance for responsible mineral supply chains

The OECD Due Diligence Guidance for Responsible Mineral Supply Chains is a global standard providing detailed recommendations to help companies respect human rights and avoid contributing to conflict and other financial crimes through their mineral purchasing decisions and practices. It is rooted in promoting responsible investment and trade in conflict-affected and high-risk areas, it has a global scope and, in its third edition, is applicable to all minerals or metals (OECD, 2016).

This work is part of a broader set of OECD activities related to responsible business conduct and human rights and the implementation of the Due Diligence Guidance for Responsible Business Conduct, based on the OECD Guidelines for Multinational Enterprises (OECD, 2018).

Implementing these recommendations helps enterprises avoid and address adverse impacts related to workers, human rights, the environment, bribery, consumers and corporate governance that may be associated with their operations, supply chains and other business relationships. In the case of mineral supply chains, the OECD Due Diligence Guidance includes concrete measures for both upstream and downstream companies to identify and mitigate risks of adverse impacts, in close collaboration with local civil society organisations, local authorities and other businesses. The Guidance also expects companies to avoid blanket disengagement and encourages them to work closely with governments to formalise, improve working conditions and reduce vulnerabilities of artisanal and small-scale mines.

A recent report on battery materials focused on cobalt and copper upstream supply chains in the Democratic Republic of the Congo (OECD, 2019) looked at responsible sourcing challenges and opportunities that exist across different modes of production, from large scale mining (LSM) to artisanal and small-scale mining (ASM). In particular, it warns about the risks of indiscriminately avoiding ASM material sourcing, given its importance to local livelihoods and its swing producer role in the market. Child labour in ASM has attracted significant attention, but it is not uniformly present across ASM sites and can often be more effectively addressed through time-bound mitigation. The report also highlighted serious risks related to corruption and the management of private and public security forces in LSM. On this basis, the report underlines the importance of action to render due diligence in the sector more comprehensive and nuanced, stressing the importance of a greater emphasis on risk mitigation to develop more responsible cobalt and copper supply chains. The report also shows that there have been a number of projects attempting to address supply chain sustainability challenges in the DRC and indicates that the DRC is committed to adopt OECD due diligence guidance to copper and cobalt.

A number of industry and multi-stakeholder initiatives, as well as market makers, have committed to developing policies and practices for responsibly sourcing cobalt in line with the OECD Due Diligence Guidance. These include the Responsible Cobalt Initiative (RCI), launched by the China Chamber of Commerce of Metals, Minerals and Chemicals Importers & Exporters (CCCMC), whose members include Chinese cobalt producers, smelters and refiners, as well as global downstream companies. The CCCMC and the Responsible Minerals Initiative (RMI), an industry initiative comprising 380 members, are also working together to roll out trainings, third-party assessments and audits and raise awareness of the OECD Due Diligence Guidance and the Chinese Due Diligence Guidelines for Responsible Mineral Supply Chains. The London Metal Exchange, the world's largest market in options and futures contracts for base and other metals (including cobalt and copper), has also introduced proposed rules requiring all brands delivering on the Exchange to apply the OECD Due Diligence Guidance. The World Economic Forum's Global Battery Alliance, a public-private partnership and collaboration platform made up of some 50 member organisations seeking to connect and scale up initiatives to transform the value chain for batteries has also issued a set of principles for responsibly sourcing cobalt and other battery materials.

Current policy developments with a focus on batteries can also chart a roadmap that will have relevance to develop similar provisions for fuel cells. This is possible even if aspects that are specifically focused on battery recycling, the circularity of critical materials and supply chain sustainability will need to be revisited and applied to different minerals, in particular platinum group metals (PGMs). One additional difference is that the large concentration of PGMs is likely to come with a positive economic value from recycling (as already indicated by the willingness of recycling companies to handle end-of-life vehicles if they include the exhaust after-treatment systems, also rich in PGMs).

