Future Regulatory, Market and Technology Trends in the Global Passenger Car and Commercial Vehicle Sectors

Key challenges to achieving net zero emissions for road vehicles

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The world is at the start of an energy revolution: the biggest energy transformation since the Industrial Revolution. The growing recognition that the carbon dioxide emissions associated with the combustion of fossil fuels leads to a dramatic increase in global temperatures is driving the need to implement strategies to reduce the carbon footprint across power- and energy-hungry sectors such as power generation, domestic heating, industrial processes and transportation. This article looks at the moves that the global passenger car and commercial vehicle segments will need to make to minimise the CO\textsubscript{2} and greenhouse gas (GHG) emissions of the sector, which is one of the largest contributors to the global CO\textsubscript{2} inventory today. A number of countries have already pledged to meet net zero GHG emissions by 2050, and more are set to follow, so this article also considers what is necessary for the ground transportation sector to hit net zero.

1. Introduction

Global car and truck manufacturers, along with their supply chains, have made huge steps to minimise vehicular emissions since the advent of the internal combustion engine (ICE). Of particular note are the criteria pollutant emissions regulations, which have focused on reducing the tailpipe carbon monoxide, hydrocarbons, nitrogen oxides (NOx) and particulate matter (PM) emissions from the global vehicle fleet. For example, since the first European regulations were introduced in the early 1990s, the permitted NOx emissions of cars have dropped by almost a factor of 15, which has been enabled by close collaboration between the car manufacturers and the substrate and catalyst suppliers. More recently, the focus has shifted to CO\textsubscript{2} emissions, as governments and regulators work towards the implementation of measures to enable the Paris Agreement climate change commitments to be met (1). Indeed, the latest view of the Intergovernmental Panel on Climate Change (IPCC) is that there are significant benefits in targeting a maximum temperature increase of 1.5°C over pre-industrial levels, rather than the 2°C Paris Agreement target, and this 1.5°C target essentially means that CO\textsubscript{2} emissions need to reduce to net zero globally by 2050 (2). This is an extremely challenging target, with massive implications for all energy-hungry sectors such as transportation, which currently accounts for around 24% of global CO\textsubscript{2} emissions (3). Moving the transport segment to net zero by 2050 means that only vehicles with zero CO\textsubscript{2} emissions can be sold from 2040 or earlier, to avoid legacy fleet emissions, since cars, buses and trucks typically stay in use for 10 years or more. Indeed, the recommendation of the Committee on Climate Change (CCC), the UK Government’s independent advisor on climate change, is that introduction date of the ban on vehicles powered by ICE should be brought forward from 2040 (which was the original plan) to 2035 “at the latest” or, more preferably, 2030 (4). Currently, around 1% of new passenger car sales globally do not have any tailpipe CO\textsubscript{2} emissions (that is, they are regarded as zero
biofuels are often only a marginal GHG emission improvement over fossil fuels, and in some cases actually have higher emissions (5). Sustainable advanced biofuels are based on wastes and residues, so their potential contribution to fuel requirements is finite. The industries that typically contribute the most to advanced biofuels are agriculture and the food industry (through residues such as organic waste sludges, manure or straw) and forestry industries, especially in the Nordics (from saw and pulp mills). Biomass resources are also already well utilised, so if the current consumption in other areas (for example, paper production) is assumed to continue, the maximum biofuel production would be able to supply around 8.5% of all road transport in the EU (5). However, the aviation and marine sectors are already making their case to use these biofuels, so while they may make a contribution to reducing road transport CO₂ in the short term (via blending into current hydrocarbon fuels), it is not expected that they will make a major contribution in the medium term and beyond.

For e-fuels, the first step in their production is to generate hydrogen via water electrolysis using renewable electricity. Hydrogen is then combined with CO₂ to form hydrocarbon fuels, with the CO₂ coming from, for example, industrial or biogenic sources, or from the direct capture of CO₂ from the air (direct air capture (DAC)). At the present time, industrial CO₂ emissions are regarded as ‘waste’, but capturing this CO₂, converting it into a hydrocarbon fuel, and then combusting it still leads to its release into the environment, and in the medium to long term it is expected that the CO₂ sources will either need to be from DAC or from ‘green’ sources such as biomass combustion.

The technologies to convert CO₂ and H₂ into both synthetic natural gas (SNG) and methanol at scale are known, and it can be expected that processes at early technology readiness level (TRL) currently under development (for example, direct electrochemical synthesis) will get more attention should there be a market. To produce e-fuels the SNG and methanol can undergo further conversion, for example to dimethyl ether or via the methanol-to-gasoline process to gasoline. However, not all pathways to the higher value e-fuels are commercially viable, and indeed the most attractive product to make, kerosene, is not accessible today as there is no large scale implementation of the reverse water gas shift reaction, which converts CO₂ into CO, which is the active carbon species in the Fischer-Tropsch reaction. Today the process is used to convert
gas and coal to liquid fuels, but there are several projects focusing on the conversion of biomass and waste to liquid fuels.

The attraction of e-fuels in the form of the hydrocarbon fuels used today is that they can be a direct drop-in for current fuels, using the same distribution network and being burned in the same kind of engines that we have today. In some applications, such as aviation and marine, their use seems likely, as discussed elsewhere in this edition of Johnson Matthey Technology Review, since liquid fuels are expected to be required for a substantial period of time in these areas due to challenges with the use of battery or hydrogen fuel cells in such applications. For ground transportation, however, their widespread use seems less likely for several reasons, including:

- cost – such fuels will be more expensive than renewable-derived hydrogen (which itself will be more expensive than the renewable electricity used to generate it), since they will use such hydrogen as a feedstock and then process it further. So the lowest cost ‘fuel’ for future ground transport vehicles will be renewable electricity for BEVs, followed by H₂ for FCEVs, and then e-fuels for ICES
- energy efficiency – a recent publication from Shell (6) concluded that the efficiency of e-fuel production (starting from renewable energy generation and using DAC as the source of CO₂), combined with the relatively low efficiency of the use of such fuel in an ICE, leads to an overall ‘well-to-wheels’ energy efficiency of around 12%. In comparison, the same study quoted the well-to-wheels efficiency of a BEV to be around 72%, and that of a FCEV around 37%

- local emissions – despite the great strides made by the vehicle makers and emission control catalyst companies, burning hydrocarbon fuels in an ICE leads to tailpipe emissions of CO, unburned hydrocarbons, NOx and PM; all of which can be avoided by the electrification of the powertrain using either electricity or hydrogen.

