MARCH 2018: **Issue 112**

THE OXFORD INSTITUTE FOR ENERGY STUDIES
A RECOGNIZED INDEPENDENT CENTRE OF THE UNIVERSITY OF OXFORD

UNIVERSITY OF OXFORD

forum

A QUARTERLY JOURNAL FOR DEBATING ENERGY ISSUES AND POLICIES

This issue of the *Oxford Energy Forum* is devoted to investigating disruptive change in the transport sector. There are three forces shaping or disrupting the road transport sector, namely: autonomous vehicles, transport electrification, and shared mobility. The interactions between the three will determine the future of energy use in transport. The determinants of these three disruptors include factors such as government policies, technological advances, infrastructure, battery costs, material supply chains, consumer behaviour, and the development of alternative fuels. The articles in this issue analyse in detail each of the three disruptors and their associated drivers and constraints, presenting a range of views on the future of transport and energy use.

The issue opens with three articles considering technological advances in automation, and challenges to the use of the internal combustion engine (ICE). *Zia Wadud* looks at the travel, energy, and carbon impacts of automated vehicles (AVs). The author argues that while improved energy efficiency of a vehicle mile, or person mile, goes some way towards reducing energy use, the other half of the equation – travel demand – has often been missing in the debate about the energy effects of vehicle automation. Automation can result in a substantial reduction in energy demand, but this is due to changes in vehicle design and vehicle operations, and by transport system optimization facilitated by vehicle automation. These are also called 'ripple effects' and they manifest themselves through two mechanisms – energy effects and travel demand effects. The author concludes that with fully self-driving cars, there is a substantial risk of increased travel and energy demand. Simultaneously, there are large uncertainties in the quantification of the net energy effects of self-driving cars, arising from car ownership versus shared mobility services. It is vital that the various mechanisms are aligned in the correct directions through appropriate policies, in order to reap the full energy and carbon benefits of automation.

Gautam Kalghatgi investigates the question of whether the advent of battery electric vehicles (BEVs) signals the end of ICEs. The author argues that there are constraints to widespread BEV production; these include availability of materials, recycling, and limitations of battery chemistry. He also argues that electricity generation needs to be sufficiently decarbonized for BEVs to have an advantage over ICE vehicles (ICEVs) on a life cycle basis in terms of GHG emissions. The cost of BEVs is expected to come down while their range increases in the future but until

CONTENTS

Disruptive change in the transport sector

then, incentives – the cost of which will have to be borne by governments or BEV manufacturers – will be required to persuade people to buy them. Even if the cost of BEVs becomes comparable to ICEVs, huge prior investments in charging infrastructure will be required. In the longer term, the lost revenue from fuel taxes, which contribute significantly to public finances, will have to be recouped. The author concludes that while full electrification in the form of BEVs will remain relevant primarily to the small passenger car sector, ICEs will continue to dominate land and marine transport for decades to come.

Chris Midgley argues that unlike the transition in the early 1900s from the horse and buggy to the ICE (which took just 13 years), EVs do not represent a comparable marked improvement in convenience and in fact they have drawbacks in costs, range, and ease of refuelling (charging). At the same time, momentum is certainly building around EVs and hybrid variants of the technology as viable alternatives to the future of mobility. Today's 3 million EVs displace less than 0.06 per cent of total global oil demand. Three years of low oil prices have stimulated strong sales of new cars, with a shift towards larger passenger vehicles compared with the small economical (miles per gallon) cars which previously dominated sales. Most of the demand has not been due to larger vehicles, but to an increase in vehicle miles travelled per capita, partly as a consequence of the rise of rideshare. The author also considers the debate on air quality around ICEs, arguing that it should not be about new car sales but about removing the old fleet and as such, scrappage schemes would have a far greater impact on air quality and fuel efficiency than any bans on ICEs kicked down the road to 2040. The author concludes that EVs 'will be an evolution, not a revolution'.

The next three articles in the issue investigate the scope for scaling up EVs in relation to the electricity system; the issues covered include battery costs, the supply chain, and the impact of vehicle electrification on the electricity grid. *David Robinson* examines the relationship of electricity to EV penetration, focusing on Europe – in particular whether the electricity system and its regulation could be barriers to this penetration. The author makes three main arguments. First, while electricity is a requirement for EV penetration, other factors are more important determinants. In future, the central reason for rapid penetration is likely to be the falling cost of EVs and batteries, the increased range of EVs, policy restrictions on ICE vehicles, and the decision by major car manufacturers to invest heavily in EVs. It also depends on other determinants of future mobility options inside cities; these include the development of AVs, shared mobility, consumer preferences, and the cost of alternative sustainable mobility options. Second, the requirement for investment in electricity infrastructure is unlikely to be a barrier to EV penetration, at least in Europe – indeed the flexibility offered by EVs could aid the integration of intermittent renewables and this should favour investment in infrastructure. Finally, current electricity regulations in some European countries are barriers to EV penetration and should be eliminated as a matter of good regulatory practice.

Simon Moores analyses the supply chain risks and opportunities underpinning energy storage technologies. The author argues that market momentum is now with lithium-ion batteries and for this first phase of the energy storage revolution the choice has been made. However, despite over $36 billion having been committed to expanding battery plants and building new supply, investment into capacity needs to be four times larger to satisfy demand for the mid-2020s, and 10 times larger for a post-2030 world. The biggest challenge is scaling the supply chain for lithium, graphite, cobalt, and nickel from the mine to the battery plant, in time to meet demand from the auto manufacturers. The demands that EV manufacturers are placing on the raw material miners, chemical processors, and cathode manufacturers are huge – they are being asked to increase their business footprint by a factor of 5–10 in a seven-year period. Major auto manufacturers will eventually have to conclude that supply chain partnerships and capital investment are the only ways to secure supplies. But this decision-making process is slow for players outside China – which is at the centre of mass market EV development and deployment. The author concludes that the energy storage revolution is unstoppable. For both countries and corporations, it should be of paramount importance to position themselves accordingly to take advantage of these issues, as those who control the lithium-ion battery supply chain will be the biggest influencers on the next generation auto and energy industries.

Next, *Constance Crozier's* article looks at whether the mass adoption of electric vehicles will place additional strain on the UK's power system. The author argues that the amount of energy is less important than the rate at which it is being taken from the grid, or the power demand. National power demand may exceed current generation capacity, and local feeders will have to cope with loads they were not designed for, leading to more frequent infrastructure failures. As increased power generation capacity is an unattractive proposition, interest in smart charging schemes – which aim to charge vehicles with minimal strain on the grid – is growing. The article analyses the national demand profile under both uncontrolled and optimal smart charging, assuming the UK fleet

to be 100 per cent electric. It concludes that if designed correctly, smart charging strategies could allow 100 per cent of the UK's personal fleet to be electrified without hitting the problem of additional generating capacity or infrastructure failures. Achieving this is non-trivial but is more likely if a strategy which minimizes consumer involvement is chosen. On the other hand, a poorly designed strategy risks sacrificing the natural diversity in consumer behaviour that the power system relies on.

The next article in the issue considers an important alternative in transport – particularly, commercial freight and marine. *Chris Le Fevre* argues that natural gas is almost certain to establish an important share in some parts of the transportation fuels market. The evidence to date suggests that this is most likely to occur in marine shipping, though penetration levels will vary between specific sectors and regions. The author identifies some key barriers to uptake, including: cost of conversion to adapt existing vessels and vehicles to burn gas; uncertainty over the differential between gas and oil prices; issues relating to the cost and availability of refuelling infrastructure; a commercial and regulatory framework that tends to favour the status quo; and finally, the fact that despite its significant environmental advantages over traditional petroleum products, gas is not a zero-carbon solution, unless biogas is the source. Overall gas usage in transport will certainly increase in the next 10 years, though there is little evidence at present to suggest that an across-the-board switch to gas is underway. It is also unwise to assume that growth trends can be projected inexorably into the future as other low-carbon technologies evolve.

The next two articles in the issue focus on the role of consumer behaviour and motivation underpinning the adoption of transformative mobility solutions. *Guy Walker* discusses the application of Human Factors methods in analysing drivers' responses to EVs. The author argues that EVs represent a significant change in the way vehicles are designed and operated. They are an attempt to support people in the travel behaviours they currently perform but in a new way, in combination with other aspects of user behaviour (re-fuelling and energy management) which will have to change entirely. The probability of unexpected behavioural side effects occurring when well-intentioned automotive technologies come into contact with drivers is high. The author cites several examples in which a technology aimed at improving fuel consumption yields the opposite effect to that intended. For instance, quieter cars tend to encourage reduced headway and more risky gap acceptance. The change yielded by a shift to EV powertrains is orders of magnitude greater than any which has already been shown to change driver behaviour in unexpected ways and the author argues that we should be prepared for human performance side effects of EVs.

Maria Kamargianni investigates the rise of Mobility-as-a-Service (MaaS), or vehicle usership versus ownership. The author notes that the significance of car ownership for Millennials has notably decreased. Instead, younger generations place much higher value on the electronic devices, such as laptops and smart phones, that they own. MaaS is a user-centric, digital, and intelligent mobility distribution model in which users' major transport needs are met via a single platform and are offered by a service provider, the MaaS operator, who is a new player in the transport market. MaaS aims to bridge the gap between public and private transport operators and envisages the integration of the currently fragmented tools and services a traveller needs to conduct a trip. Drawing from the results of a survey on how Londoners perceive car usage and MaaS, the author outlines supply- and demand-side drivers of the adoption of MaaS. The author concludes that MaaS may result in a decline of private vehicle sales, partially offset by increased sales of shared vehicles that need to be replaced more often due to higher utilization. Furthermore, vehicle miles travelled are expected to remain at the same levels or drop, as travel demand could probably stay the same. Fuel consumption is expected to drop and air quality to improve, because of a younger and more electrified car fleet.

The next three articles focus on country-specific experiences on how government policies are influencing the shift towards transformative electric mobility. *Maya Ben Dror* and *Feng An* focus on China – the world's largest market for passenger vehicles, and with the highest population of internet and mobile users. New awareness of the issues of climate change and air pollution in Chinese cities have inspired a different regulatory landscape: China is geared towards achieving industrial superiority coupled with zero-tailpipe-emissions mobility. The authors analyse the motivators and processes underpinning the development of China's passenger vehicle energy saving regulatory framework, focusing on two policy trends: the intensification of energy-consumption regulation relating to internal combustion engine cars, and the growing numbers of policies supporting New Energy Vehicle (NEV) production. Recently, these two paths have crossed, in the newly announced corporate average fuel consumption (CAFC) and NEV joint credits system. The authors conclude by identifying potential challenges to policy enforcement, including local protectionism on NEV production, and the possibility of companies abandoning their fuel-saving investments in favour of NEV investments.

Anupama Sen considers opportunities for India to 'leapfrog' to EVs, the challenges in doing so, and the likely impact on oil demand growth in transport. The author argues that a 'leapfrog' would be easier if it were possible to pre-empt growth in private vehicle ownership and target public transportation and ride-sharing services. Three features of the economy support this: the majority of trips taken are already on public or non-motorized forms of transport; ride-hailing and ride-sharing services are prevalent across Indian cities; and traffic congestion and pollution are becoming election issues – India hosts 13 of the world's 20 most polluted cities. The author argues that while India is likely to have sufficient electricity generation capacity to meet incremental EV demand, it will need to overcome structural challenges related to low capacity utilization rates, expanding charging infrastructure (much of which would have to be built from scratch), and deal with issues around affordability. The author concludes that oil demand growth in transport will only slow relative to a baseline level if policies to substitute away from oil are implemented on a widespread basis. But these will need to be backed by strong political commitment, which given a recent scaling back of ambition to electrify the entire fleet by 2030, is under question.

Frank Watson argues that Europe is at the forefront of regulating the low-carbon transportation revolution. But while the region's policymakers have put in place frameworks designed to gradually push manufacturers and consumers toward higher-efficiency lower-emissions passenger and commercial vehicles, their capacity to sustain subsidies and lost tax revenues is open to question. There are many examples where uptake of EVs has fallen dramatically when governments withdraw subsidies, or where the upcoming withdrawal of government subsidy has caused a temporary surge in uptake of EVs, before sales numbers crash immediately following the withdrawal of support. European leaders fear that the USA and China have already taken the lead in developing new low-emissions car models – Europe's share of the global passenger vehicle market fell to 20 per cent in 2017, from 34 per cent before 2008. They want to use legislation to protect strategic industries and support vehicle manufacturers in the development of technologies. In Europe, low emissions vehicles could eventually upend the market for ICEs, but they will only be a game changer if the cost of EVs and other alternatives comes down to a point where they can compete directly. Until then, uptake of low-emissions vehicles looks set to be determined by government support frameworks and policies.

The next two articles in the issue present 'big picture' analyses of the likely growth of electric vehicles and their impact, in combination with automation and shared mobility, on energy use. *Colin McKerracher* argues that the global sales of EVs will hit 1.5 million this year from just 180,000 in 2013, and are expected to continue increasing. The author argues that lithium-ion batteries are at the centre of this shift. The learning rate for EV batteries is around 18 per cent, so every doubling in manufactured volume reduces cost by about the same amount on a kilowatt hour basis. This puts EVs on track to be fully price competitive with comparable ICE vehicles beginning around 2024, with different countries and vehicle segments hitting the crossover point in different years. The author estimates that EVs will hit just under 10 per cent of global sales by 2025, 24 per cent by 2030, and 54 per cent by 2040. Due to the speed of turnover, the impact on energy markets will likely be limited until after 2025, but this would displace around 8 million barrels per day of oil demand and add around 5 per cent to global electricity demand in 2040. Constraints to this outlook include charging infrastructure, battery supply chains, and consumer adoption of EVs, which the author argues are likely to delay – rather than derail – the move to electric vehicles. The author concludes that we are heading towards a far more differentiated global auto market than we have seen in the past, with EVs here to stay.

The next article, by *Lewis M. Fulton* and *Junia Compostella*, considers the combined impact of 'three revolutions' that are underway in urban transportation around the world: vehicle electrification, automation, and shared (on-demand) mobility. The authors' research suggests a wide range of possible impacts; they outline four. First, a major shift to privately owned driverless cars could result in an increase in travel given the associated productivity savings. Second, many households may not 'demand' that automated vehicles be electric, resulting in substantially more energy use and CO_2 emissions. Third, the advent of driverless, electric, on-demand ride sharing services could cut the cost of these services by 70 per cent or more. And fourth, such low costs could encourage more people to use ride hailing, leave their own cars at home, or even reduce ownership levels. The authors compare the monetary and non-monetary ('hedonic') costs of choosing among different travel options to share some insights into the likely success of both shared mobility and automated vehicles in the household travel market. They argue that there is a strong need to pursue policies that move these revolutions in sustainable, societally optimal directions.

The issue ends with a summary of eight key takeaways from a workshop held by OIES on 'Disruptive Change

in the Transport Sector' in relation to its impact on energy use in private transport. First, despite many government announcements and strong press coverage regarding vehicle electrification, alternative technologies also exist and these are important for future mobility. Second, Level 5 autonomous vehicles are still some years away and will be context (for example: city) specific. Third, cost is one among multiple factors in the scaling up of batteries – other factors include material supply chains, manufacturing processes, location to market, and recycling. Fourth, grid management, rather than absolute generation capacity, is critical to EV adoption – electric mobility is compatible with the current power system so long as demand can be anticipated and the infrastructure adapted to it in advance. Fifth, automobile manufacturers will need to restructure their business models around value creation – for EVs, the latter is likely to move further up the supply chain, so the industry structure, as well as the structure of jobs, will have to be reorganized. Sixth, technology diffusion goes beyond cost-competitiveness and includes factors such as societal preferences and cultural shifts. Seventh, emerging markets (such as China and India) will also adopt EVs, driven primarily by government policy – but outcomes will differ as these countries have very different strategies. And finally, automation, electrification, and shared mobility imply very different types of impacts in different combinations.

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The views expressed in this issue are solely those of the authors and do not necessarily represent the views of the Oxford Institute for Energy Studies, its members, or any other organization or company.

Oxford Institute for Energy Studies is truly grateful to Catherine Gaunt and Christopher Riches for the many years of editorial and production support they have brought to the OEF; and as they move to pastures new we extend our sincere thanks and very best wishes.

Autonomous vehicles: will they reduce energy use?

Zia Wadud

This article draws heavily on 'Help or hindrance? The travel, energy and carbon impacts of highly automated vehicles', Zia Wadud, Don MacKenzie, and Paul Leiby, *Transportation Research Part A: Policy and Practice*, vol. 86, pages 1–18, April 2016, referred to within this article as: Wadud et al. (2016).

Introduction

Since the demonstration of its driverless car by Google (now Waymo) in 2012, there has been much interest from the media and the public, as well as from transport academics and policymakers. Self-driving, driverless, or fully automated autonomous vehicles are often expected to solve transport's energy use and carbon emission challenges. In particular, early media reports suggested large reductions in both energy use and carbon emissions. However, the issues require a deeper understanding.

Energy and carbon modelling

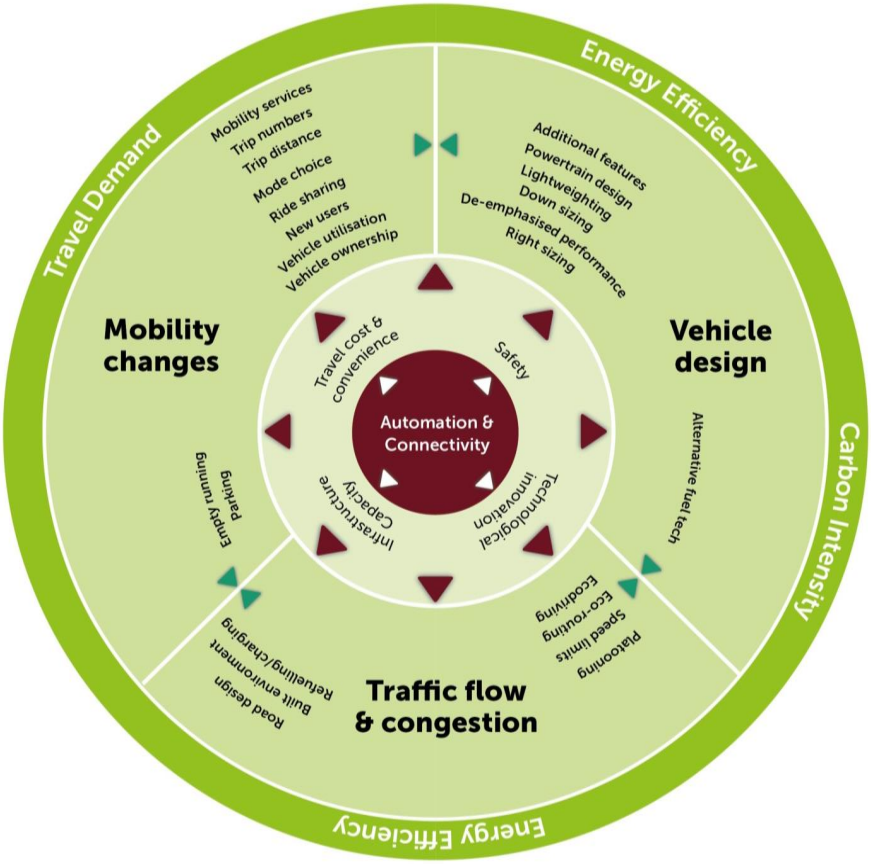
While some of the earlier reported energy efficiency benefits can indeed occur through full vehicle automation (details presented below), there is another aspect of automation with large energy and carbon implications that has not received much attention. From an energy and carbon emissions perspective, it is the 'total' energy or 'total' carbon emissions (from the transport sector) that is of prime concern; this can be simply expressed as: *Energy Use (Carbon) = Energy Efficiency of Travel × Travel Demand (× Carbon Intensity of Fuel)*

While improved energy efficiency of a vehicle mile, or person mile, goes some way towards reducing energy use from the transport sector, the other half of the equation – travel demand – has often been missing in the debate about energy effects of vehicle automation. Yet vehicle automation is also likely to make a radical change to the way people might travel in the future and a holistic picture is therefore required to understand the possible net effects of automation.

'SELF-DRIVING, DRIVERLESS, OR FULLY AUTOMATED AUTONOMOUS VEHICLES ARE OFTEN EXPECTED TO SOLVE TRANSPORT'S ENERGY USE AND CARBON EMISSION CHALLENGES.'

The ripple effects

Vehicle automation does not affect energy consumption and carbon emissions directly. Rather, it affects other innovations in vehicle technology, traffic management approaches, and mobility business models that result in changes in energy use and carbon emissions. It is therefore useful to understand these mechanisms through which energy use can be affected. Researchers have developed a ripple diagram in order to understand the primary and secondary effects of full vehicle automation ('Vehicle automation and transport system performance', Gonçalo Correia, Dimitris Milakis, Bart van Arem, and Raymond Hoogendoorn in Michiel Bliemer, Corrinne Mulley, and Claudine Moutou, (eds.) *Handbook of Transport and Urban Planning in the Developed World*, Edward Elgar, pages 498–516) and their connections



Ripple effects of vehicle automation

Source: Wadud and Anable, 2016.

to the components of energy use and carbon emissions (Automated vehicles, automatically low carbon?, Zia Wadud and Jillian Anable, Low Carbon Vehicle Partnership and Institution of Mechanical Engineering, London, June 2016, see the figure opposite).

Efficiency effects

While it is difficult to model every branch of the ripple effect, it helps identify several energy efficiency mechanisms through which energy use could change as a result of the widespread adoption of self-driving cars. For example, Wadud et al. (2016), identify the following mechanism which could reduce energy consumption:

- Traffic flow can be streamlined and optimized for fuel consumption with fully automated vehicles connected to the infrastructure through V2I (Vehicle-to-Infrastructure), with full knowledge of the traffic controller on the location and speed of the vehicles;
- On motorways, automated vehicles will be able to drive very close to each other, creating platoons; driving in platoons at high speed reduces the aerodynamic drag and thus fuel consumption is reduced (the effect is negligible at low speeds);
- Automated vehicles can be programmed to run in an eco-driving mode (driving practices that can reduce fuel consumption – some vehicles already allow optimization of driving mode to reduce fuel consumption);
- At a very high level of penetration, when crash risks are dramatically reduced (nearly 90 per cent of traffic fatalities are attributed to human errors), it may be possible to use lighter materials for vehicles, or to remove some of the currently used heavy safety features in vehicles; the reduced weight will improve fuel efficiency of the vehicles.

'… THE VALUE OF TIME "WASTED" DURING DRIVING/TRAVELLING IS ONE OF THE MAJOR DETERMINANTS OF THE CHOICE OF DIFFERENT TRANSPORT MODES …'

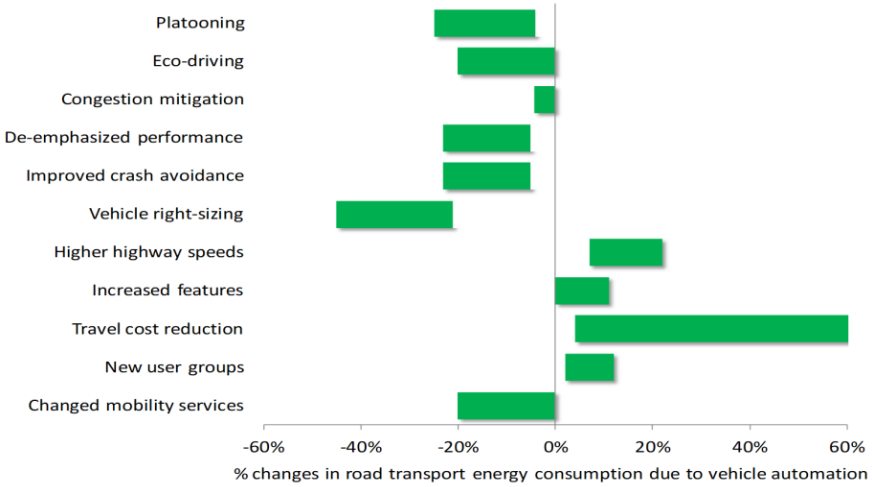
All of these mechanisms improve the 'fuel efficiency' of individual (self-driven) vehicles and have received attention from the media and non-academic literature as potential energy and carbon benefits. However, Wadud et al. (2016) also report some other mechanisms that affect the fuel or energy efficiency of the vehicle, although the direction could be either positive or negative:

- Increased safety due to full automation could result in the relaxation of speed limits, currently set on the grounds of safety, and thus result in higher vehicle speeds: this would increase energy use;
- In a potential self-driven shared-car environment, car sizes can be matched with vehicle occupancy (for example, the use of a small 2-seater for a one-person commute trip): this would decrease energy use;
- Engine performances could be lowered in automated driving, since a higher power requirement (for driving pleasure) would no longer be required: this would reduce energy consumption.

Travel demand effects

While the effects of vehicle automation on how we might travel in the future are minor for low levels of automation, at a self-driving level of automation, where no human driving input is necessary, the effects could be radical. Take, for example, the potential for a modal switch back to cars. During a journey, people generally prefer the privacy and convenience of a car, but they also appreciate the driving-free experience of public transport, especially since the time not driving can now be used in a productive manner due to the progress in information and communication technologies. Self-driving cars can combine these benefits by allowing hands-free, useful use of time in cars, making them relatively more attractive than the public transport modes. In transport modelling terminology, the value of time 'wasted' during driving/travelling is one of the major determinants of the choice of different transport modes and this wasted value of time could be lowered substantially in a driverless car. Such a change could substantially disrupt the perceived costs of travel by car and could encourage a more car-centric lifestyle, while people decide to live further from work. Indeed, researchers have shown that the people who find their time would be spent more usefully in a self-driving car, are more likely to use these automated vehicles ('Potential use and usefulness of travel time in fully automated vehicles', Zia Wadud and Fuad Yasin Huda, 97th Annual Meeting of the Transportation Research Board, Washington, DC, 2018). As a result, modal share may tilt further towards car travel. Wadud et al. (2016) report that travel and concomitant energy use and carbon emissions could increase by between 5 per cent (for a position of mid-level automation), to up to 60 per cent (for a high penetration of self-driving cars in the USA). (See the figure overleaf.)

Self-driving cars could also encourage completely new demographic groups to own cars – such as the disabled and the elderly, and also, potentially, those currently too young to drive. Whilst potentially important in advancing social inclusion, increased vehicle ownership and use would inevitably lead to increased energy use and carbon emissions. While the well-being effects of increased mobility for these vulnerable groups can be immense,



Potential impact of vehicle automation on energy demand through various mechanisms

Source: Wadud et al. (2016).

the energy effects will be the opposite. Wadud et al. (2016) find that these new user groups could increase the energy consumption of the personal vehicle fleet by 2–10 per cent in the USA (see figure above). Other researchers also report the potential for higher travel from particular demographic groups ('Estimating potential increases in travel with autonomous vehicles for the non-driving, elderly and people with travel restrictive medical conditions', Corey Harper, Chris Hendrickson, Sonia Mangones, and Constantine Samaras in *Transportation Research part C: Emerging Technologies*, vol. 72, pages 1–9, November 2016).

'SELF-DRIVING CARS COULD ALSO ENCOURAGE COMPLETELY NEW DEMOGRAPHIC GROUPS TO OWN CARS …'

One aspect related to travel demand that has received a lot of attention globally is the potential move away from individual car ownership toward new models of mobility services such as car sharing or an on-demand service facilitated by driverless cars. The argument is that since driver costs represent around a third of the cost of a traditional taxi or of Uber-type ridehailing services, self-driven automated taxis or ridehailing services could reduce the costs of these services, as these will not need a human driver (see 'Fully automated vehicles: a cost of ownership analysis to identify early adoption', Zia Wadud in *Transportation Research Part A: Policy and Practice*, vol. 101, pages 173–6, July 2017). Such a reduction in costs, along with the increased popularity of Uber-type services, shows that such a switch is not impossible, although in reality there will likely be a new equilibrium of owned versus shared vehicles. The net energy impacts of such on-demand services are still uncertain: total car travel and energy consumption could decrease as the variable out-of-pocket costs per mile become more visible to the traveller. However, this reduction could be neutralized by an increase in car travel, as the driverless shared cars or taxis travel empty when shuttling from one passenger to another (see 'Preparing a nation for autonomous vehicles: Opportunities, barriers and policy recommendations', Daniel Fagnant and Kara Kockelman, *Transportation Research Part A: Policy and Practice*, vol. 77, pages 167–81, 2015). Also, the reduced costs of automated mobility services may encourage a modal switch away from public transport, thus increasing travel by car and concomitant energy use and carbon emissions. Ridesharing – similar to Uber Pool or Lyft Line – services could, however, reduce total vehicle miles travelled (VMT) and could reduce emissions in future. The net travel impact is still quite uncertain.