Regulations on low-carbon energy vectors

Regulations on the carbon intensity of energy vectors are very diverse, reflecting the diversity of the energy vectors themselves (in particular liquid hydrocarbons, gaseous hydrocarbons, electricity and hydrogen).[29]

They include:

- Blending mandates for renewable or low-carbon fuels. This is most relevant in the transport sector for liquid and gaseous hydrocarbons, and quotas or obligations to have a certain percentage of the electricity sourced from renewable sources, generally combined with priority dispatching.

- Instruments regulating the carbon intensity of fuels. Again, most relevant in transport for liquid and gaseous hydrocarbons, but also important for the integration of low-carbon hydrogen in the fuel mix.

These two types of instruments are discussed in the following section as they have direct implications for technical aspects defining the characteristics of energy vectors, including those needed for LZEVs. More broadly, cap-and-trade regulatory schemes that have the objective to generate economic incentives to reduce emissions of GHGs or other pollutants.[30]

Regulations on vehicles, such as ZEV mandates also complement these requirements that directly regulate the fuels, along with requirements to distribute/retail alternatives to petroleum, since they regulate the availability of critical enabling technologies for fuels (i.e. the vehicles to consume them and the distribution infrastructure).

Blending mandates and renewable electricity quotas

Mandatory blending aims to ensure that there is a sustained market demand for renewable and/or low-carbon fuels. Blending mandates a scope of application primarily focused on liquid and gaseous fuels. In particular, blending mandates are currently in place in a broad range of countries for biofuels used in road transport.

Ethanol blending in gasoline is required in Brazil (27% by volume), Argentina (12%), and India (5%) (IEA, 2018). Biodiesel blending, which can come with significant sustainability challenges, is required in Indonesia (30%), Brazil (10%), Argentina (10%), Malaysia (7%) and Thailand (7%) (Christina, 2019; IEA, 2018). The European Union also has obligations for renewable fuels in transport (10% by energy content in 2020, and 14% in 2030), and so do the United States, where most of gasoline contained up to 10% ethanol by volume in 2019 (IEA, 2018; United States Energy Information Administration, 2020).[31] China also had a plan for a nationwide mandate of 10% ethanol, but this was recently suspended due to concerns over competition with food security (Gu et al., 2020).

In the United States, the national policy that requires a certain volume of renewable fuel to replace or reduce the quantity of petroleum-based transportation fuel, heating oil or jet fuel is the Renewable Fuel Standard (RFS) programme (United States Environmental Protection Agency, 2020c). In the European Union (EU), the policy instrument used for blending mandates is the Renewable Energy Directive (RED II, 2018/2001/EU). It sets 2030 as the timeframe for renewable fuel requirements in transport and updating the ambition set by the earlier version of the Directive (RED I, 2009/28/EC) for 2020, which specifies national renewable energy targets for 2020 for each country.

In Europe, the same policy instrument sets a binding share of energy from renewable sources in the Union's gross final consumption of energy in 2030 (at least 32%), leaving to EU Member States the responsibility to set national contributions as part of their integrated national energy and climate plans. As a result, the RED I and II also contain implicit renewable electricity quotas, i.e. obligations to have a certain percentage of the electricity sourced from renewable sources.

These quotas are effectively the equivalent instruments of mandatory blending of renewable and/or low-carbon fuels for the electricity sector Renewable Portfolio Standards (RPSs) are similar instruments used to set renewable electricity quotas. They are in place at the State level in the United States and at the Province level in China. Renewable electricity purchase obligations are also in place in India and in Mexico (IEA, 2019b).

Instruments regulating the carbon intensity of transport fuels

Low-carbon or clean fuel standards are regulatory policy mechanisms with the aim to reduce the life cycle greenhouse gas (GHG) emission intensity of transportation fuels/energy vectors. They include obligations to reduce the GHG emission intensity of transport fuels over time, and generally target fuel suppliers.

