automotive council UK

ADVANCED PROPULSION CENTRE UK

THE ROADMAP REPORT

TOWARDS 2040: A GUIDE TO AUTOMOTIVE PROPULSION TECHNOLOGIES

Produced by the Advanced Propulsion Centre UK on behalf of the Automotive Council UK

FURTHER INFORMATION

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ACKNOWLEDGEMENTS

The Advanced Propulsion Centre would like to thank all those who were involved in the workshop and interview process. Your input was valuable in delivering the updated set of roadmaps and ensuring they reflect the challenges facing the automotive industry. A special thanks must also go to E4tech and Appleseed Solutions for assisting the APC with the data gathering as well as Market Engineering and Spell Creative in helping write and design this report.

E4tech
Strategic thinking in sustainable energy

appleseed solutions

market engineering

THE ROADMAP REPORT

TOWARDS 2040: A GUIDE TO AUTOMOTIVE PROPULSION TECHNOLOGIES

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TECHNOLOGY ROADMAPS

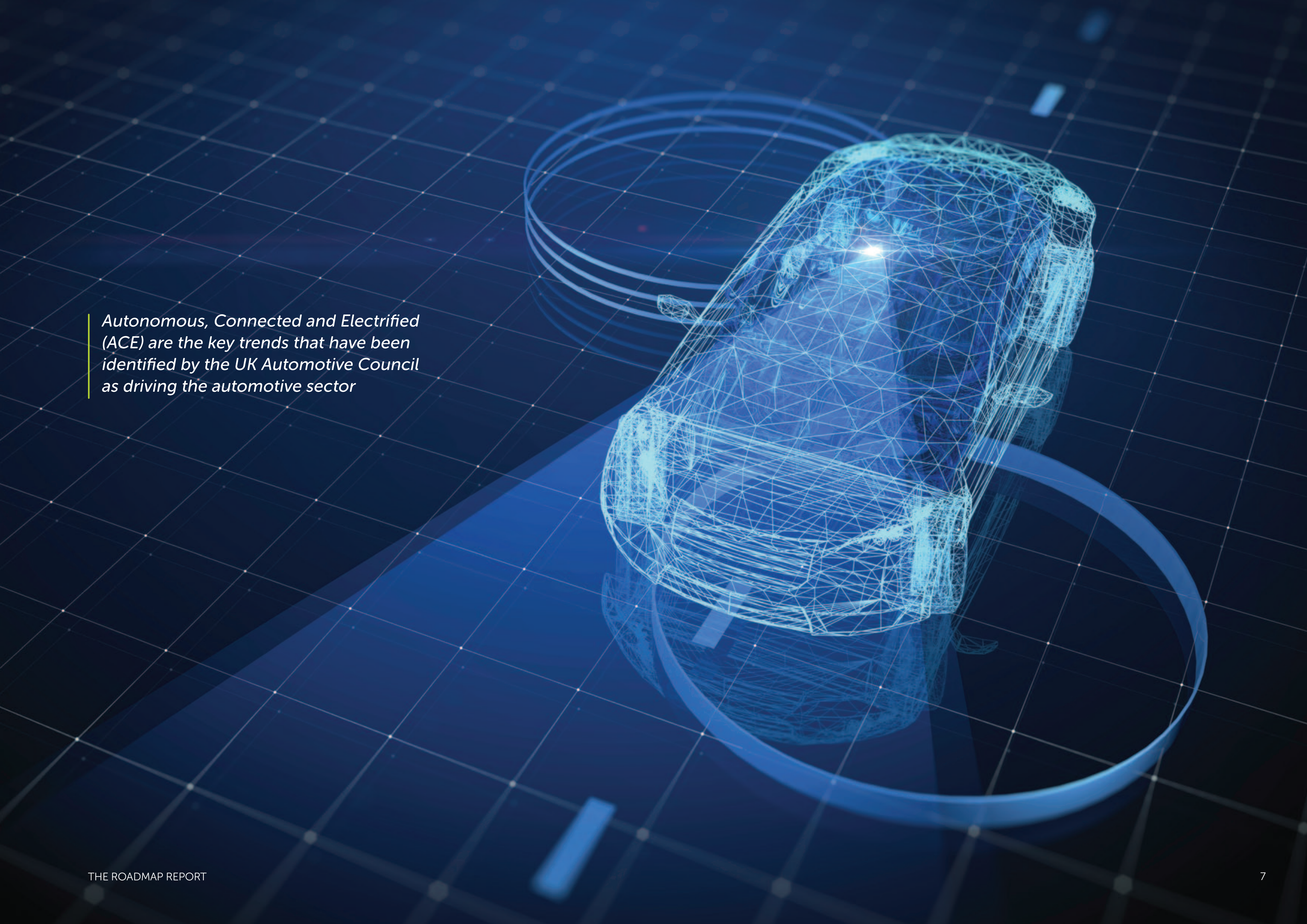
INTRODUCTION

DR. GRAHAM HOARE OBE – CHAIR OF THE UK AUTOMOTIVE COUNCIL TECHNOLOGY GROUP

In response to numerous environmental and societal pressures, the automotive sector is embarking upon a period of unprecedented technological change that has the potential to revolutionise mobility. Autonomous, Connected and Electrified (ACE) are the key trends that have been identified by the UK Automotive Council as driving the automotive sector and continue to challenge the global engineering community. These changes will take place over future vehicle development cycles, so stakeholders should respond in a considered manner and view the roadmaps as informed trajectories to the future.

Since they were first published in 2009, the Automotive Council's roadmaps have been instrumental in visualising the evolving automotive landscape and communicating a shared view of the future. Reflecting consensus at a particular point in time, the insights gathered from the roadmap report were derived from a wide range of stakeholders: from global OEMs right through to local technology developers and academia. While individuals may have differing views, it's this consensus driven approach, combined with a detailed exploration of key technologies that make these roadmaps truly world leading. The Automotive Council looks forward to continuing working with UK Government, academia and industry to ensure that the barriers to adopting new vehicle and powertrain architectures can be addressed and capitalised upon to provide sustainable benefits to us all.

> *Since they were first published in 2009, the Automotive Council's roadmaps have been instrumental in visualising the evolving automotive landscape and communicating a shared view of the future.*



Autonomous, Connected and Electrified (ACE) are the key trends that have been identified by the UK Automotive Council as driving the automotive sector