Conclusions

Wadud et al. (2016) bounds potential ranges of the energy impacts of self-driving cars in the USA through the energy efficiency and travel demand mechanisms mentioned above; these are shown in the figure above). While the numbers may differ, the general direction of the effects is also expected to be similar in other parts of the world. Increasingly, other researchers also report broadly similar results (see 'An analysis of possible energy impacts of automated vehicles', Austin Brown, Jeffrey Gonder, and Brittany Repac in Gereon Meyer and Sven Beiker (eds.), *Road Vehicle Automation*, Springer, 2014, pages 137–53 and 'Three revolutions in urban transportation', Lewis Fulton, Jacob Mason, and Dominique Meroux, UC Davis and ITDP, 3 May 2017) and highlight the associated uncertainties. The key messages are:

- Automation can result in a substantial reduction in energy demand, but this reduction is not a direct consequence of automation per se, it is rather due to changes in vehicle design, vehicle operations, and transport system optimization facilitated by vehicle automation.
- Some of the reductions in energy demand could be brought about by a higher degree of connectivity, even at a lower level of automation than that of self-driving cars. Yet, for fully

self-driving cars, there is a substantial risk of increased travel and energy demand. Thus, stopping short of fully self-driving cars may be more beneficial from an energy perspective.

- There are large uncertainties in the quantification of the net energy effects of self-driving cars, with the largest uncertainty arising from car ownership versus shared mobility services. Given these uncertainties, it is vital that the various mechanisms discussed here are aligned in the correct directions through appropriate policies, in order to reap the full energy and carbon benefits of automation.

Is it really the end of internal combustion engines?

Gautam Kalghatgi

The transport of goods and people is central to modern society. The world has around 1.2 billion light duty vehicles (LDVs) and around 380 million commercial vehicles which are almost entirely (> 99.9 per cent) powered by combustion engines – land and marine transport primarily by internal combustion engines (ICEs) and air transport by jet engines. Around 95 per cent of transport energy comes from liquid fuels derived from petroleum and nearly 60 per cent of all petroleum produced goes to make transport fuels. LDVs, mostly passenger cars, account for around 44 per cent of transport energy demand globally (International Energy Outlook 2017, US Energy Information Administration) and most run on gasoline. The global demand for transport fuels is very large – on average, over 4.8 billion litres each of diesel and gasoline and around 1.2 billion litres of jet fuel daily (Oil Market Report, 11 August 2017, International Energy Agency). This demand is expected to grow, almost entirely in non-OECD countries, at an average annual growth rate of around 1 per cent. Could this massive and increasing demand for transport be met by powertrains which do not rely on combustion?

There is much current interest in electric vehicles. Many governments have announced the desire to eventually ban cars powered by ICEs, though it is often not clear if the intention is to

'AROUND 95 PER CENT OF TRANSPORT ENERGY COMES FROM LIQUID FUELS DERIVED FROM PETROLEUM …'

ban *all* ICEs or ban vehicles with *only* ICEs without any electrical assistance. In any case, this has led to a belief in some quarters that all transport can and will be powered only by electricity and the ICE will quickly disappear. The other, perhaps longer-term, alternative to the ICE is the fuel cell powered by hydrogen, which requires a credible global hydrogen infrastructure to be built. This article focuses only on electrification and argues that the ICE will continue to dominate land and marine transport for decades to come. Alternative fuels for combustion engines (such as biofuels, natural gas, and methanol from coal) will grow but start from a low base and these also have constraints on unlimited and rapid growth. Hence credible projections suggest that even by 2040 around 90 per cent of transport energy will come from petroleum (International Energy Outlook 2017; 2017 Outlook for Energy: A View to 2040, ExxonMobil).

Electrification of transport

There are different degrees of electrification. The lithium-ion battery, along with the associated power electronics, is the single most expensive component of an electric vehicle and its size and cost depend on the degree of electrification and the vehicle size and range using only electricity.

Only battery electric vehicles (BEVs) derive all their energy from electricity from the grid. All other 'electric' vehicles have hybrid powertrains and derive some or all of their energy from an ICE. Different levels of hybridization enable fuel saving to different degrees. In full parallel hybrid electric vehicles (HEVs), such as the Toyota Prius, a battery and an electric motor enable the ICE to run more efficiently and also to recover energy from braking, but all the energy comes from the ICE. Plug-in HEVs (PHEVs) have a relatively larger battery than HEVs and allow a limited range on electricity alone.

The number of BEVs and PHEVs has been growing very fast but at the end of 2017 was still only estimated to be around 3 million globally – ~0.25 per cent of the total number of LDVs. If BEVs were to constitute even 20 per cent of the global LDV fleet (expected to number around 1.7 billion in 2040) their numbers would have to increase by more than a hundred-fold in the next 20 years or so. There are serious constraints on such massive and fast growth of BEVs, as discussed below. However, HEV technology is expected to become very widespread since it offers car manufacturers a proven way to reduce fuel consumption and CO_2 emissions to meet the stringent targets set by many governments.

Environmental considerations: BEVs have a greenhouse gas (GHG) impact resulting from the generation of electricity. In addition, high levels of GHG emissions are associated with battery manufacture and these increase with the battery capacity; such emissions could constitute a significant portion of the GHG emissions over its life for a BEV with a large battery. If the energy system is not sufficiently decarbonized, the life cycle GHG impact of BEVs could be worse than that of conventional vehicles.

BEVs do not produce any exhaust pollutants and policy initiatives in favour of full electrification in many countries are driven by concerns about local air quality in urban centres – in particular the impacts of particulates and nitrogen oxides (NO_x). However, if electricity generation is near urban centres, as in Beijing, and if coal remains a part of the energy mix, the impact on local air quality of fine particulates, sulphur dioxide (SO_2), and NO_x could be worse for BEVs compared to ICE vehicles (ICEVs) ('Well-to-wheels energy consumption and emissions of electric vehicles: mid-term implications from real-world features and air pollution control progress', Wenwei Ke, Shaojun Zhang, Xiaoyi He, and Jiming Hao, *Applied Energy*, vol. 188, pages 367–77, February 2017).

Even if the energy system supporting BEVs is completely clean and green, BEVs have a very significant impact on human toxicity, freshwater ecotoxicity, and freshwater eutrophication, emanating from the vehicle supply chain. In one study, the human toxicity potential (HTP) of a BEV, primarily caused by the production of metals required for batteries, has been estimated to be three to five times worse in comparison to a similar sized ICE which impacts human health via exhaust pollutants (*Battery Electric Vehicles vs. Internal Combustion Engine Vehicles: A United States-Based Comprehensive Assessment*, John W. Brennan and Timothy E. Barder, Arthur D. Little, 2016). These issues have not attracted much popular attention because all this pollution happens in faraway places where the metals needed are mined and the total number of BEVs has been small. Cobalt, required for battery production, is mostly sourced from the Democratic Republic of Congo (DRC); this has been classed as a 'conflict mineral' as it is extracted in a conflict zone and sold to perpetuate the fighting. There have already been stories in the mainstream media about children working in cobalt mines in the DRC and connecting their plight to EVs. If the number of BEVs has to increase by several hundred-fold, this environmental impact cannot be ignored.

'IF THE ENERGY SYSTEM IS NOT SUFFICIENTLY DECARBONIZED, THE LIFE CYCLE GHG IMPACT OF BEVS COULD BE WORSE THAN THAT OF CONVENTIONAL VEHICLES.'

Full electrification in the form of BEVs will remain relevant primarily to the small passenger car sector for some time to come because of the limitations on cost, weight, charging times, and the environmental impacts of batteries. For instance, Tesla recently introduced their 36 tonne (80,000 lb) truck with a 500-mile range. Realistic estimates suggest that the battery pack would have a charge capacity of at least 1000 kilowatt hour (kWh), take at least eight hours to charge with a Tesla 125 kW supercharger, weigh at least 5 tonnes more than a comparable diesel engine, and cost as much as an entire conventional Class 8 truck. So even though the BEV heavy duty truck might be technically feasible, it might not be commercially attractive, and if deployed in large numbers would have serious environmental impacts.

There is also some fanciful talk about purely electric air and marine transport. As an illustration, an Airbus A320neo carries 26,370 litres of fuel – namely around 256,000 kWh of fuel energy. A battery pack capable of carrying so much energy, assuming a future energy density of 180 Wh/kg, would weigh 1420 tonnes – 18 times the maximum take-off weight of the aircraft. A battery pack that could hold as much energy as the 4.5 million gallons of fuel carried by the large container ship *Benjamin Franklin* would weigh around five and a half times the dead weight tonnage of the ship.

Moore's law for microchip development (stating that computer processing power will double approximately every two years) is often invoked to suggest that the energy density and the cost of batteries will improve quickly and significantly to make BEVs more practical and cheaper than ICEVs. However, battery capacity cannot improve very much more unless new battery chemistry is developed and commercially deployed. Unlike the premise of Moore's law (electrons do not take up space in a microchip, so their size does not limit processing capacity) ions in a battery do take up space, and potentials are dictated by the thermodynamics of the relevant chemical reactions. Gains in performance in the fields of materials, energy, and transportation range mostly from 1.5 to 3 per cent a year, as do the declines in cost, proceeding at rates that are lower by an order of magnitude than those seen in microelectronics ('Moore's Curse', Vaclav Smil, IEEE Spectrum, 19 March 2015).

'BATTERY CAPACITY CANNOT IMPROVE VERY MUCH MORE UNLESS NEW BATTERY CHEMISTRY IS DEVELOPED AND COMMERCIALLY DEPLOYED.'

Availability of materials needed for battery production: If BEV numbers are to increase by a factor of several hundred, there will be significant pressure on the availability and cost of materials needed for batteries. The extraction process for lithium is laborious and the reserves, though abundant, are concentrated in a few countries, such as China and Chile, which might be unable or unwilling to ramp up the production rates to meet increasing global demand. BEVs will also need much more cobalt, nickel, and copper, which might have limited availability. The increasing cost of these materials will put a brake on the reduction in battery pack cost that is hoped for.

Recycling batteries: As the number of BEVs grows, the recycling of batteries will become increasingly important, both to salvage material to reduce the impact from the supply chain and to dispose of waste safely. Recycling lithium-ion batteries is complicated because of the way they are assembled and because the battery packs will vary in shape, will be large and heavy, and contain many different materials. Very many details need to be worked out to set up a commercially and environmentally viable recycling system ('The future of automotive lithium-ion battery recycling: charting a sustainable course', Linda Gaines, *Sustainable Materials and Technologies*, vol.1–2, pages 2–7, December 2014). The weight of batteries to be handled will be exceptionally large compared to, for example, lead–acid battery recycling – the battery pack in a Tesla S weighs 544 kg.

Impact on the power sector and charging infrastructure of full electrification: People will not buy BEVs unless a convenient and quick charging infrastructure is available. Changes to electricity generation and distribution will also be required if the aim is to replace conventional cars by BEVs.

In the document 'Our energy insights. Forecourt thoughts: Mass fast charging of electric vehicles' (Orlando Elmhirst, National Grid, April 2017) the UK's National Grid discusses the challenges to be faced in meeting total electric energy and peak power demand, as the number of BEVs increases to form a significant proportion of the car park. In the UK, 43 per cent of car owners have no garage access and will need public charging facilities; as for the rest, too many domestic charging points would overstress the electricity network. Thus any significant penetration of electricity in the transport sector would require large prior investments in charging infrastructure, additional power generation, and new approaches to grid management.

'ELECTRICITY GENERATION NEEDS TO BE SUFFICIENTLY DECARBONIZED FOR BEVS TO HAVE AN ADVANTAGE OVER ICEVS.'

Other economic consequences of full electrification: Currently BEVs are subsidized in many ways and such incentives will be needed to encourage customers to buy BEVs until they can compete with ICEVs on cost and convenience. As BEV numbers grow, the cost of such subsidies will increase. In addition, governments will have to find ways of recouping fuel taxes, which contribute significantly to public finances, perhaps by taxing electricity or imposing a mileage tax, increasing the total cost of ownership of the BEV.

Autonomous driving and BEVs: It is often suggested that autonomous drive technology will help the deployment of BEVs. However, the sensors, additional computing, and data processing needed by autonomous cars will require an additional 1.5 kW to 2.75 kW of power. Also, the car will need heating in the winter and air conditioning in the summer, which would require 3 to 5 kW of power. An autonomous car being used for taxi service/ride sharing in a city would be expected to be on call for 24 hours a day. If it has a 50 kWh battery, the additional energy requirement over 24 hours would be two to three times its battery capacity before it travels any distance at all. In fact, a more sensible option for autonomous driving would be an HEV, which is powered by an ICE and not a BEV.

Conclusion

BEVs simply shift their emissions impact from the tailpipe to somewhere else, while many governments appear to be promoting BEVs on the assumption that they are zero-emission vehicles. Electricity generation needs to be sufficiently decarbonized for BEVs to have an advantage over ICEVs on a life cycle basis in terms of GHG emissions. While this may be true in some areas, it will not happen for decades in rapidly growing markets like China and India, because coal will continue to be an important part of the electricity generation mix. Also, in such areas, if electricity generation is not sufficiently distant from urban traffic centres, the impact on urban air quality of pollutants like particulates, NO_x, and SO_2 could be even higher for BEVs compared to ICEVs. Other serious environmental problems associated with the production of metals required for batteries will also loom larger if BEV numbers grow, even if these problems are exported to countries which produce these metals. Meanwhile, ICEs with better control and after-treatment systems, and assisted by partial electrification, will continue to evolve to reduce both their GHG and pollution impacts.

The cost of BEVs is expected to come down while their range increases in the future, but until then incentives will be required to persuade people to buy them. The cost of these

incentives will have to be borne by the governments promoting this change, or be forced on to BEV manufacturers via legislation. Even if the cost of BEVs becomes comparable to ICEVs in the future, huge prior investments in charging infrastructure and extra electricity generation to enable such change will be required. In the longer term, the lost revenue from fuel taxes, which contribute significantly to public finances in most countries, will have to be recouped.

The existing transport system, built around the ICE, meets an essential need and supports a large number of jobs. Dismantling such a system abruptly, say by banning the production of ICEs as some politicians suggest, will have huge economic and political impacts. The very large investment needed to build a new system based around BEVs has to be balanced against environmental or other benefits assessed honestly on a life cycle basis.

'ICES WILL CONTINUE TO POWER TRANSPORT, PARTICULARLY COMMERCIAL TRANSPORT, TO A LARGE DEGREE FOR DECADES TO COME AND WILL CONTINUE TO IMPROVE.'

Full electrification of all transport would not be possible in the short term in any case since commercial transport – heavy duty road, air, and shipping – cannot be realistically run on electricity alone and will continue to be powered by ICEs. Converting even 20 per cent of light duty vehicles to BEVs will require their numbers to increase by over a hundred-fold. Such a large increase will have a huge impact on the environment, and on the price and availability of materials required for battery production which may not be sustainable.

ICEs will continue to power transport, particularly commercial transport, to a large degree for decades to come and will continue to improve. There will also be a role for low-carbon and other alternative fuels where they make sense. In the longer term, as electricity generation is decarbonized and battery technology improves, there will be an increasing role for BEVs and the required charging and recycling infrastructure will evolve. Meanwhile, there will certainly be increasing electrification, particularly of LDVs in the form of hybridization to improve ICEs. There needs to be a balanced approach to improve the sustainability of the transport sector using all available technologies, taking into account environmental, economic and social impacts, and energy security.

Too early to write off oil – EVs will be an evolution not a revolution

Chris Midgley

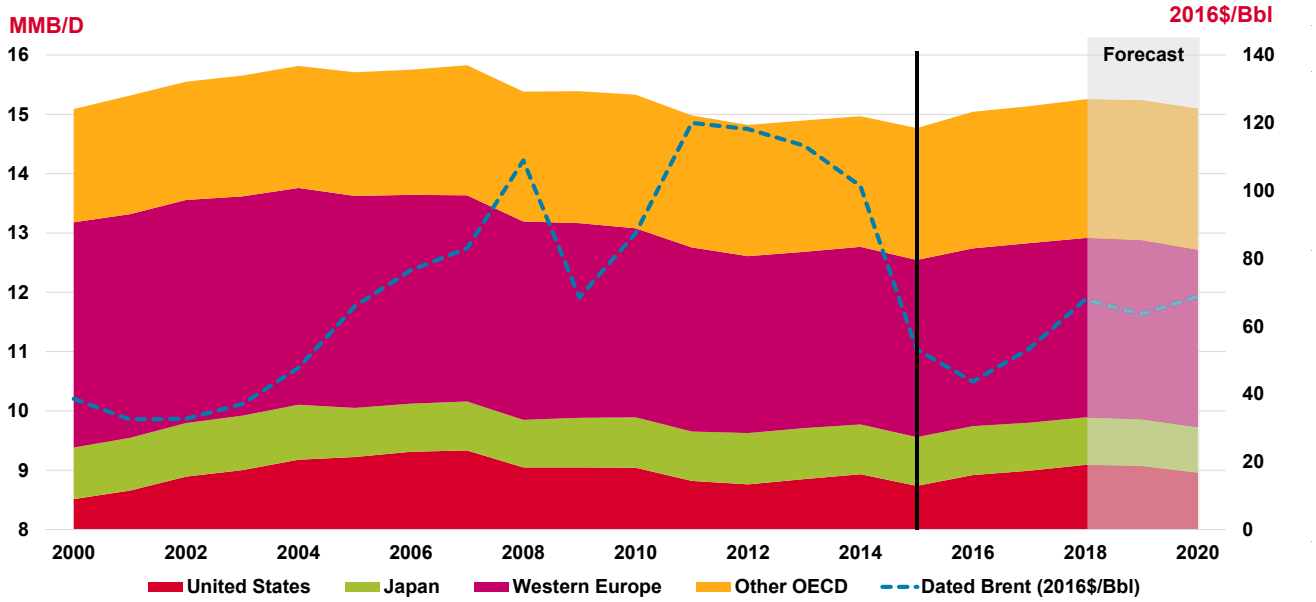
While there may be a lot of talk in the media about peak oil demand, it's far too early to be thinking about the demise of fossil fuels in the near term. Elements of the energy transition are upon us, but despite some straight-line correlations to desired outcomes, this transition is likely to be far more complex and provide us with many surprises to both the upside and downside along the way.

Uncertainty around future oil demand

Three years of low oil prices have stimulated strong sales of new cars, with a shift towards larger passenger vehicles (SUVs and light trucks), rather than the small economical (in terms of miles per gallon) cars which had dominated sales during the period of high oil prices pre-2015. Up until this point, oil demand for passenger vehicles had been steadily declining, as the vehicle fleet became increasingly efficient (see the figure opposite above). In 2016, this trend reversed in the OECD, with demand increasing for the first time in 11 years. Interestingly, most of the demand has not been due to the larger vehicles (although this arrested declines) but has been due to an increase in vehicle miles travelled per capita, partly as a consequence of the rise of rideshare. While car ownership may no longer be the priority for many, the growth of 'Mobility as a Service' has made road transport more accessible and affordable to a growing middle class – benefiting from the convenience of transport that picks you up and drops you off wherever and whenever you want, compared with the 'inconvenience' of public transport (such as buses and trains).

'THREE YEARS OF LOW OIL PRICES HAVE STIMULATED STRONG SALES OF NEW CARS, WITH A SHIFT TOWARDS LARGER PASSENGER VEHICLES …'

With the ever growing population of middle-income earners, air travel continues to grow year on year (4.9 per cent) and the demand for goods and services has seen shipping and commercial road transport demand increase year on year by 3.6 per cent and 2.2 per cent respectively. With growing urbanization and a buoyant global economy, this trend is likely to



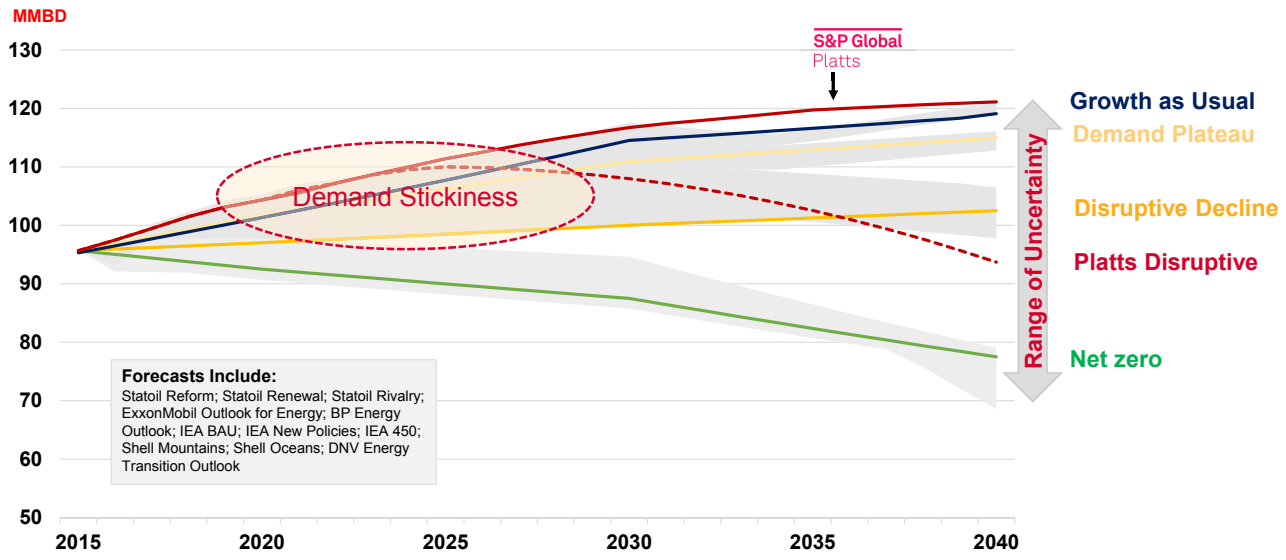
OECD passenger car oil demand (2000–20)

Source: S&P Global; MI/SNL; Platts.

continue providing strong 'demand stickiness' for fossil fuels in the near term, which many commentators have failed to factor in when considering the future trajectory for oil demand (see the figure below). The range of uncertainty in future demand has grown substantially, making planning for the future and investments far more challenging across the industry.

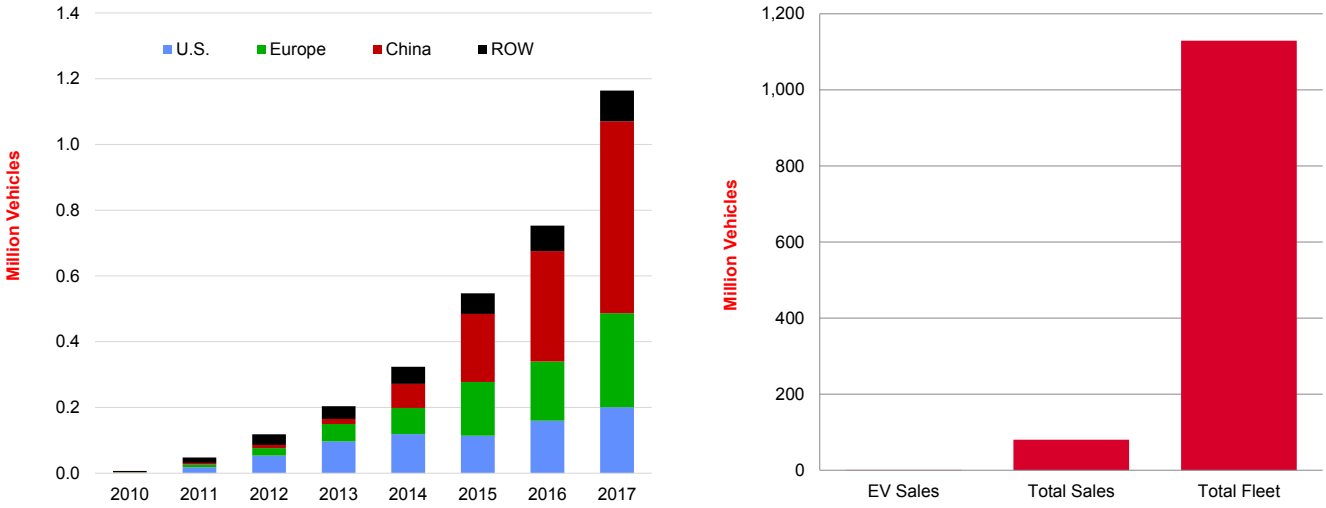
Efficiency standards and electric vehicles

Sixty per cent of oil demand comes from transportation, with the predominant focus being on passenger vehicles, which make up just 25 per cent of that demand. Today, dozens of countries have fuel efficiency standards for passenger vehicles, while just a handful have them for heavy duty commercial trucks. In the passenger vehicle sector all the hype is around electric vehicles (EVs), yet despite a 55 per cent growth in EV sales last year, overall sales amount to less than 2 per cent of new car sales, and less than 0.2 per cent of the total fleet (see the figure overleaf). Today's 3 million EVs displace less than around 60,000 b/d, or less than 0.06 per cent of total global demand.



Forecasts of oil demand

Source: S&P Global; MI/SNL; Platts.



Electric vehicle sales, including plug-in electric hybrid vehicles (PHEVs) and battery electric vehicles (BEVs) (left); total vehicle sales and total vehicle fleet in 2017 (right)

Source: S&P Global; MI/SNL; Platts.

Unlike the transition in the early 1900s from the horse and buggy (when it took just 13 years for the Internal Combustion Engine to wipe out almost all the buggies), EVs do not represent the same marked improvement in convenience or quality of life, and in fact have drawbacks in costs, range, and ease of refuelling (charging). Momentum is certainly building around EVs and hybrid variants of the technology as viable alternatives to the future of mobility. Plug-in ranges are increasing and charging times are falling.

EVs have fed anxiety over the future of oil as the world's primary source of transport fuel. However, EVs are likely to remain a small part of the overall global vehicle fleet unless the technology improves significantly and the cost of production falls. The cost of batteries has certainly come down significantly over the last seven years (from $1000 per kilowatt hour (kWh) to around $200/kWh) but at the same time demand for the key metals lithium and cobalt above tripled (see the figure opposite top), thus increasing the cost of the raw materials from 10 per cent to 40 per cent of the battery pack. In some countries with high oil prices, battery costs may come down to compete with internal combustion engines. However, as battery prices decrease, the cost of metals is likely to increase in line with demand, resulting in the raw materials' cost increasing to around $75/kWh (see the figure opposite top). This represents a floor price which will limit the competitiveness of batteries unless manufacturers can dramatically improve energy density (therefore reducing the amount of metals required).

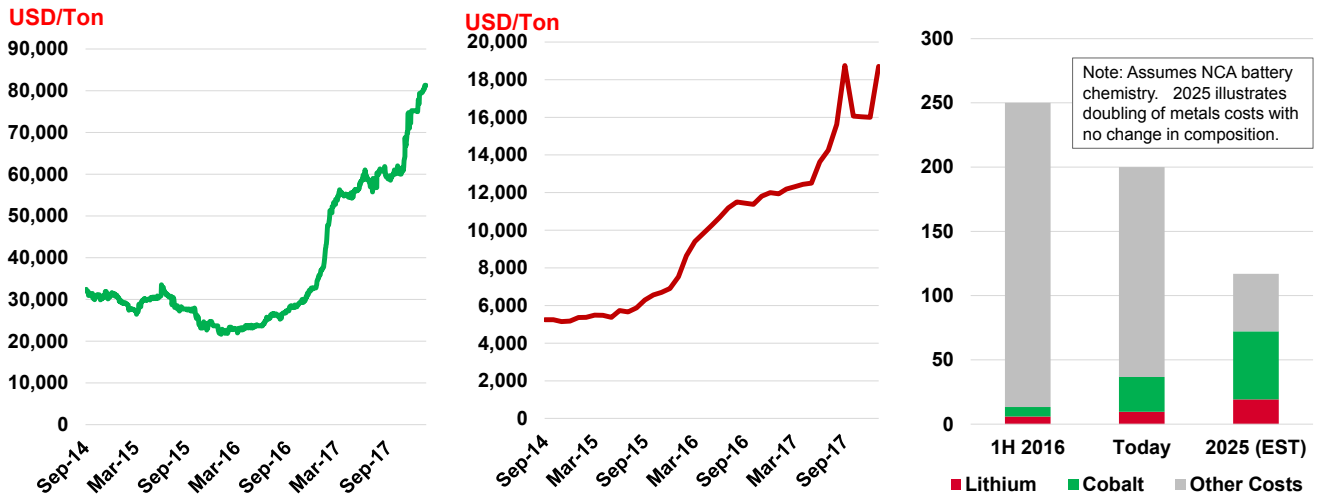
Government policies

Government subsidies have, in some countries, helped to give massive upsurges in demand for BEVs. However, this has hit the treasury coffers twice: through the cost of subsidies, and in the loss of revenues from duties on fuels. It has been seen that the swift removal of such subsidies has resulted in an equally swift decline in sales. Addressing the budget balance (the UK generates $30 billion per annum from road taxes and duties) is one issue, but if governments are serious about EVs they need to be investing in the charging infrastructure not in subsidies.

'… IF GOVERNMENTS ARE SERIOUS ABOUT EVS THEY NEED TO BE INVESTING IN THE CHARGING INFRASTRUCTURE NOT IN SUBSIDIES.'

In reality, governments have become increasingly focused on air quality. Following the VW scandal, diesels have been marred by bad press. While old diesels have high NO_x and particulates emissions (damaging to health) it is worth noting that new Euro 6 diesels have emissions comparable to EVs. With less acceleration and being lighter (not carrying the battery weight), they also create less stirring up of road dust and less tyre and brake degradation. The debate on air quality should not be about new car sales but about removing the old fleet; scrappage schemes would have a far greater impact on air quality and fuel efficiency than any bans on internal combustion engines kicked down the road to 2040!