So, while it is expected that biofuels and e-fuels will play a significant role in the aviation and marine areas, the focus of this article is on ground transportation, where BEVs and FCEVs are expected to be the major technologies. This is consistent with, for example, the views of Martin Daum, Member of the Board of Management of Daimler AG, responsible for trucks and buses: “Truly CO₂-neutral transport only works with battery-electric or hydrogen-based drive” (7).

2. Tailpipe Emission Regulations

The regulations in the passenger car and commercial vehicle sectors focus on emissions from the tailpipe, and historically the main focus has been on criteria pollutants, which have enabled major improvements in urban air quality to be made. The focus is now shifting to CO₂, and Figure 1 shows the current and incoming CO₂ regulations for cars in various countries and regions around the world (8), illustrating the substantial reductions required going forward.

The European regulations for 2025 and 2030 require reductions of 15% and 37.5% respectively over the 2021 legislation. These regulations are intended to continue to drive the decarbonisation of the automotive industry, and the fleet average

![Fig. 1. Historical and future global CO₂ passenger car regulations. Values normalised to the New European Driving Cycle (NEDC) (8)](https://doi.org/10.1595/205651320X15898840921326)
CO₂ emissions required in 2030 will require extensive electrification of the fleet. Indeed, Herbert Diess, CEO of the VW Group, has stated that these 2030 regulations will require at least 40% of VW’s European sales to be electric vehicles (BEV and plug-in hybrid electric vehicles (PHEV)) in 2030 (9).

Legislation on CO₂ and GHG is also tightening in the commercial vehicle sector, with the next set of European regulations requiring a 15% drop in CO₂ emissions from today by 2025, and a 30% reduction from today in 2030. This 2030 target is expected to lead to significant hybridisation of the commercial vehicle fleet, along with some completely electrified vehicle sales. Trucks, buses and coaches are responsible for about a quarter of CO₂ emissions from road transport in the EU and for some 6% of total EU emissions (10), so introducing low and zero emission vehicles in this sector is critical to support global moves towards net zero.

The electrification of the bus market is already underway, with over 400,000 battery electric buses in use in China today (out of around 425,000 BEV buses worldwide). Some Chinese cities, such as Shenzhen, have completely transitioned to battery-powered buses, with around 16,500 such vehicles on the road. Many other cities worldwide are committed to moving away from diesel and towards zero emission buses in the coming years. For example, 13 cities have signed the C40 Fossil Fuel-Free Streets Declaration (11), and will procure only zero emission buses from 2025. These are: Auckland, Barcelona, Cape Town, Copenhagen, London, Los Angeles, Mexico City, Milan, Paris, Quito, Rome, Seattle and Vancouver. London has committed to increase its BEV fleet from 120 to 300 by 2020, and in Paris 80% of the fleet will be e-buses by 2025. Oslo has gone further, and will have fossil fuel-free public transport by 2020, while in the Netherlands all new buses will be zero emission by 2025, with the whole fleet being all-electric by 2030. These commitments will lead to improved urban air quality and a reduced CO₂ footprint, as long as the electricity used to charge the buses is from low carbon sources, as discussed later.

California often takes a mandate-based approach to regulations, in order to drive the development and initial implementation of new technologies. Within the commercial vehicle sector they are proposing an Advanced Clean Trucks mandate, which will require original equipment manufacturers (OEMs) with more than 500 truck sales in California to sell an increasing proportion of zero emission trucks, starting in 2024, per the schedule outlined in Table I. The intention of the California Air Resources Board (CARB) is to accelerate the first wave of zero-emission trucks, which are seen as essential if net zero targets are to be met, particularly since the commercial vehicle market is widely regarded as being significantly more difficult to decarbonise than the passenger car fleet. The schedule outlined in Table I will lead to a ZEV truck fleet of around 100,000 vehicles in California’s roads in 2030, rising to around 300,000 in 2035.

**Table I Proposed ZEV Percentage Schedule: Overview of the Proposed Californian Advanced Clean Trucks Regulation**

<table>
<thead>
<tr>
<th>Model year</th>
<th>Class 2B–3 8501–14,000 lbs</th>
<th>Class 4–8 Vocational 14,001 lbs and greater</th>
<th>Class 7–8 Tractor 26,001 lbs and greater</th>
</tr>
</thead>
<tbody>
<tr>
<td>2024</td>
<td>5%</td>
<td>9%</td>
<td>5%</td>
</tr>
<tr>
<td>2025</td>
<td>7%</td>
<td>11%</td>
<td>7%</td>
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<tr>
<td>2026</td>
<td>10%</td>
<td>13%</td>
<td>10%</td>
</tr>
<tr>
<td>2027</td>
<td>15%</td>
<td>20%</td>
<td>15%</td>
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<td>20%</td>
<td>30%</td>
<td>20%</td>
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<tr>
<td>2035</td>
<td>55%</td>
<td>75%</td>
<td>40%</td>
</tr>
</tbody>
</table>
3. Life Cycle Carbon Dioxide Emissions

Of course, tailpipe emissions are only part of the CO₂ story, since the emissions associated with the manufacture of the vehicle and the fuel also need to be considered in any holistic analysis. For BEVs the manufacture of the battery generates significant levels of CO₂, estimated to be around 175 kg CO₂ kWh⁻¹ of battery capacity (12), and with vehicle batteries typically having between 30 kWh and 100 kWh of stored energy, this leads to upstream emissions of 5–17.5 tonnes of CO₂ per battery pack. In addition, the electricity used to charge the battery has associated CO₂ emissions, unless it is generated from renewable sources such as wind or solar power. For example, UK electricity currently has a carbon intensity of around 200 g CO₂ kWh⁻¹ (13), which is below the average of European Union countries, while Norway (extensive use of renewable hydroelectric power) and France (predominantly nuclear power) have much lower carbon signatures.

The hydrogen used to power FCEVs is typically generated in one of two ways: either through electrolysis (in which an electric current is used to split water into hydrogen and oxygen) or the steam reforming of methane. The former route is, therefore, subject to the same CO₂ emission challenges (and opportunities) as the BEV, while the latter route generates relatively high levels of CO₂ which in future will need to be abated using carbon capture utilisation and storage (CCUS) technology, in which the CO₂ generated by the process is captured with high efficiency (which can be around 95%) and then either stored (for example, in depleted oil and gas fields) or used for other purposes (for example, to make chemicals).