FOREWORD

NEVILLE JACKSON – DEPUTY CHAIR OF THE UK AUTOMOTIVE COUNCIL TECHNOLOGY GROUP

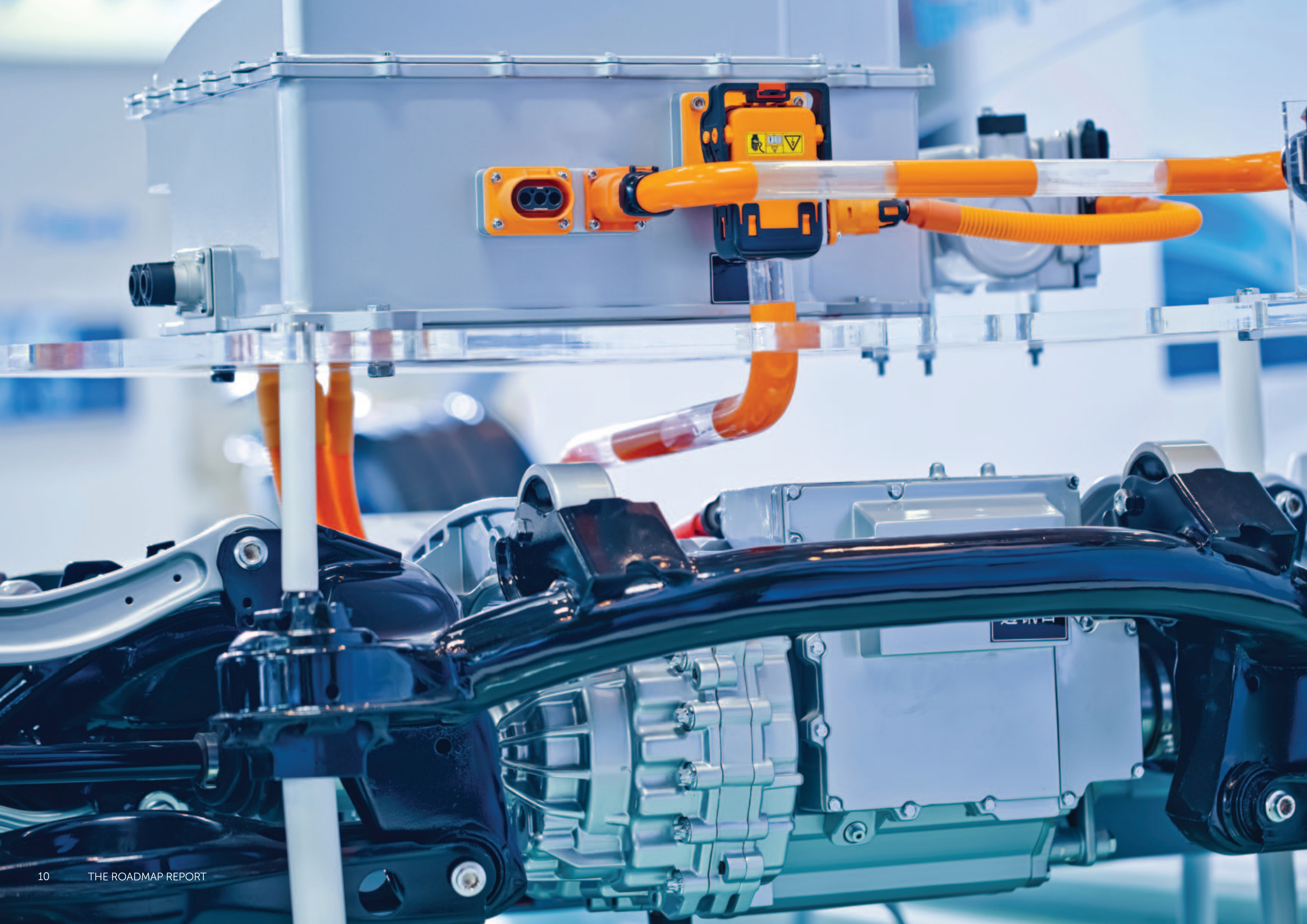
The updated set of propulsion roadmaps in this report build upon the foundations of the Automotive Council Technology Group roadmaps created in 2013 and reflect today's complex landscape. Whilst the longer term vision for sustainable, clean and low or near-zero carbon transport is now well established, this will only be realised if we can find a technically and economically viable pathway to get to this vision. The 2018 roadmap report astutely identifies the key trends that will determine future powertrain development and summarises how future vehicles and technologies might evolve to meet both customer and environmental requirements.

The report rightly identifies that in the short term, vehicle tailpipe emissions will drive powertrain choices in order to meet legally binding CO_2 targets and emission limits. However as the impetus to decarbonise the global economy intensifies and new mobility business models emerge, there is a need to develop powertrains that satisfy a wider range of societal and environmental demands.

An important theme throughout this report is that the automotive sector must not only understand the life cycle impacts of vehicle manufacturing, but also understand the role for transport fuels and energy vectors within the wider energy system and its associated infrastructures.

I hope this report resonates not only with those organisations in existing automotive supply chains but also those outside the automotive sector as it will require more than just UK automotive to overcome future challenges in mobility.

An important theme throughout this report is that the automotive sector must not only understand the life cycle impacts of vehicle manufacturing, but also understand the role for transport fuels and energy vectors within the wider energy system



SUMMARY

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ORGANISATIONS ENGAGED WITH THE APC ROADMAPPING ACTIVITY

- OEM
- Supplier
- Technology Developer
- Engineering Service Provider
- Academia
- Other

This document provides a thoroughly researched overview of the technology trends that will determine how the automotive industry meets pressing environmental and sustainability challenges. Covering each of the major sectors, including passenger cars, commercial vehicles, busses and off-highway, it describes the direction that technologies are most likely to take, illuminates the technical and manufacturing challenges that affect their adoption and discusses the impact of wider initiatives encompassing social and infrastructure changes.

Information can be viewed by sector, at-a-glance in the tables and graphical roadmaps, or reviewed in more detail through the written commentary. Written for a wide range of stakeholders, including industry leaders, politicians, legislators and investors, each roadmap is based on the learning of a wide range of industry experts so provides professional opinion supported by numerical targets, with sufficient technical detail to inform technology developers and strategists.

It is evident that optimum results can only be achieved through 'joined up' thinking, first at a powertrain system level, then moving out to consider energy policy and the wider transport system. By placing the discussion of the technology trajectories within this context, the document indicates where investment, including support from government, will deliver the greatest benefits.

The roadmaps are not intended to assess the UK's capability to deliver on the identified technology streams or to map out skills, supply chain, financing, policy or regulatory requirements. However, they provide a valuable tool to help identify specific targets and technology trajectories in these areas, helping to ensure that related decisions are taken based on the best available expertise.

ABBREVIATIONS USED

ADAS	Advanced Driver Assistance Systems
BEV	Battery Electric Vehicle
CAV	Connected Autonomous Vehicle
CFD	Computational Fluid Dynamics
CNG	Compressed Natural Gas
ECU	Electronic Control Unit
EV	Electric Vehicle (FCEV and BEV)
FCEV	Fuel Cell Electric Vehicle
g	Gram
GaN	Gallium Nitride
GHG	Green House Gas (predominantly CO2)
GWh	Gigawatt-hour
H2	Hydrogen
HGV	Heavy Goods Vehicle
HVEMS	High Volume E-Machines Supply (an APC-funded project into future manufacturing methods)
IGBT	Insulated Gate Bipolar Transistor
IPM	Interior Permanent Magnet
JIVE 2	Joint Initiative for hydrogen Vehicles across Europe (second stage of a fuel cell bus project)
kg	Kilogram
km	Kilometre
kW	Kilowatt
kWh	Kilowatt hour
l	litre
Li-S	Lithium-Sulfur
LNG	Liquefied Natural Gas
LPG	Liquefied Petroleum Gas
MaaS	Mobility-as-a-Service
mm	Millimetre
MOSFET	Metal-Oxide-Semiconductor Field-Effect Transistor
NdFeB	Neodymium/Iron/Boron (Neodymium magnet)
NiMH	Nickel Metal Hydride
NVH	Noise, Vibration and Harshness
OEM	Original Equipment Manufacturer (vehicle manufacturer in this document)
PEM	Proton Exchange Membrane (type of fuel cell)
PHEV	Plug-in Hybrid Electric Vehicle
SiC	Silicon Carbide
SMC	Soft Magnetic Composite
SOFC	Solid Oxide Fuel Cell
SPM	Surface-mounted Permanent Magnet
TPS	Thermal Propulsion System (internal combustion engines of all types)
ULEZ	Ultra Low Emissions Zone
V	Volt
VECTO	Vehicle Energy Consumption Calculation Tool
VOC	Volatile Organic Compound
WLTP	Worldwide harmonised Light Vehicle Test Procedure
xEV	generic abbreviation for a mild hybrid, full hybrid, PHEV, BEV and FCEV
ZEV	Zero Emissions Vehicle

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TRENDS AND DRIVERS AFFECTING THE AUTOMOTIVE INDUSTRY

OVERVIEW

A number of economic, environmental and social factors are influencing future vehicle designs and powertrain choices. Many areas of automotive propulsion technology are now advancing more quickly than at any time in the last 100 years. The lack of a single, agreed solution to these diverse drivers is leading to a substantial diversion from known technologies, with the range of technology choices now wider than it has ever been and growing.