With new cars being much cleaner, the focus should move to the greenhouse gases (GHG) footprint – which would be greatly superior for EVs powered on 100 per cent renewables. However,

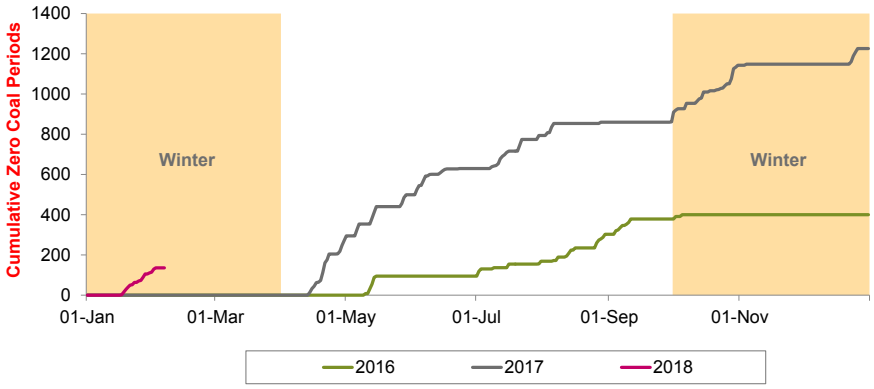


Global average LME cobalt cash price (left); global average lithium carbonate price (centre); battery pack price (USD/kWh) (right)

Source: S&P Global; MI/SNL; Platts.

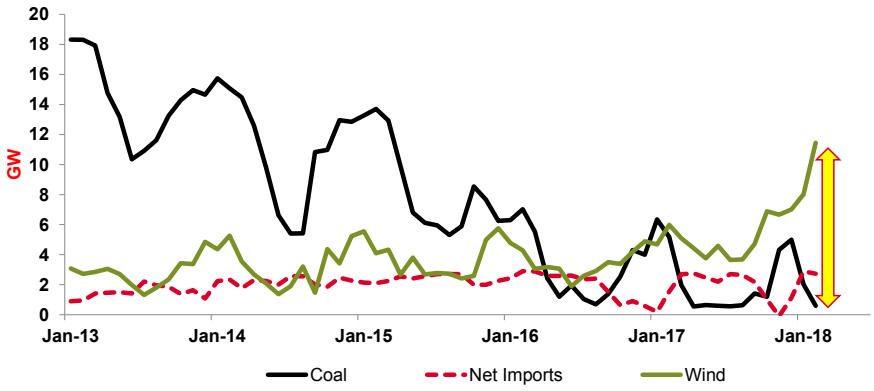
charging infrastructure and habits are unlikely to be conducive to taking advantage of renewable peak electricity production and may often pull 'dirty electrons' from marginal coal-generated electricity, resulting in a much higher CO_2 emissions/km than conventional vehicles. While the UK has had far more zero coal hours in 2017 than since coal generation was introduced, it has also seen generation peak at 8 GW in the same months, as it has been called on to export electricity to France due to nuclear outages (see figures to the right and overleaf). Therefore, governments must find ways to decarbonize the grid and find solutions to energy storage to manage the intermittency of renewable supply.

In places like China, where a larger proportion of car sales are to first-time buyers, the change may be far more dramatic especially as China Inc. sees the opportunity to leapfrog the technology and take the lead in the development of batteries, EVs and, furthermore, autonomous vehicles (AVs). The impact of the uptake of AVs is complex. Vehicle miles travelled are likely to increase, but quicker fleet turnover could hasten ultimate efficiency gains.



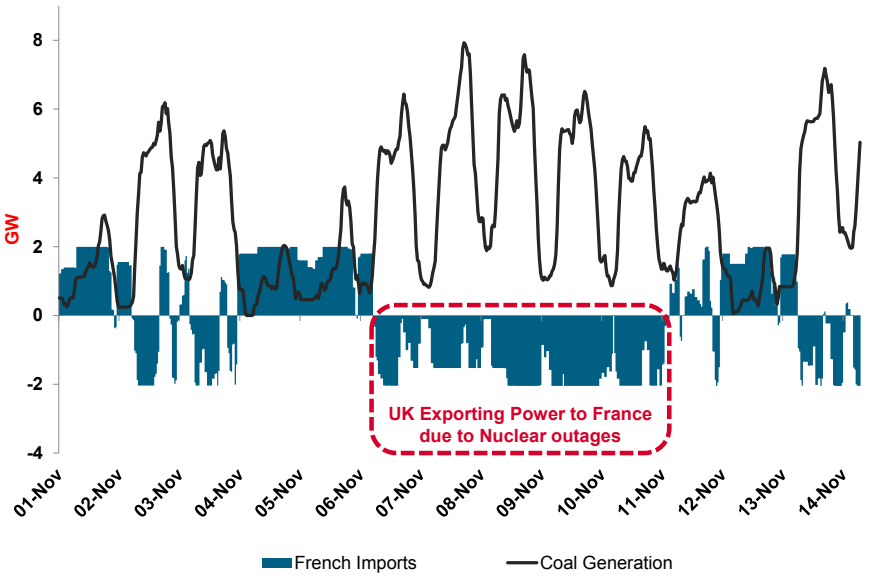
UK cumulative zero coal running periods by year

Source: S&P Global; MI/SNL; Platts.



UK monthly generation mix (GW)

Source: S&P Global; MI/SNL; Platts.



Coal helps fuel UK exports to France (November 2017)

Source: S&P Global; MI/SNL; Platts.

Future oil demand and alternatives

S&P Global Platts Analytics' projections are that oil production will have to increase in order to meet rising demand from road transport for years to come – from around 100 million b/d today to just under 125 million b/d in 2040 (under the S&P Global Platts Analytics 'most likely' reference case). Even with aggressive penetration of EVs it will take until late in the next decade before an inflection point in oil demand is observed, with most demand destruction in the next 10 years coming from fuel efficiency rather than EV displacement.

However, while all the focus is on passenger vehicles, we believe commercial road transport could be the game changer with faster turnover of the fleet. Heavy-duty trucks and long-distance coaches are infeasible for EVs and these travel the largest proportion of road miles in their sector. There are a number of options and pathways for this sector. Dual-fuel engines provide the opportunity to greatly improve efficiency – using diesel when the torque is needed to accelerate or go up hill, but using LNG, gasoline, or ethanol when cruising (most likely 85 per cent of the time). To get closer to zero emissions, the LNG or ethanol would need to be sourced from 100 per cent renewable sources, such as renewable natural gas from biodigestors/landfill and second-generation ethanol, which would be challenging.

'… OIL PRODUCTION WILL HAVE TO INCREASE IN ORDER TO MEET RISING DEMAND FROM ROAD TRANSPORT FOR YEARS TO COME …'

Alternatives for this sector could involve the use of fuel cells and hydrogen; this could become the biggest disruptor, not only enabling the commercial fleet to turn over quickly but also providing a clean option for passenger vehicles, and one which also has the benefits of range and fast recharging. Distributed hydrogen, produced at small scale in retail sites, could solve issues of distribution cost and energy storage by utilizing low-cost electrons during low-demand periods to produce the hydrogen. In a hydrogen mobility study by the Intistut für Elektrochemische Verfahrenstechnik (IEK-3), it was identified that hydrogen infrastructure would be cheaper once the passenger vehicle fleet hit one million – this would happen much faster if commercial road transport went first and retailers provided distributed solutions.

Other potentially significant disruptors could come in aviation and chemicals. Public and corporate pressure (moral regulation) may force airlines to decarbonize by using a drop-in (or straightforward replacement) fuel produced from renewable biofuels/gas or from a conversion of renewable power to liquid form. The rapidly rising awareness of the current plight of our oceans (caused by plastic waste) is encouraging increased corporate action (self-regulation) in the use of recycled plastics and reductions in packaging.

Conclusions

There is no denying that we are at the start of a transition. Big oil companies are already adapting rapidly by investing heavily into the production of cleaner fuels (including liquefied natural gas) and by installing charging points into their service station networks. Some are going a step further by investing in power generation, distribution, and battery storage. To achieve the objectives of the Paris Agreement, we are going to need to focus our minds not just on electric mobility but on more disruptive areas – including the other 80 per cent of oil demand!

(The data and analysis in this article is based on the author's article in Changing Lanes, recently published by S&P Global Platts.)

Electric vehicles and electricity

David Robinson

Introduction

There is a broad policy consensus that penetration of electric vehicles (EVs) will rise throughout the world. In European cities, EVs could reach close to 100 per cent by 2050. This article, with a focus on Europe, examines the relationship of electricity to EV penetration – in particular whether the electricity system and its regulation could be barriers to this penetration, or indeed be assisted by them.

The article makes three points:

1 While electricity is a requirement for the penetration of EVs, other factors are more important determinants of penetration.

2 The requirement for investment in electricity infrastructure is unlikely to be a barrier to EV penetration, at least in Europe – indeed the flexibility offered by EVs could aid the integration of intermittent renewables and this should favour investment in infrastructure.

3 Current electricity regulations in some European countries are barriers to EV penetration and should be eliminated as a matter of good regulatory practice.

'THE ELECTRICITY SYSTEM IS GENERALLY JUST REACTING TO THE PENETRATION OF EVS – WHICH IS MAINLY BEING DETERMINED AT THIS STAGE BY PUBLIC POLICY SUPPORT.'

1. What is driving EV penetration?

Electricity charging networks and generation capacity are obviously necessary for the penetration of EVs. The cost of electricity, the approach to charging, and the potential to sell vehicle to grid (V2G) services are also relevant. However, the electricity system is generally just reacting to the penetration of EVs – which is mainly being determined at this stage by public policy support.

The IEA's *Global EV Outlook 2017* details the significance of public policy support for EV penetration. Many governments (such as the UK and France) have adopted targets for EV penetration or policies to promote them. Policy support typically includes either demand-side subsidies or supply-side obligations (for example zero-emission vehicle, or ZEV, mandates), or some combination of these. Norway, for instance, has provided substantial fiscal and other incentives for consumers to buy EVs. California, on the other hand, has introduced ZEV mandates, which embed a system of tradable credits, for automakers to sell a set proportion of zero-emission vehicles. In most countries, we also see tightening emission standards (for CO_2, NO_x and particulates), with a growing number of national or local governments introducing low-emissions zones, diesel bans, and full phasing out of gasoline and diesel vehicles.

In its 2011 EU Transport White Paper, the Commission outlined a road map that halves the use of conventionally fuelled cars in urban transport by 2030 and phases them out entirely by 2050. The justification for public policy support is primarily related to the environment, although reduced dependence on imported oil is also relevant. (See *Electric Vehicles in Europe*, European Environment Agency Report No 20/2016, 23 September.)

- First, EVs help to meet EU climate change targets. While greenhouse gases (GHG) from all other major economic sectors in the EU have fallen in recent decades, road transport's emissions have risen and in 2014 were about 17 per cent above 1990 levels. Furthermore, the contribution of road transport to total EU GHG emissions increased from 13 per cent in 1990 to 20 per cent in 2014.
- Second, EVs help to reduce local air pollution, especially NO_2 and particulates. Most large cities today are concerned about the impact of local pollution on the health of their citizens. The EU's annual limit for NO_2 was widely exceeded across 19 Member States in 2013, mainly at roadside locations, and a number of Member States report particulate matter (PM) levels that are higher than EU air quality standards allow, resulting in a significant number of premature deaths. As a consequence, the European Commission has brought infringement proceedings against a number of Member States, and many cities have introduced restrictions on diesel and gasoline vehicles.
- Third, road traffic noise harms human health and well-being. According to the European Environmental Agency, in 2012 almost 90 million people living in cities were exposed to long-term average noise levels that exceeded EU thresholds.

These justifications for policy support have been questioned.

- Some studies argue that the main externality in relation to private vehicles is congestion – although this is not a consensus view.
- The potential for EVs to reduce GHG

emissions is limited, especially where electricity remains carbon intensive.

- Even though subsidies are justified when fossil fuel externalities are not internalized, at some point subsidies may be financially unsustainable. Furthermore, as the cost of EVs falls, they may not require policy support.
- Many people employed in the transport business will resist restrictions on their conventional vehicles and oppose the introduction of autonomous EVs.
- Privately owned EVs are not the only form of zero carbon mobility; governments may choose to support other forms.

These and other qualifications certainly do not vitiate the public policy case to support EVs, and they can all be challenged. But they could condition EV penetration in future. For instance, concerns over congestion in Norway and in other countries could lead to measures other than electrification of personal vehicles, including improved public transport, mobility sharing, bicycle lanes, pedestrian areas, and urban planning that limits access to all private vehicles.

In future, the central reason for rapid penetration of EVs is likely to be the falling cost of EVs and batteries, the increased range of EVs, policy restrictions on internal combustion engine (ICE) vehicles, and the decision by major car manufacturers to invest heavily in EVs. For instance, according to the IEA, by April 2017, nine global original equipment manufacturers (OEMs) had publicly announced their willingness to create or significantly widen their electric model offer over the next five to ten years. Several Chinese OEMs also announced very significant electric car production capacity scale-up plans (see *Global EV Outlook 2017*).

When the purchase costs of EVs are below those of equivalent ICE vehicles, the economic benefits of EVs will be more evident. This is primarily due to the superior energy efficiency of EVs (three to four times more efficient than ICEs) and related savings in fuel costs, but also to the lower maintenance costs and remaining subsidies. Most forecasts suggest that purchase price equivalence will be reached well before 2030. Ignoring subsidies and fuel savings, Bank of America Merrill Lynch argued in the autumn of 2017 that the inflection points (at which the cost of ICEs and EVs are equivalent) could be 2024 (Europe–diesel), 2027 (USA), 2028 (Europe–petrol), and post-2030 (China).

'WHEN THE PURCHASE COSTS OF EVS ARE BELOW THOSE OF EQUIVALENT ICE VEHICLES, THE ECONOMIC BENEFITS OF EVS WILL BE MORE EVIDENT.'

Finally, the penetration of EVs depends critically on other determinants of future mobility options inside cities. These include: the development of autonomous vehicles, shared mobility, consumer preferences (to not own or drive vehicles, the 'cool effect' of EVs), and the cost of alternative sustainable mobility options.

2. Electricity investment will not be a barrier to penetration

People often ask whether electricity networks and generation will be able to cope with the increased penetration of EVs. In Europe, the electricity system should not be a barrier because the investment requirements are well within historic norms in the sector, as explained below. Furthermore, penetration of EVs will provide flexibility to the electricity system, facilitating the integration of intermittent renewables. However, there is uncertainty about what the investment costs will be, primarily in relation to the choice of the charging infrastructure.

Charging infrastructure options

There are many possible charging infrastructure models, including the following:

- *Home charging*: This produces relatively few electricity problems as it can be done overnight and in a flexible way. But this depends on the specific city – both its physical layout and its regulations. For instance, in the UK, National Grid (NG) argues that home charging is only really suitable for a minority of homes – those with private drives. Flats raise further complications – in some cases there will be access to collective parking but for many there will not be.
- *Roadside charging points:* A substantial EV fleet requires a significant network. This raises public policy problems, such as whether non-EVs be allowed to park at charging points. If so, this limits their availability for EVs and wastes an expensive asset; on the other hand, denying owners of ICE vehicles most of the available parking space would be difficult. The problem is essentially one of congestion, although EV penetration will reduce the number of ICE vehicles. Furthermore, it is not possible to generalize about the electrical implications.
- *Fleets:* Central overnight charging of fleet vehicles is probably the most efficient model for EVs. One would expect fleets of autonomous vehicles and shared vehicles to be EVs. But will this model of car sharing be applicable to private transport? To assess this, one would need to address questions such as how far consumers are prepared to forego the optionality of a private vehicle and rely on hiring as needed, and how public policy makers will view the issues.
- *Fast charging at gas stations:* This is certainly going to be needed. However, the implications for

electricity are very different from the previous options; there could be significant additional local capacity and generation needs. But those in turn depend on how fast the charging will need to be. In any case, as illustrated below, the investment requirements do not seem to pose serious problems.

- *Battery replacement:* This would allow flexible recharging and, in terms of the customer experience, is probably closest to the current model of a quick in-and-out to the garage. However, it is difficult to see a business model without strong public policy support (for example on standardizing battery and vehicle design) and it could be expensive – presumably you would need to have a lot more batteries than cars.

There are three conclusions. First, there are many options and it is not clear which will dominate, although fast charging will probably be central. Second, all would require public policy support or facilitation, at least at the outset, and it may be necessary for government to give positive guidance on the way forward to avoid or reduce the risk of stranded investment. Third, electricity considerations are unlikely to determine the choice and it is not even obvious which option is best from the electricity point of view. Decisions are going to be made in response to a combination of other factors – such as infrastructure, consumer preferences, and policy considerations – and the electricity industry will then need to respond.

Investment in electricity generation and networks – UK example

Investment in the electricity sector could be a barrier to EV penetration if policy was unclear and the investment did not occur. On the other hand, the analysis below for the UK suggests that investment requirements to support high EV penetration are well within historic norms. The analysis should also work for Europe since most European countries use similar vehicles and have similar driving patterns. The analysis for North America and the rest of the world may be different, but to the extent that penetration occurs quickly in Europe, this could well accelerate penetration elsewhere.

'ANALYSIS … FOR THE UK SUGGESTS THAT INVESTMENT REQUIREMENTS TO SUPPORT HIGH EV PENETRATION ARE WELL WITHIN HISTORIC NORMS.'

In its Consumer Power scenario, National Grid (NG) assumes 90 per cent penetration of EVs by 2050 and concludes that this would increase demand by 46 TWh, compared to 308 TWh in 2016 (see *Future Energy Scenarios*, National Grid, July 2017). That increase is only 12 per cent of assumed 2050 consumption (383 TWh). This implies that EVs would increase electricity consumption by about 15 per cent over 30 years, below historic norms. Since electricity demand has gone down 11 per cent since 2008, there might not even be an overall increase in demand.

As far as peak demand is concerned, it depends on the charging scenario, since a sensible charging structure would encourage off-peak charging (thereby reducing peak demand). NG estimates an increment of 18 GW, or about 30 per cent of today's peak demand. This probably reflects a central planner's caution (in other words, everyone charges at the same peak time). Even with that as a worst-case scenario, it would require construction of only about 600 MW of new capacity a year over the period – well below levels of construction over past decades. For instance, compare the requirement of 18 GW over 30 years with the construction of about 30 GW of gas capacity in the 20 years from 1990.

It might be argued that electricity will have to cope with problems arising from the intermittency of new renewables and that EVs could be the straw that breaks the camel's back, but that argument is unconvincing.

- First, the intermittency challenge is likely to lead to more flexible market structures and to more storage and demand response, which is precisely what EVs can offer to the electricity system.
- Second, it will almost certainly be easier to try out some of the new ideas to integrate transport, for instance through vehicle to grid (V2G) sales.

As regards infrastructure costs, the UK's Committee on Climate Change published an analysis earlier this year (see *Plugging the Gap: An Assessment of Future Demand for Britain's Electric Vehicle Public Charging Network*). Two key points stick out.

- The cost is again fairly modest. They say about £530 million would be needed by 2030 to stay on track for the 2050 target (less than £50 million a year – this compares with the £8 billion or so a year being spent currently on renewables).
- Over 90 per cent of the cost is for roadside charge points.

They assess the infrastructure cost of fast charging at filling stations on motorways and major roads as more or less trivial (£30 million over the period). This is consistent with a thought piece by NG which says it might actually be easier from an electricity point of view to focus on fast charging rather than roadside or home charging, because it would mean less extensive strengthening of local distribution systems. However, not everyone takes this view in favour of fast charging, and it could reflect NG's preference for charging directly from its high voltage transmission network.

In conclusion, assuming European conditions are roughly similar to those in the UK, investment in electricity infrastructure in itself should not be a barrier to penetration of EVs in Europe. Indeed, EVs contribute flexibility to the electricity system and are key to the integration of intermittent renewables. The issues lie elsewhere, and particularly in the area of policy and consumer preferences.

3. Energy sector regulatory and fiscal barriers to EV penetration

The current taxation and regulation of energy in some European countries forms barriers to EV penetration.

Taxation

In many European countries, taxation does not fully internalize the negative environmental externalities of gasoil and gasoline. Furthermore, many countries recover the cost of public policies (notably renewable subsidies, for example) through electricity, even though these policies aim to meet a wider public good. These policies make electricity more expensive relative to fossil fuels and discourage a shift towards EVs. Good public policy would tax fully the negative externalities and shift policy costs from electricity to general taxes or share them with other energies.

'THE CURRENT TAXATION AND REGULATION OF ENERGY IN SOME EUROPEAN COUNTRIES FORMS BARRIERS TO EV PENETRATION.'

The rising cost of fossil fuels (from higher taxation and tighter emission restrictions) will penalize the owners of ICE cars and small trucks. Governments should consider ways to compensate the losers, for instance via tax rebates, better public transport, or in other ways.

Finally, the penetration of EVs will eventually lead to a decline in revenues from fossil fuel taxes. These revenues must be recovered elsewhere to pay for road and other infrastructure, most likely through congestion or other road charging.

Electricity pricing structure

Current tariff structures neither adequately reflect the variation in wholesale energy prices nor the impact of demand on networks' congestion and costs. The result is poor signals for shifting demand to periods when electricity prices are low and networks are underutilized; this lack of appropriate signals raises the cost of charging EVs because consumers charge during periods of peak demand. Furthermore, fixed costs and public policy costs are often recovered through variable charges. This not only provides inefficient signals (in other words, variable charges which are higher than true variable costs will discourage consumption), but also encourages consumers to generate their own electricity when cheaper electricity is available from the system, or to leave the system altogether. Regulators should introduce dynamic prices reflecting real-time marginal system costs and recover only fixed system costs through the fixed component of tariffs. This will encourage EV charging in off-peak periods, when system costs and market prices are low.

Market design

Current design in most countries discourages the sale of distributed energy resources (DERs) – such as V2G services – in local or wholesale markets. Furthermore, wholesale market cost/price signals are not passed on to most retail customers, because wholesale markets and retail price signals are both distorted. Proposed reforms include allowing DER full access to wholesale markets, creating local markets for DER services (with these markets managed by an independent Distribution System Operator), and considering new market structures where prices reflect the value of flexibility (see for instance Malcolm Keay and David Robinson's 'The Decarbonised Electricity System of the Future: The "Two Market" Approach', OIES Energy Insight 14, June 2017).

Electric charging infrastructure

The absence of an adequate charging infrastructure slows EV penetration, whereas slow penetration discourages investment in infrastructure. To solve this chicken-and-egg problem, some companies have proposed that the government guarantee a minimum network of charging in cities and highways, to be provided either by distribution companies or through competitive tenders. This is one option. All possible solutions require public policy decisions with respect to the choice of the charging infrastructure design. Since there is potential for stranded network or generation assets, policy makers need to make some judgement with respect to how these risks should be shared. In all cases, there is potential to introduce competition in the development of the infrastructure.

'THE ABSENCE OF AN ADEQUATE CHARGING INFRASTRUCTURE SLOWS EV PENETRATION, WHEREAS SLOW PENETRATION DISCOURAGES INVESTMENT IN INFRASTRUCTURE.'

Beyond barriers

Public policy to favour sustainable mobility is not only, or primarily, about the elimination of electricity sector barriers to EV penetration, and guidance with respect to the charging infrastructure. Where governments

support EV penetration, they should also adopt active policies on the supply or demand side. The Norwegian experience of subsidizing EVs was successful in terms of EV penetration, but very expensive and favoured wealthy people. The supply-side approach, such as the ZEV mandates in California, imposes less cost on government budgets and appears to favour innovation. Of course, governments may choose other means of achieving sustainable transport policy goals, including support for public transport, sharing models, the use of bicycles, and low-carbon urban planning.

Conclusions

EV penetration will certainly accelerate. Although electricity is necessary for this penetration, it is not the key driver, nor need it be a barrier. Other public policy goals, societal changes, and technology are more important determinants. Nor is it yet clear precisely how EV penetration will affect the electricity sector, especially because this depends on consumer behaviour and the nature of the charging infrastructure which is still undefined or incomplete in most countries.

'IN EUROPE AT LEAST, THERE IS AN ECONOMIC CASE FOR ELIMINATING EXISTING FISCAL AND REGULATORY BARRIERS TO THE PENETRATION OF EVS.'

The analysis here suggests that investment in electricity generation and networks should not be an important barrier to the penetration of EVs, at least in Europe. On the contrary, it may offer an important source of flexibility, especially in the integration of growing volumes of intermittent renewable energy. However, in Europe at least, there is an economic case for eliminating existing fiscal and regulatory barriers to the penetration of EVs.

What about the rest of the world? The USA may take a more evolutionary path, due to higher private vehicle use and lower public policy pressure. However, the USA has hitherto been where the greatest innovations have occurred; it is likely to be at the forefront of other innovations. Developments everywhere will thus be affected by what occurs in the USA – for instance autonomous vehicles and the electrification of buses and trucks. It is also noteworthy that major US OEMs such as GM have decided that the future is electric. If costs fall substantially, EV penetration could rise quickly, especially for fleets, where decisions are based on 'spreadsheets'. It is even harder to predict penetration in the major developing countries. However, if EVs do in fact penetrate quickly in the developed world, it is likely that this will accelerate penetration in the developing world. Furthermore, if renewables are any indication, it is very likely that EVs will be manufactured in China and other emerging countries, and that this will significantly reduce costs and accelerate penetration everywhere.

Energy storage technologies: the supply chain risks and opportunities

Simon Moores

Energy storage is not a new concept. We store energy in our phones, laptops, and power tools every day and recall and use this energy on demand.

However, the widespread adoption of energy storage – most critically in our vehicles and for our homes, offices, and energy distribution networks – is only just gathering pace owing to low-cost and abundant lithium-ion battery cells.

This trend was given impetus by the rise of lithium-ion battery megafactories – a term created by Benchmark Mineral Intelligence to describe the widespread expansion of battery cell production capacity around the world. Huge battery plants are now being constructed that are an order of magnitude larger than their predecessors.

In 2014, Tesla announced their Gigafactory in Nevada with 35 GWh of new cell production – the equivalent of 500,000 pure electric vehicles (EVs). At the time, this was the first ever plant to have a capacity of over 10 GWh.

'HUGE BATTERY PLANTS ARE NOW BEING CONSTRUCTED THAT ARE AN ORDER OF MAGNITUDE LARGER THAN THEIR PREDECESSORS.'

This sparked a global battery 'arms race' that has now led to a total of 17 megafactories in the pipeline, nine of which are in China and only two of which are based in the USA. In terms of production capacity from these megafactories, China will have 64 per cent and the USA just 13 per cent. The remainder of the planned plants are in Korea, Poland, and Sweden.

Despite this new 289 GWh of capacity adding to a global lithium-ion cell production of 80 GWh in 2016, according to Benchmark Mineral Intelligence data, the industry is still drastically short of capacity to meet projected demand of 550–650 GWh of battery cells by 2025.

These lithium-ion batteries will be targeted for use in the two largest growth markets – EVs and stationary/utility storage – the two uses that underpin the energy storage revolution.

Both markets are in their infancy. However, as these applications mature over the next 10 years, the scale of application and its disruptive effect on established auto and energy industries will be unprecedented.

Pure EVs – from cars to electric buses – are only entering the marketplace today and all are based on lithium-ion battery technology.

Consumer choice of pure EVs (vehicles that are 100 per cent battery powered and where a combustion engine plays no part) are beginning to become numerous. For example, 2017 saw the launch and/or rolling out of the pure EVs of Tesla's Model 3, Chevrolet's Bolt, and Nissan's new LEAF. These are the first sub-$35,000 pure EV offerings for the consumer and they have ushered in the era of the semi-mass market EV.

As we approach 2020, we are seeing every single major auto manufacturer announcing aggressive pure EV plans, all based on lithium-ion technology. Volkswagen Group, Daimler/Mercedes, Toyota, and Honda, for example, are all planning to sell lithium-ion powered EVs in millions of units annually post-2020. Meanwhile, the trend in e-buses has also started to gain traction outside of China, due to the efforts of California-based Proterra. These are much larger buses that have lithium-ion batteries up to ten times the capacity used in EVs.

The second major energy storage trend is that of stationary/utility storage. At Benchmark, we see the utility storage sector being at the same stage of development as EVs were in 2009: a limited number of installations around the world, with industry momentum increasing.

'THE BIGGEST CHALLENGE … IS SCALING THE SUPPLY CHAIN FROM THE MINE TO THE BATTERY PLANT IN TIME TO MEET DEMAND FROM THE AUTO MANUFACTURERS.'

Rise of lithium-ion technology

The lithium-ion battery is not new technology; however, its widespread commercial use has until now been limited to portable personal technology (mobile phones, laptops, power tools), hybrid vehicles, and a handful of EVs.

The lithium-ion technology currently in use is not just represented by a single variety of battery but comprises a selection of different lithium-ion types or chemistries; the ones of note are:

- Lithium Cobalt Oxide (LCO) – used in portable technology;
- Nickel Manganese Cobalt (NMC) – used in EVs and utility storage devices;
- Nickel Cobalt Aluminium (NCA) – used in EVs.