Therefore, a full CO₂ life cycle analysis (LCA) of BEVs and FCEVs is required to paint a true picture of the carbon intensity of these vehicles. Some LCA studies are now being published and one of the most thorough is the one carried out by the International Council on Clean Transportation (12) who calculated the g km⁻¹ CO₂ emissions over the life of the Nissan Leaf BEV (with 30 kWh battery pack, lasting for the life of the vehicle), which they assumed would cover 150,000 km in its lifetime, and compared it to the average and the lowest emitting European cars powered by ICEs. In addition, Toyota have analysed the LCA of a FCEV (14), and these values have been updated for this paper based on Johnson Matthey’s knowledge of the CO₂ emissions when making hydrogen from CH₄ (with and without carbon capture and storage (CCS)).

Figure 2 shows the LCA CO₂ from the European car with average CO₂ emissions in 2017, along with the most fuel efficient ICE-based car in that year (which was in fact a hybrid), together with a BEV being operated on electricity with the EU average CO₂ footprint (the UK’s level is a little...
lower than this average), and that in Norway, whose extensive use of hydroelectric power reduces the CO$_2$ emissions during electricity generation to zero. The FCEV LCA is also shown, based on hydrogen generated from steam methane reforming (SMR) with and without CCUS, and based on electrolysis using Norwegian electricity. It is clear that BEVs and FCEVs have significantly lower CO$_2$ LCA than ICE-based cars today, and this gap will increase further as the carbon footprint of electricity generation continues to drop (see Section 4). (Note that this analysis does not include the recycling or disposal of the vehicles and their components).

A very recent BEV vs. ICE life cycle analysis subdivided passenger car GHG emissions into use-phase emissions (from driving the car), and production of all components (including, for example, emissions during mining of raw materials) and end-of-life emissions (15). This study concluded that driving a BEV is already lower in life cycle CO$_2$ emissions than petrol cars in 95% of the world. The only exceptions are countries such as Poland, where the electricity network is still mostly based on coal-fired power generation. In countries with a heavily decarbonised power system, such as Sweden and France which have large amounts of renewable and nuclear generating capacity, the average lifetime emissions from BEVs are up to 70% lower than petrol cars. In the UK, which is rapidly phasing out coal but still has a reasonable amount of gas-fired power plants, emissions are around 30% lower. The authors also point out that the advantages of BEVs will continue to grow, as power systems around the world become less carbon-intensive. The study projected that by 2050 half of the cars on the roads could be BEVs, leading to a reduction in global CO$_2$ emissions of up to 1.5 billion tonnes per year, which is the same as the total current CO$_2$ emissions of Russia.

This focus on LCA is already having a profound impact in the automotive sector. For example, the incoming VW ID.3 BEV is the first vehicle in the company’s history to be built with a CO$_2$ neutral balance sheet, covering the supply chain (for example, only green energy is used in the production of the battery cells), production (using only green energy at the Zwickau, Germany, manufacturing plant), use phase and recycling, with any currently unavoidable CO$_2$ emissions being offset by investments in climate protection projects (16).

4. Net Zero Carbon Dioxide and Greenhouse Gas Commitments and Their Implications

Governments, states and regions are proposing, and in some cases (such as the UK) committing to, net zero GHG or CO$_2$ emission targets over the coming years. Indeed, at the time of writing two countries (Bhutan and Suriname) are already carbon neutral, 15 countries have set defined dates to become net zero, and other countries and regions, such as Germany and the EU, are discussing when to implement such a target. Within Europe, Norway plans to become net zero by 2030, Sweden by 2045 and Denmark, France and the UK by 2050. The implications of this are clear: road transport needs to decarbonise rapidly. As outlined above, a 2050 net zero target means that sales of new ICE powered vehicles need to stop by 2040 at the very latest, and preferably at some point during the 2030s, since cars and trucks are often on the road for 10–15 years or more before being scrapped.

This will be a substantial undertaking, requiring all new cars, trucks and buses to be powered by either batteries or hydrogen fuel cells on this timescale. As discussed above, this move to zero (tailpipe) CO$_2$ or GHG vehicles is only part of the challenge. The electricity used to charge the batteries, and the hydrogen used in the fuel cell vehicles, must also be generated in a very low or zero carbon manner, such as through renewable electricity or advanced CH$_4$ reforming with CCUS.

Many countries are driving down the CO$_2$ emissions from power generation. For example, the UK almost halved the carbon footprint of its electricity generation between 2013 and 2017, and one future projected UK pathway to 2050 is shown in Figure 3, from analysis for the National Grid’s Future Energy Scenarios 2019 document (17). This “Two Degrees” scenario foresees significant increases in renewable use, along with a large reduction in natural gas use and the cessation of coal-fired power generation, leading to a reduction in carbon intensity from 120 g CO$_2$ kWh$^{-1}$ in 2019, to just 14 g CO$_2$ kWh$^{-1}$ in 2050. This scenario is consistent with the UK achieving the 2050 decarbonisation target with large-scale centralised solutions. Net zero targets will demand the decarbonisation of road transport (and other forms of transport), and will require strong governmental and regional policies to drive and support the uptake of zero
emission vehicles. Extensive public charging and hydrogen refuelling infrastructure will be necessary, and the vehicles must be attractive and affordable options, with features that suit today’s and tomorrow’s lifestyles and transport needs.

The passenger car sector is largely driven by price, convenience and lifestyle: will my vehicle get me comfortably from A to B; can it carry the things I need to take with me; is it a sensible financial choice, in terms of purchase price, fuel price and overall cost of ownership (including likely resale value); and can I easily and conveniently refuel the car after driving the kind of distances that matter to me?

The main questions asked in the commercial vehicle market relate to how this purchase will help the business. The total cost of ownership (TCO) is a critical make-or-break calculation in this sector, as is the requirement for a very high level of vehicle uptime; so a long driving range and rapid refuelling are important here, as is the total load that can be carried by the vehicle.

Given the very different requirements in the two segments, they are considered separately in the subsequent analysis of critical drivers.