TAILPIPE EMISSIONS LEGISLATION

LOCALISED REGULATION

THE WIDER ENERGY SYSTEM

RDM/Aurrigo driverless pod

CONNECTED AND AUTONOMOUS VEHICLES

MOBILITY-AS-A-SERVICE

LIFE CYCLE REGULATION

1.1 TAILPIPE EMISSIONS LEGISLATION

Given the limitations of tailpipe regulation, its impact on powertrain strategy will be most profound in the short to medium term. In the long term life cycle analysis could emerge as a more significant driver.

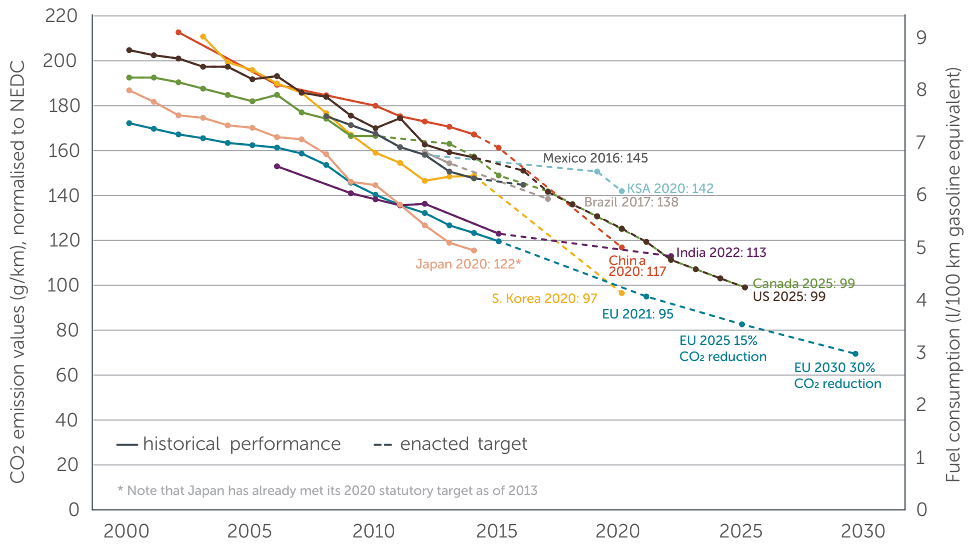
Despite widely reported discrepancies between official tests and the real world, tailpipe regulation has been successful in reducing both CO_2 and pollutant emissions from new vehicles. However, the time taken to renew the vehicle parc means that the CO_2 and air quality benefits are not immediately seen. To provide further certainty in European markets, post-2020 CO_2 emission proposals were introduced by the European Commission in November 2017 (as shown in the top graph). The Commission also suggested that it might consider extending the use of Real Driving Emissions (RDE) to CO_2 after 2025.

For the time being, air quality has superseded CO_2 as the main driver for powertrain strategies in urban areas and this is reflected in various national and local policies. It is expected that as Euro VI trucks, Euro 6c light duty vehicles and zero emissions tailpipe capable vehicles replace older ones in the fleet, the focus will return to CO_2 and achieving the proposed EU light duty CO_2 targets for 2025 and 2030.

Electric Vehicles (EVs, which includes BEVs and FCEVs) can achieve the required pollutant emissions and CO_2 standards, however short and medium term solutions are required to enable the automotive industry to transition into the longer term vision of cleaner transport systems.

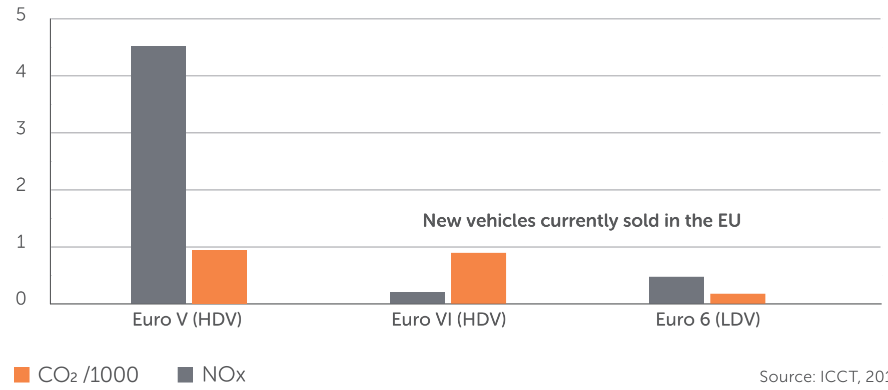
Heavy duty vehicles including buses, trucks and off-highway vehicles have been affected by pollutant emissions legislation more profoundly than CO_2 regulation (as shown in the bottom graph). However if the European Commission's proposed heavy duty CO_2 reduction targets for 2025 and 2030 are enacted, it will bring Europe more in line with CO_2 and fuel efficiency standards established in Japan and the US. It is expected that the 15% reduction in CO_2 by 2025 and 30% reduction in 2030 could create an even greater market demand for new fuel saving technologies in the heavy duty sector.

Historical fleet CO_2 emissions performance and current standards (gCO_2/km normalised to NEDC) for passenger cars



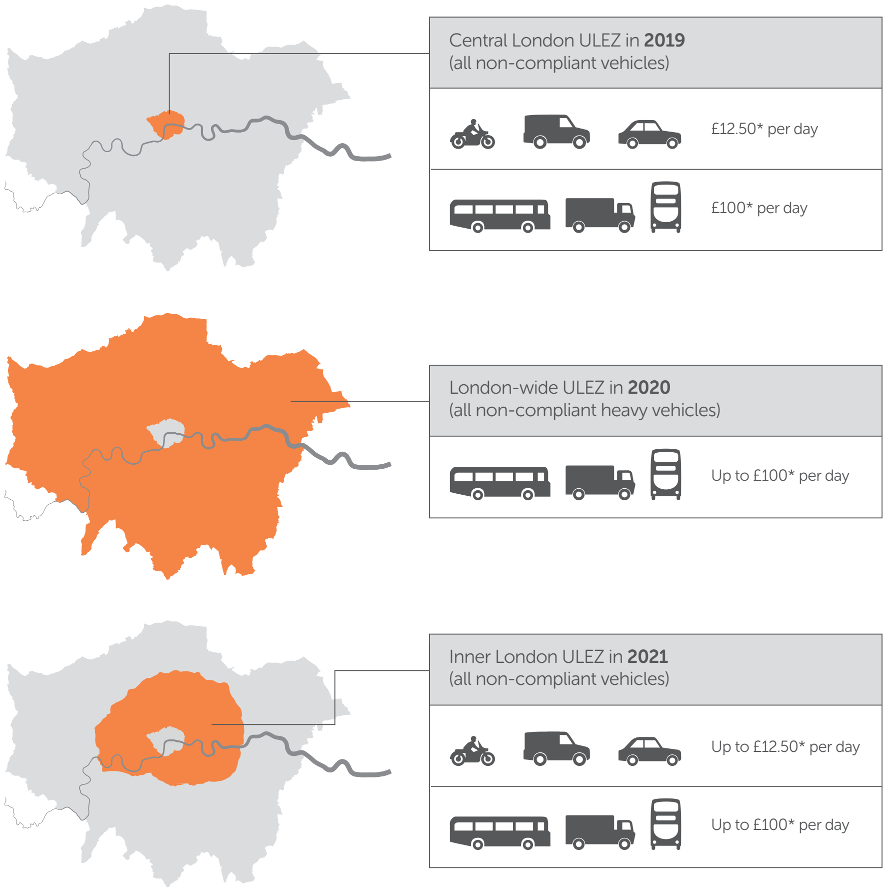
Source: ICCT, 2017

Real-world gaseous emissions [g/km]



Source: ICCT, 2016a

London Mayor's ULEZ Proposal



ULEZ standards: Petrol – Euro 4; Diesel – Euro 6/VI; Motorcycle and L-Cat – Euro 3
*ULEZ charge levels are indicative only and refer to the current scheme proposals

Source: Transport for London, 2017

1.2 LOCALISED REGULATION

Localised rather than national policy is already impacting powertrains and evolving societal changes could sustain the influence of local policy in the longer term. The UN (2016) forecast that by 2030, 60% of the global population will live in cities, increasing the influence of local and regional authorities in determining transport, health and energy policy.