These chemistries are all lithium-based, despite the naming convention, and the critical raw material inputs are: *lithium, graphite, cobalt, and nickel*.

While other metals, such as copper and aluminium, are also used in a lithium-ion cell the speciality nature of the aforementioned minerals and metals – in other words, the need to process into a battery-grade chemically derived product that is tailored for each customer – increases the complexity of the supply chains.

In short, we are dealing with niche, speciality chemicals and minerals rather than commodities. The biggest challenge for this handful of specialities is scaling the supply chain from the mine to the battery plant in time to meet demand from the auto manufacturers.

Lithium: a speciality, volume problem

Lithium, the highest profile input into a lithium-ion battery, is sourced from Chile, Argentina (brine extraction), and Australia (traditional rock mining) and is also processed into battery grade material in the USA and China.

Lithium carbonate and lithium hydroxide are the base chemicals sought by the battery industry and the industry's demand profile is expected to increase eight-fold in a 10-year period to 2027. Demand pressures from the battery industry have already forced prices of these chemicals up by a factor of four in the last two years.

In 2017, the quantity of lithium carbonate equivalent (LCE) used in lithium-ion batteries equated to 80,000 tonnes. By 2027, even conservative estimates have battery demand closer to 650–700,000 tonnes. A complete evolution of the industry is required to take lithium from the niche into the mainstream.

Not only does lithium need to scale its extraction capacity but also its battery grade processing capacity, to meet the requirements of battery customers; this is an additional, specialized step. The USA has two major players in the lithium industry: Albemarle Corp. and FMC Lithium are among the world's largest lithium producers, sourcing predominately from brine operations in Chile and Argentina, respectively. Both producers have processing capacity in North Carolina.

In terms of lithium resources, the USA produces lithium chemicals from a small brine operation in Nevada.

Clayton Valley is one hotspot of exploration for new lithium brine, together with the Arkansas Smackover oilfield brine resource. Recent hard rock exploration for spodumene in North Carolina has also occurred, in a bid to secure domestic US lithium.

Graphite: an anode processing problem

Graphite anode, the largest input into a lithium-ion battery in kilograms, has a similar scaling issue. Graphite in batteries comes from two sources, naturally mined flake graphite and synthetic, man-made graphite.

In 2017, graphite anode used in lithium-ion batteries equated to 121,000 tonnes. By 2027, battery demand could be over one million tonnes.

Natural flake graphite mining is dominated by China with more than 70 per cent of global production in 2017, a position with which only Brazil can compete (producing 14 per cent of the world's 673,000 tonnes). This flake graphite is then sent to spherical graphite plants – all of which are presently located in China – to be processed into anode material.

Just under 60 per cent of the lithium-ion battery industry's anode is derived from natural graphite, with synthetic graphite – produced from graphitizing petroleum coke and tar pitch at very high temperatures – accounting for around 40 per cent.

Due to lower production cost, environmental and CO_2 impact issues, and ease of scaling supply, battery customers are trending towards using more natural graphite anode in their cells, but are still blending with synthetic graphite. The knowhow in blending different anode materials with differing raw material signatures is a matter of skill and intellectual property that will separate out the leaders of the pack.

While large flake graphite mines are being developed outside of China in Mozambique, Canada, and the USA, processing capacity to make anode material is still lagging. The USA has two graphite companies seeking to mine and process flake graphite for battery grade material in Alabama and Alaska.

Cobalt and nickel

The battery raw material with the second-highest profile is *cobalt*, mainly because 63 per cent of it was mined by the Democratic Republic of Congo (DRC) in 2017 and because China dominates the refining step in the supply chain, with over half of global capacity. Headlines regarding cobalt mined illegally in the DRC have dominated the cobalt discussion, despite the amount of illegal material in the market being relatively low – under 5 per cent of global supply (which was 104,000 tonnes per annum (tpa) in 2017). However, illegal cobalt in the supply chain has greatly concerned end users of batteries, mainly due to the corporate social responsibility impact on their businesses.

'ILLEGAL COBALT IN THE SUPPLY CHAIN HAS GREATLY CONCERNED END USERS OF BATTERIES …'

Major end users have moved to try to eliminate unethical cobalt from the supply chain and this has opened opportunities for developers of new mines based in the USA (Idaho), Australia, and Canada that could guarantee the provenance of their raw material.

In addition, cobalt's geological occurrence as a secondary mineral to nickel and copper means that it is produced as a by-product of these metals. There is only one small primary cobalt mine in operation in the world, in Morocco.

This means that the fortunes of cobalt – now driven by battery demand – are still at the mercy of nickel and copper commodities, which are driven by industrial demand. This is causing long-term planning issues for the EV supply chain.

Cobalt used in lithium-ion batteries equated to 44,000 tonnes in 2017, but this is set to increase to 120,000 tpa by 2027. While opportunities for producers outside the DRC are available, the sheer volume of new supply needed by the market means there will be no EV industry without DRC cobalt.

Most of the refining of cobalt to a battery grade material will occur in China.

Nickel – a raw material associated with cobalt but also mined individually – is growing in importance for lithium-ion battery consumers. The trend of using more nickel in a cathode and less cobalt is one that is just beginning in the commercial lithium-ion space.

For NMC formulations – a chemistry that will be number one in the EV and utility storage space – the industry has traditionally used a 1:1:1 formula: 1-part nickel, 1-part manganese, and 1-part cobalt. However, 5:2:3, 6:2:2, and 8:1:1 nickel-rich formulations are now being introduced into lithium-ion battery production lines around the world. This is a move that will see battery grade nickel demand grow from 15,000 tpa in 2017 to anywhere between 300,000 and 400,000 tpa by 2027, depending on which chemistries take hold.

While nickel metal is a commodity that is produced in the millions of tonnes a year, the battery grade chemical is a specialist material, with only a handful of major producers outside China. These include Japan's Sumitomo

Metals Mining, which operates mines and processing plants, and Belgium's Umicore. The vast majority of battery grade nickel sulphate is produced in China.

Interest in the market has seen major nickel miners such as Vale, BHP Billiton, and Rio Tinto seek to enter the battery grade space. However, not all nickel deposits can produce a commercially viable battery grade material. High and lower grade class 1 nickel deposits are the most suitable, yet the most capital intensive, to move into production.

Competing technologies to lithium-ion

Vanadium flow: For stationary storage applications, vanadium flow batteries have been the most talked about as being best-in-class for this application due to their superior lifetime versus that of lithium-ion batteries. The challenge for this market is finding a champion for the technology, with only a handful of producers competing for market share. The upfront cost of the technology is more expensive than lithium-ion and despite offering a longer lifetime, this is discouraging some buyers.

Vanadium flow is heavily reliant on the vanadium raw material that is processed into the form of vanadium pentoxide. Vanadium raw material output totalled 72,000 tonnes in 2016; however, vanadium pentoxide used in batteries represented less than 3 per cent of this demand.

Manufacturers of vanadium flow batteries will likely need to control or own their own raw material source, to minimize the raw material supply and price fluctuation risk, which can be very disruptive to the adoption of this technology. A major positive of this technology is that vanadium can be recycled, and some producers are looking at raw material leasing options for financing new battery installations.

Solid state: Solid state batteries are the most promising successor to lithium-ion, but this is a technology that is still many years from widespread commercial adoption.

Unlike a lithium-ion battery, a solid state battery has no liquid components and it uses a lithium metal or silicon anode. The gains in changing the anode are the main theoretical benefits over a lithium-ion battery; others include higher energy density and faster charging.

Solid state technology in the commercial world saw some activity in mid-2017. UK-based Dyson revealed that it aims to enter the EV market using solid state by 2020. This was made possible because of its 2015 acquisition of Sakti 3, a US-based solid state technology developer. A second, more recent, boost came from Porsche's confirmation that it will also seek to use solid state batteries in its 911 and Boxster post-2020 production models.

'SOLID STATE BATTERIES ARE THE MOST PROMISING SUCCESSOR TO LITHIUM-ION, BUT THIS IS A TECHNOLOGY THAT IS STILL MANY YEARS FROM WIDESPREAD COMMERCIAL ADOPTION.'

Widescale solid state battery adoption is far from guaranteed and it is yet to be seen whether solid state can work safely in real world scenarios. But the technology is widely tipped as the successor to lithium-ion in a post-2030 world.

2025 vision: lithium-ion here to stay, supply chains need to evolve

While there are huge opportunities with the energy storage revolution, there are also huge risks.

The demands that EV manufacturers are placing on raw material miners, chemical processors, and cathode manufacturers are huge – they are being asked to increase their business footprint by a factor of 5–10 in a seven-year period. At present, there is little desire to share the risks – both capital and commercial – of building new mines or of expanding their businesses, to meet this new demand.

Major auto manufacturers will eventually have to conclude that supply chain partnerships and capital investment are the only ways of securing lithium, graphite, cobalt, nickel, or lithium-ion battery cells. But this decision-making process is slow for players outside China and risks de-railing any form of revolution in the energy storage industry.

Market momentum is now with lithium-ion batteries – for this first phase of the energy storage revolution the choice has been made, certainly for EVs. Over $35 billion has been committed to expanding lithium-ion battery plants, while the lithium industry has raised $1 billion to build new supply.

However, this investment is short by some way. The investment into lithium-ion battery capacity needs to be four times larger to satisfy demand for the mid-2020s and it needs to be 10 times larger to create a new blueprint for a post-2030 world. The lithium industry, as an example, will need to raise $7–10 billion to keep pace with this new capacity and demand for EVs.

The USA is very active on EV innovation, mainly due to the activities of Silicon Valley-based companies like Tesla and Proterra. US involvement in the raw material-to-cathodes-to-battery-cell links in the supply chain is very limited, however, with the sway of industrial power lying in Asia-Pacific countries – most notably China, Japan, and Korea.

The energy storage revolution is global and unstoppable. In order to take advantage of this, it should be of paramount importance for countries and corporations to position themselves accordingly, and longer term (around 10-year) decisions need to be made.

Where we stand today, in 2018, China is not only at the centre of mass market EV development and deployment, but also of cathode production, battery grade raw material refining, and the building out of new battery cell capacity.

'THOSE WHO CONTROL THE LITHIUM-ION BATTERY SUPPLY CHAIN WILL BE THE BIGGEST INFLUENCERS ON THE NEXT GENERATION AUTO AND ENERGY INDUSTRIES.'

Those that control raw material and chemical/cathode refining knowhow and capacity will control the lithium-ion battery supply chain. Those who control the lithium-ion battery supply chain will be the biggest influencers on the next generation auto and energy industries.

The grid impacts of e-mobility

Constance Crozier

Introduction

In the UK, transportation currently accounts for 22 per cent of total greenhouse gas emissions (2014 figures for UK greenhouse gas emissions). Electric vehicles (EVs) represent a greener alternative to conventional vehicles and could contribute significantly to our carbon reduction targets.

EVs do not produce exhaust fumes, which are currently responsible for the high level of air pollution in cities. Even when considering the emissions resulting from electricity generation, EVs produce less overall. This is because they have higher energy efficiencies than conventional vehicles. The level of reduction in emissions depends on the electricity source, with renewable generation resulting in 'zero-emission' vehicles.

A large number of subsidies for partially and fully electrified vehicles have been introduced in Europe, aiming to accelerate the uptake of EVs. These, along with the falling price of batteries, have led to a rapid initial adoption – surpassing 2 per cent of new car sales in the UK, and an astonishing 50 per cent in Norway.

This article lays out the ways in which the mass adoption of EVs will present a challenge to the power system, and how this could be addressed.

Background

Pure EVs (which do not include an internal combustion engine) and plug-in hybrid vehicles (which have both a battery and engine) charge their batteries via an external connection to the grid. Some hybrids rely on excess power from their internal combustion engine to charge their battery. However, these have much lower overall efficiencies and are not eligible for subsidies. Charging of EVs will materially increase the demand for electricity, and this may have negative consequences for the operation of the grid.

'CHARGING OF EVS WILL MATERIALLY INCREASE THE DEMAND FOR ELECTRICITY, AND THIS MAY HAVE NEGATIVE CONSEQUENCES FOR THE OPERATION OF THE GRID.'

A Tesla Model S 100D battery holds more energy than is consumed by seven and a half average UK homes in a day. However, the *amount* of energy is less important than the *rate* at which it is being taken from the grid, or the *power demand*. In order to operate, the electricity grid requires that, at any time, roughly the same amount of power is being put in to and taken out of it. This is referred to as *supply–demand balancing*. Accurately predicting consumers' demand for power throughout the day is key to achieving this. Errors in estimates can be difficult to correct as power stations can take a long time to change the amount of power they are generating; nuclear power is the slowest, taking several hours to turn up or down.

An increase in power demand could impact the operation of the power system at both the national and local levels. On the national side, the power demanded could exceed the total generation capacity – meaning that all power stations running at maximum output could not produce enough supply to balance the demand. This is an expensive problem, necessitating the creation of additional power stations.

At the local level, an increase in peak demand could damage infrastructure.

Households are supplied with electricity by low-voltage feeder networks that are designed to tolerate a specific 'after diversity maximum demand' (ADMD). This is the peak demand per half hour, averaged over all households on the network. Some high-power household appliances rely on the natural variation between households to avoid unacceptably high demand. For example, kettles and microwaves are often rated above the ADMD, but they are both typically in operation for much less than half an hour, and the chance that every household on the feeder network uses them at the same time is small. Contrastingly, a vehicle charger is likely to be on for several hours and the chance of overlapping with other vehicles on the feeder network is much higher. Violation of the specified ADMD is likely to cause the transformer to overheat and it could need to be replaced.

It is not clear which of these levels (national or local) will be the pinch point – namely which will become a problem first. However, by avoiding an increase in the peak power demand, both problems will be eliminated.

Charging level

As it is the power demanded (rather than the total amount of energy) which taxes the power system, much will depend on the rate at which people charge their cars. Available chargers range from 3.5 kW slow chargers to Tesla's 145 kW supercharging stations. There is an approximately linear relationship between the power rating of the charger and the time it would take to charge an EV battery from 0 to 80 per cent. Slower charging reduces the individual contribution of a vehicle charger to the national power demand but increases the probability that vehicles will be plugged in at the same time.

At the end of 2016 there was roughly 78 GW (Plant capacity: United Kingdom DUKES 5.7, Digest of UK Energy Statistics) of installed generation capacity in the UK. This figure includes a lot of solar, which is not always available; furthermore, 10 GW of the total capacity is not owned by major power producers. Therefore, peak demand problems will likely occur before the 78 GW level is hit.

'AS IT IS THE POWER DEMANDED … WHICH TAXES THE POWER SYSTEM, MUCH WILL DEPEND ON THE RATE AT WHICH PEOPLE CHARGE THEIR CARS.'

Assuming a generous limit of 70 GW, we can estimate the number of vehicles that would have to be charging at the same time in order to reach this limit. At off-peak times 36 per cent of the UK's 32 million vehicles could slow charge simultaneously, while only 0.87 per cent could be supercharged. At peak times these numbers decrease to 17 per cent and 0.4 per cent respectively. It should be noted that, as they are mainly available in city centres and petrol stations, supercharging off-peak seems unlikely. It is clear that the lower charging powers are less likely to overload the power system, and they are also better for the health of the vehicle batteries ('BU-401a: fast and ultra-fast chargers', Battery University). There is no reason why vehicles couldn't be charged at lower than 3.5 kW, other than it would take a long time.

Smart charging

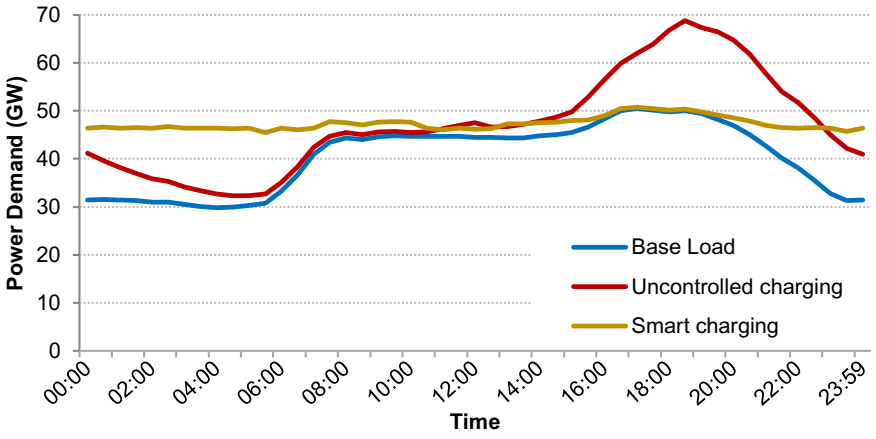
Increasing the UK's power generation capacity is an unattractive proposition, so interest in smart charging schemes is growing rapidly. Broadly, these scheme aims to charge vehicles with minimal strain on the grid.

EV charging can be considered an elastic demand – it matters not when exactly my vehicle is charging, provided it is charged by the time I need it. The same could be said for all electronic devices charging, but for smaller batteries the effort involved is not currently worth the potential savings. In contrast, most electric household devices have an inelastic demand for electricity; if lights are not drawing power then it will be dark. This flexibility offers the potential to manipulate the power demand profile – charging the vehicles at times when other electricity demand is low.

Smart charging can be achieved by either delaying or shifting charging in time, or by scaling the power at which individual vehicles charge. The degree of control given to vehicle owners is also a variable. One could imagine a system where the user has minimal control, perhaps only inputting a deadline by when their vehicle should be charged. An algorithm would then choose when and how fast the vehicle would actually charge. This could be considered the best-case scenario for the power system; all vehicles automatically participate in the scheme and the charging profiles that are optimal for the grid can be chosen.

'SMART CHARGING CAN BE ACHIEVED BY EITHER DELAYING OR SHIFTING CHARGING IN TIME, OR BY SCALING THE POWER AT WHICH INDIVIDUAL VEHICLES CHARGE.'

A simpler, more popular suggestion is to use a variable electricity price. For some households in the UK this already exists – Economy 7 tariffs offer two fixed electricity prices, with the seven off-peak hours being cheaper. It is hoped that consumers would delay charging their vehicles until off-peak times in order to save themselves money. In some ways this represents the other extreme; the consumer has



The UK national power demand on a Wednesday in January under both uncontrolled and smart charging of a 100 per cent electric fleet

complete control and optimality is far from guaranteed.

As the existing trough in energy demand occurs overnight, it follows that the most effective smart charging strategies will be those where vehicles can charge overnight. This points towards charging at home, as this is where the majority of cars will be parked overnight. Currently, in order to possess an at-home charger, consumers need off-road parking – to which 43 per cent of vehicles do not have access. However, public street chargers in residential areas with pay-as-you-go meters could still allow these vehicles to charge at home.

Results

By analysing the behaviour of conventional vehicles, the likely behaviour of a large EV fleet can be predicted. If the UK fleet were 100 per cent electric, the national demand profile under both uncontrolled and optimal smart charging are shown in the figure above. A Wednesday in January was selected because the highest power demands are currently seen around this time. It was assumed that every vehicle would charge every day that it was used, meaning that each vehicle only needs to refill the energy it expended that day.

The blue line shows the base electricity demand without any EV charging. Peak demand occurs around 6 p.m., when people arrive home and begin cooking, and the lowest levels occurs overnight when both domestic and industrial demand is low.

The red line shows the total demand if EV users charged at 3.5 kW (slow charging) and plugged in immediately after the completion of their final journey for the day. The charging exacerbates the variation in electricity demand, increasing the peak by 20 GW. The capacity of the new Hinkley Point C power plant is going to be 3.2 GW, meaning that we would need another six of these in order to meet this increase. This scenario would also result in poor use of resources; not only would we require the extra power stations but they would be out of operation throughout most of the day.

The yellow line shows the total demand in a perfect smart charging scenario – where the charge schedules for all EVs are dictated so as to flatten overall demand. In this case, all charging could be completed during the trough in existing electricity demand. This is a strong result as it means that, taking into account individual vehicle availability, all vehicles could be charged without increasing the national peak demand for electricity.

At the local level, the effect on ADMD can also be estimated, and the results are displayed in the table below. Here both the optimal smart charging strategy, and the tariff-pricing schemes have been considered. The effects of the latter are hard to model because so much depends on the response of consumers to the pricing. In this article an extreme case was considered: all charging between 5 p.m. and 9 p.m. was banned. This is equivalent to a pricing scheme that successfully incentivizes all consumers to avoid charging their vehicles during peak times.

The introduction of EVs with uncontrolled charging nearly doubles ADMD, far surpassing the 1 kW safety point, while optimal smart charging (flattened load) completely avoids the increase. Unfortunately, the same cannot be said for tariff pricing (off-peak charging); the increase is worse than if no smart charging were attempted. This is partially a product of the assumptions used. By assuming that each vehicle charges every day but the vehicles are not on charge for long, we can say that natural diversity ensures that not too many are charging at the same time. However, when a specific time window is banned, many vehicles begin charging at the same time. In reality a pricing scheme would be unlikely to achieve 100 per cent adoption, so this effect wouldn't be quite so pronounced.

Household ADMD under various charging regimes

Without EVs	Uncontrolled charging	Flattened load	Off-peak charging
0.7 kW	1.5 kW	0.7 kW	2.2 kW

Conclusion

In conclusion, the mass adoption of electric vehicles will place additional strain on the power system. National power demand may exceed the current UK generation capacity, requiring additional power stations, and local feeder networks will have to cope with loads for which they were not designed, leading to more frequent infrastructure failures. However, if designed correctly, smart charging strategies could allow 100 per cent of the UK's personal fleet to be electrified without hitting either problem.

'A POORLY DESIGNED STRATEGY RISKS SACRIFICING THE NATURAL DIVERSITY IN CONSUMER BEHAVIOUR THAT THE POWER SYSTEM RELIES ON.'

Achieving this is non-trivial but is more likely if a strategy which minimizes consumer involvement is chosen. On the other hand, a poorly designed strategy risks sacrificing the natural diversity in consumer behaviour that the power system relies on.

The future of natural gas as a transport fuel

Chris Le Fevre

The development of natural gas as a transport fuel continues to excite interest from gas companies, equipment suppliers, and transport users. The early doubts over practicality and availability have largely been answered and the focus is turning towards questions over how comprehensive and rapid the uptake of gas in the transport sector might be. Whilst the prospects are promising in some sectors, as this article will seek to demonstrate, there is still a great deal of uncertainty over where and how demand is likely to evolve over the next decade.

Disruptive aspects

A useful starting point might be to briefly review the characteristics of gas in transport that might be labelled as disruptive.

- Gas can provide some significant environmental advantages over traditional petroleum products. This is most notable in the use of LNG as a marine fuel as an alternative to heavy fuel oil or marine diesel. LNG typically produces lower emissions of carbon dioxide (CO_2) and virtually no nitrogen oxides (NO_x), particulate matter (PM), or sulphur oxides (SO_x). This latter feature is particularly important in the context of the International Maritime Organization (IMO) limits on sulphur in fuel oil. These are presently 0.1 per cent in the mandated emission control areas in North America and Europe and 0.5 per cent globally from 2020. Today the limit on sulphur content is 3.5 per cent, so there could be significant disruption to traditional marine fuel supply chains impacting fuel suppliers, traders, wholesalers, and users.

'LNG TYPICALLY PRODUCES LOWER EMISSIONS OF CARBON DIOXIDE AND VIRTUALLY NO NITROGEN OXIDES, PARTICULATE MATTER, OR SULPHUR OXIDES.'

- The lack of particulate emissions from the use of gas in transport means that the fuel could also make inroads into the road transport sector (particularly heavy goods vehicles) with a similarly disruptive impact.
- The marginal cost of gas in transport is generally lower than that of oil-based products, though the capital cost of the new vessel or vehicle may be higher – particularly if a dual-fuel option is adopted. Gas prices are increasingly linked to gas trading hubs, and price movements will not necessarily track oil prices to the extent that they might have done in the past; this could disrupt traditional pricing arrangements in the transport sector.
- Gas in transport is a relatively new market and also has the potential to disrupt the existing gas supply chain. This could occur, for example, through providing opportunities for new entrants who could introduce innovative approaches to marketing and pricing – such as through trading relatively small parcels of LNG.
- The utilization of LNG in marine and land transport markets underpins and enhances a growing cryogenic supply chain that provides a realistic alternative to traditional pipeline-based distribution. Furthermore, this example of small-scale LNG can help create development models that may have increasing relevance for markets that were hitherto too small, remote, or impoverished for the utilization of gas.

Barriers to uptake

The advantages of natural gas, however, are not completely overwhelming and there are a number of barriers that could hinder uptake:

- As already noted, there is a cost of conversion to adapt existing vessels and vehicles to burn gas and for this reason it is, in most cases, only a realistic option for new build.
- Whilst gas is generally cheaper than oil, the differentials have tended to narrow since 2015 with the fall in oil prices. Nevertheless, the discount of LNG over gas oil remains at least $5/MMBtu and this is likely to be the most relevant differential once the IMO restrictions are introduced worldwide in 2020. What is not clear is how oil product prices will adapt to the changed market dynamics; there is no guarantee that existing differentials will be maintained.
- This uncertainty over pricing is also playing in to a wider caution amongst shipping users regarding what is still an emerging technology; issues relating to the cost and availability of refuelling infrastructure are not always clear. LNG is not the only route to meeting IMO compliance and alternatives such as deferring vessel replacement and using diesel or installing sulphur scrubbers may be seen as the lower-risk option at this stage. However, according to trade group SGMF there are now 46 ports supplying LNG as a marine fuel and the number of bunkering sites continues to grow.
- The present commercial and regulatory framework tends to favour the status quo. For example, ship owners usually charter their vessels to operators and so do not benefit from any fuel cost savings associated with a switch to LNG. There is also inconsistency between (and sometimes within) countries regarding the licensing and control of LNG re-fuelling. Harmonizing standards and operations across all prospective markets remains an important policy objective.
- A final barrier for gas is that it is not a zero-carbon solution, unless biogas is the source. This is unlikely to be the case for LNG, although there are examples of biogas in the transport supply chain for CNG-fuelled cars and trucks.

'HARMONIZING STANDARDS AND OPERATIONS ACROSS ALL PROSPECTIVE MARKETS REMAINS AN IMPORTANT POLICY OBJECTIVE.'

Areas of adoption

The use of gas as a marine fuel is most likely where some or all of the following conditions are met:

- The vessels operate primarily or exclusively in areas subject to the IMO limit on sulphur of 0.1 per cent.
- The vessels are large with regular and predictable journey patterns, implying high levels of utilization.
- Operators are also owners of their vessels.
- Vessels follow routes that allow easy access to LNG fuelling facilities.
- There is a relatively high level of vessel turnover – in other words, a high frequency of new build or major re-fits.
- There are high levels of government support for new investment favouring LNG.

These conditions suggest that the most prospective markets would be Ro–Ro ferries, cruise ships, bulk carriers, and large container vessels operating in the Baltic/North Sea region or coastal North America. Other categories that might fit some of the foregoing conditions include tugs and dredgers in ports in those regions with LNG bunkering facilities.

One other important shipping category is LNG tankers. These have for many years used boil-off LNG as a fuel. As Howard Rogers ('The LNG Shipping Forecast: costs rebounding, outlook uncertain', Energy Insight 27, OIES 2018) has recently pointed out, there has been a switch from traditional steam turbine propulsion to more efficient duel-fuel diesel engines (DFDE). A fully laden DFDE vessel can sail using only LNG from natural boil-off – though in order to optimize fuel consumption at the required vessel speed, a mix of LNG and fuel oil is usually consumed.

Some examples of LNG usage elsewhere include:

- Ro–Ro ferry operators in the Baltic such as Fjord Line; the company has been operating LNG-fuelled ferries between Norway and Denmark since 2013. The Norwegian government has been a very proactive exponent of LNG as a marine fuel.
- Carnival Cruise lines has seven LNG-fuelled cruise ships on order with delivery dates between 2020 and 2022. When operational, these will have a combined LNG fuel requirement of 30,000 tonnes of LNG per annum. It should be noted that the company has a total annual fuel usage of 32 million tonnes and so could, alone, represent a very significant long-term market for LNG.
- United European Car Carriers (UECC) operates two dual-fuelled car and truck carriers between Southampton and St Petersburg. Another company, SIEM, is introducing similar vessels in 2019 to ship Volkswagen cars from Europe to the USA.
- French container shipping company CMA CGM has announced that all of its new vessels will be equipped to run on LNG.

Overall, according to DNV (in its LNGi 2017 status update), there are 119 LNG-fuelled vessels in operation (60 of which are in Norway) with a further 125 under construction. This, however, represents only a very small proportion of the total fleet, which stood at over 90,000 merchant vessels in 2017.

There is clearly a great deal of activity – what does this mean in terms of future demand for LNG? The answer is still subject to a great deal of uncertainty. At present, data on usage is either inconsistent or unavailable. Furthermore, many of the vessels that are being built are dual-fuelled so may end up using a mix of LNG and diesel, or very low sulphur fuel oil. But perhaps most importantly, there is no guarantee that the factors currently favouring LNG over other fuels will remain constant in the long term. It has been noted that LNG does not deliver a zero-carbon option; other technologies such as hydrogen or hybrid electric propulsion could become the preferred choice.