5. Passenger Car Market

5.1 Customer Pull

Deloitte recently carried out a survey (18) looking to identify and rank the key consumer concerns that prevent people buying BEVs today. The results are shown in Figure 4, and highlight the critical importance of vehicle price, driving range and access to charging infrastructure. Recent research in the USA shows that, among those who have considered buying an electric vehicle, but have not, the lack of charging stations is the main reason why (19). This work also found that private charging stations are just as important: in the USA nearly 80% of electric vehicle owners charge their vehicles at home, and almost 15% at work, with the rest at public stations.

5.2 Vehicle Price, Ownership Cost, Range and Fuelling Infrastructure

Vehicle range and fuelling infrastructure can be considered together, since, particularly for BEVs, the further the driving range between recharging, the less concern there is about not being able to find a suitable charge point. However, Mark Reuss,
GM President, believes that: “Just as demand for gas mileage doesn’t go down when there are more gas stations, demand for better range won’t ease even as charging infrastructure improves. People will still want to drive as long as possible between charges” (19). The BEV price is also strongly linked to its range, since, for a given battery chemistry, the vehicle range depends upon the size (capacity) of the battery (amongst other things), which impacts its cost.

5.2.1 Vehicle Price and Ownership Cost

Starting with the vehicle price and operating cost, Bloomberg New Energy Finance have looked at the trend in battery pack pricing, which shows a strong rate of reduction from around US$1000 kWh⁻¹ in 2010 to US$200 kWh⁻¹ in 2017 (20) and then US$156 kWh⁻¹ in 2019, as shown in Figure 5.
There is a rule of thumb in the BEV industry that when battery pack prices reach around US$100 kWh\(^{-1}\), which BNEF forecast will be around 2024, the price of a BEV will be approximately the same as a similar ICE-powered vehicle. Therefore, the price of BEVs is going in the right direction, and at a good rate. FCEVs are relatively expensive at present (for example, the Toyota Mirai retails for around US$58,500) since only a few thousand FCEVs are sold annually, so mass production practices and supply chain economies of scale have not yet been brought to bear. It is clear that the prices of both BEVs and FCEVs will reduce significantly going forward, as more of them are made and sold.

The operating costs of ZEVs are also important, and here there is more data for BEVs than for FCEVs. A study in the USA found that most BEV owners report their average cost of operation to be about one-third of that paid by the owners of gasoline-powered cars (19). And while most private owners tend to pay more attention to the initial vehicle purchase price, fleet owners focus strongly on lifetime costs (maintenance, fuel and ancillaries) because they want to know exactly how much they will be spending over the time they own the vehicle. BEVs, because of their low fuel (electricity) costs and relative simplicity (uncomplicated motors, fewer moving parts) are cheaper to own and maintain than their conventional, ICE-powered counterparts. A recent report from New York City’s fleet management agency analysed fuel and maintenance costs for 1893 vehicles of its 9196 light-passenger vehicles. It found servicing costs with all-electric vehicle models were significantly lower than for gasoline, hybrid, and plug-in hybrid models (21). Figure 6 summarises the nine year TCO of a typical BEV, hybrid and gasoline car from their fleet, which contains 149 Nissan Leaf, 1131 Toyota Prius and 62 Ford Fusion vehicles. The study found that, despite the higher initial purchase price of the BEV and its associated charger, its TCO was slightly lower than the hybrid electric vehicles (HEV) and significantly below that of the gasoline vehicle, due to its much lower fuel and maintenance costs. In fact, in this study, the operating costs of the BEV were just 22% those of the gasoline car.

There are fewer studies on FCEV operating costs, but the expectation is that the maintenance costs will be similar to those of BEVs, since the electric drivetrains are very similar. One critical parameter in the TCO calculation for BEVs and FCEVs is the cost of the electricity and the hydrogen. Electricity costs vary significantly around the world, and even across Europe, where, for example, domestic electricity costs €0.17 kWh\(^{-1}\) in the UK and €0.30 kWh\(^{-1}\) in Germany. These differences significantly impact the operating cost of BEVs as a function of geographical location.

Hydrogen is relatively expensive today, around US$10 kg\(^{-1}\) at the pump in the US and €10 kg\(^{-1}\) in Europe, with 1 kg being typically enough for around 70–80 miles of driving. Figure 7 shows the current production cost of hydrogen via various routes, with the cost from steam reforming of natural gas with carbon capture and storage (to ensure the hydrogen is low carbon) falling in the range US$1.50–2.80 kg\(^{-1}\), with the production cost of hydrogen from renewables being much higher, from US$3.00–7.50 kg\(^{-1}\) (22). A recent report from Bloomberg New Energy Finance projects that renewable hydrogen costs in advantaged areas (for example those with plentiful sunshine for solar power generation) may fall to as low as US$1.40 kg\(^{-1}\) by

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**Figure 6.** Total cost of ownership of BEVs, HEVs and gasoline cars operated by New York City’s fleet management agency over nine years (21)

**Figure 7.** Production cost of hydrogen via various routes (22)
2030 (23). While the ultimate net zero compliant target is to make ‘green’, zero carbon hydrogen, i.e. using electrolysis powered by renewable electricity, in many parts of the world ‘blue’ hydrogen, made using advanced CH₄ reforming with CCUS, will be significantly cheaper in the short to medium term, making it a more economically attractive option, while still having a low carbon footprint. To manage the costs associated with the energy transition it is likely that blue hydrogen will be used extensively while the cost of green hydrogen comes down to an economically acceptable level. For example, the Committee on Climate Change’s Net Zero report for the UK Government forecasts that around 80% of the UK’s hydrogen will be blue in 2050, with the 20% balance being green (4).

Taking an intermediate hydrogen production cost of US$2 kg⁻¹ would likely result in a price at the pump of around US$4.50 kg⁻¹ (€4.10 kg⁻¹ at November 2019 exchange rates) on the 2030 timescale, once the costs of compression, storage and distribution of hydrogen at scale are added. Based on these assumptions, Table II shows the fuel cost of cars powered by a gasoline engine, a battery and a fuel cell travelling 10,000 miles a year in the UK and Germany, in 2020 and 2030. Table II shows that the BEV has the lowest annual fuel cost in 2020, in both the UK and Germany, with the FCEV second and the gasoline car having the highest fuel expenditure. Indeed, the BEV has almost half the fuel cost of the gasoline car in Germany, and around 30% of the gasoline fuel cost in the UK. In 2030, the ranking of fuel cost remains the same in the UK (gasoline > FCEV > BEV), but the FCEV hydrogen cost is much closer to the BEV charging cost as a consequence of the projected reduction in hydrogen price on this timeframe. In contrast, in 2030 in Germany the FCEV has the lowest annual fuel cost, due to the anticipated reduction in hydrogen price, and because domestic electricity is significantly more expensive in Germany than in the UK. Of course, electricity prices will change in future, as the grids evolve, but this analysis gives a directional perspective based on today’s prices.