These mechanisms are grounded on the definition of progressively tightened regulatory thresholds/limits for the average life cycle (i.e. including production, distribution and use) GHG emission intensity of transport fuels/energy vectors. These include gasoline, diesel oil and jet kerosene blends distributed by regulated parties. The latter are typically fuel suppliers and/or other entities that produce, import, distribute or sell transportation fuels.

Key examples include the European Fuel Quality Directive (FQD) and California's Low Carbon Fuel Standard (LCFS) (California Air Resources Board, 2020d; European Commission, 2020c). The latter has been inspirational for the development of similar policies in Oregon and other States in the United States, as well as British Columbia in Canada (Gladstein, 2019). Canada's nationwide Clean Fuel Standard, currently being finalised (Government of Canada, 2020), has also been drawing from the LCFS (Murphy, 2020). RenovaBio, the Brazilian national policy on biofuels, is also regulating the carbon intensity of fuels (Agência Nacional do Petróleo Gás Natural e Biocombustíveis, 2020).

Europe's FQD (98/70/EC) initially aimed to reduce air pollution and improve air quality, making sure that regulations on tailpipe pollutant emissions from transport vehicles had a mirroring regulatory development on the fuel side. This was due to the importance of coordination on the engine and fuel sides to ensure the proper functioning of exhaust after-treatment devices. Key regulatory requirements of the FQD include the phase out of lead and the reduction of sulphur content. The 2009 update of Europe's FQD also introduced the obligation, for EU Member States, to require that fuel suppliers reduce the greenhouse gas (GHG) emission intensity of automotive fuels. The binding reduction limit set in the 2009 update of the FQD for 2020 is 6% compared to the GHG intensity of all automotive fuels used in 2010 (in addition to interim steps in earlier years) (Steininger & Lonza, 2020).

California's low carbon fuel standards (LCFS) uses a credit-based system whereby fuels with a carbon intensity that are lower than the regulated threshold generate credits and fuels with higher GHG emission intensity generate deficits. Conventional fuel suppliers can reduce the number of deficits they generate by reducing the carbon intensity of their fuels through efficiency improvements to their production system, or blending in lower-carbon components. In any given year, regulated parties need to have enough credits to compensate for any deficits created by the sale of carbon intensive fuels. Credits are generated by low carbon fuel producers, each credit represents a tonne of emissions reduced beyond that year's target. As the target progressively tightens, low carbon fuel producers must continue to reduce the carbon intensity of their product, or see the incentive for their fuels decline over time. Regulated entities can trade credits and also use credits banked from previous years to ensure they meet the policy requirements.

Given that policies that regulate the carbon intensity of fuels (including FQD and LCFS) do not include mandates for any particular fuel or technology, they permit a broad range of compliance strategies, remaining technology-neutral. However, thanks to the progressively tightened limit values, the LCFS also has the capacity to incentivise solutions that offer the best performance in terms of GHG emission reduction, rewarding them with lasting economic incentives.

At current LCFS credit prices and targets, the effective subsidy generated by the credits for light electric vehicles is about USD 0.17/kWh and USD 0.27/kWh for electric trucks and buses (Murphy, 2020). Recent analysis estimated that this would sum to about USD 60 000-70 000 over the first five years of life for a heavy freight truck in drayage service (ICF, 2019; Murphy, 2020).

The resources needed for these incentives are drawn from a limited increase in the overall fuel price. For this reason, the LCFS has significantly enhanced features for technology development in comparison with a carbon tax or a cap-and-trade scheme. Additionally, LCFS revenue remains in the transport sector. This is because the revenue flows by way of transactions between deficit generators and credit generators, unlike a cap-and-trade system, or a carbon tax where revenue can be appropriated by the governing agency for any approved purpose.