In Europe and China, a popular policy for managing poor local air quality is to restrict vehicle access by establishing controlled emissions zones. Over time these zones are likely to transition into zero tailpipe emissions zones, something which is already planned for areas such as Central London and Oxford in the UK. Other 'soft' policy mechanisms are emerging such as increased parking charges for (usually older) diesel vehicles and additional surcharges for driving older cars in cities.

However a risk associated with this type of local response is the creation of numerous local standards, making it increasingly difficult for consumers to comply. This pressure will be most felt by heavy duty fleet operators who may need to enter numerous cities across many jurisdictions. Therefore legislative harmonisation, at a national or supranational level, would be beneficial to ensure organisations can respect local legislation without incurring disproportionate costs.

In California the approach has been different. Instead various state governments have adopted the ZEV regulation which stipulates OEMs must sell a percentage of xEVs (electrified and electric vehicles) based on their sales across 10 US states. For 2018 the legislation requires approximately 2.5% of sales to be ZEVs and by 2025 it will require roughly 8% of sales to be ZEVs. If OEMs do not supply zero emission vehicles in the various states, they can face considerable barriers in selling other vehicles in that jurisdiction.

In the medium term, as vehicles become increasingly connected, smart cities may be able to communicate with electrified vehicles and turn their thermal propulsion systems off to ensure compliance with zero emission zones. In the longer term, as congestion increases and cities become space-constrained, cities will prioritise seamless mobility solutions that are space effective and can transport goods as efficiently as possible. This will benefit mass transit systems over personalised mobility and incentivise goods delivery methods that push very large vehicles further away from city centres.

1.3 THE WIDER ENERGY SYSTEM

The immediate priority for OEMs is to produce vehicles that meet tailpipe emission standards, with the potential impact this has on the energy system a secondary concern. However, as the number of PHEVs and BEVs increase, this presents two problems for the electricity grid, both of which could influence powertrain development.

The first problem concerns the ability of local distribution network operators to manage the increased electricity demand. Significant additional pressure could be placed on the distribution system, especially as battery capacity increases and 7kW home charging becomes more widespread. This impact intensifies in areas where there are 'clusters' of plug-in vehicles and could accelerate the need to reinforce local electricity grids (Electric Nation, 2018). One mitigation approach being investigated by the automotive sector is the use of vehicle-to-grid strategies which help manage demand but could result in more complex power electronics technologies, such as bi-directional chargers. This is currently being trialled by Nissan in the UK who are using vehicle-to-grid technologies in collaboration with Enel.

Other solutions to this challenge are load balancing, potentially using batteries removed from end-of-life vehicles, and smart charging. The former allows energy to be stored off-peak and then used to charge the vehicle on-demand without significantly increasing peak demand on the grid. The second allows the electricity supplier to manage demand, potentially using dynamic pricing to encourage charging during off-peak periods.

The second problem stems from the immature nature of the charging infrastructure. The first obstacle to mass market EV adoption is the ability to conveniently charge vehicles in areas where consumers do not have access to off-road parking. Potential solutions to overcome this obstacle have been installing charging stations in public lamp posts or inductive charging placed in strategic locations such as parking bays and traffic lights. The latter approach would also enable opportunity charging for taxis and buses but require investment in the road infrastructure.

Another obstacle to mass market adoption, which is an inconvenience to consumers, is the myriad of charging options and standards that have emerged which can frustrate early adopters. OEMs are now beginning to cluster around certain charging standards and form joint rapid charging networks (such as the IONITY charging network in Germany) but no clear standard is emerging. Some companies such as Continental and Renault are trying to mitigate this issue by using the on-board power electronics to enable plug-in vehicles to use multiple charging stations, as seen in the Renault ZOE.

However whilst a significant proportion of road transport will be electrified, it's predicted that not all vehicles will be electrified within the next two decades. The energy system therefore requires other energy vectors to help power road transport, especially in locations where the electricity grid infrastructure is immature. In Brazil, for example, the high penetration of biofuels could encourage novel TPS architectures or solid oxide fuel cells (which can run on hydrogen reformed from the biofuel), whereas Japan's promotion of the hydrogen economy is stimulating the production of vehicles using Proton Exchange Membrane fuel cells.

Moreover heavy duty commercial vehicles and off-highway vehicles will also need alternative energy sources. The high power demands of battery electric trucks and construction equipment could put extreme pressure on local electricity grids as rapid charging will be desirable to minimise downtime. The combined demand from all such vehicles could be so great as to make battery electrification of the entire commercial vehicle fleet infeasible.

Finally the well-to-wheel impacts of vehicles is expected to be legislated as a first step towards full life cycle analysis, therefore the source of the fuel will be under greater scrutiny, putting more pressure on energy suppliers to decarbonise their generation. This raises issues for electricity generated by burning fossil fuels, and hydrogen reformed from fossil fuels.

1.4 CONNECTED AND AUTONOMOUS VEHICLES

CAVs could revolutionise powertrain and vehicle design through the transition to Mobility as a Service (MaaS, see section 1.5). Although this is expected to reshape personal transportation, for propulsion technology the impact is more likely to stem from a change in the vehicle ownership model and full autonomy, rather than connectivity.

CAVs are already used in the mining and agricultural sectors. For these and other heavy duty vehicles it is expected that the impact of CAV technology on the propulsion system will be mainly the addition of significant extra control functionality. For passenger cars, CAVs will provide an increasingly seamless experience between the consumer's personal smart technology and the one in the car. The impact on the propulsion system is currently limited to managing energy consumption, such as pre-heating of the vehicle and the setting of drive styles.