It is expected that governments will tax electricity and hydrogen as the proportion of BEVs and FCEVs on the road increases, to cover the lost revenues from diesel and gasoline taxation, so projections on the future TCO of BEVs and FCEVs are complicated by this.

### 5.2.2 Vehicle Driving Range

In 2018 the average BEV could travel around 225 km (140 miles) between charges; as we move into the early years of the 2020s this will increase to around 400 km (250 miles) or so by a combination of higher energy density battery materials and the use of larger batteries (see for example Figure 8). This increased range is expected to reduce BEV range anxiety for people considering a BEV purchase.

As discussed elsewhere in this journal, one of the main development targets of ongoing battery materials research is to increase the energy density of the cathode, to increase vehicle range. Over the next few years the industry will see moves from nickel manganese cobalt (NMC) 532 (i.e. around 50% Ni, 30% Mn and 20% Co) and NMC622 to NMC811 – each new generation increases the Ni content of the cathode, which is the component principally responsible for the energy density at current voltage windows. We will also see further evolution in the nickel cobalt aluminium (NCA) battery chemistries used by Tesla and others. NMC811 also has a significantly reduced level of Co. The trend to low Co loadings is partly driven by concerns about Co availability, sustainability and future pricing, and also by the need to continue to increase the Ni content to enable higher energy density. Beyond this, the widespread introduction

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**Table II Estimated Annual Fuel Cost of Cars Powered by a Gasoline Engine, a Battery and a Fuel Cell in the UK and Germany, in 2020 and 2030**

<table>
<thead>
<tr>
<th>Application</th>
<th>UK 2020</th>
<th>UK 2030</th>
<th>Germany 2020</th>
<th>Germany 2030</th>
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</thead>
<tbody>
<tr>
<td>Gasoline car</td>
<td>€1540</td>
<td>€1386</td>
<td>€1465</td>
<td>€1318</td>
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<tr>
<td>Battery electric car</td>
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<td>€720</td>
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<tr>
<td>Fuel cell car</td>
<td>€1250</td>
<td>€482</td>
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<td>€482</td>
</tr>
</tbody>
</table>

Notes: Gasoline car fuel economy 45 miles per gallon (mpg) in 2020, 50 mpg in 2030; November 2019 fuel prices in both cases BEV assumed to charge on domestic electricity, which will be cheaper than charging using the public infrastructure
Current domestic electricity prices: €0.17 kWh⁻¹ in UK, €0.30 kWh⁻¹ in Germany; same prices used for 2020 and 2030
H₂ price: €10 kg⁻¹ in 2020; €4.10 kg⁻¹ in 2030
BEV efficiency of 0.26 kWh mile⁻¹ in 2020, and 0.24 kWh mile⁻¹ in 2030
FCEV efficiency 80 miles kg⁻¹ H₂ in 2020, 85 miles kg⁻¹ H₂ in 2030

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of solid-state battery technology is expected as we move into the 2030s, which could result in a significant further increase in vehicle range for a given battery weight and volume, as well as potentially increasing battery safety since the solid state electrolytes will not be flammable, unlike the current organic liquid based electrolytes.

FCEVs can already travel around 400 miles between refuelling (24), and this can be increased by increasing the size of the on-board hydrogen tank, and by the expected increases in vehicle and fuel cell efficiency going forward. However, the hydrogen refuelling infrastructure is less well developed than the charging infrastructure, which is one of the factors currently limiting the penetration of FCEVs.

5.2.3 Vehicle Fuelling and Charging Infrastructure

The development of the BEV charging infrastructure is already well underway, with over 175,000 public charge points in place across Europe in November 2019 (see Figure 9) (25) including more than 21,000 in the UK. The expectation is that most passenger car charging will occur overnight at home and at the workplace (at slow charging rate), which limits the requirement on the number of public chargepoints. The EU Alternative Fuels Infrastructure directive sets a target of one public charging point for every 10 EVs, which implies that a Net Zero Europe would need up to around 20 million public chargepoints, assuming a similar size vehicle parc as that today (for example the natural growth in the fleet from now to 2050 is balanced by an increase in shared mobility), and that 80% of EU passengers cars are powered by batteries, with the balance being FCEVs. From the 2018 number in Figure 9 below (the last full year for which there is data), this would represent a Compound Annual Growth Rate (CAGR) of around 16.8% between 2018 and 2050. Angela Merkel, the German Chancellor, recently said that she wants to have one million public charge points in Germany by 2030, up from around 21,000 today (this would represent a CAGR of around 38%). Based on the EU Directive target, this would be enough to charge around 10 million vehicles, a significant proportion of the number of cars on Germany’s roads (which is around 47 million today).

On the FCEV side, a number of governments have set formal targets for both the number of FCEVs on the road and the number of hydrogen refuelling stations (HRS) to enable this (see Table III). For example, China intends to have over one million FCEVs on its roads in 2030, supported by over 1000 HRSs. Last year Chinese FCEV subsidies totalled US$12.4 billion (26), and China is cutting

Fig. 8. Estimated real-world driving ranges of incoming BEVs. Quoted NEDC and World Harmonised Light Vehicle Test Procedure (WLTP) ranges have been converted to estimated real-world ranges using: NEDC to real-world factor 0.6; WLTP to real-world factor 0.77. Source: public disclosures and analysis by author
subsidies to BEVs and PHEVs to focus on developing other clean options such as hydrogen. In addition, China has deployed more renewable energy than any other country but its utilisation is relatively low, opening the possibility of using some of this electricity to generate hydrogen via electrolysis, to drive elements of a hydrogen-based economy, including FCEV-based transportation.

Both Japan and Korea also have broad government-driven strategies based on hydrogen, to reduce their heavy reliance on imported oil, as well as to meet their GHG reduction commitments and generate further growth opportunities for their automotive industries. The three FCEV leaders today are Toyota, Honda and Hyundai.