Regulatory implications for transport energy vectors

The effectiveness of blending mandates and instruments regulating the carbon intensity of energy vectors depends on their capacity to accurately account for emissions across the life cycle. The production (well-to-tank) and use (tank-to-wheel) phases in particular.

These are specific to each production pathway and have been the focus of a significant body of technical research. Findings have been incorporated in the regulatory texts (in particular for the elaboration of accounting methodologies and the provision of default values for specific pathways). Not surprisingly, the RFS in the United States, the FQD and the RED I and II Directives in Europe and California's LCFS include provisions on these aspects, as well as minimum eligibility requirements for alternative fuels to be generating credits and/or be accounted in compliance evaluations.[32] For petroleum fuels and biofuels, these rely on the well-to-wheel analysis of the Joint Research Centre of the European Commission, Eucar and Concawe in Europe for the FQD and RED frameworks (JEC, 2020). The Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation (GREET) model of the Argonne National Laboratory feeds into the LCFS and the RFS frameworks (Argonne National Laboratory, 2020). For petroleum fuels, California's LCFS also relies on the Oil Production Greenhouse Gas Emission Estimator (OPGEE) model, used to assist regulated parties in determining carbon intensity values for crude oil used (California Air Resources Board, 2020b).[33]

A number of additional sustainability criteria have been developed do tackle concerns over the production of biofuels. They largely address competition with food crops and direct and indirect land-use change (which has an impact on the capacity of the fuels to deliver GHG emission reductions). Despite remaining challenges, such as the way to account for indirect land-use change and, more broadly, the change that using the biofuel imparts on the rest of the economy, these criteria are actively used to define eligibility of different biofuel production pathways and for financial support by public authorities. For example, in Europe, fuels produced from feedstocks with "high indirect land-use change risk" are capped below the 2019 consumption level and need to be phased out by 2023 (European Commission, 2020f).

In the case of electricity and hydrogen, well-to-tank emissions are calculated on the basis of the Greenhouse Gases, Regulated Emissions, and Energy use in Transportation (GREET) model developed by the Argonne National Laboratory for California, first looking at a set of production pathways that have already been assessed, and then eventually developing new pathways. This follows a logical approach similar to the one used for fossil fuels and biofuels, and has the advantage to rely on a single modelling framework (California Air Resources Board, 2020c).

The default choice for electricity is to rely on the average State-level carbon intensity, calculated and updated annually.[34] The mechanism also allows opting in for renewable electricity (zero tank-to-wheel and well-to-wheel emissions) or smart charging programmes (allowing the determination of carbon intensities according to hourly grid average, seasonally adjusted). These are also available for the use of electricity in electrolysers, and require a specific application, requiring the evaluation of a complete set of operational data (feedstock, energy, and material input consumption, energy production, direct facility emissions, and any indirect emission impacts), and third-party verification.

A number of predetermined carbon intensity values for hydrogen, (including hydrogen transported in gaseous or liquid form, produced via steam methane reformation or electrolysis, and from renewable or fossil-derived feedstocks) are available for reporting hydrogen produced in California and dispensed to vehicles under the LCFS, requiring approvals following a lighter pathway application process. Other pathways can also be approved, but they require more detailed data/information sharing.

California's LCFS was also designed to deploy alternative fuel infrastructure by allowing for credit generation for public DC Fast chargers and hydrogen refuelling stations even if there is no initial demand, by accounting for capacity parameters over limited time periods (five to fifteen years) (Murphy, 2020).[35]

In Europe, well-to-wheel emission characteristics are addressed through the concept of Guarantees of Origin (GoO). The RED II requires Member States or designated competent bodies to apply appropriate mechanisms to ensure that the guarantees of origin are issued, ensuring that this process complies with the CEN - EN 16325 standard. The latter specifies requirements for Guarantees of Origin of electricity from all energy sources. This standard establishes the relevant terminology and definitions, requirements for registration, issuing, transferring and cancellation in line with EU Directives. It covers also measuring methods and auditing procedures. These Guarantees of Origin contain details on the attributes of the energy source concerned (including energy produced and fuels required to do so, measured by authorised bodies), the method and the quality of its production. They may be traded and/or used for Disclosure/Labelling.