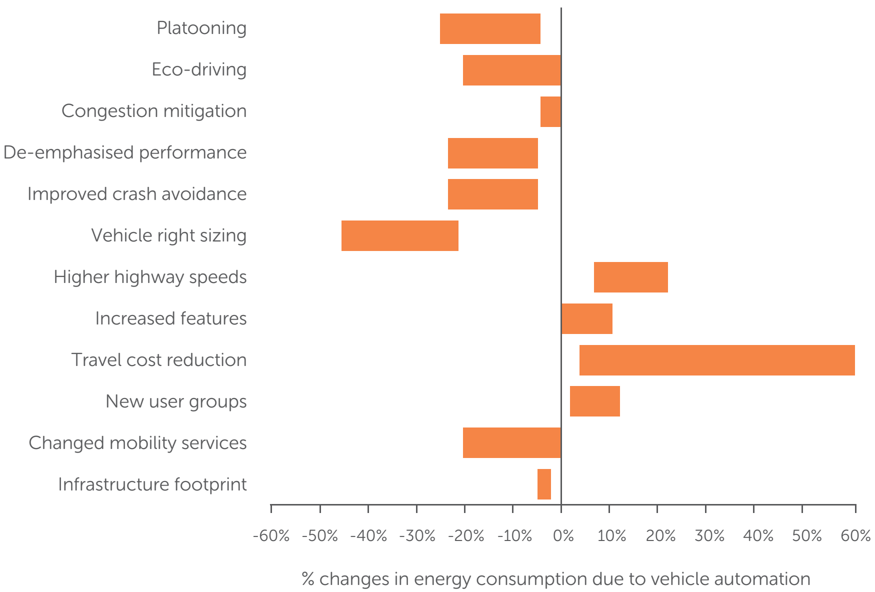
The growing availability of real-time accurate information about traffic, roads, charging infrastructure and other relevant conditions is increasingly used for vehicle energy management purposes. Zero tailpipe emissions-capable vehicles in low emissions zones are a good example of this, where geo-fencing technology will directly impact the control of the propulsion system, as demonstrated by the Ford Transit zero tailpipe emissions-capable vehicle project. Automatic transmissions are already beginning to use geographic data to inform gear change points. This type of data combined with other reasons for changing speed such as congestion or red traffic lights, will increasingly be used to inform the energy management decisions made by hybrid vehicles.

As autonomous features become more embedded in new vehicles, it will allow further light weighting and powertrain downsizing as vehicles will operate within a narrower operating window, reducing the need to cope with driver misuse. As the industry approaches Level 5 automation, it is also likely that the need for multiple powertrain specifications will be greatly reduced as powertrains will be rightsized for the service each CAV is performing.

In the very long term, as advanced CAV features are embedded into the majority of vehicles on the road, they are expected to have a profound impact on the propulsion system, primarily through greater reductions in vehicle weight from reduced crash and body structures. This would in turn require significantly less energy, further reducing the vehicle weight leading to lower power requirements for the propulsion system.

Finally autonomy and connectivity will enable the propulsion system to be better utilised and integrated into wider energy system. For example through using the vehicle's fuel cell to power the home, power tools and other equipment or using the battery for grid balancing and other control purposes. Cities, local authorities and large organisations could also utilise CAVs to provide grid balancing services in times of peak demand.

Automated vehicle factors and their respective impacts on fuel consumption



Source: US Energy Information Administration, 2017

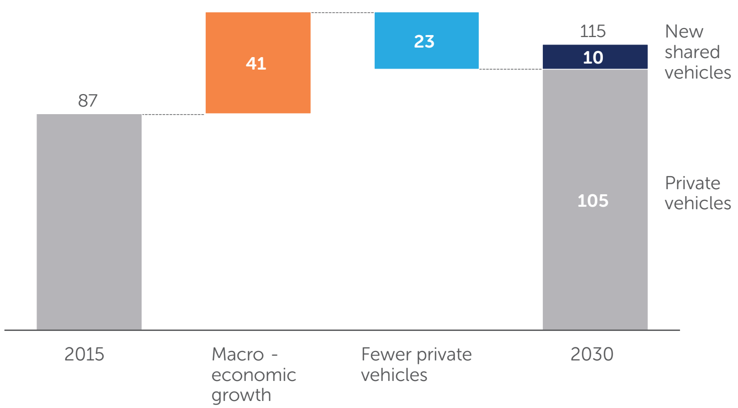
1.5 MOBILITY-AS-A-SERVICE

Mobility-as-a-service may not affect powertrain development in the short term but, as services mature, this could change the requirements for reliability and overall vehicle design, through changes to drive cycles and the operating environment. The underlying disruptor is a significant change to the vehicle ownership model, which is already underway through mobility companies in urban areas and leasing of vehicles for personal use.

Shared usage is expected to drive high levels of utilisation of the vehicle, which will have significant impact on the propulsion system, its lifespan and maintenance requirements. Requirements for high levels of vehicle utilisation (including grid services) are expected to influence the specification of the on-vehicle energy storage, its capacity and density. Moreover powertrains could increasingly become commoditised, as entertainment systems, comfort and appealing human machine interfaces are more likely to incentivise the usage of shared vehicle

In the long term, mobility providers could hold the connection to the end-customer and will therefore choose the propulsion system. Some OEMs might elect to become mobility providers, therefore becoming fully vertically integrated and controlling a larger proportion of the vehicle life cycle.

Current and future annual global vehicle sales, millions



Source: McKinsey, 2017

1.6 LIFE CYCLE REGULATION

Despite not being a regulatory requirement, life cycle analysis is already undertaken by a number of OEMs in order to assess the social and environmental impact of their existing vehicle platforms. However, as the focus shifts beyond tailpipe emissions, legislation to control the full environmental impact of vehicles will affect future decisions on powertrain technologies. Some life cycle legislation has already been enacted through regulation such as the European Union's End of Life Directive, but as yet its impact on low-volume alternative powertrain technologies has been minimal. However if regulators transition from discrete legislation on tailpipe emissions and recycling to more holistic legislation that controls the full environmental impact of vehicles, this will significantly influence future decisions on powertrain technologies.

Whole life emissions regulation is currently implemented by the industrial sector and it has been recognised that this presents issues for cross-sector industries such as transportation. A life cycle approach might be adopted after 2030 and is being considered by the EU. This is likely to include vehicle production, in-service life, disposal, end-of-life recycling as well as ensuring the materials can be reused as part of a circular economy. It could well include Green House Gas emissions and other external factors associated with vehicle manufacturing which will need to be addressed, such as waste materials, water use, land degradation and volatile organic compounds (VOC) emissions.

Today's electrified powertrain technologies depend upon a wide range of materials such as nickel, neodymium, cobalt, natural graphite and platinum which are not only costly but can incur a significant environmental and societal cost in their extraction. This will encourage the automotive industry to commercialise new powertrain components that can be easily recycled using environmentally friendly processes.

2 HOW TO USE THE ROADMAPS

2.1 ROADMAP CATEGORIES

The Automotive Council roadmaps track a range of technologies as they are researched, prototyped and improved. There are two categories of roadmap – Product roadmaps and Technology roadmaps.

PRODUCT ROADMAPS
(see sections 3 to 5 of this report)

Product roadmaps focus on the future of different products. The three product roadmaps are:

- Passenger car
- Bus
- Commercial and off-highway

TECHNOLOGY ROADMAPS
(see sections 7 to 11 of this report)

Technology roadmaps focus on the future development of specific technologies. The five technology roadmaps are:

- Electrical energy storage
- Electric machines
- Power electronics
- Thermal propulsion systems
- Lightweight vehicle and powertrain structures