South Korea’s Ministry of Trade, Industry, and Energy announced in June 2018 that along with private entities it would invest US$2.2 billion through public-private partnerships to speed up development of the FCEV ecosystem in the country by 2022 (27). The government plans to use subsidies to reduce the cost of FCEVs to around US$25,000 by 2025, around half the current price, and to reduce the market price of hydrogen to US$2.50 kg\(^{-1}\). In addition, Hyundai has announced plans to invest US$6.5 billion in FCEV production facilities and related research and development activities by 2030 to produce 500,000 FCEVs in 2030 (28). The South Korean government aims to generate US$36 billion worth of added value a

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**Table III Government and State Targets for the Size of the FCEV Fleet and Number of Hydrogen Refuelling Stations**

<table>
<thead>
<tr>
<th>Country or state and target count</th>
<th>Today</th>
<th>2020</th>
<th>2025</th>
<th>2030</th>
</tr>
</thead>
<tbody>
<tr>
<td>Japan HRS</td>
<td>90</td>
<td>160</td>
<td>320</td>
<td>900</td>
</tr>
<tr>
<td>Japan FCEVs</td>
<td>2000</td>
<td>40,000</td>
<td>200,000</td>
<td>800,000</td>
</tr>
<tr>
<td>China HRS</td>
<td>30</td>
<td>&gt;100</td>
<td>&gt;300</td>
<td>&gt;1000</td>
</tr>
<tr>
<td>China FCEVs</td>
<td>1500</td>
<td>5000</td>
<td>50,000</td>
<td>&gt;1,000,000</td>
</tr>
<tr>
<td>South Korea HRS</td>
<td>20</td>
<td>310 (2022)</td>
<td>–</td>
<td>520</td>
</tr>
<tr>
<td>South Korea FCEVs</td>
<td>–</td>
<td>16,000</td>
<td>–</td>
<td>1,800,000</td>
</tr>
<tr>
<td>California HRS</td>
<td>35</td>
<td>94</td>
<td>200</td>
<td>–</td>
</tr>
<tr>
<td>California FCEVs</td>
<td>–</td>
<td>23,000 (2021)</td>
<td>47,200 (2024)</td>
<td>–</td>
</tr>
<tr>
<td>France HRS</td>
<td>20</td>
<td>–</td>
<td>100 (2023)</td>
<td>700 (2028)</td>
</tr>
<tr>
<td>France FCEVs</td>
<td>–</td>
<td>–</td>
<td>5200 (2023)</td>
<td>36,000 (2028)</td>
</tr>
<tr>
<td>Germany HRS</td>
<td>43</td>
<td>100</td>
<td>400 (2023)</td>
<td>1000</td>
</tr>
<tr>
<td>UK HRS</td>
<td>14</td>
<td>31</td>
<td>–</td>
<td>–</td>
</tr>
</tbody>
</table>

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**Fig. 9. Growth in the number of public charging points in Europe (25)**

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year and create 420,000 new jobs in the market by 2040.

6. Vehicle Refuelling Rates

Another important comparison between BEVs and FCEVs is their respective refuelling rate, as shown in Table IV. FCEVs can refuel in around five minutes, corresponding to an energy input per second of around 4 MW which, while slower than the 20 MW typical of gasoline and diesel fuelling, is much faster than that of BEVs, where even Tesla superchargers can only deliver a maximum rate of 0.12 MW. The introduction of ultra-fast chargers is just starting in Europe and North America, with a maximum refuelling rate of 0.35 MW, still a factor of 10 slower than fuelling a FCEV with hydrogen. These differences in fuelling rate are particularly important for some applications, for example high utilisation fleet vehicles and vehicles which do a lot of long distance driving (and heavy commercial vehicles).

7. Raw Material Use and Recycling

There are challenges in both the BEV and FCEV supply chains. For BEVs there are some concerns around Co availability and the ethics around some mines in the Democratic Republic of Congo, where around 50% of the world’s Co is mined. In addition, the projected increases in BEV penetration will likely lead to supply chain pressure on commodities such as Ni (which is a key component in the battery itself) and copper (which is used to move electrons around on the vehicle, and throughout the charging infrastructure), which will put upward price pressure on BEVs. The FCEV supply chain is not well developed today because vehicle volumes are so low, so there is work to do to build the volumes required to support this technology going forward, for example around the fluoropolymer and hydrogen tank components. However, one of the most expensive fuel cell constituents, platinum, already has a highly developed supply chain, and there is plenty of Pt above ground that will be accessible via autocatalyst recycling.

On recycling, the importance of developing cradle-to-cradle supply chains for future technology has never been greater. There is a legal imperative for vehicle OEMs to ensure their vehicles are extensively recycled, and there are components of high value (and relative scarcity) in both FCEV membrane electrode assemblies (MEAs) and BEV batteries, so it is essential that effective recycling loops are set up going forward. Neither FCEV MEAs nor BEV batteries are recycled to a large extent today, and optimised processes do not exist for either option, but work is ongoing to develop such processes.

8. Projections of the Future Passenger Car Powertrain Mix

A number of factors will determine the proportion of BEVs and FCEVs in the future powertrain mix, with different countries, regions, OEMs and consumers making different choices. There is broad consensus, however, that BEVs are likely to dominate the passenger car ZEV sector, based on their relatively low cost and TCO, the rapidly growing charging infrastructure, the increased range of incoming BEVs and the fact that all major OEMs are bringing attractive BEVs to market over the coming years (and most OEMs also have fuel cell vehicles in small scale production (Honda, Hyundai and Toyota) or have fuel cell programmes in advanced stages of development). FCEVs are likely to play a role in the high mileage, high utilisation end of the passenger car and light commercial vehicle sectors, where their range and refuelling time advantages over BEVs are attractive.

There are many views of the rate at which the global powertrain will shift from the ICE to electrification (BEV and FCEV). LMC, an automotive global forecasting and market intelligence provider, has recently published its view of the evolution of the global passenger car powertrain out to 2050. Their base case scenario (Figure 10(a)) reflects their current “most likely” view of progress in technology, policy and cost, and they see BEVs with the major share in the ZEV space with over 40% of global car sales by 2050. FCEVs, helped by major growth in renewable electricity generation, become significant by 2035, exceeding 20% of global sales by 2050. Hybrids, though squeezed by
ZEVs, remain important in some markets, including Japan, and make up around 20% of global vehicle sales in 2050, with the 2050 ICE sales dominated by India.