The RED II also requires that a similar approach shall be used for hydrogen, which is not yet covered in the CEN - EN 16325 standard. The inclusion of hydrogen-related production pathways is currently ongoing in the context of the CEN/CENELEC technical committee CEN/CLC/JTC 14 (energy management and energy efficiency in the framework of energy transition), working group 5 (guarantees of origin related to energy). The work shall be completed by July 2021. The focus of this work, developed in close liaison with European Commission, is the inclusion of different hydrogen production pathways (from renewables and non-renewable energies) in the CEN - EN 16325 standard. Key examples include hydrogen production from renewable electricity (through electrolysis), hydrogen production from fossil fuels (in particular natural gas), with or without carbon capture and storage, and cases where hydrogen is produced as a by-product of industrial processes.

In Europe, the CertifHy project is developing pre-normative research on a GoO scheme. The project will define the scheme's governance, as well as its processes and procedures over the entire GoO life cycle: from auditing hydrogen production plants, certification of green or low-carbon hydrogen production batches, through issuing, trading to usage of GoOs.

Priorities for regulatory development on transport energy vectors

Further work and research is needed to develop life cycle assessment of technologies using hydrogen to enhance the production of synthetic biofuels (Hannula, 2016). This extends beyond road transport to other hydrogen-based fuels, and in particular ammonia. Given the different approach used in the case of GoOs and other fuels in Europe, it will also be important to ensure consistent treatment applies to all options. This may require introducing the same flexibilities offered to electricity by the GoO to other low-carbon fuels. For example, the fact that renewable electricity can be produced in a given location and consumed elsewhere, thanks to contractual arrangements.

Hydrogen is also subject to additional considerations, given the higher losses occurring across other components of its life cycle when used for transport and distribution. This is covered by the use of GREET (which includes transport and refuelling processes) in the case of California, and not falling within the scope of GoOs. It will therefore need targeted corrections in Europe.

The energy losses from energy production and use on transport vehicles (i.e. due to fuel production, transport, distribution and conversion into mechanical work) affects the life cycle emissions of all energy vectors. The energy efficiency of energy production and use is especially important for both electricity and hydrogen, for two reasons. Firstly, these energy vectors are subject to different handling practices than those used for liquid hydrocarbons. Secondly, the end-use energy conversion technologies that they require (i.e. the powertrains: fuel cell and hydrogen on-board storage, batteries and electric motors) are also different from ICEs and gasoline or diesel fuel tanks. In particular, the grid-to-wheel efficiency of electric powertrains is better than a comparable ICE, despite variations that depend on the duty cycle and power requirements of the vehicle.

Life cycle energy efficiency is especially important in the accounting methods used to evaluate renewable energy contributions to blending mandates and fuel standards regulating carbon intensity. This is because more energy efficient powertrains (e.g. BEVs) come with a comparative disadvantage if their energy use is directly compared with less energy efficient ones (e.g. ICEs).

This is achieved through Energy Economy Ratios (EER) in the California's LCFS and through corrective efficiency factors in the FQD and RED framework in Europe. In California, EERs are set to 3.4 for electric cars, 5 for heavy electric trucks and buses, 2.5 for fuel cell cars, and 1.9 for fuel cell heavy vehicles (Murphy, 2020). In Europe, renewable electricity used on road transport vehicles counts four times its energy content towards the 14% renewable energy requirement for 2030 (and 1.5 times when used in rail transport) (European Commission, 2020f).