Most recent forecasts expect LNG usage in marine transport to be in the range of 8 to 20 million tonnes by 2025, which represents between 2 and 5 per cent of the marine fuels market. Given the uncertainties, the lower end of this range is most likely, with perhaps 15–30 million tonnes demand by 2030. According to a DNV forecast ('Maritime forecast to 2050', 2017), the LNG share of total marine fuel consumption will grow to 32 per cent by 2050.

Land transport

Much of the interest has been on developments in the maritime sector, due to the relatively larger scale of demand. Land-based applications for gas in transport – both LNG and CNG (compressed natural gas) – could also become significant in certain markets and indeed there are already examples where the fuel has made headway.

China is probably the most advanced country in this area, with a well-developed inland LNG supply chain and the largest LNG-fuelled fleet in the world – in 2016, there were more than 200,000 LNG-powered vehicles. Global road transport demand could reach 10 bcm by 2030, though this may not all be sourced from the international LNG market.

'LAND-BASED APPLICATIONS FOR GAS IN TRANSPORT – BOTH LNG AND CNG – COULD ALSO BECOME SIGNIFICANT IN CERTAIN MARKETS.'

Italy has for many years been at the forefront in Europe – promoting CNG in automotive transport using incentives to encourage the manufacture and purchase of gas-fuelled cars. The number of vehicles and refuelling stations has continued to grow and there are now around a million CNG-fuelled cars and light commercial vehicles, representing some 2.4 per cent of the total fleet. Future growth is likely to be strongly dependent on increasing the role of biogas in the supply chain.

Whilst for a user the distinction between LNG and CNG may not seem great, this is not the case from a supply perspective. The differences are apparent in a number of dimensions:

- There are clearly very different physical characteristics and these are reflected in the alternative supply chains and markets. CNG is generally sourced through an extension of an existing pipeline distribution network, whilst LNG is mainly provided at import terminals or intermediate bunkering facilities. Unlike CNG, LNG cannot be used in cars and small commercial vehicles whilst CNG is unlikely to be adopted for marine use.
- The CNG market is most likely to evolve at a national, or even regional/city, level and thus will have the potential to cater for widely differing characteristics between or within countries.
- CNG will most probably develop within retail markets and involve traditional and/or incumbent players
- CNG has to compete with a wider range of alternatives than LNG including, most notably, electric vehicles.

Given these distinctions, CNG is more likely to establish a meaningful presence where there is strong state support for both vehicle purchase and fuel price, to make it attractive in comparison to other fuels. The provision of a low-carbon option will almost certainly include a heavy reliance on biogas, which may face supply constraints in the long term. Overall, the expectation is that CNG transport markets will only develop on a piecemeal basis and are likely to be much less disruptive than LNG.

Conclusion

Natural gas is almost certain to establish an important share in some parts of the transportation fuels market. The evidence to date suggests that this is most likely to occur in marine shipping, though penetration levels will vary between specific sectors and regions. There is no doubt that where gas does gain a foothold it is likely to disrupt existing markets – not only for oil, but also for gas. Overall usage will certainly increase in the next 10 years, though there is little evidence at present to suggest that an across-the-board switch to gas is underway. It is also unwise to assume that growth trends can be projected inexorably into the future as other low-carbon technologies evolve.

'NATURAL GAS IS ALMOST CERTAIN TO ESTABLISH AN IMPORTANT SHARE IN SOME PARTS OF THE TRANSPORTATION FUELS MARKET.'

Electric vehicles: the human factor

Guy Walker

The wheels have fallen off countless utopian transport dreams after coming into contact with actual people. Essentially, we have been trying to support people in the travel behaviours they currently perform but in a new way, or expecting them to change those behaviours entirely, or both. Unfortunately, people do not always behave in ways that engineers expect. Could electric vehicles (EVs) be next in line for a bruising encounter with the human factor? Or could the science of Human Factors be used to help realize their potential?

For a scientific discipline which foregrounds 'designing for human use' the term 'human factors' is a little ambiguous. It is both a noun and a verb. It is also synonymous with the word 'ergonomics'. To be clear, according to the International Ergonomics Association, Human Factors (the proper noun) is '*the scientific discipline concerned with the understanding of interactions among humans and other elements of a system, and the profession that applies theory, principles, data and methods to design in order to optimize human well-being and overall system performance*'. The circumstances which normally prompt the involvement of Human Factors professionals are the presence of a particular sort of irony: a situation in which the effects of well-intentioned technologies either fail to materialize, or else are the reverse of what was expected. EVs are far from immune to ironies of this sort. However, what if the user behaviour you want is also the behaviour which seems easiest and most natural for drivers to perform? This is where the science of Human Factors can help.

Objects in the mirror appear closer

EVs represent a significant change in the way vehicles are designed and operated. They are an attempt to support people in the travel behaviours they currently perform but in a new way, combined with other aspects of user behaviour (especially re-fuelling and energy management) which will have to change entirely. The full human factors implications of these changes are currently unknown, but there are some clues in the ways in which current vehicles have evolved over the past 40 years.

'EVS REPRESENT A SIGNIFICANT CHANGE IN THE WAY VEHICLES ARE DESIGNED AND OPERATED.'

In straightforward automotive engineering terms, cars have become faster, more powerful, heavier, and more sophisticated. These trends have been extensively researched by colleagues in the UK's Centre for Sustainable Road Freight. In a 2017 article in the *International Journal of Sustainable Transportation* ('Emissions, performance, and design of UK passenger vehicles'), using a large dataset of 35,000 distinct vehicle models, Martin, Bishop, and Boies reveal a 22 per cent reduction in emissions for turbocharged petrol-powered vehicles and a dramatic 38 per cent increase in so-called 'power density'; all in the 10 years spanning 2001 to 2011. Technological development over the preceding 40 years has allowed '*vehicle performance to be decoupled from the size of the engine, thus increasing engine power while reducing engine displacement volume*' (page 13 of Emissions, performance, and design of UK passenger vehicles). This is what a recent trend – called 'downsizing' – achieves. The number of engine cylinders across the passenger vehicle fleet is currently declining at the rate of approximately 5 per cent per year, while allied technologies such as turbocharging and direct injection are increasing likewise.

What results are small, high tech, highly tuned engines that weigh under 100 kg and occupy the footprint of an A4 sheet of paper. Why is this important? Because in order to make potentially unruly 'racing technologies' like turbochargers suitable for road use, the focus is already having to switch to 'usability'. This is not a straightforward engineering question. Consider the following example, from Chapter 2 ('Sound Optimization for Downsized Engines' by Alois Sontacchi, Mattias Frank, Franz Zotter, Christian Kranzler, and Stephan Brandl) of the 2016 book *Automotive NHV Technology* edited by Anton Fuchs, Eugenius Nijman, and Hans-Herwig Priebsch:
'*the sound of two-cylinder [downsized] engines yields half the perceived engine speed of an equivalent four-cylinder engine at the same engine speed. As a result, when driving, the two-cylinder [downsized] engine would be shifted to higher gears much later, diminishing the expected fuel savings*.' (page 13 of the Sontacchi et al. chapter).

What we have here is a classic Human Factors irony. A technology aimed at improving fuel consumption yields the opposite effect to that intended. In this particular study:
'*the optimal theoretical gear change [for fuel economy] should happen at around 2000 revolutions per minute (rpm). Studies under practical conditions show for an examined two-cylinder engine [..] that the typical gear change occurs*

almost at 4000 rpm' (page 14 of the Sontacchi et al. chapter).

With an acoustic device that could imitate the sound of a larger four-cylinder engine – and with no other changes made to the vehicle – drivers shifted gear sooner. It was more interesting that drivers rated throttle response and engine/drivetrain smoothness as being significantly better, even though it was identical. Clearly, there is not only a technological disconnect between vehicle performance and engine size, but also between 'objective' engineering properties of automotive systems and the 'subjective' psychological properties of drivers. This disconnect arises because of how a vehicle feels to the driver. This is of vital importance to the development of EVs.

Tales of the unexpected

In the discipline of Human Factors, driving would be called a manual control task. Drivers operate the vehicle's 'control inceptors' (the pedals and steering wheel, for example) by moving their arms and legs; this movement, in turn, is a product of human decision-making and cognition. Characterizing driving as a manual control task makes the whole activity part of a 'tracking loop'. Drivers have to perceive the state of their environment and issue 'command inputs' in order to neutralize 'errors' in vehicle speed or direction. The vehicle's response to these demands is fed back to the driver through: the changing effort (or weight) needed to manipulate the controls, the vehicle's motion in response to control inputs, changes in engine sounds, and myriad other sensations resulting from the driver–vehicle–road interaction. What Human Factors research reveals is that drivers are highly sensitive to this feedback, something in the order of '*...the difference in feel of a medium-size saloon car with and without a fairly heavy passenger in the rear seat*' ('Tyre Characteristics as Applicable to Vehicle Stability Problems' by T.J.P. Joy and D.C. Hartley, in *Proceedings of the Institution of Mechanical Engineers* (Automobile Division), vol. 7 (1), page 119, 1953).

'DRIVERS WHO RECEIVED THE QUIETER INTERNAL CAR NOISE … CHOSE TO DRIVE FASTER THAN THOSE WHO RECEIVED LOUDER CAR NOISES.'

Human Factors research also shows that having detected these subtle feedback cues, drivers use them for all manner of purposes, many of which are unexpected. In the case of engine noise, for example, it has been found that '*drivers who received the quieter internal car noise […] chose to drive faster than those who received louder car noises*' (see 'The development, validation, and application of a video-based technique for measuring an everyday risk-taking behavior: Drivers' speed choice' by Mark S. Horswill and Frank P. McKenna in *Journal of Applied Psychology*, vol. 84(6), pages 977–85, 1999). Not only that, but quieter cars – and EVs are quiet cars – tend to encourage reduced headway and more risky gap acceptance (see 'The effect of vehicle characteristics on drivers' risk-taking behaviour', by M.S. Horswill and M.E. Coster in *Ergonomics*, vol. 45(2), pages 85–104, February 2002). Meanwhile, as in-car displays become larger (the Tesla Model S has a 430 mm touchscreen, for example) it is worth pointing out how research shows that drivers rely less on visual cues such as speedometers, instead relying on engine and road noise to monitor their speed (see 'Strategies of visual search by novice and experienced drivers', by Ronald R. Mourant and Thomas H. Rockwell in *Human Factors: The Journal of the Human Factors and Ergonomics Society,* vol. 14, pages 325–35, 1972, for example). And so it goes on.

The automotive sector is not unique in these Human Factors issues. In fact, nearly identical issues have been encountered already in the aviation sector. Here too a shift has taken place. Propulsion technologies have changed from piston engines and propellers to jets, from manual flying to automation, and from mechanical control systems to so-called 'fly-by-wire'. The performance benefits of each new technical capability are unquestioned, but there have been unexpected side effects. Reducing pilot feedback and interaction '*has raised concerns about potential negative effects of removing peripheral visual, tactile, and auditory cues, as these may help pilots monitor automated system activity and maintain situation awareness'* ('Team play with a powerful and independent agent: Operational experiences and automation surprises on the airbus A-320' by N.B Sarter and D.D. Woods in *Human Factors*, vol. 39 (4), pages 553–69, December 1997, page 558). From China Airlines Flight 140 in 1994 to the more recent Air France 447 crash in 2009, this lack of feedback, and a disconnect between human pilots and electronic flight management systems, continues to give rise to so-called 'automation surprises'. Human Factors research based on a sample of 164 pilots revealed no fewer than 133 such 'surprises'. The majority of them stemmed from a lack of feedback. The human factor in this gets worse.

Despite drivers, like pilots, being highly sensitive to vehicle feedback and using it within the driving task, they are not self-aware of when a lack of feedback is diminishing their 'Situation Awareness' to hazardous levels. Situational awareness (SA) is about 'knowing what is going on' (see 'Toward a theory of situation awareness in dynamic systems' by Mica R. Endsley in *Human Factors*,

vol. 37 (1), pages 32–64, March 1995). The process of driving requires drivers to know about the vehicle's current position in relation to its destination, the relative positions and behaviour of other vehicles and hazards, and also how these critical variables are likely to change in the near future (see 'Situation awareness during driving: explicit and implicit knowledge in dynamic spatial memory', by Leo J. Gugerty in *Journal of Experimental Psychology: Applied*, vol. 3(1), pages 42–66, 1997, and 'Situation Awareness for Tactical Driving', Rahul Sukthankar's unpublished doctoral dissertation, Carnegie Mellon University, Pittsburgh 27 January 1997). Moment-to-moment knowledge of this sort enables effective decisions to be made in real time and for the driver to be '*tightly coupled to the dynamics of [their] environment*' ('Où sont les neiges d'antan?' by Neville Moray and Thomas B. Sheridan in *Human Performance, Situation Awareness and Automation: Current Research and Trends*, by Dennis A. Vincenzi, Mustapha Mouloua, and Peter A. Hancock, Psychology Press, 2004). This is not a trivial matter. Poor situation awareness is a greater cause of accidents than improper speed or driving technique (see 'Situation awareness during driving: explicit and implicit knowledge in dynamic spatial memory').

In our own studies, using a driving simulator, we recreated the feel of an EV and experimented by gradually providing more feedback, such as engine noise, steering feel, and whole-body vibration (see *Human Factors in Automotive Engineering and Design*, by Guy H. Walker, Neville A. Stanton, and Paul M. Salmon, Ashgate, 2015; *Vehicle feedback and driver situation awareness*, by Guy H. Walker, Neville A. Stanton, and Paul M. Salmon, CRC Press, 2018). Driver Situation Awareness was measured and, not surprisingly, the more feedback provided by the vehicle in the form of engine noise, steering feel, and so on, the better the drivers' Situation Awareness and driving performance. What was interesting, however, was that when asked directly how situationally aware they felt, drivers in the study reported almost exactly the same level of Situational Awareness. This is despite very significant differences in vehicle feel and their 'objective' Situation Awareness results showing otherwise. If drivers are not self-aware of these changes, despite their performance being shown to change, then it falls to vehicle designers to be aware on their behalf.

'POOR SITUATION AWARENESS IS A GREATER CAUSE OF ACCIDENTS THAN IMPROPER SPEED OR DRIVING TECHNIQUE.'

Threats and opportunities

The Human Factors issues around EVs are significant and numerous. While normally couched in more common topics such as 'range anxiety' and refuelling, there are other subtle, but by no means less powerful, issues at stake. Digging beneath the surface reveals both just how sensitive drivers are to how their vehicle feels and responds, and the diversity of driver responses based on these sensations. This sensitivity stands in stark contrast to the dramatically increasing power, authority, and autonomy of future vehicles. The probability of unexpected behavioural side effects occurring when well-intentioned automotive technologies come into contact with drivers is high.

The change yielded by a shift to EV powertrains is orders of magnitude greater than any which has already been shown to change driver behaviour in unexpected ways. Frankly, it would be surprising if there were not human performance side effects of EVs, and we should be prepared for them. This is where the science of Human Factors can help. While there are indeed numerous human performance pitfalls with EVs, there are, of course, opportunities as well. Human Factors can help to identify and exploit them. The field of Human Factors is highly pragmatic, with a focus on practical solutions. It makes extensive use of methods (see, for example, *Human Factors Methods: A Practical Guide for Engineering and Design*, (2nd Edition), by Neville A. Stanton, Paul M. Salmon, Laura A. Rafferty, Guy H. Walker, Chris Baber, and Daniel P. Jenkins, Ashgate, 2013) which can be used to identify driver needs, characterize their performance, model interactions, predict some of those normally unexpected side effects, and ensure that EVs are designed for human use.

The promise inherent in the application of Human Factors is simply this: the behaviour you want becomes the behaviour which, to users, also seems the easiest and most natural for them to perform. Certainly, the advice for EV designers contemplating the need for Human Factors input is simply 'the earlier the better'.

'… IT WOULD BE SURPRISING IF THERE WERE NOT HUMAN PERFORMANCE SIDE EFFECTS OF EVS, AND WE SHOULD BE PREPARED FOR THEM.'

Perspectives on Mobility-as-a-Service: from vehicle ownership to usership

Maria Kamargianni

The changing transport landscape

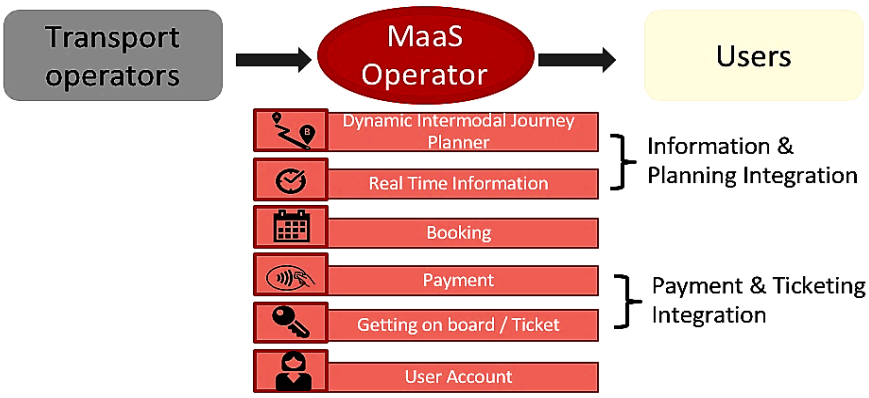
For mobility – the sector that includes public and private transport for people and goods – change has been the name of the game for decades. Yet, over the first decade of this century, automotive players have experienced one of the largest strategic shifts in the history of the car. Tightening CO_2 regulations on a global basis, and lately the Paris Agreement, have both forced the industry to adopt disruptive technologies faster than anticipated. In addition, technological advances and the rise of a sharing economy have unveiled new opportunities for products and services in the transport sector. New mobility services – such as peer-to-peer mobility and vehicle sharing – have challenged the taxi and public transport establishment and personal vehicle ownership. Disruptive innovations like these have the power to redefine industries and users' behaviour. While the Baby Boomers' vehicle buying habits were fuelled by the car's role as a status symbol, the significance of car ownership for Millennials has notably decreased. Instead, younger generations place much higher value on the electronic devices, such as laptops and smart phones, they own. While young Baby Boomers obtained their ultimate sense of freedom from owning their own cars, today teenagers and young adults achieve the same through mobile communication devices (see 'Social networking effect on next generation's trip making behavior. Findings from a latent class model', Maria Kamargianni and Amalia Polydoropoulou, presented at the 93rd Annual Meeting of the Transportation Research Board (TRB), Washington, DC, 16 January, 2014). This changing transport landscape

'OVER THE FIRST DECADE OF THIS CENTURY, AUTOMOTIVE PLAYERS HAVE EXPERIENCED ONE OF THE LARGEST STRATEGIC SHIFTS IN THE HISTORY OF THE CAR.'

has triggered the development of new mobility concepts, such as Mobility-as-a-Service (MaaS).

The Mobility-as-a-Service concept

'Mobility-as a-Service' has been marketed as a new transport concept that may change or disrupt current models of transport provision, particularly in urban areas. MaaS is a user-centric, digital, and intelligent mobility distribution model in which users' major transport needs are met via a single platform and are offered by a service provider, the MaaS operator, who is a new player in the transport market (see: 'The business ecosystem of Mobility-as-a-Service', Maria Kamargianni and Melinda Matyas, 96th Transportation Research Board (TRB) Annual Meeting, Washington, DC, 8–12 January 2017). Public transport modes are usually the backbone in this concept, while MaaS aims to increase their usage by offering convenient solutions for the first and last mile of the trips. MaaS aims to bridge the gap between public and private transport operators and envisages the integration of the currently fragmented tools and services a traveller needs to conduct a trip (planning, booking, access to real-time information, payment, and ticketing; see the figure below). It has the potential to curtail dependence on private vehicles and deliver seamless mobility as it allows integration and cooperation across transport operators, the bundling of transport services, and their provision to travellers as a single product. Through MaaS, travellers could have access to easy, flexible, reliable, price-worthy, and seamless everyday transit from A to B that includes combinations of public and on-demand transport and shared vehicles. In addition, MaaS initiates new concepts for mobility products; for example, users can buy either all the modes needed for a single trip (pay-as-you-go) or monthly mobility plans, including different amounts of transport services, based on their needs, through a single interface.



The Mobility-as-a-Service concept

The MaaS model covers several concepts that have been extensively discussed in the transportation sector during the last decades. These are the integration, interconnectivity, and optimization of the transport services, smart and seamless mobility, and sustainability. The model also includes concepts that have recently emerged via the Internet of Things and the sharing economy, such as the term 'as a service' and personalization. Although there are already mobility services that cover these terms (such as car sharing and on-demand transport), they usually operate in silos and are not integrated with other modes – especially with public transport.

MaaS initiatives around the world

Although the MaaS concept has only recently emerged, it has attracted the interest of several public and private actors around the world. However, there are only limited insights about how this concept works in real life and what the opportunities and barriers are. As such, over the last two years, several demonstrations have been initiated to provide insights about what is needed in order to materialize MaaS. Currently (to our best knowledge), there are current MaaS demonstrations in 16 cities around the world. The criteria used for identifying MaaS demonstrations are: the integration of public transport modes in terms of planning, plus either booking or ticketing and payment. (Intermodal journey planners are not considered as MaaS demonstrations. In addition, the integration of solely public transport modes is not considered as MaaS.) Seven cities are about to start demonstrations, while four demonstrations have been completed.

Most of the MaaS demonstrations take place in Europe, where the cities are dense and space for additional private vehicles is now limited. Most of these demonstrations focus on how to deal with the business models of this concept – the commercial agreements, the data that is required, and the integration of the numerous ticketing technologies into a single interface. Only a few demonstrations focus on exploring the demand side – such as changes in citizens' trip characteristics – to provide insights to the public; these are the Whim demonstrations in Birmingham and Helsinki, the Ubigo in Gothenburg, and the MaaS4EU in Manchester, Budapest, and Luxembourg.

What is needed for MaaS: the London case study

The supply side: London has changed substantially over the past two decades, both in terms of transport activity and in terms of economic and

MaaS demonstrations around the world

	City	Country
Active demonstrations	Birmingham	UK
	Dundee	UK
	Graz	Austria
	Hamburg	Germany
	Hanover	Germany
	Helsinki	Finland
	Lyon	France
	Portland	USA
	Québec City	Canada
	Senigallia	Italy
	Shanghai	China
	Stuttgart	Germany
	Tampere	Finland
	Turku	Finland
	Utrecht	Netherlands
	Vienna	Austria
Demonstrations about to start	Amsterdam	Netherlands
	Antwerp	Belgium
	Budapest	Hungary
	Dubai	UAE
	Luxembourg City	Luxembourg
	Manchester	UK
	Stockholm	Sweden
Completed demonstrations	Ghent	Belgium
	Gothenburg	Sweden
	Las Vegas	USA
	Singapore	Singapore

Source: A Google map that plots all known MaaS demonstrations can be found at https://www.google.com/maps/d/viewer?mid=1GcceDug1ixg2-Ri1k1ckfMpqNV0OT5Gg&ll=51.21944750000001%2C4.40246430000002&z=8

social characteristics. The period from 2000 onwards saw significant improvements in the capacity, quality, coverage, and ticketing integration of public transport modes, and the congestion charge zone was introduced. New mobility services, such as vehicle sharing and ride-hailing schemes, have also been initiated offering convenient alternatives to private car usage. At the same time, Transport for London (TfL) freely released its key data, allowing for hundreds of new products and services to be developed that respond to Londoners' growing demand to access information about transport services via their smartphones. In addition, payment for accessing most of the available transport modes in the city has become easier as most of the private transport operators and the city's public transport operator accept NFC (Near Field Communication) and contactless payment technologies.

However, London's traffic congestion is getting worse and the same is happening with air quality. Improvements in vehicle technology alone cannot solve the problem. More vehicles need to be taken out of the network. London could lead a revolution in both car use and in car ownership over the next decade, by separating the two. Meanwhile, the public and private mobility services that operate in silos should be integrated to offer convenient alternatives to private car usage. MaaS that is built on transport system integration, the Internet of Things, and the principles of a sharing economy could contribute towards this vision. The availability of a variety of transport mode alternatives, together with a level of advanced data openness, makes London a promising city to initiate MaaS. The missing element is the integration of the transport modes in terms of planning, booking (wherever this is needed), ticketing, and payment.

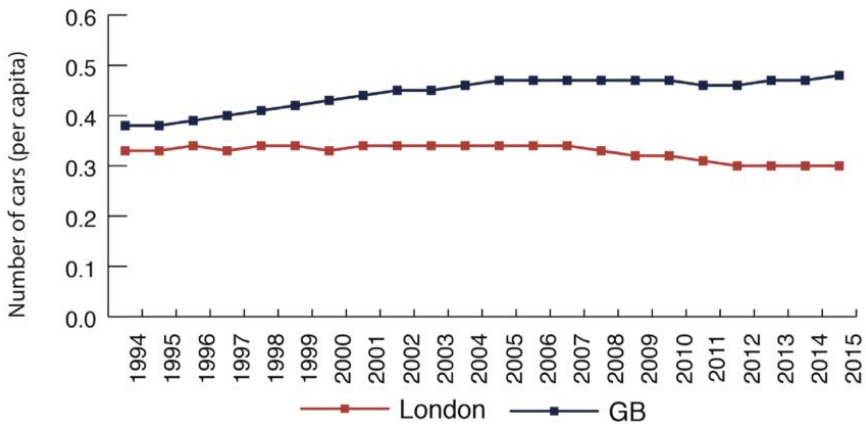
The demand side: The effect of the aforementioned efforts has been successfully reflected in a change in habits over the past decade; an increasing number of Londoners have been willing to take up alternative transport services rather than sticking to their own cars, and there has been a slow but steady decrease in car ownership (see 'Travel in London' Report 10, TfL, 2017, and the figure below).

'LONDON COULD LEAD A REVOLUTION IN BOTH CAR USE AND IN CAR OWNERSHIP OVER THE NEXT DECADE, BY SEPARATING THE TWO.'

Since there is no available official data in terms of how Londoners perceive car usage and MaaS, MaaSLab at UCL Energy Institute has conducted a survey to explore these issues. This survey, in which 1570 individuals living in Greater London (within the M25) participated, took place between November 2016 and February 2017 (see: 'Londoners' attitudes towards car-ownership and Mobility-as-a-Service: Impact assessment and opportunities that lie ahead', Maria Kamargianni, Melinda Matyas, Weibo Li, and Jakub Muscat, MaaSLab – UCL Energy Institute Report, prepared for TfL, January 2018). The results for the car owners (58 per cent of the sample) indicate that owning and using a car in the city is a hassle. More specifically:

- The majority of car-owning participants claimed that driving in London is a pain-point. Congestion and finding a parking spot are the main contributing factors to this feeling.
- Fifty-five per cent of the car-owning participants stated that congestion is a huge problem when they drive, and 52 per cent stated that it takes them a lot of time to find a parking space when they use their vehicles.
- One in four car-owning participants stated that they would like to have access to a car without owning one.

In terms of non-car owners, 67 per cent of them believe that there is no need to own a car in London, regardless of their age or the zone they live in. Fifty-nine per cent of them also believe that owning a car is a big hassle. In general, there is a dissatisfaction about car ownership and usage in the city. However, there are some promising results regarding shared mobility. Eighty per cent of the participants in this survey are aware of the car sharing (car clubs) concept, while 10 per cent of the participants are members of



Number of licensed cars per capita

Source: Vehicle licensing statistics 1994–2015, Department for Transport.

such a scheme. The majority of both car owning (51 per cent) and non-car owning (63 per cent) participants agree that car sharing is a great way to have access to cars without owning one. Furthermore, 65 per cent of non-car owners and 47 per cent of car owners believe that car sharing is a better way of using cars than everyone buying their own.

In general, the idea of car ownership has been established for almost a century now, and car manufacturers have invested significant amounts of money in building the 'dream' and status of owning a car. Car sharing schemes have only been around for a decade, yet Londoners seem to have accepted this new concept quite quickly and a significant percentage of them (more than one in three) are willing to use them in the future, instead of purchasing their own cars.

In terms of MaaS, it has been found that this concept could be used to introduce more people to public and shared transport modes. Half of the respondents stated that they would try modes they had previously not used. MaaS has the potential to impact both car owners' and non-car owners' behaviour. Thirty-three per cent of car owners agree that MaaS would help them depend less on their cars, while a quarter of them would even be willing to sell their cars for unlimited access to car sharing. Out of non-car owning participants, 36 per cent stated that they would delay purchasing a car and 40 per cent stated that they would not purchase a car at all if MaaS were available. Even though there is still much to learn about MaaS, these are some initial promising insights, indicating that the demand side is quite close to making the transition from vehicle ownership to usership. MaaS, if designed, structured, and priced appropriately, could boost the shift away from private vehicle ownership by helping car owners depend less on their private vehicles and delay or diminish the need for non-car owners to purchase them.

'CAR SHARING SCHEMES HAVE ONLY BEEN AROUND FOR A DECADE, YET LONDONERS SEEM TO HAVE ACCEPTED THIS NEW CONCEPT QUITE QUICKLY.'