LMC’s “Progressive” scenario (Figure 10(b)) is based on increases in public and political pressure to get the world to act more rapidly to mitigate climate change, leading to more aggressive decarbonisation policies and faster adoption of BEVs and FCEVs. Within this scenario, ICE-only sales cease in the mid-2040s and ZEV sales reach over 90% of demand by 2050, with BEVs accounting for over 60% of global sales, and FCEVs around 30%. Even this “Progressive” case does not represent a net zero scenario globally, since this would require sales of ICEs, HEVs and PHEVs to stop before 2040, and this scenario still has ICE-containing powertrains making up over 40% of global sales in 2040. However, it could be consistent with a scenario in which Europe moves to net zero in 2050 with the rest of the world following behind and achieving net zero just after 2060.
9. Commercial Vehicle Market

As outlined above, CO₂ legislation for commercial vehicles is becoming stricter in all the major economies, and on top of the CO₂ regulations, California is planning to introduce a zero emission vehicle mandate as part of its Advanced Clean Trucks regulatory package. By 2030, this will require 15% of Class 7 and 8 trucks (i.e. vehicles over 11.8 tonnes) sold in the state to be zero emission. While batteries are expected to be the technology of choice in the lighter segments, fuel cells are becoming seen as the most likely solution to decarbonise the larger trucks. As in the passenger car sector, governments planning net zero commitments will need to transition their commercial vehicle fleets from diesel to electricity and hydrogen as they move through the 2030s, to ensure a zero emission fleet by 2050.

OEMs are beginning to position themselves for this new reality; for example, Daimler Trucks recently announced that they plan for all new trucks and buses in the triad markets of Europe, Japan and the North American Free Trade Agreement (NAFTA) to be CO₂-neutral when driving by 2039 (i.e. tank to wheels) (29). They plan to achieve this using a combination of BEV and FCEV, with battery electrics in series production by 2022 in all core regions and hydrogen fuel cell-based series production vehicles by the end of the 2020s. Daimler Truck AG and the Volvo Group, two leading companies in the commercial vehicle industry, have signed a preliminary non-binding agreement to establish a new joint venture to develop, produce and commercialise fuel cell systems for heavy-duty vehicle applications and other use cases in the second half of the 2020s. Daimler will consolidate its current fuel cell activities in the joint venture and the Volvo Group will acquire 50% in the joint venture for approximately €600 million (30).

Cummins are also investing in both battery-based powertrain technology and hydrogen and fuel cells, including acquiring a US$290 million controlling stake in Hydrogenics, a leading fuel cell and hydrogen production technologies provider (31). CNH Industrial have entered into a US$250 million strategic and exclusive heavy-duty truck partnership with Nikola Corporation (32), pioneers in the introduction of zero emission heavy duty trucks powered by hydrogen fuel cell and battery technology. The deal with CNH gives Nikola access to the European commercial vehicle market, as well as to IVECO’s global manufacturing and sales network. In addition, Nikola now has Nel (electrolysis) and Hanwha (solar energy) on board to develop a clean H₂ infrastructure to power these fuel cell vehicles, where conditions allow, supporting the moves towards net zero.

TCO is the critical factor in the long-haul truck sector. Recent analyses by Cummins (33) and AVL (34) have shown that BEV trucks are not viable for this sector due to the high cost, size and weight of batteries for the required range (their weight would reduce payload) and the relatively long recharging time for such large batteries (which would reduce vehicle utilisation significantly). These studies show that the FCEV solution is strongly preferred due to the long range, rapid refueling times and overall TCO. A hydrogen price of €3.50–5.00 kg⁻¹ is estimated to lead to TCO parity even with today’s diesel-based trucks once such FC trucks are made in significant volumes (100,000 or so); as outlined earlier, the hydrogen price is expected to drop to around €4 kg⁻¹ by 2030.

In the medium duty distribution truck sector, where driving ranges are lower than in the long-haul space, BEVs are expected to play a significant role, and for some such distribution applications BEVs already have a lower TCO than current diesel trucks. CARB estimates that the TCO of battery trucks will be lower than diesel trucks by 2024 for many local truck applications (35). They also project that FCEVs will approach the TCO of diesel by 2030.

The development of the fuelling infrastructure for zero emission commercial vehicles is generally regarded as an easier proposition than that for passenger cars, since many commercial vehicles (especially buses and distribution trucks) return to a depot overnight. For BEV-based vehicles this requires charging infrastructure at their home depots and along the parts of the strategic road network along which they operate, for cases where top-up charging away from the depot is required. For longer distance buses, coaches, and medium and heavy commercial vehicles, the fuel cell powertrain is expected to be widely employed, requiring HRSs at home depots and along the strategic road network. Depot-based HRSs for centralised refuelling have the advantage of increased utilisation, reducing the cost of the hydrogen delivered. A recent report from the Hydrogen Council projects that the cost of hydrogen refuelling infrastructure per vehicle should ultimately drop to below the cost of the BEV recharging infrastructure due to the significant economies of scale available from increasing the size of the distribution network and the
introduction of larger retail stations (36). Their analysis led them to conclude that the cost of investment per kilogram of pumping capacity from a HRS will decline roughly 70% over the next 10 years, from about US$6000 for a small station in 2020 to an estimated US$2000 for a large station in 2030. Such a cost trajectory further increases the attractiveness of the hydrogen fuel cell solution for large and longer distance commercial vehicles, since it significantly reduces the TCO of these vehicles.

There are far fewer projections of the future uptake of zero emission commercial vehicles than there are for passenger cars, but it is clear that the commercial vehicle sector needs to develop and implement zero emission vehicles rapidly to support broader decarbonisation initiatives and, particularly, moves to net zero. KGP, a consultancy that provides services to the automotive and related industries worldwide, has developed a “2°C Scenario” for the commercial vehicle market (Figure 11) (37), projecting that the sales of “Electric” commercial vehicles, i.e. those powered by BEV and FCEV, would need to increase from around 87,000 in 2019 to over one million per year by 2030, to be on a trajectory to enable the GHG emissions from the commercial vehicle sector to be aligned with the Paris Agreement’s aim of limiting the global temperature increase due to GHG emissions to 2°C above pre-industrial levels. This level would correspond to around 25% of new sales of commercial vehicles globally.