One additional consideration, especially important for heavy vehicles, is that there are significant differences between PHEVs and BEVs and that efficiency gaps also vary significantly across mission profiles. For example within missions with frequent stops, due to the use of ICEs in off-design working conditions and the absence of regenerative braking, unless the ICEs are electrified. As a result, the development of energy efficiency ratios or multipliers emerges as an area calling for significant improvements, likely to require the collection of data from early deployment cases and, especially in the case of Europe, the integration of hydrogen in future development of the RED and FQD legislative frameworks.

Notes

1 A national vision for a transition to a hydrogen economy in the United States dates back to 2001. It was an integrated strategic plan for the research, development, and demonstration of hydrogen and fuel cell technologies to 2011 (United States Department of Energy, 2020b). The United States conducts comprehensive efforts to overcome the technological, economic, and institutional barriers to the development of hydrogen and fuel cells. The H2@Scale initiative outlines the potential for wide-scale hydrogen production and utilisation. The initiative also funds transformational research and development of innovative hydrogen concepts that will encourage market expansion and increase the scale of hydrogen production, storage, transport, and use, including in the transport sector (GreenCarCongress, 2016; United States Department of Energy, 2020a).

2 Some of the LZEV technologies (e.g. automotive batteries) have also been considered as better suited for light vehicles, initially, and only later gain relevance for heavy vehicles. This is due to the larger light vehicle market size, seen as a feature that was more likely to enable technology demonstration, learning and economies of scale. This placed a greater time pressure to establish a broad regulatory framework, mostly focused on light vehicles, leading to a greater initial focus on applications that are most likely to use the technology, and only later an incentive to ensure that the regulatory framework is also fit for heavier applications.

3 The definitions of light- and heavy-wheeled vehicles are not harmonised globally. Key texts providing a set of definitions relevant to differentiate heavy vehicles from light vehicles are the Special Resolution (S.R.1) adopted by the Executive Committee (AC.3) of the 1998 Agreement (on global technical regulations for wheeled vehicles, equipment and parts which can be fitted and/or be used on wheeled vehicles) of the World forum for the harmonisation of vehicle regulations (WP.29) of the United Nations and the Consolidated Resolution on the Construction of Vehicles (R.E.3), applicable for UN Regulations annexed to the 1958 Agreement concerning the Adoption of Harmonized Technical United Nations Regulations for Wheeled Vehicles, Equipment and Parts which can be Fitted and/or be Used on Wheeled Vehicles and the Conditions for Reciprocal Recognition of Approvals Granted on the Basis of these United Nations Regulations (United Nations, 2020c). The discussion developed in this report focuses on vehicles of S.R.1. categories 1-2 (designed for the carriage of more than eight passengers, whether seated or standing, in addition to the driver) and 2 (power driven vehicle with four or more wheels designed and constructed primarily for the carriage of goods) with a maximum mass exceeding 3.5 t (unless otherwise specified). According to the R.E.3, these are vehicles in the categories M3 (essentially consisting of buses), N2 (essentially medium trucks) and N3 (including trucks weighting more than 12 t). Some of the vehicles in the M2 category (minibuses with a maximum mass up to 5 t) are also within the scope of the discussion.

4 Key industry examples related to vehicles include the European Association of Automotive Suppliers (CLEPA), the International Organization of Motor Vehicle Manufacturers (OICA), the International Motorcycle Manufacturers Association (IMMA), the Japan Auto Parts Industries Association (JAPIA) and the Motor and Equipment Manufacturers Association (MEMA). For charging infrastructure, key examples include consortia like CharIn and CHAdeMO.

5 UN GTRs are regulatory texts developed in the framework of the 1998 Agreement of the World forum for the harmonisation of vehicle regulations (WP.29) amongst governments that include all major automotive markets, committing themselves to implement these regulations into national legislation, when voting in favour of their establishment. These regulations require a system or an agency for market surveillance and enforcement of production compliance (Cuenot, 2020).

6 Fire hazards and harmful gasses are two other main hazards associated with REESSs.

7 Power-take-off components are additional power-consuming components added by second stage manufacturers, taking the power directly from the powertrain through a power-take-off device. This device is standardised allowing compatibility of different add-on systems on different base trucks.