Conclusion

MaaS seems a promising concept that could cover citizens' mobility needs without the requirement to own their own vehicle. This concept has the potential to boost the transition from vehicle ownership to usership. However, although it may result in a decline of private vehicle sales, this decline is likely to be partially offset by increased sales of shared vehicles that need to be replaced more often due to higher utilization and related wear and tear. Furthermore, vehicle miles travelled are expected to remain at the same levels or drop, as travel demand could probably stay the same. Fuel consumption is expected to drop and air quality to be improved because of a younger and more electrified car fleet.

Finally, when the era of connected and autonomous vehicles comes, MaaS systems and autonomous vehicles will exist in symbiosis. MaaS users will only need one account to access the autonomous vehicle services supplied by different public transport and shared mobility providers. MaaS could prepare the transport ecosystem for a smooth transition to autonomous vehicles.

'MAAS COULD PREPARE THE TRANSPORT ECOSYSTEM FOR A SMOOTH TRANSITION TO AUTONOMOUS VEHICLES.'

Government policy and regulatory framework for passenger NEVs in China

Maya Ben Dror and Feng An

China plays an instrumental role in shaping the future of mobility and transportation. It is the country that not only has the world's largest market for passenger vehicles, but also the highest population of internet and mobile users. While the regulatory policies that govern China's automobile sector were initially designed to steer the nation's automobile growth at the turn of the century, new awareness of the issues of climate change and air pollution in Chinese cities have inspired a different regulatory landscape: China is geared towards achieving industrial superiority coupled with zero-tailpipe-emissions mobility. The path to new energy vehicles (NEVs) unfolds in two parallel policy trends:

- intensification of energy-consumption regulation over internal combustion engine cars,
- increased favourable policies in support of NEV production.

Recently, these two paths have crossed, in the newly announced corporate average fuel consumption (CAFC) and NEV joint credits system. Despite ambitious policy goals, the effectiveness of China's new policy approach to zero-emission passenger mobility has yet to be seen but is expected to be revealed soon. This article reviews the motivators and processes through which China's passenger vehicle energy saving regulatory framework has developed. It then examines advances in NEV policy, and finally, it concludes with some concerns surrounding China's novel CAFC–NEV credits policy.

The evolution of energy saving auto policy in China

China's total oil consumption in 2016 reached 556 million tons, translating to a record oil import dependence rate of 65.5 per cent. Transportation accounted for over half of that volume. Passenger vehicles are held responsible for 20 per cent of national oil demand, and about 90 per cent of total gasoline consumption. Vehicle energy management is therefore designed first and foremost to curb oil consumption in defence of China's national energy security.

'CHINA IS GEARED TOWARDS ACHIEVING INDUSTRIAL SUPERIORITY COUPLED WITH ZERO-TAILPIPE-EMISSIONS MOBILITY.'

Fuel consumption (FC) regulation targeted passenger vehicles first, because the proportional growth of passenger vehicles within the transportation sector was, and still is, fierce (see 'Vehicle technologies, fuel-economy policies, and fuel-consumption rates of Chinese vehicles', Hong Huo, Kebin He, Michael Wang, Zhiliang Yao, *Energy Policy*, vol. 43, pages 30–6, April 2012). China has been the largest automobile market in the world for eight consecutive years. About 25 million vehicles have been produced and sold in China over the past year alone. Although the market is already large, the rate of car ownership per capita in China is still low (less than 230 for 1000 people), hence the potential for fuel saving and emissions mitigation from the passenger vehicle sector is large.

With the awakening of the Chinese government to urban air quality during China's 'airpocalypse' in winter 2013 and the active position it took in global climate negotiations soon after, the transport sector was targeted as a path for carbon emissions mitigation and air quality improvements. According to a report (*China Vehicle Environmental Management Annual Report*) released by China's Ministry of Environmental Protection (MEP) in 2017, motor vehicles account for 30–40 per cent of urban PM 2.5 pollutants in many of China's large cities. Passenger cars in particular are identified as a predominant source of carbon monoxide (CO) and hydrocarbons (HC) pollutants, reaching 49 per cent and 40 per cent, respectively. Although car registration restrictions have been imposed in close to a dozen cities, there is still a steady annual growth in car ownership (of about 2 per cent).

As one of China's pivotal industries, energy saving regulation in the auto sector is also perceived as a tool to nudge the auto sector into technological leadership (see 'China's fuel economy standards for passenger vehicles: Rationale, policy process, and impacts', Hongyan H. Oliver, Kelly Sims Gallagher, Donglian Tian, and Jinhua Zhang, *Energy Policy*, vol. 37 (11), pages 4720–9, November 2009). China has joined global efforts to significantly strengthen motor vehicle fuel economy standards (see 'Structure and impacts of fuel economy standards for passenger cars in China', David Vance Wagner, Feng An, and Cheng Wang, *Energy Policy*, vol. 37 (10), pages 3803–11, October 2009). China's State Council, in its 'Made in China 2025' plan, has put forward a bold national passenger vehicle average FC target of 5.0 litres/100 km

'… ENERGY SAVING REGULATION IN THE AUTO SECTOR IS ALSO PERCEIVED AS A TOOL TO NUDGE THE AUTO SECTOR INTO TECHNOLOGICAL LEADERSHIP.'

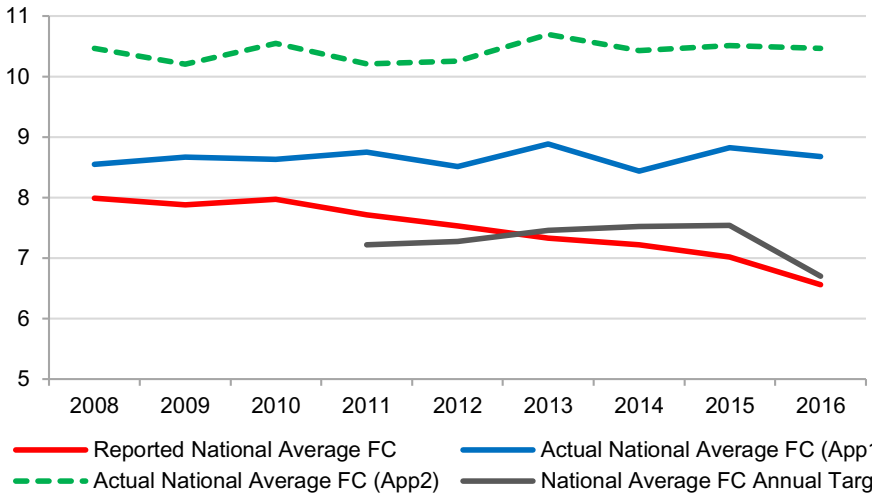
by 2020, and in a subsequent Ministry of Industry and Information Technology (MIIT) announcement, a 4 litres/100 km goal by 2025 was set. These targets are indeed aligning China's energy saving vehicle production with global standards.

However, aggressive vehicle fuel economy targets have not fully translated themselves into real-world oil consumption savings. Although China's national average FC has fallen by 14 per cent since 2009 (according to test cycle-based reporting), studies documenting actual FC levels point to a 1.5 per cent reduction over this period. (See 'From laboratory to road international: A comparison of official and real-world fuel consumption and CO_2 values for passenger cars in Europe, the United States, China, and Japan', Uwe Tietge, Sonsoles Díaz, Zifei Yang, and Peter Mock, ICCT White Paper, 5 November 2017; '2016 Real-world Passenger Vehicle Fuel Consumption Analysis', Lanzhi Qin, Maya Ben Dror, Liping Kang, Hongbo Sun, and Feng An, Innovation Center for Energy and Transportation, December 2017.)

As can be seen in the figure top right, although the national annual FC targets have been reportedly met since 2013, levels for the actual national average FC were at least 1.9 litres/100 km higher than the target in 2016. China's conventional vehicle energy saving policy regime may have served industrial alignment well, but it has not proven sufficiently effective in significantly bringing down energy consumption and emission levels in the real world.

The Chinese government has recently intensified its regulation over the auto regime using the two existing regulatory frameworks:

First: it has adjusted the FC regulatory regime. Most predominant are the following changes:



Trends of reported, actual, and target national annual average FC values (litres/100 km)

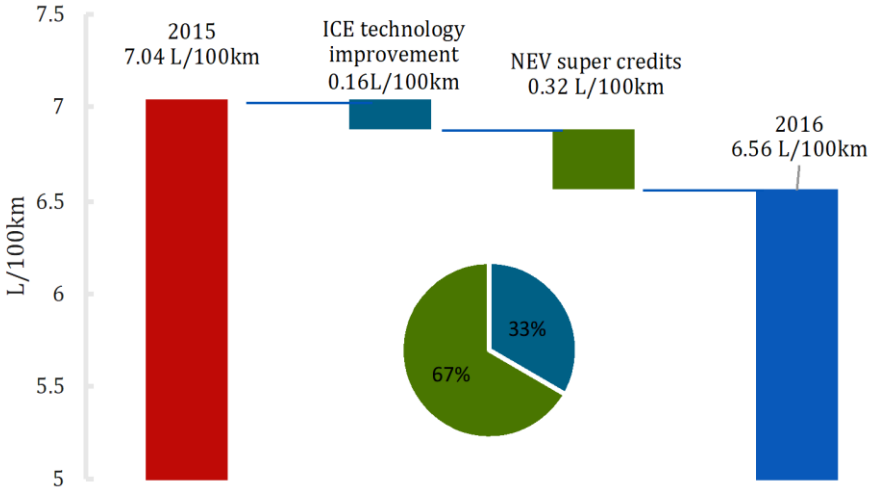
Resources: Reported national FC source is Ministry of Industry and Information Technology (MIIT). China passenger vehicle fuel consumption inquiring system (http://chinaafc.miit.gov.cn/n2257/n2280/index.html).

The actual FC datasets, sourced directly from two mobile apps, are used in the figure:

App1 refers to the BearOil mobile App for semi-automated actual FC calculations;

App2 refers to the automated OBD-logger mobile App for actual FC calculations (as well as other vehicle and trip information).

a) China enacted a flexibility mechanism in its corporate average FC standard calculations; this allowed every electric car produced to count as five vehicles with zero FC. According to this new mechanism, if a company's CAFC level surpasses its annual CAFC target, the company can transfer any excess of 'CAFC credits' to affiliated companies or bank them for future years. Between 2015 and 2016, 60 per cent of national CAFC reductions were attributed to NEV super credits



NEVs assist achievement of energy efficiency targets for traditional cars towards 2020

Source: iCET (December 2017), China Passenger Vehicle Fuel Consumption Development Annual Report 2017.

calculations, while only 30 per cent resulted from energy conserving technological upgrades in internal combustion vehicles. This is shown in the figure below (namely, the CAFC fuel consumption reduction requirement);

b) the Ministry of Industry and Information Technology (MIIT) commissioned the China Automotive Technology Research Center (CATARC) to draft China's first own vehicle test cycle (China Auto Test Cycle); this is projected to be tested between 2022 and 2023;

c) China's fuel consumption label standard (first introduced in 2010) was modified in May 2017. The new label emphasizes vehicle urban FC levels (as opposed to a mix of rural and urban driving conditions) and compares the vehicle FC with the average national FC for the same production year. Perhaps most significantly, it introduces a dedicated label for the energy consumption of vehicles with electric powertrain.

Second: China transitioned its new energy vehicle (NEV) regulatory regime from an 'experimental' to a 'commercial' phase.

China's NEV policy approach

China's assessment of NEV market potential started in 2009 with a classic 'pilot policy,' the '10 Cities, 1000 Vehicles' programme. It quickly expanded to include 39 cities. In 2012, the State Council issued a strategic plan for the NEV sector that outlined a goal of 500,000 NEVs by 2015, and a target of 5 million NEVs for 2020.

The top–down approach to NEV development has become more effective with the introduction of robust economic policy instrumentation; this covers tax reductions and subsidies, charging infrastructure, and R&D, and totals some $7.2 billion. In 2013, a NEV subsidy was enacted, followed by several local matching subsidies. In 2015, charging infrastructure roadmaps were drafted to accommodate the 5 million vehicle target and in the following year a dedicated fund was formed to support local implementation. A cross-ministry agreement for accelerating residential charging infrastructure was reached, removing some of the institutional barriers to NEV commercialization.

'EV100 SYMBOLIZED CHINA'S RECOGNITION OF THE ROLE OF THE MARKET IN ADVANCING EV COMMERCIALIZATION …'

In 2014, China initiated the formation of a semi non-governmental organization (NGO) with more than 100 members, dedicated to the advancement of vehicle electrification, titled 'EV100'. EV100 symbolized China's recognition of the role of the market in advancing EV commercialization, primarily in the areas of battery and infrastructure improvements. More recently, and as a result of policymakers' interaction with the industry, a target for NEVs was put forward: in 2025 they would represent 20 per cent of the market for new car sales (projected at 35 million). The new targets are based on technology roadmaps developed by MIIT and its affiliated research arms, marking the shift to inclusiveness and an information-based NEV policy regime.

China's NEV market was ranked first in the world as of 2015, with production totalling 517,000 and recorded sales reaching 507,000. Electric vehicle (EV) sales accounted for 409,000 (a 65.1 per cent annual increase) while plug-in hybrid electric vehicle (PHEV) sales reached only 98,000 (a 17.1 per cent annual increase). In 2016, as many as 263 models were available on the Chinese market, accounting for 1.4 per cent of market sales. Eighty per cent were produced by domestic manufacturers. Micro EVs, termed A0/A00 type, have accounted for the majority of EV sales to date.

As a result of the pilot approach, together with widespread protectionism by local governments, some cities are better positioned to accommodate the commercialization of NEVs than others. NEVs in Beijing and Shanghai amounted to 6–8 per cent of local new car ownership, nearly 100,000 vehicle sales through 2016 each. However, a scandal of subsidy circumvention was revealed in early 2016, where vehicle sales were fabricated to achieve subsidy eligibility (see 'Subsidy fraud leads to reforms for China's EV market', Hongyang Cui, International Council on Clean Transportation, 30 May 2017). Such sales have likely served local governments in their efforts to reach the annual NEV sales targets 'on paper'. In December 2016, an additional requirement for subsidy eligibility was added – a 30,000 km e-range for non-private vehicles. Addressing the issue that EVs tended to be produced in a low quality classification that covered vehicles with slow speed, short range, and small size, the revised subsidy policy also required vehicles to have a minimum constant speed of 100 km/h over a distance of 30 km and a Mass Energy Density (MED) of the battery system (for battery electric vehicles – BEVs) of no less than 90 Wh/kg. The revised subsidy policy also increased benefits for vehicles with reduced energy consumption. The current national subsidy grants are between RMB20,000 (for vehicles with an e-range of 100 to 150 e-km) and RMB44,000 (for vehicles with an e-range of 250 km or over).

Recognizing that the top–down approach alone would not position China's NEV industry know-how at the forefront of global NEV development, it was then announced that subsidies would be phased out towards 2023

and be gradually replaced by market-based mechanisms and demand-side initiatives.

CAFC and NEV credits joint mechanism

The two auto policy regimes – one for conventional internal combustion engine (ICE) vehicles and another for NEVs – which have been separate to date, have been merged through a novel credit system 'CAFC and NEV credits joint management mechanism'. The new policy, released in September 2017, will go into effect on 1 April 2018. The regulation combines the CAFC policy as enacted in 2012, and adds yet another 'flexibility mechanism', the 'NEV credits' system (on top of the NEV preferential calculation termed 'NEV super credits') to ease implementation.

The stated goal of the new policy is to:

- advance overall vehicle energy efficiency by requiring a minimal production of new energy vehicles (BEVs, PHEVs, and FCVs), the equivalent of California's zero-emissions vehicles;
- promote the healthy growth and development of an auto industry that funds and innovates a new generation of vehicles and does not only manufacture traditional (fuel consuming) automobiles;
- perform as an implementation strategy of 'The People's Republic of China Energy Conservation Law'.

The exchange and transfer of NEV credits is a core part of the policy and is included in the CAFC management system.

According to the new policy, all domestic vehicle manufacturers and importers with ICE (excluding NEVs) vehicle volume exceeding 30,000 units are required to comply with the NEV credits requirement according to their manufacturing or importation volume of the relevant year. NEV credit stock is based on the gap between actual and required volume of NEV credits produced, which is determined at 10 per cent and 12 per cent for 2019 and 2020, respectively. While NEV credits can be traded freely within their year of production, they cannot be banked (apart from during a grace period between 2018 and 2019). CAFC credits are calculated on the basis of the gap between the actual and targeted annual FC, multiplied by production or importation vehicle volume (in other words: CAFC = FC gap × vehicle volume). Negative CAFC credits can be compensated for by producing or purchasing NEV credits (on a ratio of 1:1) or using banked or transferred CAFC credits from affiliated companies.

'AT PRESENT, THERE ARE MORE THAN 100 PASSENGER CAR MANUFACTURERS IN CHINA AND NEARLY 30 IMPORTERS.'

The governing institutional structure of CAFC and NEV credits is complex. It includes several MIIT departments, the National Development and Reform Commission, the Ministry of Finance, the Ministry of Commerce, the General Administration of Customs, the General Administration of Quality Supervision, Inspection and Quarantine, and other government agencies. This complexity increases coordination challenges and hinders prospects for adequate enforcement. Given the existence of corruption within NEV production and FC reporting, weak enforcement poses major challenges to effective implementation.

At present, there are more than 100 passenger car manufacturers in China and nearly 30 importers. Over 2,900 new models were added to MIIT's Fuel Economy website in 2016 alone. The high volume of vehicles and new models creates enormous enforcement challenges. The dual management scheme governing both CAFC and the new NEV credits system is increasing the pressures on governing entities.

Challenges ahead

As policy enforcement evolves, new challenges arise. The three predominant challenges can be summarized as follows:

a) A gradually adopted hypothesis among key researchers is that there is a local tendency to protect certain brands and therefore NEV market competitiveness is being compromised, delaying the introduction of better quality models to China, limiting consumer choice, and potentially holding back consumer satisfaction rates. Overcoming local protectionism and making more NEV models available for consumers in Chinese cities can greatly impact the commercialization of NEVs.

b) The combination of the new NEV credits system with the CAFC standard regime is likely to drive companies to abandon their fuel-saving investments in favour of NEV investments – probably not in the form of direct R&D but rather through the merging and acquisition of existing NEV manufacturers. Also, issues of governance and enforcement of even the CAFC regulation on its own, let alone the CAFC and NEV joint mechanism, may hinder effective implementation.

c) A call for consumer education and higher-quality production reflects a new approach to commercialization, transparency, and inclusiveness. Yet a government supervised consumer reporting channel (such as the fuel consumption reporting on a dedicated US-EPA platform) is lacking.

Can India 'leapfrog' to electric vehicles?

Anupama Sen

Transportation accounts for roughly 40 per cent of India's oil demand. It is the world's sixth largest car market, with over 3 million units sold in 2016. Car sales have been increasing by an average of around 2 million units annually over the last few years, with the majority of new sales going to fleet expansion. Unlike developed markets, where the majority of new cars are replacing ageing vehicles, the average Indian car is roughly five years old. Most sales growth is accounted for by two wheelers, reflecting the entry of new consumers into the passenger vehicle market. Consequently, India's oil demand has surged in recent years, with growth hitting record highs in 2015 (303 thousand barrels/day) and 2016 (380 thousand barrels/day). Although oil demand growth fell in 2017 due to a combination of weather and policy-induced shocks (including demonetization and the troubled introduction of a Goods and Services Tax), as its economy continues to expand and incomes rise, the number of cars is set to increase exponentially. This article looks at the opportunities for India to 'leapfrog' to electric vehicles (EVs), the challenges to be faced in doing so, and the likely impact on oil demand growth in transport.

'IT IS THE WORLD'S SIXTH LARGEST CAR MARKET, WITH OVER 3 MILLION UNITS SOLD IN 2016.'

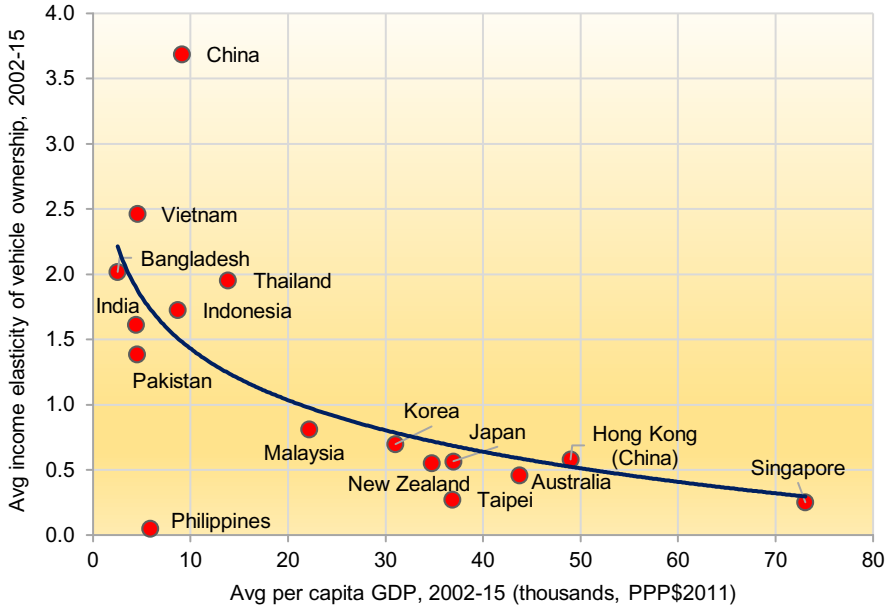
Per capita income and vehicle ownership – a well-established relationship

In OECD countries, the growth of the vehicle stock, measured in terms of vehicle (or car) ownership, has followed a clear path, varying closely with changes in per capita income. This relationship has been formalized in existing literature (see 'Vehicle Ownership and Income Growth, Worldwide: 1960–2030', J. Dargay, D. Gately, and M. Sommer, *Energy Journal*, vol. 28(4), pages 143–70, 2007) where it can be seen that the rate of growth of vehicle ownership is:

- relatively slow at the lowest levels of per capita income,
- around twice as fast at middle-income levels (~$3,000–$10,000 per capita),
- about as fast as income growth rates at higher income levels.

It reaches saturation at the highest levels of income and when plotted, the relationship resembles an 'S' shaped curve.

This historical relationship between per capita income and vehicle ownership implies that *ceteris paribus*, as the developing non-OECD countries climb to higher levels of per capita income, vehicle ownership could follow a trajectory similar to that followed by OECD countries, increasing oil demand for transportation. As opposed to those in developed countries, citizens of developing countries also tend to purchase their first vehicles as their incomes increase, often moving up the ladder of mobility from two wheelers to four wheelers. The figure below provides a more detailed picture of the responsiveness of car ownership to changes in income levels for 18 countries in the Asia-Pacific region, of which over half are non-OECD countries; it plots the historical ratio of the average annual percentage growth in car ownership to the average annual percentage growth in per capita income, which is widely considered a broad measure of the income elasticity of car (or vehicle) ownership (see 'Gasoline Demand in Non-OECD Asia: Drivers and Constraints', A. Sen, M. Meidan, and M. Mahesh, OIES Paper WPM 74, November 2017 – hereafter



Income elasticity of car ownership vs per capita income, 2002–15

Source: Sen et al. (2017)

Sen et al. (2017)). Growth rate ratios for each country are plotted on the vertical axis and compared with each country's average income (measured by per capita GDP on the horizontal axis) over the period 2002–15.

The figure shows that car ownership grew almost twice as fast as income for lower and middle-income Asian countries (that is, income elasticity was around 2.0). For China, it grew 3.7 times as fast, whereas for Vietnam it was nearly 2.5. For India, it was around 1.7 times as fast. The figure also shows that the higher a country's income level (Singapore, for example, which is part of non-OECD Asia), the lower its income elasticity of car ownership – at very high levels of income, the rate begins to approach zero as saturation is reached.

These broad estimates of income elasticity of car ownership can be combined with forecasts on GDP and population to project forward estimates of car ownership levels in both OECD and non-OECD Asian countries, holding constant all other factors that may be likely to influence growth in the car (or vehicle) fleet. Based on these estimates, India's car ownership level could increase from roughly 7 per 1000 people in 2002, to 43 by 2021. An arbitrary nonlinear regression function fitted by least squares and based on the 'S' curve or Gompertz distribution, suggests a lower 'plateau', or level of saturation, of car ownership in Asia than that seen in other OECD countries – at around 400 cars per 1000 people (see Sen et al., 2017). Previous estimates for countries in Western Europe have put the plateau in excess of 500 per 1000 people and close to 800 in the USA.

The potential and motivation to 'leapfrog'

In consumer theory, the demand for gasoline is a 'derived' demand. It is not gasoline itself which gives benefit to the consumer, but the end product – namely, mobility (see 'Long-Run Gasoline demand for passenger cars: the role of income distribution', K. Storchmann, *Energy Economics*, vol. 27, pages 25–58, 2005). In theory, a 'leapfrog' is therefore possible if oil were to be substituted in transport in a widespread manner. A 'leapfrog' would arguably be easier if it were possible to pre-empt the growth in private vehicle ownership and target public transportation and ride-sharing services. Three features of the Indian economy support this:

'… INDIA'S CAR OWNERSHIP LEVEL COULD INCREASE FROM ROUGHLY 7 PER 1000 PEOPLE IN 2002, TO 43 BY 2021.'

1 the majority of trips taken are already on public or non-motorized forms of transport;
2 ride-hailing and ride-sharing services (such as Uber, and its Indian competitor, Ola) are already prevalent across Indian cities;
3 traffic congestion and pollution are beginning to become election issues – India hosts 13 of the world's 20 most polluted cities (as per the World Health Organization).

Given this context, the policy motivation to 'leapfrog' comes primarily from fiscal pressures. The Indian government originally planned to save the country an estimated $60 billion in energy bills by 2030 (whilst also decreasing carbon emissions by 37 per cent), by switching the country's transportation system towards EVs; however, in early 2018 it backtracked from a declaration to electrify the country's entire vehicle fleet by 2030, to a more modest target of 30 per cent of the fleet. The target is underpinned by India's low per capita ownership of vehicles, with the potential to 'leap' directly to a new mobility paradigm which involves shared, electric, and 'connected cars' (in other words, through Autonomous Vehicle technologies). This could leverage India's inherent advantages in technology and favourable demographics, while offsetting pressures that would have otherwise developed from higher import bills (India imports 80 per cent of its oil consumption). To achieve this goal, government Think Tank NITI Aayog has recommended offering fiscal incentives to EV manufacturers, while simultaneously discouraging privately owned petrol and diesel fuelled vehicles.

An Indian 'EV revolution' – prospects and challenges

India's current base for EVs is low, at 4,800 vehicles in 2016, representing 0.2 per cent of the total fleet. The government is targeting 6 million electric and hybrid vehicles on the roads by 2020 under the 'National Electric Mobility Mission Plan' and 'Faster Adoption and Manufacturing of Hybrid and Electric Vehicles (FAME)' programme. The 'fully electrified' target for 2030 implied a stock of over 50 million EVs, but even a lower number will be challenging, given current inadequacies in the supply chain.

Currently, there is only one EV maker in India (Mahindra & Mahindra), which plans to expand production capacity from 500 to 5000 units a month by mid-2019. However, other Indian automakers are also gearing up. The Tata Group is working on a comprehensive hybrid and EV strategy that includes developing lithium batteries as well as charging stations. Tata Motors is in the process of introducing the first batch of five diesel

'THE GOVERNMENT IS TARGETING 6 MILLION ELECTRIC AND HYBRID VEHICLES ON THE ROADS BY 2020 …'

hybrid buses to the city of Mumbai and is also planning to trial its electric buses in New Delhi, Bangalore, and Mysore as it aims to win more orders from state transport undertakings. Overseas collaboration may also be needed to meet the target, as current supply chains are inadequate. But the government's 'Make in India' policy which prioritizes domestic manufacturing, and its preference for locally made components, could slow EV development.

While automakers prepare to meet the challenge of new vehicle demand, the power sector needs to build capacity and also improve Plant Load Factors (PLFs) and distribution networks. India has around 330 GW of installed generating capacity, with 57 GW of renewables and 198 GW of thermal. Assuming an electric vehicle has a 100 kilowatt hour (kWh) battery size, the annual additional power demand for 6 million EVs is expected to be 93 terawatt hours, which would require 10 GW of power plant capacity in 2020. A lower number of 2 million EVs would take roughly 3 GW of power plant capacity, which represents 1 per cent of installed capacity (see 'Electric vehicles adoption: potential impact in India', EY, June 2016).

'EVS OFFER AN OPPORTUNITY TO ENCOURAGE DISTRIBUTED GENERATION, REDUCING DEPENDENCE ON ELECTRICITY DISTRIBUTION COMPANIES …'

While India is likely to have sufficient capacity to meet incremental EV demand, it will need to overcome structural challenges that are keeping power capacity at low utilization rates, particularly in the coal and gas sectors. Electricity distribution infrastructure is inefficient with large transmission losses, and power theft is endemic, deterring private investments while leaving state utilities with poor finances that restrict their capacity to upgrade. Current power capacity is largely underutilized despite the fact that urban areas face erratic power cuts, and the country is aiming to electrify more rural areas. This implies that upcoming power capacity projects have already been earmarked for solving current challenges. Additional stress on the power grid from EVs will require a revamp of the sector to improve efficiencies at current power plants as well as in the distribution network.