2.2 ROADMAP DIAGRAMS

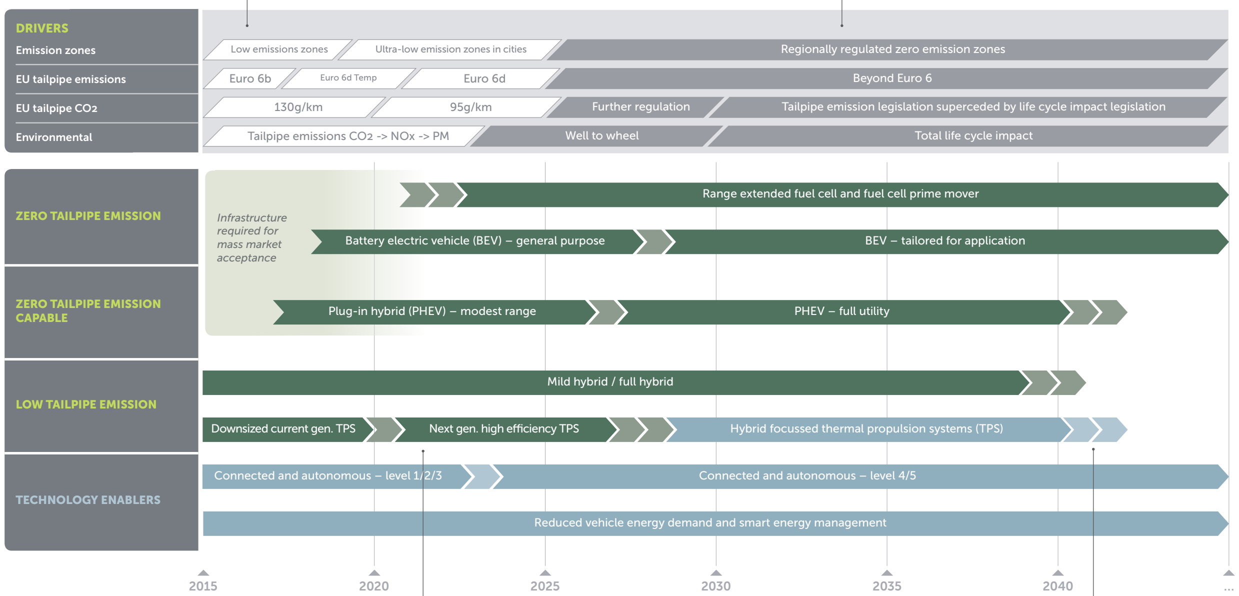
Each roadmap section in the report begins with a roadmap diagram. The roadmap diagrams show a condensed view of how different technologies will be influenced, developed and adopted over time. The predictions in the short term have higher confidence than those in the long term. Furthermore, highly disruptive technologies cannot be forecast with confidence and are therefore not captured.

Set drivers
The drivers illustrated in white are 'set drivers'. Set drivers have been defined and agreed (e.g. new emission legislation) and will come into force at a fixed time.

Predicted drivers
The drivers illustrated in grey are 'predicted drivers'. We expect predicted drivers to be adopted over time – however the timing is not currently defined by legislation.

Drivers
Each roadmap diagram details the legislative and environmental 'drivers' which will influence technology developers

Related technologies
Related technologies and developments are grouped into sub-categories (e.g. Zero Tailpipe Emission).



Time frame
The diagram details developments up to 2040 and beyond.

Technology development
Technologies are represented by coloured bars – indicating the development of new technologies and the transition between technologies.

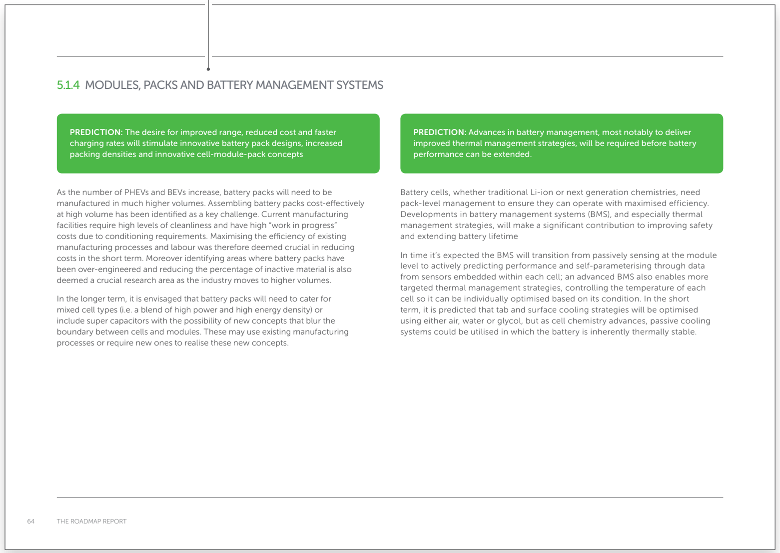
Time frame uncertainty
The chevrons indicate the current uncertainty of how quickly technologies will be adopted or phased out.

1 chevron = some uncertainty
2 chevrons = considerable uncertainty

2.3 PREDICTIONS AND SUPPORTING INFORMATION

Predictions and supporting information are included in each section to help organisations understand how the market will develop in the coming years.

PREDICTION: Rapid advances in lithium-ion technology could displace some existing battery chemistries but are also stimulating research into alternatives



5.1.4 MODULES, PACKS AND BATTERY MANAGEMENT SYSTEMS

PREDICTION: The desire for improved range, reduced cost and faster charging rates will stimulate innovative battery pack designs, increased packing densities and innovative cell-module-pack concepts

PREDICTION: Advances in battery management, most notably to deliver improved thermal management strategies, will be required before battery performance can be extended.

As the number of PHEVs and BEVs increase, battery packs will need to be manufactured in much higher volumes. Assembling battery packs cost-effectively at high volume has been identified as a key challenge. Current manufacturing facilities require high levels of cleanliness and have high "work in progress" costs due to conditioning requirements. Maximising the efficiency of existing manufacturing processes and labour was therefore deemed crucial in reducing costs in the short term. Moreover identifying areas where battery packs have been over-engineered and reducing the percentage of inactive material is also deemed a crucial research area as the industry moves to higher volumes.

In the longer term, it is envisaged that battery packs will need to cater for mixed cell types (i.e. a blend of high power and high energy density) or include super capacitors with the possibility of new concepts that blur the boundary between cells and modules. These may use existing manufacturing processes or require new ones to realise these new concepts.

Battery cells, whether traditional Li-ion or next generation chemistries, need pack-level management to ensure they can operate with maximised efficiency. Developments in battery management systems (BMS), and especially thermal management strategies, will make a significant contribution to improving safety and extending battery lifetime

In time it's expected the BMS will transition from passively sensing at the module level to actively predicting performance and self-parameterising through data from sensors embedded within each cell; an advanced BMS also enables more targeted thermal management strategies, controlling the temperature of each cell so it can be individually optimised based on its condition. In the short term, it is predicted that tab and surface cooling strategies will be optimised using either air, water or glycol, but as cell chemistry advances, passive cooling systems could be utilised in which the battery is inherently thermally stable.

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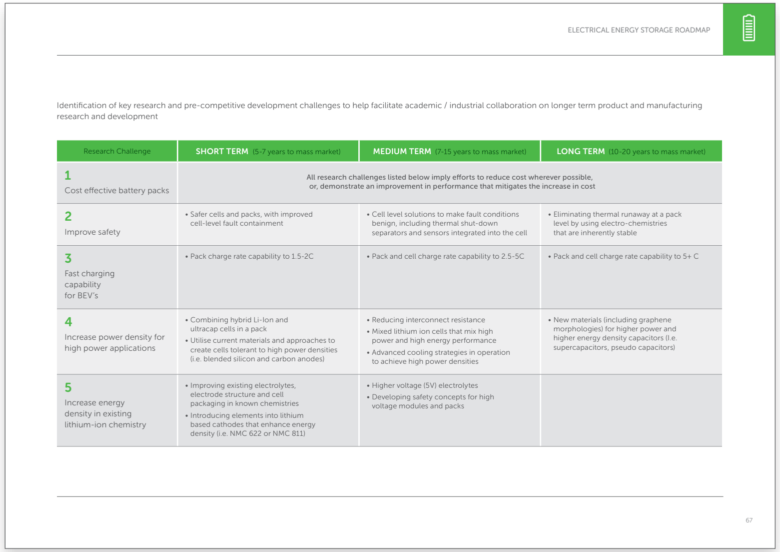
2.4 SHORT, MEDIUM AND LONG TERM CHALLENGES

The five technology roadmap sections conclude with a summary of the short, medium and long term challenges which lie ahead for each technology. The summaries include analysis from the APC technology spokes and a table detailing the future challenges.