8 Given the limitations surrounding development of a specific test to evaluate single cell thermal runaway, the UN GTR 20 currently requires the manufacturer to submit engineering documentation, and an initial test procedure as part of the regulation. This is to demonstrate their system design that provides a warning to occupants to allow safe egress from the vehicle in the event of a single cell thermal runaway due to internal short circuit. With this approach, manufacturers are obliged to implement and validate the countermeasures to minimise or prevent single cell thermal runaway and its propagation in the battery. Future developments aim to include a consistent test procedure to replace the interim documentation requirement. One area of open discussion are the triggering methods tor thermal runaway tests. At ISO, where the focus in on the development of test procedures, basic triggering methods at cell level have been defined but those for pack or vehicle level were still under development. The UN work also includes pass-fail criteria and suitability of tests for regulatory purposes.

9 Other topics currently listed as priorities for the update of the UN GTR 20 (foreseen for late 2020) include: water immersion, long-term fire resistance, battery rotation and vibration (an aspect that some stakeholders see as more relevant for durability performance than safety), flammability, toxicity and corrosiveness of vented gas, thermal propagation and methods of initiation in battery system, post-crash REESS safety assessment and stabilisation procedures, protection during AC and DC charging and feeding process. The ongoing activities developed to update the UN GTR 20 also include work on light electric vehicles (Cuenot, 2020).

10 Hydrogen refuelling stations excluded from the scope of UN GTR 13, and covered by the ISO 19880 standard for refuelling stations, while the fuelling station/vehicle interface falls within the scope of the ISO 17268 standard.

11 Review input from Elena Hof (NOW, Germany).

12 In the case pf pantographs, there are no commonly agreed safety concepts and power supply circuits are not interoperable with other DC charging and therefore not interoperable. This is not a major issue, since buses with pantographs are likely to be operated in a specific context, but it can have consequences on residual value.

13 The IEC 61851-23 (DC electric vehicle charging station) and 61851-24 (digital communication between a DC EV charging station and an electric vehicle for control of DC charging) standards also covers vehicle-to-grid (i.e. the exchange of information between the vehicle, the charger and beyond) and enable DC bi-directional charging. Currently, this is most relevant for CHAdeMO, since there are currently no CCS chargers and EVs for V2G in the market.

14 The protocol ISO 15118-20 that addresses the bi-directional power flow is still under review, and not yet integrated in the IEC framework.

15 In particular the possibility of EVs to deliver net savings with mission profiles capable of managing requirements on battery capacity (Cazzola et al., 2018).

16 Other topics being developed include a protocol for the management of electric vehicle charging and discharging infrastructures (future IEC 63110), interoperability and safety of dynamic wireless power transfer for EVs (future IEC 63243). Future work of the IEC/TC 69 is foreseen for the cyber security framework of EV charging and the management of distributed energy storage systems for EVs capable to perform smart charging and vehicle to grid (V2G) functions, managed by a common aggregator (Delaballe, 2020).

17 Automated charging may also have impacts on the requirements on contact location, likely to differ between different vehicle categories, even if functional requirements can be common. This includes the case of pantographs, both relevant for buses and electric road systems, as well as charging automation (via conductive inlets or underbody connection), eventually paired with automatic parking.

18 Other priorities include functional requirements for conductive charging (including vehicle-to-grid applications), methods for the determination of charging time, compatibility markers for EVs and chargers, interoperability and automated electrified vehicles.

19 This is similar to and inspired by the ISO 19880-1 standard and includes filling protocols, as already mentioned.

20 This is an issue hampered by limited availability of suitable metering equipment and that was addressed by a weight-based approach in Japan. The same approach has already been successfully adopted in California, and it is under development in Europe, where the project METROHYVE is dealing with the hydrogen metering issue in fuelling stations.