Policy makers could, however, see utility in EVs not only for transportation but also for their benefits to the power sector. EVs offer an opportunity to encourage distributed generation, reducing dependence on electricity distribution companies and setting up commercially sustainable microgrids, especially in remote areas. Batteries used in EVs usually have a vehicle lifetime of eight to ten years, but they have significant potential after that for alternative uses, in particular as cheap storage for renewable energy capacity. EVs could help improve the utilization of existing domestic coal capacity by providing demand assurance to sustain a certain baseload. With most of the charging expected to be carried out during off-peak hours, utilities could manage their base load better, rather than relying on expensive sources for generating peak load. India's largest power generation utility (NTPC) aims to set up charging stations – with plans to halve the cost of setting these up (down to $1,500 each) as a way of expanding its market. There is thus scope for baseload management at current capacity to improve low PLFs to over 70 per cent, to absorb the strain of millions of EVs on the power grid. In order for the EV push to conform with India's COP21 commitments, electricity will need to be generated from renewables, of which the government plans to generate 175 GW by 2022 (100 GW from solar power).

While the power sector can accommodate the expansion of EVs by improving utilization rates, the biggest infrastructure challenge comes from expanding the charging infrastructure, much of which would have to be built from scratch. The challenge facing expansion of the retail fuel network has been the dearth of reliable power supply in small towns and remote highways. If such fuel stations were also to meet the demand of charging EVs during power cuts and low voltage periods, the owners would have to set up generators. To incentivize the build out of charging stations, the government is considering using a private retail method, using the same model for distributed charging as was the case for privately owned phone booths, implying that anyone could set up a charging station and earn a small income from it.

The up-front price of the vehicle is also likely to be a limiting factor, as they currently cost more than those based on internal combustion engines. Measures (such as selling EVs without batteries which will then be swapped out rather than embedded) are being considered that could reduce the initial cost of buying an EV for the individual user by as much as 50 per cent (see 'India Leaps Ahead: Transformative Mobility Solutions for All', NITI Aayog, May 2017). Such an option would allow drivers to buy the car and lease the battery, which can then be switched when they need to recharge. In order to build scale rapidly, India's government is considering an EV-based public transport system, with the sale of auto-rickshaws and buses containing batteries that can be swapped after a certain distance. Auto-rickshaws travel between 80 km and 130 km daily, so batteries could, in theory, be swapped at around the 40 km mark. With close to 95 per cent of buses in the country travelling on routes of 30 km per trip, batteries could be swapped at the

terminal point where the bus turns around for the return journey (see 'India's electric vehicle revolution will begin with autorickshaws running on swappable batteries', Quartz India, 9 June 2017). While battery leasing and swapping arrangements would solve both the challenge of providing charging stations that charge batteries rapidly, and the issue (for the user) of the high purchase cost of an EV, considerable investment would still be required to set up a network of battery swapping stations, and there would also need to be a convergence in technology across the industry. The right incentives for the sector will need to be found to overcome these issues, but success is possible.

Adopting a shared ownership model over an individual ownership model could bring down the cost of both ownership and travel. India's ride hailing companies are also partnering with manufacturers to grow their fleets (Ola with Mahindra, for example) by offering discounts on cars, vehicle financing, and maintenance plans to drivers.

'ADOPTING A SHARED OWNERSHIP MODEL OVER AN INDIVIDUAL OWNERSHIP MODEL COULD BRING DOWN THE COST OF BOTH OWNERSHIP AND TRAVEL.'

EVs are coming, but India's oil story isn't over

India has roughly 31 million passenger cars and 150 million two and three-wheeler vehicles. The country consumes an average of 0.5 million barrels/day (mb/d) of gasoline and 1.56 mb/d of diesel. EVs are unlikely to severely dent India's gasoline demand growth over the next five years, given the low starting base. The target of 6 million EVs by 2020, if realized, could potentially displace roughly 90,000 barrels/day (b/d) of fuel demand in the country. Given the current limitations of charging infrastructure and the challenges of ramping up domestic manufacturing, a lower achievement of, say, 2 million EVs would displace around 30,000 b/d of fuel demand (see Sen et al., 2017).

EV adoption could pick up pace in the post-2020 timeframe, once charging infrastructure grows. The impact on fuel demand could be large if commercial vehicles such as trucks are also electrified. The Indian government has already set in motion efforts to electrify the currently diesel-dependent railways, which will lead to further displacement of fuel. Oil demand growth in transport is likely to slow relative to a baseline level, if policies to substitute away from oil in transport are implemented on a widespread basis, but these will need to be backed by strong political commitment, which given the recent scaling back of ambition, is under question.

Europe shifts gears

Frank Watson

The low-carbon transport revolution is in its infancy. Europe's regulators are helping it to grow fast, creating a blueprint for other regions to follow. Meanwhile, the disruptive power of technology could force change more quickly than regulation.

Europe is at the forefront of regulating the low-carbon transportation revolution. The region's policymakers have put in place frameworks designed to gradually push manufacturers and consumers toward higher-efficiency lower-emissions passenger and commercial vehicles. But their capacity to sustain subsidies and lost tax revenues is open to question.

Behind this drive is the EU's target to cut greenhouse gas emissions from transport by at least 60 per cent by 2050 from 1990 levels. European policymakers also want to be '*firmly on the path towards zero*' by that date.

Regulators are working in tandem with automakers and infrastructure providers to clear the way for alternative drive-trains, including electric vehicles (EVs) and other technologies, to gradually phase out the fossil fuel-burning combustion engine.

Their challenge is to achieve this historic transition while preserving economic growth and jobs, boosting Europe's share of the global car market, and reducing its dependence on fossil fuel imports.

Consequences of subsidy removal

There are many examples around the world where uptake of EVs has fallen dramatically when governments withdraw subsidies. This has been seen in areas such as the US state of Georgia, Hong Kong, and Denmark, where sudden policy changes or withdrawal of government incentives have seen an immediate negative impact on EV sales.

'… THERE IS A CLEAR CONNECTION BETWEEN GOVERNMENT SUPPORT MECHANISMS AND CONSUMERS' WILLINGNESS TO PURCHASE LOWER EMISSIONS VEHICLES.'

In some cases, the upcoming withdrawal of government subsidy has caused a temporary surge in uptake of EVs as consumers attempt to qualify for subsidies in a closing window, before sales numbers crash immediately following the withdrawal of support. At the moment, there is a clear connection between government support mechanisms and consumers' willingness to purchase lower emissions vehicles.

However, this situation may not remain the case indefinitely.

Effects of technology in cost reductions

If the unit cost of EVs and other low-emissions vehicles falls far enough, this would allow low-carbon cars, vans, and trucks to compete directly with their internal combustion engine counterparts, enabling governments to rein in the cost of supporting such technologies with direct subsidies.

Some EV makers claim that their next generation of EVs will indeed be cost-competitive with combustion cars on a full lifecycle analysis basis, although this may depend on further scaling up of battery production rates that would further reduce their cost.

At the global level, for fuel consumption in road transport, the largest contributor is in the heavy-duty vehicle (HDV) segment. Countries and regions with fuel efficiency and greenhouse gas emissions standards for HDVs include the USA, China, Europe, India, Japan, and Canada. This is the sector where oil demand could see significant impacts from lower emissions vehicles.

Daimler was the first company to present the concept of a fully electric truck for urban distribution of up to 25 tonnes, with the Mercedes Benz Electric Truck in 2016. US car and battery maker Tesla has since unveiled a fully electric semi-truck for production in 2019; this has a 500 mile range, and the company plans a global network of mega chargers for refuelling e-trucks.

US parcel delivery service UPS in December 2017 said it had pre-ordered 125 of Tesla's new electric trucks and plans to convert up to 1,500 trucks to EVs by 2022 in New York City alone. Walmart and PepsiCo have similarly placed advance orders, in addition to European organizations including Norway's national postal service.

Technology is playing catch up. But manufacturers are racing to produce more capable EVs and governments will eventually withdraw subsidies. Meanwhile, cost will probably remain a major consideration for consumers.

Air quality and fossil fuel-related concerns

However, in cities, concerns over urban air quality, along with prohibitive legislation on conventional transport fuels such as diesel, are of greater concern. Diesel may outperform gasoline on greenhouse gas emissions but it lags in terms of air pollutants.

Diesel vehicles have become a target for policymakers across Europe. Engines powered by the fuel were

'FRANCE ANNOUNCED IN JULY 2017 THAT IT WOULD BAN SALES OF ALL GASOLINE AND DIESEL CARS BY 2040 …'

lauded in the 1990s and 2000s as a way to reduce greenhouse gas emissions and improve fuel efficiency.

Many European governments had put incentives in place for consumers to switch to diesel from gasoline engines. However, this trend was beginning to change even before the details of the Volkswagen engine emissions scandal emerged in 2015.

All mass-produced cars sold in the EU from September 2015 must meet the Euro 6 standard, which limits harmful air pollutant emissions from cars and vans, and new rules seek to enforce real-world driving emissions standards.

France announced in July 2017 that it would ban sales of all gasoline and diesel cars by 2040, and the UK followed suit later that month in announcing the same target and timeline. The delivery of such long-term targets would have to be achieved by future governments. Nevertheless, this could be the start of a wider trend, with other countries and cities announcing their own bans on polluting vehicles.

This increases the regulatory risk for auto companies who may be considering investing in more diesel and gasoline engine production lines, and for consumers who may struggle to find second-hand buyers for diesel or gasoline cars when seeking to upgrade to a new version in a few years' time.

These national goals to phase out combustion engines have been driven in some cases by legal action against governments that have been failing to meet EU air quality targets, as well as a general awareness of the health impacts of toxic air in cities. EVs are the obvious winners from these regulatory shifts.

As a result, changes are happening very quickly in this space. Some automakers, for example Sweden-headquartered Volvo, have already said they will stop making combustion-only cars and switch to hybrid and pure electric vehicles from 2019.

And Germany's VW plans to expand EV production on a massive scale. In March, VW said it had awarded contracts worth EUR20 billion to battery manufacturers and has plans to build 16 EV production factories by 2022, targeting production of 3 million EVs per year by 2025.

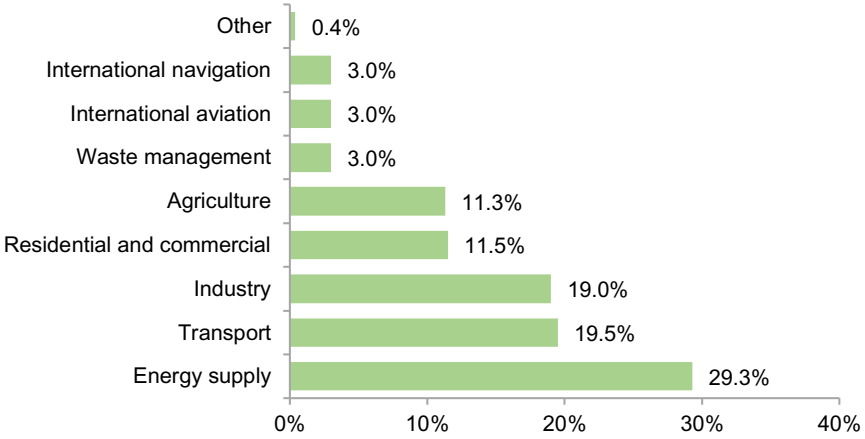
Europe has been a self-styled global climate leader, pushing decarbonizing policies since the mid-2000s, including an EU-wide carbon emissions cap-and-trade system since 2005. Other measures include the EU 2030 renewable energy and energy efficiency targets, and national policies to phase out coal from power generation.

With the exception of aviation, transport emissions lie outside the scope of the carbon market. Of the total greenhouse gas emissions left unregulated by Europe's carbon market, transport contributes 35 per cent, putting it firmly in regulators' sights. At the global level, transport contributes about 20 per cent of total greenhouse gas emissions (see the figure below), but this is expected to rise as other sectors, such as electricity generation, continue to decarbonize.

'AT THE GLOBAL LEVEL, TRANSPORT CONTRIBUTES ABOUT 20 PER CENT OF TOTAL GREENHOUSE GAS EMISSIONS …'

Passenger cars and light commercial vehicles have been subject to a CO_2 regulation in the EU since 2009. Initially, the target was set at an average of 130 g CO_2/km for new passenger cars for 2015, and this has been tightened to 95 g CO_2/km for 2020.

By comparison, the US Environmental Protection Agency 2016 standards for light-duty vehicles require LDVs to meet an estimated combined average emissions level of 250 g CO_2/mile (about 153 g CO_2/km). China has standards for air pollutants in LDVs similar to Euro 5 standards, but not for greenhouse gases; these apply to new vehicles sold in China in January 2017 for gasoline and from January 2018 for diesel. More stringent China 6 standards will apply in 2020 and 2023.



Global greenhouse gas emissions by sector, 2014

Note: In the EU, transport is the only sector where greenhouse gas emissions are still rising (EC).

Source: European Environment Agency, quoting Intergovernmental Panel on Climate Change (IPCC) figures for 2014.

Aside from local air pollutants, many see transportation as a sector where further progress can be achieved on reducing greenhouse gas emissions, particularly in light of the 2015 Paris Agreement on climate change. The Accord entails periodic stock-takes of global progress on meeting a two degrees Celsius limit on global temperature increase by 2100 from pre-industrial levels.

It is widely acknowledged that the sum of the so-called Nationally Determined Contributions – each country's voluntary emissions target and action plan – will not be enough to meet the long-term global temperature target. This means governments will be under pressure to raise their ambition as part of the global stock-taking process, and this could impact the transportation sector as well as all other emissions-intensive industries over the long term. This raises regulatory risks for investments that companies make today, as well as for those providing funding for them.

Industry bodies are also pushing for change. VDA, Germany's automobile association, argues it will not be possible to maintain the speed of CO_2 reduction achieved in the past by further optimizing the internal combustion engine. A more fundamental shift to low-carbon forms of transport will be required, which could include EVs, fuel cells, compressed natural gas (CNG), and liquefied natural gas (LNG).

In a 2017 report (*More climate protection by a more comprehensive and better CO_2 regulation*), the VDA stated: '*The legislators should encourage market penetration of vehicles with alternative power trains … On the one hand, this has a positive impact on CO_2 emissions from road traffic, and on the other may generate faster economies of scale, which then makes vehicles with alternative power trains competitive even sooner*.'

'… IT WILL NOT BE POSSIBLE TO MAINTAIN THE SPEED OF CO_2 REDUCTION ACHIEVED IN THE PAST BY FURTHER OPTIMIZING THE INTERNAL COMBUSTION ENGINE.'

European leaders fear that the USA and China have already taken the lead in developing new low-emissions car models and they want to use legislation to protect strategic industries and support vehicle manufacturers in the development of technology such as EVs or hydrogen fuel cells.

Europe's share of the global passenger vehicle market has been hit hard, falling to 20 per cent in 2017 from 34 per cent before 2008, according to the European Commission.

Cleaner air is a bonus of the transport revolution for Europe's regulators. However, on CO_2 emissions, the contribution made by EVs is dependent on decarbonizing the electricity generation sector – a goal that has only partially been achieved so far, with EU member states moving at very different speeds according to internal politics and access to domestic and imported energy resources.

The EU's Clean Mobility Package

The European Commission released the EU's Clean Mobility Package in November 2017, which includes new targets for EU fleet-wide CO_2 emissions of new passenger cars and vans that will apply from 2025 and 2030 respectively. For both new cars and vans, the average CO_2 emissions will have to be 30 per cent lower in 2030 than in 2021, according to the proposed regulations.

This use of average fleet emissions has been deployed to mitigate the level of disruption experienced by carmakers: it allows them to continue to produce some higher emissions vehicles, so long as they make enough low emissions vehicles to keep the average within the agreed target.

The EU's proposals will be boosted by financial instruments to ensure swift deployment, and the package includes the Clean Vehicles Directive, which seeks to promote clean mobility solutions in public procurement tenders, providing a boost to demand and deployment, according to the EC.

European transport regulators have also signalled that they are open to fuel cell and hydrogen vehicles, and EU officials are working on ways to allow the market to pick the best technology for each case. Helping to reduce the region's EUR1 billion/day fossil fuel bill is another incentive for Europe to shift towards the use of home-grown energy, and cleaner vehicles are seen as a way to support that goal.

As is the case in all regions, there are limits on the extent to which governments will be prepared to fund the uptake of low-emissions vehicles, bearing in mind the need to control public expenditure and maintain tax revenue streams from the use of liquid fuels. If the cost of EVs and other clean vehicles falls far enough to compete directly with combustion engines, it is reasonable to expect governments to scale back financial support mechanisms for them.

Technology has enormous potential to disrupt markets, and some experts are of the view that sections of industry may be underestimating the impact of low emissions transport, given the multiple benefits pertaining to energy security, climate change mitigation, urban air quality, and grid management (through EVs as a distributed system of battery storage). (See 'How soon will electric vehicles make a significant dent in oil demand?', The Barrel, S&P Global, Platts, 19 February 2018.)

Conclusions

A fierce debate is raging among analysts about how quickly such a transformation may play out, not least because there are so many variables: speed of technological change; changes in battery costs; consumer attitudes; environmental regulatory changes; taxation policy; commitment to recharging infrastructure roll-out; and cost and availability of liquid fossil fuels, battery metals, and other raw materials needed for new vehicle types (including lithium, cobalt, nickel, and copper).

'LOW EMISSIONS VEHICLES COULD EVENTUALLY UPEND THE MARKET FOR INTERNAL COMBUSTION ENGINES, BUT THEY WILL ONLY BE A GAME CHANGER IF THE COST … COMES DOWN.'

In Europe, low emissions vehicles could eventually upend the market for internal combustion engines, but they will only be a game changer if the cost of EVs and other alternatives comes down to a point where they can compete directly. If electric trucks cut costs for commercial logistics companies, they are likely to switch. The same can be said for consumers if EVs become more affordable to the average family than their combustion engine equivalents. Until then, uptake of low-emissions vehicles looks set to be determined by government support frameworks and policies.

(This content is an expanded version of an article which first appeared in *Changing Lanes*, an S&P Global special report on transport and future energy markets, released in February 2018.)

Electric vehicles: the road ahead

Colin McKerracher

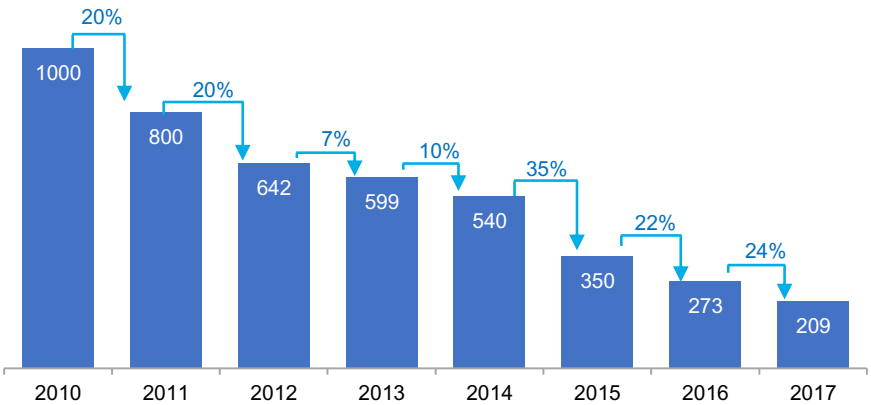
Global electric vehicle sales (battery electric vehicles (BEVs) and plug-in hybrids (PHEVs)) will hit around 1.5 million this year, driven by a mix of falling technology costs, policy support, and industrial strategy. This is remarkable progress – just 180,000 EVs were sold globally in 2013 – and while their share of vehicle sales is still only 1–2 per cent in most markets today, there is growing consensus that EVs will take a much larger share in the years ahead.

Lithium-ion batteries are at the centre of this shift. At Bloomberg New Energy Finance, we have been gathering data on EV battery prices since 2010 (see the figure on the right). Since then, prices have dropped 79 per cent and battery energy density has improved by 5–7 per cent per year. The price of the average lithium-ion battery pack in 2017 was $209 per kilowatt hour (kWh), but despite the recent rapid progress, further declines will be needed in order to enable real mass market adoption. This looks achievable. The learning rate for EV batteries is around 18 per cent,

'THIS PUTS EVS ON TRACK TO BE FULLY PRICE COMPETITIVE WITH COMPARABLE INTERNAL COMBUSTION ENGINE VEHICLES BEGINNING AROUND 2024.'

so every doubling in manufactured volume reduces cost by about that amount on a kilowatt hour basis. This puts EVs on track to be fully price competitive with comparable internal combustion engine vehicles beginning around 2024. Different countries and vehicle segments will hit the crossover point in different years, but by 2030 EVs should be competitive in almost all segments.

Of course, the up-front price is only one metric. Parity, in terms of total cost of ownership, will come between one and three years sooner, depending on factors such as fuel costs and



Average lithium-ion battery pack prices (USD/kWh)

Note: Value is a weighted average price (cell + pack) for battery electric vehicles, plug-in hybrids and stationary energy storage.

Source: Bloomberg New Energy Finance.

annual mileage, and many automakers will opt to simply take a reduced margin on the vehicles they sell while battery costs remain high. Most of this can be achieved with incremental improvements to lithium-ion battery chemistry, but new battery chemistries are also making the slow march from the lab to the manufacturing floor.

Technology progress is not the only driver. Fuel economy regulations are getting tighter and will be increasingly difficult to meet without a significant share of electric vehicles in the mix. The European fleetwide CO_2 targets will require around 13–18 per cent of all vehicle sales in the region to be electric by 2025, depending on the mix of plug-in hybrids and pure electrics. If diesel sales fall further – and they almost certainly will – then this jumps up to 15–21 per cent. Urban air quality continues to rise up the political agenda in cities from Beijing to London, with urban dwellers pushing their municipal governments to move faster than their national counterparts. EVs receive generous purchase subsidies in most major economies, but this will get expensive beyond the initial 3–4 per cent of buyers.

Industrial policy is playing a big role as well. China is the world's largest EV market; it accounted for half of all EV sales in 2017 and will likely hold a similar share this year. China's recently introduced 'New Energy Vehicle' quota requires automakers to sell a set percentage of electric or fuel cell vehicles beginning in 2019, which it will ratchet up over time. The country is aiming for EVs to make up all new vehicle sales growth from now to 2025. Concerns around oil imports and air quality are often cited as the drivers behind this, but China is also trying to position its automakers to export vehicles globally in the 2020s. The technology shift to EVs could provide a once-in-a-generation window to leapfrog established brands and a globally competitive auto sector is a significant source of employment and innovation.

In response to all this, automakers have dramatically increased their commitments to electrification over the last 18 months. Almost all global automakers are launching a slew of plug-in hybrids and pure electrics, beginning in 2020. While the first batch of EV models were mostly small cars, the next wave will be skewed much more heavily towards SUVs. This segment has grown quickly over the last few years and generally has higher margins, giving automakers a bit more of a cushion until battery prices fall further. There are about 180 different EV models on the market today. By 2021 this is set to rise to over 250 and based on automakers' statements, 47 per cent of the new models will be in the SUV segment.

'WE ESTIMATED THAT EVS WILL HIT JUST UNDER 10 PER CENT OF GLOBAL SALES BY 2025, 24 PER CENT BY 2030, AND 54 PER CENT BY 2040.'

There are also many new entrants, most famously Tesla, which has definitely accelerated the pace at which other automakers would have otherwise launched mainstream EVs. An electric drivetrain is far simpler than an internal combustion one, but producing thousands of high quality cars every day is still hard. The top five global automakers by volume in 2025 will all likely be companies in the top 10 today.

All this paints a very rosy picture of the future for EVs and indeed in our annual EV Outlook at Bloomberg New Energy Finance, we estimated that EVs will hit just under 10 per cent of global sales by 2025, 24 per cent by 2030, and 54 per cent by 2040. This would involve just over 500 million EVs on the road by 2040 and would be a major shift in the composition of the global vehicle fleet, which today has around 1 billion vehicles. Because of the speed of turnover, the impact on energy markets will likely be limited until after 2025, but this would displace around 8 million barrels per day of oil demand and add around 5 per cent to global electricity demand in 2040. This includes the impact of shared mobility and autonomous vehicles, an area of high uncertainty which of course could end up moving faster.

Those figures refer to passenger vehicle sales, and other segments will likely go electric sooner. Electric buses, for example, are already gaining traction, particularly in China. We estimate there are already over 300,000 electric buses on the road in China today. Cities like Shenzhen have already fully switched over their municipal bus fleet and other cities are following. In 2017 around 12.5 gigawatt hours of lithium-ion batteries went into Chinese electric buses, compared to 30.6 gigawatt hours of batteries going into all light duty EVs globally. If those Chinese e-buses were replacing relatively inefficient diesel ones, then electric vehicles were already displacing around 1.5 per cent of China's total oil demand in 2017.

Barriers and things to watch

There are still several big factors that could impact EV uptake.

1 EV charging infrastructure is still challenging

The number of public charging points is rising steadily and hit over 500,000 in 2017, up from just over 150,000 in 2014. China is pushing the hardest here, and the numbers in Europe and North America are also rising quickly. Charging speeds are also picking up – five years ago 'fast' chargers generally operated at 50 kW while the

latest stations being rolled out today will be capable of 350 kW. This brings charging time down to around 15–20 minutes for an 80 per cent charge, once there are vehicles that can actually support this level of charging. But in many countries the power grid quickly becomes a limiting factor. The odds of spare distribution grid capacity lining up exactly with the needs of charging stations is low. We will see many more charging network operators dropping new and used batteries at these stations to help alleviate these issues (and avoid peak demand charges), but this can be an expensive proposition and charging network operators already struggle to make money. Most charging takes place at home, but widely available public charging will be needed to convince many new buyers to join the EV ranks.

2 Battery material supply constraints present another potential challenge for the EV industry

The lithium-ion battery market is in the midst of a very rapid scale up, with manufacturing capacity set to rise from around 120 GWh today to over 350 GWh by 2021, based on statements from manufacturers. There will be enough manufacturing capacity, but there are some question marks over the supply of key materials.

This is the latest arena for skirmishes between resource optimists and pessimists. There are good reasons to be concerned whether there will be enough cobalt, lithium, nickel, and graphite to meet aggressive EV demand forecasts. Supply chains for these materials are still relatively immature and prices for cobalt and lithium carbonate rose 129 per cent and 26 per cent respectively in 2017. But price signals are powerful forces that drive substitution and bring new supply online. The last 40 years have not been kind to those betting that we will 'run out' of key materials, and there are enough reserves of all of these to support significant electrification over the next 10–15 years.

'EV ADOPTION RATES WILL BE VERY DIFFERENT FOR HOUSEHOLDS WITH A SECOND CAR AND A GARAGE THAN THEY WILL BE FOR A SINGLE CAR, APARTMENT-DWELLING FAMILY.'

However, timelines for bringing on new supply matter and so does geographic concentration. Lithium supply looks as if it is now on a firm footing, but further spikes in cobalt prices, together with political risks in the Democratic Republic of the Congo (where most cobalt reserves are), could mean some bumps in the road to an electric future. Still, the effect is likely to delay – rather than derail – the move to electric vehicles. Already, lower-cobalt battery chemistries are coming online and even if cobalt prices were to double again, the impact on the final price of an average battery is around 10–15 per cent.

3 Consumer adoption is notoriously difficult to predict

Look back to the fawning media coverage of how Tata's Nano (a low-cost car city car launched in 2008) would rewrite the story of India's automotive market – 10 years later, the car is a footnote, not a headline. There are good reasons to believe that once EVs are cost competitive, people will buy them in large numbers. Norway made EVs cost competitive through taxation and incentives, and EVs went from 6 per cent of sales to 39 per cent of sales in just four years. Not many governments can afford to follow this example, but the battery cost curve should be able to do what the Norwegian government did 10 years ahead of schedule. EVs also win on several categories such as noise and acceleration, but there are still behavioural changes needed on refuelling patterns and in most cases we still do not know exactly how the real middle market will react.

In all likelihood, we are heading towards a far more differentiated global auto market than we have seen in the past. EV adoption rates will be very different for households with a second car and a garage than they will be for a single car, apartment-dwelling family. Some countries and cities will jump far ahead due to factors as varied as grid and charging investments, housing stock, and cultural factors. No transition this big will be without setbacks, but electric vehicles are here to stay.

Three revolutions in urban passenger travel

Lewis M. Fulton and Junia Compostella

Three revolutions are underway in urban transportation around the world: vehicle electrification, automation, and shared (on-demand) mobility. We do not yet know the manner in which each of these will unfold or how they may interact; the way in which these changes take place will have major implications for cities over the coming decades. Our modelling work suggests a wide range of possible impacts, and a strong need to pursue policies that move these revolutions in sustainable, societally optimal directions. This generally means reducing the numbers of vehicles on the roads, and parked, as well as dramatically cutting energy use and CO_2 emissions. To do this it seems likely that we will need to dramatically increase the extent to which rides are shared, public transit is expanded and used intensively, and active modes (walking/cycling) increase their share of trips. The effects of achieving these conditions under a three revolutions future was the focus of recent research at the University of California, Davis. This commentary summarizes and extends this work.