ELECTRICAL ENERGY STORAGE ROADMAP

Identification of key research and pre-competitive development challenges to help facilitate academic / industrial collaboration on longer term product and manufacturing research and development

Research Challenge	SHORT TERM (5-7 years to mass market)	MEDIUM TERM (7-15 years to mass market)	LONG TERM (10-20 years to mass market)
1 Cost effective battery packs	All research challenges listed below imply efforts to reduce cost wherever possible, or, demonstrate an improvement in performance that mitigates the increase in cost		
2 Improve safety	• Safer cells and packs, with improved cell-level fault containment	• Cell level solutions to make fault conditions benign, including thermal shut-down separators and sensors integrated into the cell	• Eliminating thermal runaway at a pack level by using electro-chemistries that are inherently stable
3 Fast charging capability for BEV's	• Pack charge rate capability to 1.5-2C	• Pack and cell charge rate capability to 2.5-5C	• Pack and cell charge rate capability to 5+ C
4 Increase power density for high power applications	• Combining hybrid Li-Ion and ultracap cells in a pack • Utilise current materials and approaches to create cells tolerant to high power densities (i.e. blended silicon and carbon anodes)	• Reducing interconnect resistance • Mixed lithium ion cells that mix high power and high energy performance • Advanced cooling strategies in operation to achieve high power densities	• New materials (including graphene morphologies) for higher power and higher energy density capacitors (I.e. supercapacitors, pseudo capacitors)
5 Increase energy density in existing lithium-ion chemistry	• Improving existing electrolytes, electrode structure and cell packaging in known chemistries • Introducing elements into lithium based cathodes that enhance energy density (i.e. NMC 622 or NMC 811)	• Higher voltage (5V) electrolytes • Developing safety concepts for high voltage modules and packs	

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Nissan LEAF

3

PRODUCT ROADMAPS

PASSENGER CAR

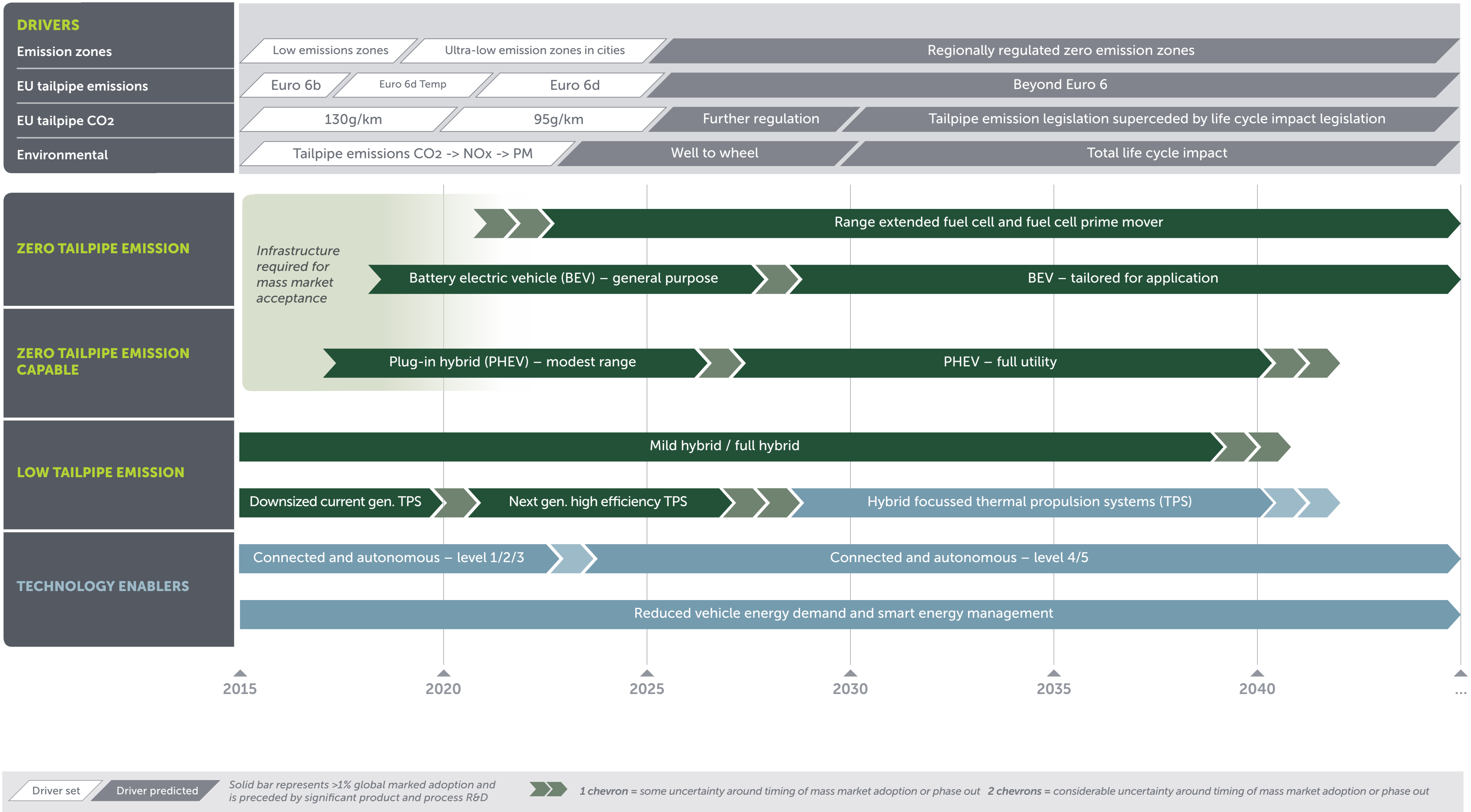
OVERVIEW

The 2018 passenger car roadmap acknowledges that tailpipe emissions (both CO_2 and pollutants) will be the main drivers of powertrain strategy in the short to medium term, with the emphasis moving away from outdated test procedures to more accurate and demanding simulations of ‘real world’ driving. A stratification of passenger car powertrain options is anticipated, with customers able to choose from a zero tailpipe emission vehicle or a selection of hybridised vehicles ranging from a mild to a plug-in hybrid. This section identifies and discusses the key technologies for each powertrain type.

> *Tailpipe emissions (both CO_2 and pollutants) will be the main drivers of powertrain strategy in the short to medium term*

Jaguar i-Pace

PASSENGER CAR



3.1 LOW TAILPIPE EMISSIONS

PREDICTION: Thermal propulsion systems will become part of a hybrid system, instead of the sole propulsion device

Thermal propulsion systems (TPS, largely internal combustion engines) for passenger cars are expected to evolve through more ambitious downsizing with higher levels of boost, advanced valve train control and more precise injection and breathing strategies to achieve higher efficiencies. However, in order to achieve low pollutant emissions, more sweeping changes, involving newer architectures and novel combustion cycles, are required. Examples include Nissan's variable compression ratio engine scheduled for launch in 2019 and Mazda's new HCCI engine accompanying their existing SkyActiv range.

These alternative TPS designs, though a significant departure from existing approaches, offer a cost-effective route to reducing tailpipe emissions in the short to medium term. They should help the TPS to transition from being the sole propulsion device to operating as part of a wider propulsion system, with their design optimised for operation in a mild, full or plug-in hybrid vehicle. Volvo's announcement of their aspiration to sell only electrified vehicles by as early as 2019 underlines the immediacy of this transition.

Prototype Mazda with SkyActiv-X engine

PREDICTION: In the short to medium term, mild and full hybrids are seen as a more cost-effective route to lower CO_2 and pollutant emissions than EVs

Mild and full hybrid powertrains differ mainly in their operating voltages; both can provide cost-effective solutions for reduced CO_2 and pollutant emissions but neither offers significant range nor performance in zero tailpipe emissions mode.