21 Review input from Elena Hof (NOW, Germany).

22 Review input from Vincent Mattelaer, Toyota.

23 As a result, hydrogen refuelling stations run the risk to use inaccurate techniques for sampling (with potential contamination issues), inappropriate sampling devices (for example stainless steel) or incorrect sampling cylinders that all may impact the outcome of the sampling.

24 Key examples include: the Directorate for the Internal Market, Industry, Entrepreneurship and SMEs and the Joint Research Centre of the European Commission, the Ministry of Industry and Information Technology (MIIT) in China and the China Automotive Technology and Research Center (CATARC), the Ministry of Land, Infrastructure, Transport and Tourism (MLIT) in Japan, the Ministry of Land, Infrastructure and Transport (MOLIT) in Korea and the Environmental Protection Agency (EPA) and the National Highway Traffic Safety Administration in (NHTSA) the United States.

25 China also has a complementary certification pathway using simulation, for the so called variants.

26 For medium and heavy engines certified as tractor engines, CO_2 emissions are measured using a steady-state cycle. For medium and heavy engines certified as both tractor and vocational engines, the steady-state cycle is combined with a transient cycle (sometimes referred to as the FTP engine cycle). All other engines are tested based on the transient cycle (United States Environmental Protection Agency, 2020b).

27 In the United States, although GEM doesn't directly model these powertrains, hybrids and PHEV can be given credit in GEM using the powertrain test procedure (CFR 40, part 1037.550) to generate the fuel maps, rather than the engine fuel mapping procedures.

28 Carbon leakage refers to the situation that may occur if, for reasons of costs related to climate policies, businesses were to transfer production to other countries with less strict emission constraints (European Commission, 2020a)..

29 Despite the focus given here to carbon intensities, it is important to bear in mind that electricity and hydrogen are also subject to life cycle emissions of air pollutants occurring in the tank-to-wheel and other upstream phases of their production, like all other fuels. Other emissions that have relevance from a life cycle assessment perspective, but are not discussed here, relate to the material and processes needed to manufacture and operate the facilities producing electricity and hydrogen.

30 Cap-and-trade regulatory schemes on GHG emissions, like the European Emission Trading Scheme, generally exclude energy end-use in buildings and transport and focus on the energy transformation and industrial sectors. Nevertheless, they remain relevant from transport because they have the capacity to affect carbon intensities of transport energy vectors, falling within the scope of emissions occurring in extractive industries and energy transformation – including refining and electricity generation.

31 The U.S. Environmental Protection Agency (EPA) also proposed regulatory changes to allow gasoline blended with up to 15% ethanol (E15) to take advantage of the 1-psi Reid Vapor Pressure (RVP) waiver for the summer months that has historically been applied only to E10.

32 In Europe, calculation methods related with the FQD and RED frameworks are laid out in Council Directive (EU) 2015/652.

33 In Europe, upstream characteristics of the fuels are not accounted for in the FQD framework, but the regulation includes reporting obligations on origin of crudes used to make automotive fuels and of imported automotive fuels. Due to the fact that the Directive addresses Member States and not industry directly (as in the case of Regulations), rules developed by each member state are not harmonised.

34 Electricity is characterised by different carbon intensities across different times, depending on the primary energy sources used of its generation, an issue that is further complicated by a broad range of end-uses and power draws.

35 California has also a requirement that 33% of hydrogen fuel must come from renewable sources (Murphy, 2020).

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Regulations and Standards for Clean Trucks and Buses

This report reviews progress on technical standards for heavy vehicles that could enable trucks and buses with zero or near-zero emissions. It focuses on plug-in and fuel cell electric vehicles that use technologies at the forefront of green and inclusive economic development. It includes information on technical standards on charging and refueling infrastructure, and identifies remaining barriers and opportunities for their future development. The report offers valuable insights for all stakeholders involved in the transition to carbon-free mobility and clean energy.

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