The recent report from the IPCC (2) recommends that the target temperature increase should be at or below 1.5°C, implying that a faster rate of uptake of zero emission commercial vehicles will be required. Approaches to increase ZEV penetration include increasing the stringency of CO₂ tailpipe regulations, and introducing mandates for ZEV fleet levels (such as those proposed within the Advanced Clean Trucks rule by CARB). Interestingly, 30 businesses including Nestle and Unilever recently signed a letter to the new European Commission president Ursula von der Leyen and new EU climate chief Frans Timmermans, calling for legally binding zero-emission truck and van sales targets for 2025 and 2030 (38). They pointed out that these sales targets need to be ambitious, to drive a huge increase in the supply of zero-emission vehicles compared to a business-as-usual scenario, and to put Europe on track to meeting its 2030 climate targets. The businesses believe that binding sales targets will accelerate the uptake of zero-emission vehicles, make air in cities cleaner, put European vehicle-makers at the forefront of innovation while at the same time making Europe less dependent on oil imports. The signatories also say that the EU’s 2030 emissions reduction target must be increased to 55% and the bloc should go climate-neutral by 2050; the latter is the target already proposed by the European Commission.

Overall, therefore, the commercial vehicle sector is becoming increasingly aware of its need to develop zero emission vehicles to play a major role in the decarbonisation of road transport, and extensive work is underway to develop and bring such vehicles to market. Governments and regulators have a significant role to play in creating the right policy framework to drive the initial introduction of such vehicles into the marketplace, and then to encourage their further uptake to enable net zero and air quality targets to be achieved.

10. Summary

The demand for cleaner urban air and massive reductions in CO₂ and other GHG emissions is increasing both from the public and from regulators and governments in many countries and regions. Net zero GHG targets have been set and legislated in several geographies, and more are
Transportation is currently a major emitter of criteria pollutants (including CO, hydrocarbons, NOx and PM) and of CO2, and the decarbonisation of this sector requires the transition from ICE-powered vehicles to battery electric and fuel cell electric zero emission powertrains. Of course, the minimisation of the carbon footprint of such vehicles is contingent on the electricity and hydrogen used to fuel them being low or zero carbon. In the case of BEVs this means the electricity grid needs to be decarbonised, and this is occurring at good pace in many countries, accelerated by the ongoing reductions in the cost of renewable energy derived from, for example, solar and wind. For FCEVs it means decarbonised electricity to generate green hydrogen by the electrolysis of water, and the addition of CCUS technology to advanced reforming plants, to convert CH4 into blue (low carbon) hydrogen. The low carbon hydrogen infrastructure and distribution network will constitute part of the transition towards a broader hydrogen economy in many countries, supporting moves to net zero across industry, power generation (including seasonal energy storage to enable increased renewable power generation) and heating for buildings, as well as transportation.

The decarbonisation of the passenger car sector will be driven by rapid uptake of BEVs, which will occur as their purchase costs continue to fall, their driving range continues to increase, and the required charging infrastructure is rolled out worldwide. BEVs are also expected to play a significant role in urban bus and distribution truck applications. FCEVs are expected to dominate the long haul trucking segment as it decarbonises, due to their cost, weight, range and charging time advantages over battery-based technology. They will also likely play a role in inter-city buses and distribution trucks, and in larger passenger cars and sport utility vehicles (SUVs) for applications and customers requiring a long driving range and rapid refuelling.

There is no doubt that net zero targets at the state, country and regional level will be challenging to meet on the 2050 timeframe recommended by the IPCC, but the surface transportation sector is developing and introducing the technologies to enable this. As long as governments and regulators put in place an appropriate set of policy measures and incentives to encourage the early implementation and subsequent mass uptake of zero emission vehicles, the car, van, bus and truck segments will make a huge contribution to global moves towards decarbonisation and the development of net zero economies worldwide.

References

5. C. C. Ambel, “Roadmap to Climate-Friendly Land Freight and Buses in Europe”, European Federation for Transport and Environment AISBL, Brussels, Belgium, 22nd June, 2017, 36 pp
7. ‘Daimler Trucks & Buses Targets Completely CO2-Neutral Fleet of New Vehicles by 2039 in Key Regions’, Daimler AG, Stuttgart, Germany, 25th October, 2019, 4 pp
11. ‘Our Commitment to Green and Healthy Streets: C40 Fossil-Fuel-Free Streets Declaration’, C40 Cities Climate Leadership Group Inc, New York, USA, 24th August, 2018
13. ‘How Close is Great Britain’s Electricity to Zero-Carbon Emissions?’, Drax Power Station, Selby, UK, 15th May, 2019


16. 'CO₂ Neutral ID.3: Just Like That', Volkswagen, Wolfsburg, Germany, 11th January, 2019


19. M. Reuss, ‘GM President: Electric Cars Won’t Go Mainstream until We Fix These Problems’, CNN Business Perspectives, Atlanta, USA, 25th November, 2019


21. M. J. Coren, ‘New York City Says Electric Cars are Now the Cheapest Option for Its Fleet’, Quartz, New York, USA, 18th March, 2019


24. ‘All-New NEXO’, Hyundai Motor UK, Walsall, UK, October, 2018


28. ‘Hyundai Motor Group reveals FCEV Vision 2030’, Hyundai Motor Company, Seoul, South Korea, 11th December, 2018

29. ‘CO₂-Neutral Fleet of New Vehicles’, Daimler AG, Stuttgart, Germany, 25th October, 2019, 4 pp

30. ‘Volvo Group and Daimler Truck AG are Planning to Form a Joint Venture’, Daimler AG, Stuttgart, Germany, 21st April, 2020

31. ‘Cummins Closes on its Acquisition of Hydrogenics’, Cummins Inc, Columbus, USA, 9th September, 2019

32. ‘CNH Industrial to Lead NIKOLA’s Series D Round with $250 Million Investment. Parties Announce Strategic Partnership to Industrialize Fuelcell and Battery Electric Heavy-Duty Trucks for North America and Europe’, CNH Industrial, London, UK, 3rd September, 2019, 4 pp


34. W. Resende, ‘Fuel Cell for Trucks: A Pathway to Zero Emission Transport?’, AVL List GmbH, Graz, Austria, 4th June, 2019

35. ‘Advanced Clean Truck: Workgroup Meeting’, California Air Resources Board, Sacramento, USA, 25th February, 2019, 37 pp


37. A. Woodrow, ‘Decarbonisation: Electric or ?’, Integer Emissions Summit, Indianapolis, USA, 20th November, 2019


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