'THREE REVOLUTIONS ARE UNDERWAY IN URBAN TRANSPORTATION AROUND THE WORLD: VEHICLE ELECTRIFICATION, AUTOMATION, AND SHARED (ON-DEMAND) MOBILITY.'

- As of 2017, battery electric and plug-in hybrid vehicles have reached 1–3 per cent sales shares in most OECD countries (and much higher in a few, such as Norway); some projections see this share rising as high as 30 per cent by 2030, with a hundred million or more EVs in service at that point.
- Automated vehicles are further behind but costs are declining rapidly, regulatory frameworks are emerging, and commercial vehicles are expected to begin appearing as Level 3 or Level 4 (fully autonomous but limited to certain driving modes) around 2018/19, and Level 5 (completely driverless) a few years later.
- Shared mobility, both in terms of ride hailing and car sharing, is now well developed and widespread around the world, though it still represents a low share of trips in most cities. But on-demand ride hailing appears to be increasing rapidly in many places.

Some directions the changes could take

How might these three revolutions co-evolve? There are a number of potential directions, and complex potential dynamics. These include:

1 Automated vehicles in households could increase travel and traffic

A major shift to privately owned driverless cars could result in an increase in travel, since people may be willing to be in their vehicles for longer periods, given the opportunities to be productive and more comfortable if they are not driving them. While automated vehicles should reduce the road space requirements of each vehicle (more compact spacing) and improve traffic flow (for example, there would be fewer accidents), the net effects of possible increased vehicle travel on congestion and energy use are difficult to predict.

2 Automation with or without electrification?

Household automation does not guarantee electrification: for example, early Uber self-driving test vehicles in Pittsburgh were non plug-in hybrids. Many households may not 'demand' that automated vehicles be electric, and may also want these vehicles to be large, comfortable, and powerful (which can be achieved with EVs as well, but these features are not required). Such a scenario would result in substantially more energy use and CO_2 emissions than one combined with electrification, and could lead to an overall increase in CO_2 compared to a 'base' scenario without automation (given additional vehicle miles travelled (VMT) and despite some efficiency gains from automation).

'THE ADVENT OF DRIVERLESS, ELECTRIC, ON-DEMAND RIDE SHARING SERVICES COULD CUT THE COST OF THESE SERVICES BY 70 PER CENT OR MORE.'

3 The impacts of very low cost on-demand mobility

The advent of driverless, electric, on-demand ride sharing services could cut the cost of these services by 70 per cent or more, since the driver cost would be eliminated while fuel and maintenance costs would also be reduced given those characteristics of EVs. With high mileage driving, the capital cost of cars would also drop, since they could be amortized over many hundreds of thousands of kilometres, potentially bringing the per-km capital cost to very low levels.

4 Could private cars (and other modes) be left behind?

Such low costs could encourage more people to use ride hailing for urban (and even some non-urban) trips, and leave their own cars at home or even

User monetary and non-monetary cost types for different travel choice options

Monetary costs	Non-monetary costs
Vehicle purchase	Travel time (driving)
Vehicle maintenance	Travel time (passenger)
Fuel	Parking search time
Insurance	Walking time
Cleaning	Driving stress
Parking	Shared trips (e.g. lack of privacy)
Driver	EV range, charging anxiety
TNC charges	Car ownership negatives (maintenance, registration, inspections etc.)
Tolls	Car ownership positives (car pride, guaranteed ride, can leave personal belongings in the car)
Registration	Perceived environmental cost

Source: Authors' list.

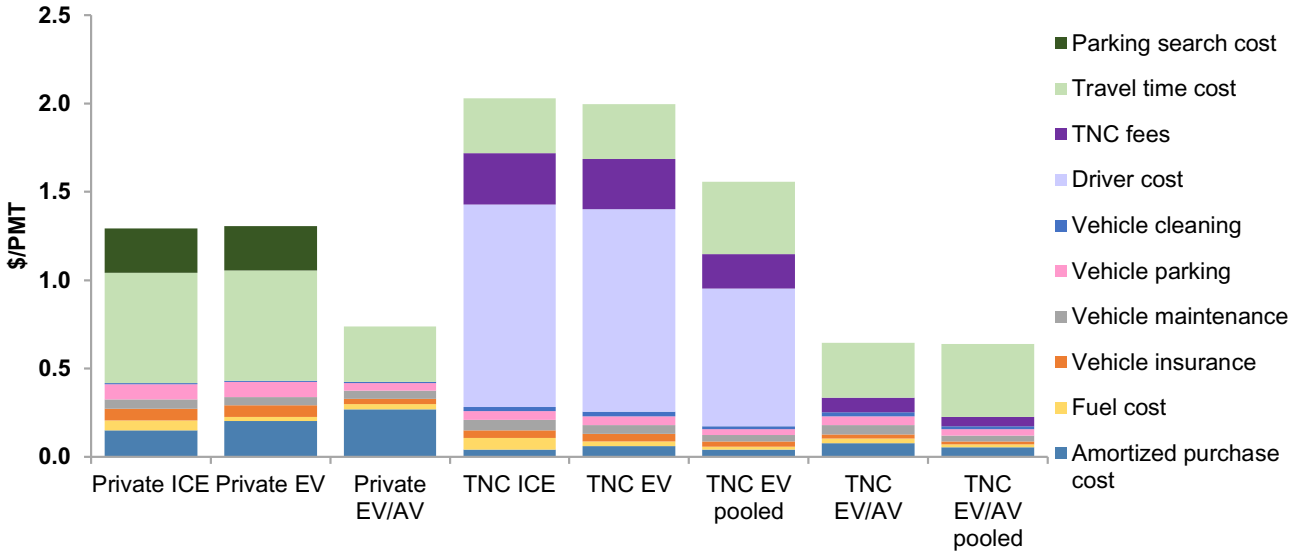
reduce ownership levels. They might even choose door-to-door ride hailing over public transit systems, since costs may become similar. Similarly, very low-cost ride hailing could even reduce the interest of riders in actually sharing rides; what might have been interesting when a $15 ride could be cut to $10 with sharing becomes much less interesting as a $3 ride cut to $2. One of the core concepts of ride sharing services that provides societal benefits is the actual sharing – in principle a shared trip means one less vehicle trip, one less car in use. This benefit could be quite large with substantial sharing – for example, in 2016 the International Transport Forum (see the document 'Shared Mobility: innovation for liveable cities') modelled a hypothetical system for Lisbon that could meet all of the city's trip demands with only 3 per cent of the current vehicle stock, if these were 8 and 16 seat vehicles (vans and buses), intensively shared. But very low-cost services would probably not lead to such an outcome.

Thus there are many dynamics in play here, and it is difficult to gauge their potential net effects on urban travel.

Possible effects of costs

In our research in this area, we have been comparing the costs of choosing among different travel options, to gain some insights into the likely success of both shared mobility and automated vehicles in the household travel market. We have learned that while monetary 'out-of-pocket' costs are important factors among the different options, non-monetary or 'hedonic' costs may be much more important. These hedonic costs may include many different factors, as can be seen in the table above left.

UC Davis has begun to estimate a number of these costs, as shown in the figure below. This figure compares the cost per mile travelled, from the point of view of the consumer, for private and Transportation Network



Midsize vehicles (dollars per passenger mile travelled) in 2025

Source: Authors' analysis.

Company (TNC) trips, and breaks these costs down by cost component. For each situation, it includes internal combustion engine (ICE), electric, and automated vehicle choices. It also includes pooled ride choices for the TNC options, where separate riders share a ride with a discounted price. These costs are built up using the monetary cost categories listed in the table on the previous page, and two of the non-monetary costs: travel time (while driving the vehicle or while being a passenger); and the search/inconvenience time of parking one's car when this applies.

The figure reflects myriad assumptions made, related to costs and prices in the San Francisco area and projected to 2025, particularly for the costs of EVs and automated vehicles. Some of the key assumptions include:

- Battery costs are assumed to decline over time, to under $200/kWh by 2025; AV costs also decline to under $10,000 per vehicle by that year.
- Private vehicles are amortized over 100,000 miles of driving, while TNC vehicles are amortized over much longer distances, since they are driving much more intensively. This causes their per-mile capital cost to be far lower than for household vehicles.
- Insurance, maintenance, and other operating costs are based on a review of such costs in California in 2017, and on estimated costs in the future. Electric vehicles are assumed to have much lower maintenance costs than ICE vehicles; automated vehicles are assumed to have much lower insurance costs than driven vehicles by 2025, given their safety advantage.
- Parking is assumed to cost about $5 per trip, and a trip length of 15 miles is assumed; this makes parking a fairly important cost.
- Driver costs for TNC trips are estimated based on current average costs (and driver revenues) in California. A similar approach is used for TNC overhead costs and resulting fees per PMT.
- The value of time is assumed to be $15/hour when driving and half that when a passenger (whether in a driven vehicle or an AV). The time associated with parking and walking to the destination is assumed to be five minutes, twice per trip.
- Shared or pooled trips provide a 40 per cent discount per rider, but there is an increase in time cost due to additional pickups and drop-offs. This is assumed to be five minutes, twice per trip.

'NON-MONETARY COSTS ARE IMPORTANT, PARTICULARLY WHEN HAVING TO DRIVE AND PARK ONE'S OWN VEHICLE.'

Of course, the costs shown in the figure may vary widely by time, location, trip type, and even across the population, particularly for perceived non-monetary cost levels. But the averages shown here are nonetheless revealing. The figure shows that TNC trips are expensive, whether in ICE or electric vehicles; pooled trips can be considerably cheaper. The non-monetary costs are important, particularly when having to drive and park one's own vehicle. A private automated vehicle may be perceived as far cheaper given the time and parking advantages (this assumes the automated vehicle provides door-to-door service and then parks itself). Meanwhile, the TNC automated vehicle provides services that are quite competitive with a private vehicle, but given even a five minute delay during pickup and dropoff (due to multiple riders), the pooled TNC ride has little advantage over the individual ride, even at a modest time cost. Finally, if one were to neglect the purchase cost of private vehicles (since for existing car owners this is a sunk cost and probably not considered when making the decision each day regarding how to travel), the private EV/AV would actually become the cheapest option (since the 'Amortized purchase cost' would be eliminated).

These comparisons only scratch the surface of what could be investigated in terms of costs. The wide range of non-monetary, hedonic costs shown in the table above could be estimated (though some would be difficult) and included in a figure similar to the one in this article. It may show, for example, that many people would attach an even greater penalty to sharing, if they prefer not to be in cars with strangers, particularly if there is no driver. The variation in valuations of costs may also be considerably affected by location and across the population. This type of analysis could help better understand the likelihood that in the future many or most people will choose TNC vehicle trips, automated vehicle trips, and shared vehicle trips, or not. This in turn will likely be critical in determining whether the future of urban travel will be dominated by household vehicles (and the possible increases in traffic associated with automated household vehicles) or by TNC vehicles, perhaps in conjunction with other modes such as transit. UC Davis continues to work in this area and is collecting travel behaviour data to help answer these important questions.

Disruptive change in the transport sector – eight key takeaways

(This article summarizes eight key takeaways from a workshop held by OIES on 'Disruptive Change in the Transport Sector' in relation to its impact on energy use in private transport.)

#1. Despite many government announcements and strong press coverage regarding vehicle electrification, there are alternative technologies which are also important for future mobility.

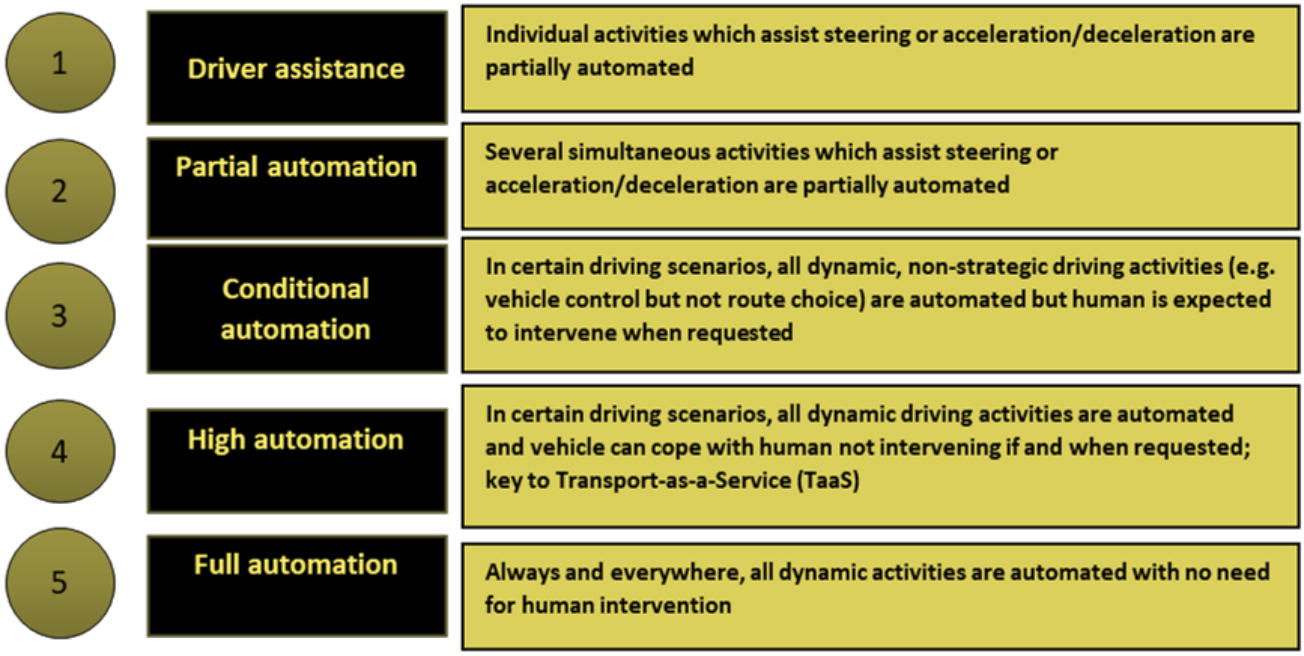
While vehicle electrification is being driven by government policy around the world, many other technologies are being developed through private investment. Many technologies target improvements to passenger vehicle fuel economy through improving the efficiency of the Internal Combustion Engine (ICE):

- Homogenous charge compression ignition, and spark-controlled compression ignition, could improve engine efficiency by 20 to 30 per cent, alongside lower emissions of NO_x and soot.
- The utilization of high-octane fuel in the engine only at moments when it is needed (octane-on-demand), can improve the efficiency of fuel use.
- A move towards refining higher octane fuels that could be utilized by vehicles with a higher compression ratio would reduce the CO_2 footprint of each mile travelled.

'MANY TECHNOLOGIES TARGET IMPROVEMENTS TO PASSENGER VEHICLE FUEL ECONOMY THROUGH IMPROVING THE EFFICIENCY OF THE ICE.'

While the potential for all these technologies is well known, the problem lies in aligning standards of auto companies, regulators, and oil companies, in order to catalyse the shift to higher ICE efficiency.

Another technology under consideration *is onboard* CO_2 *emissions capture*: capturing 30–50 per cent of CO_2 before it leaves the car's tailpipe. However, the economics of small-scale carbon capture are less favourable than at large stationary point-source locations (such as power plants). An added complexity is onboard storage, as CO_2 has to eventually be removed from the car. Fuel cells and hydrogen (which produces more megajoules of energy per kilogram compared with other energy sources) are technologies actively being considered in the transportation systems of countries such as Japan, with the main challenges being cost, infrastructure, and onboard hydrogen storage, as systems to contain it have not yet been developed at scale. Technologies to enable connectedness, including vehicle-to-vehicle, vehicle-to-infrastructure, and people-to-mobility



Levels 1–5 of vehicle autonomy in transport

Source: 'Connected and Autonomous Vehicles', UK House of Commons Briefing Paper No. CBP7965, June 2017.

connectivity, along with *shared mobility* (ride-sharing and ride-hailing), could have a significant disruptive impact on vehicle ownership and energy use in transport.

#2. Level 5 autonomous vehicles are still some years away and will be context-specific.

Although technologies to deploy Level 5 autonomy – dispensing with the need for a human driver present, see the figure on the previous page – may exist five to ten years from now, its deployment will depend upon many factors including public opinion, politics, and regulatory and licensing frameworks. Level 5 autonomy technology entails the solving of two key machine-learning problems:

- the generation of a very accurate model or reconstruction of the world around us that we see at any given moment (for instance using traffic CCTV footage);
- the ability to use this model to make predictions for a specific urban environment.

Level 5 autonomy, when first implemented, is more likely to be limited to certain environments in Western cities. Fully autonomous vehicles will need the requisite supporting infrastructure (for example, AVs need to be able to communicate with designated charging points) and remote operation of Level 5 AVs will entail regulations around safety and privacy.

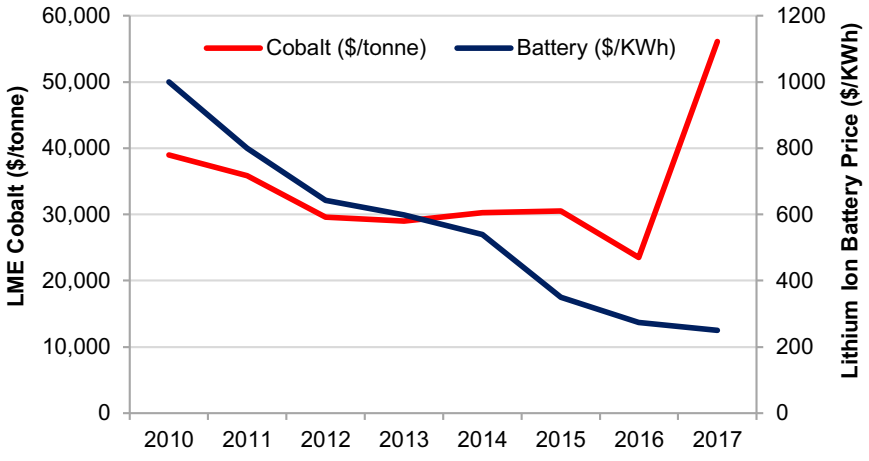
The impact of Level 5 AVs on energy use is unclear and may not necessarily change energy consumption; however, they may enable other changes (such as cost reductions, new mobility types/sharing, and electrification) that would affect energy consumption. Automation by itself is certain to push up vehicle miles travelled, but the extent to which this is allowed to increase is contingent on government policies. Research suggests that business travellers are likely to be early adopters, due to benefits associated with the productivity of travel time. Fully automated vehicles bring about an equilibrium with public transport. If Level 5 AVs induce a switch from public to private transport (given associated cost reductions), the number of Vehicle Kilometres Travelled could increase. Similarly, if Level 5 AVs remove the incentive for ride-sharing (which is primarily cost-driven), this could also increase energy use. If Level 5 autonomy enables the matching of on-demand mobility to the right vehicle size, there are likely to be substantial energy savings. Level 5 AVs, in combination with electrification and ride-sharing, could therefore bring about significant disruptions in transport.

'LEVEL 5 AVS, IN COMBINATION WITH ELECTRIFICATION AND RIDE-SHARING, COULD BRING ABOUT SIGNIFICANT DISRUPTIONS IN TRANSPORT.'

On the other hand, Level 3 autonomy (where a human driver is able to take back control of the vehicle at a moment's notice) is more likely to be seen within the next two to three years, in highway environments.

#3. Cost is one among multiple factors in the scaling up of batteries.

Popular debate has focused around cost reductions in battery technologies that could enable EVs to compete with ICEs. Battery costs declined by 12 to 14 per cent on average per year from 2000 to 2015, and costs in 2016 stood at a low-to-high range of roughly $200–$300/kilowatt hour (kWh). The US Department of Energy is targeting $125/kWh by 2022, which many argue could bring battery and EV technologies within the ballpark of cost competitiveness with ICEs. This, however, depends on other factors that affect costs and payback periods, such as fuel taxes, EV purchase subsidies, annual kilometres driven, *inter alia* (and ignoring uncertainties around non-cost factors, such as technology diffusion and consumer preference). An interesting dynamic also playing out at present (see the figure below) is the fact that battery prices are continuing to decline, even though raw material prices are beginning to increase. There are three potential reasons for this:



Lithium-ion battery price (RHS) vs cobalt price (LHS)

Source: Bloomberg New Energy Finance; London Metals Exchange (LME).

- Some battery manufacturers (for example in Asia) may be sacrificing margins in order to capture market share.
- There is global overcapacity of lithium-ion batteries – global lithium-ion battery production capacity is around 116 Gigawatt hours (GWh)/year and could reach 290 GWh/year by 2021. However, passenger EV sales have not kept up with this growth – total passenger EV battery demand last year was around 21 GWh.
- Issues relating to supply chain bottlenecks. Raw materials for batteries (lithium, cobalt, graphite, nickel, aluminium, copper, and manganese) are concentrated in a few countries and production is subject to their regulatory frameworks and operating environments.

Analyses of scale should therefore consider not just battery chemistries but also material supply chains, manufacturing processes, location to market (for example, the co-location of battery plants and EVs, as batteries are more safely transported within EVs), and recycling. Each of these has associated opportunities and challenges.

#4. Grid management is critical to EV adoption.

The International Energy Agency estimates that additional generation needed to meet EV demand in the two degree scenario will represent only 1.5 per cent of total electricity demand by 2030. Rather than the level of absolute capacity, it is the management of the grid which will be critical to EV adoption. The development of electric mobility is therefore compatible with the current power system so long as demand can be anticipated and the infrastructure adapted to it in advance. Successful grid management entails the optimization of the plant fleet. If

'RATHER THAN THE LEVEL OF ABSOLUTE CAPACITY, IT IS THE MANAGEMENT OF THE GRID WHICH WILL BE CRITICAL TO EV ADOPTION.'

this is absent, peak loads in countries where EVs are adopted on a large scale could increase significantly. Optimization involves predicting 'charging hotspots' and planning load management and infrastructure around them. The power industry needs to work out how to manage the uncertainties around EVs – such as in which regions/cities they are most likely to be developed. Solutions being proposed to reduce these uncertainties involve '*controlled charging*' and '*smart charging*'. These then may require the development of incentives to influence consumer behaviour and reduce uncertainties around grid charging. There may also be a space for 'integrators' or agents in the power industry, whose role it would be to gather information from various entities and to manage demand. Technological solutions such as '*fast charging*' and '*wireless charging*' are proposed as ways to enable grid optimization – however, interoperability will be necessary to optimize grid management.

#5. Automobile manufacturers will need to restructure their business models around value creation.

Uncertainties faced by the auto industry around EV adoption include: which consumers will adopt EVs, how fast, and where? And, what will the effects of EV adoption be alongside automation and mobility – will this lead to higher or lower car ownership and sales? At the same time, governments around the world are currently implementing regulations which mandate auto manufacturers to increase their EV production in the near future.

Auto manufacturers face three key challenges in this regard:

- Auto companies need to allocate investments now, but face uncertainty over future demand for EVs. One way to hedge against this future risk has been to announce EV models in nearly every consumer segment. Consequently, the EV businesses of many auto companies are not profitable, as the consumer uptake of EVs has been slow relative to the production of EV models.
- Profitability at present comes almost entirely from the sale of vehicle units. If automation, electrification, and mobility lead to a net drop in sales, auto companies will have to reorient their business models, and move from relying on individual sales to continuous customer engagement throughout the life of the product – not just at the point of sale.
- EVs have far fewer parts than ICE vehicles – one estimate puts these at around 18,000 compared with 30,000 for a conventional vehicle, translating into a smaller number of jobs in EV production. Auto companies will face pressure to preserve as many jobs as possible while making the transition to EV manufacturing. As EV motors are scaled up, value creation is likely to move further up the supply chain, so the industry structure, as well as the structure of jobs, will have to be reorganized accordingly.

#6. Technology diffusion goes beyond cost-competitiveness.

Most arguments around EV adoption focus on cost (price) as the key variable influencing consumer preference in the uptake of new technologies; however, this is not the only variable, particularly in countries where markets are not fully developed. EV adoption by a consumer effectively involves 'fighting' against an existing ecosystem built around the ICE. A

focus on the economic (cost) element risks entirely dismissing both the political and cultural factors involved in EV adoption and the diffusion of new technologies in general. The diffusion of new technologies can be understood through multiple perspectives:

'EV ADOPTION BY A CONSUMER EFFECTIVELY INVOLVES "FIGHTING" AGAINST AN EXISTING ECOSYSTEM BUILT AROUND THE ICE.'

- '*Stimulus–response*': the idea that if a technology is 'simply put out there' people will adopt it. This dominates much of the current thinking around EV adoption .
- *The dissemination of information*: if consumers are given complete information about the benefits of the technology, they will buy more EVs.

Sociologists and geographers study EV adoption not just in relation to the purchase of EVs, but also to the way in which EVs become embedded within everyday practices. The '*domestication approach*', sets out three types of 'work' involved in technology adoption on the part of the adopter:

- *cognitive work* involves learning about the new technology and what it does;
- *symbolic work* involves developing a set of cultural categories to make sense of the technology;
- *practical work* involves embedding the technology in everyday activities.

No single approach can be generalized to understand the diffusion of different technologies. The factors underpinning household adoption of EVs are also different from those affecting the commercial adoption of EVs. In the latter, the overriding factor is cost. But in the former, the relevant factors are not just linked to economics but also to societal preferences and cultural shifts – for example, research shows that millennials tend to drive less and own fewer cars.

#7. Emerging markets will also adopt EVs, driven primarily by government policy – but outcomes will differ.

China and India – the world's largest and fifth-largest automobile markets, respectively – could account for over 50 per cent of the increase in global oil demand to 2035. Transportation forms around 55 per cent of oil demand in China and 40 per cent in India. As their per capita incomes rise, historical data shows that vehicle ownership will grow exponentially. Fundamentally, both countries are aiming to switch to EVs to improve energy security by reducing long-term oil import dependency. Another key driver has been the move (provincial in China and state-level in India) to regulate rapidly worsening urban air quality. India's government aspires to move to a completely electrified vehicle fleet by 2030, and China's government anticipates that sales of 'New Energy Vehicles' will reach 5 per cent of total vehicle market demand by 2020 and 20 per cent by 2025. Both countries face similar challenges in scaling up electric mobility, to which both governments will respond differently given their different governance structures (centralized policy in China, whereas in India policy will require buy-in from state governments). Outcomes will accordingly differ:

- *Employment opportunities will be central to the adoption of EVs:* China's EV policy sits within its industrial strategy based on domestic manufacturing. India's supply chains to support domestic EV manufacturing are weak, but it will want to avoid repeating its experience with solar panels, where despite massive increases in solar capacity, 80 per cent of the market was dominated by Chinese imports.
- *The pace of EV uptake is likely to differ across provinces/states:* Chinese provinces use a lottery system at the city level for vehicle sales, from which EVs were exempt, until recently. Cities also administer ICE vehicle prohibitions to control pollution. Indian states have had to impose court-mandated bans on older diesel vehicles, which have been challenged in the courts by state public transport corporations. In India, it may also be difficult to commit a future government to a permanent ban.
- *Social equity issues are relevant*: EVs in developed countries are purchased by richer consumers, often as a second vehicle. In emerging markets, tax revenues from transport fuels comprise a large proportion of government finances. Similarly, ICE bans on older vehicles tend to impact poorer consumers who purchase second-hand cars.

#8. Automation, electrification, and shared mobility imply very different types of impacts in different combinations.

The net impact on energy use of disruptive change in transport will come from a combination of automation, electrification, and shared mobility. Interactions between the three are not clearly understood. However, the net impact will not be determined by absolute numbers of EVs, but by vehicle kilometres travelled (VKT) or vehicle miles travelled (VMT), as the three disruptors will manifest in the ways in which they change people's travel behaviour.

'THE NET IMPACT ON ENERGY USE OF DISRUPTIVE CHANGE IN TRANSPORT WILL COME FROM A COMBINATION OF AUTOMATION, ELECTRIFICATION, AND SHARED MOBILITY.'

- *Automation* on its own is likely to massively reduce the cost of travel, but if automation removes any incentive to ride-share, it could lead to an increase in VKT and consequently in energy use and emissions.
- *Vehicle electrification* in addition to automation, would result in lower energy use, as oil is substituted away in transport (the emissions implications of this scenario would depend on the source of electricity).
- *Shared mobility*, in addition to automation and electrification, could reduce vehicle ownership and VKT, bringing about massive reductions in energy use – estimated at 50 per cent lower over the automation plus electrification scenario by 2050.

The big questions lie around how quickly the world can get to such a scenario, whether the three disruptors will occur in combination, and what implications the interaction between automation and shared mobility in exclusion, or between electrification and shared mobility in exclusion, will be.

The full version ('Disruptive Change in the Transport Sector: Eight Key Takeaways'*) can be found on the OIES website.*

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Annual Subscription (four issues) £90.00
Oxford Energy Forum. ISSN 0959-7727. Published by Oxford Institute for Energy Studies, Registered Charity 286084.