Full hybrid technology has mainly been adopted by Japanese OEMs, such as Toyota, Honda and Nissan, using economies of scale to reduce costs and offering full hybrid powertrains across their various product ranges. In contrast, mild hybrids seems to be preferred by European OEMs as they can be used in both diesel and gasoline thermal propulsion systems whereas full hybridisation is less compatible with diesel powertrains.

A strategy popular with OEMs is to supplement the standard 12V electrical architecture with a 48V system. This enables enhanced energy regeneration capability and allows the propulsion system to cope more effectively with the transient nature of city and urban journeys. Various mild hybrid architectures are possible, with the ones achieving higher efficiency gains requiring more fundamental vehicle changes. As mild hybrids become more sophisticated, it is expected that the TPS and the electrified components will need to be co-developed to achieve greater consistency of emission reductions.

Depending on policy, it is possible that both current mild and full hybrid architectures will eventually phase out as they do not offer consumers sufficient zero tailpipe emissions capability. Nevertheless some OEMs view full hybrids as a potential long term solution as they mitigate the infrastructure challenges associated with plug-in vehicles. However it was acknowledged that significant advancements in their on board electrical energy storage must occur if full hybrids are to achieve the zero tailpipe emission range required to navigate urban areas.

3.2 ZERO TAILPIPE EMISSIONS CAPABLE

PREDICTION: Plug-in hybrids, though providing some electric range, may need to evolve to ensure future compliance and greater zero tailpipe emissions capability

The sustained growth of plug-in hybrid (PHEV) sales has been driven by a mixture of local regulation manifesting in local emission zones, soft incentives, such as company car tax relief in the UK, as well as the ambitious supranational CO_2 targets set for 2025 and 2030.

Current generation PHEVs typically achieve a modest electric range of between 10 and 40 miles – which is enough to navigate an emissions zone but not adequate for inter-city driving. With today's technology, the choice of when to operate in electric mode is made manually, leading to variations in the utilisation of the electric capability. This questions the scope of the emissions certification and creates challenges in enforcing future zero emissions zones.

Current PHEVs have also proved challenging to perfect as integrating the electrical and thermal propulsion systems requires significant system engineering capability. This has led to heavier powertrains which contain separate cooling systems and more high voltage wiring compared to mild and full hybrids. However the larger battery capacity and power rating can enhance performance over other forms of hybrid vehicles.

In order to meet future regulatory standards, PHEVs are likely to evolve, increasing their electric range using batteries capable of delivering higher energy density and power density. A more abundant recharging infrastructure in urban areas will also drive uptake as consumers will be able to easily recharge and make the majority of their journeys using the electric range. In addition, improvements in city communication infrastructure could enable the intelligent charging of PHEVs ahead of entering a zero emissions zone, where the vehicle would then recognise it was entering a geo-fenced emissions zone and switch off the TPS. In the roadmap, PHEVs extend beyond 2040 as they offer zero tailpipe emissions capability.

3.3 ZERO TAILPIPE EMISSIONS

PREDICTION: Increasing the range is the short term priority for Battery Electric Vehicles (BEVs) but as range reaches an acceptable level, a shift to mobility business models could change their design

Battery electric vehicles (BEVs) produce no CO_2 or pollutant emissions at the tailpipe, however significant barriers to mass adoption are their greater up-front cost, limited range and recharging inconvenience compared to other powertrain options. Therefore in the short-to-medium term, the focus will be to overcome these three barriers so that BEVs are comparable to conventional powertrains.

However, as improvements take effect in battery, motor and power electronics technologies, the roadmap illustrates that range may no longer be the primary driver of BEV powertrain innovation. Instead, understanding the duty cycle becomes more important as new mobility business models may drive the development of vehicles tailored differently for specific applications.

In the roadmap, BEVs start to displace conventional propulsion systems in the next 5-10 years, assuming that they become cost competitive on a total-cost-of-ownership basis. BEVs are expected to dominate beyond 2040 but this depends on the availability of a sufficient charging infrastructure. The automotive industry must therefore work with the energy system operators to ensure BEVs (and PHEVs) are powered by a supply of sustainable energy. If emissions are to be based on total life cycle impact, a focus is also required on the use of materials, manufacturing and end-of-life processes for electric drives and batteries.

PREDICTION: Fuel cell vehicles need infrastructure investment and economies of scale of fuel cell stacks to stimulate mass market acceptance

Like BEVS, fuel cell electric vehicles (FCEVS) offer zero tailpipe emissions but mass market introduction is uncertain due to their relatively high purchase cost and immature refuelling infrastructure at present. Current sales volumes are measured in hundreds per year, well short of mass market levels (defined as 1% of global sales in the roadmap). However, the latest KPMG executive survey cited fuel cell technology as the top trend to 2025 and this is reflected in public announcements from OEMs such as Toyota, Honda, Hyundai, Daimler and GM. For example, Toyota maintain they are on track to manufacture 30,000 FCEVs by 2020 and Honda and GM committed $85 million to build a new fuel cell manufacturing venture in southeast Michigan. From a powertrain perspective, significant cost reductions are required for both the fuel cell stack and hydrogen storage tanks, which are expected to come largely from economies of scale.

FCEVs could become more attractive if the costs of reinforcing the electricity grid becomes too high and a hydrogen infrastructure proves more cost competitive. FCEV uptake could be further simulated if hydrogen production can complement the electrical grid by storing surplus energy generated from renewable sources. In this scenario, fuel cell vehicles and refuelling stations could provide grid balancing services during peak demand.

3.4 ENABLERS

PREDICTION: Providing a resilient and seamless refuelling infrastructure will be a critical enabler for the mass market acceptance of vehicles with new powertrains

Mass market adoption of BEVs and FCEVs is highly dependent on introducing a refuelling/re-charging infrastructure capable of handling the significant energy demand from transport. However as the infrastructure is established, consumers must also be incentivised to change their refuelling behaviour to enable the transition to these powertrains.

Meeting environmental objectives for BEVs will require further reduction in the carbon footprint of electrical power generation. The same criteria apply for hydrogen powered vehicles such as FCEVs; a widespread network of refuelling stations will be required, supplied with sustainably generated hydrogen.

It is likely that transport will increasingly become part of a highly complex energy system. For electrification this not only means sufficient availability of re-charging points but also active demand management (the smart grid) to ensure that the electricity distribution network can be adapted cost-effectively.

Toyota Mirai being refuelled at an ITM Power station

PREDICTION: Existing principles of lightweighting and smart energy management will remain relevant to all powertrain architectures

In addition to powertrain related innovations, two broad strategies exist for reducing energy demand: reducing the energy required to move a vehicle (largely through weight reduction) and better utilisation of the given energy by improving efficiency.

Vehicle weight can be reduced through the use of innovative materials, better manufacturing processes and more efficient design but lightweighting must be considered against other concerns. It is important to assess the fuel economy/range improvements, emissions advantages and total cost benefit against the implications for crashworthiness and safety as well as the total life cycle impact.

A number of strategies exist for utilising energy more efficiently in the vehicle. These include: reducing electrical loads and improving energy conversions efficiencies; greater integration of vehicle systems such as heating ventilation and air conditioning systems (HVAC) and increasing the energy recovered during braking. As autonomous vehicles become more widely adopted, the increased energy demand from computing and sensors for autonomous operation will require careful management.

Vehicle weight can be reduced through the use of innovative materials, better manufacturing processes and more efficient design

Westfield autonomous pod

PREDICTION: Connected and autonomous features will improve efficiency across all powertrain types but the more advanced stages of autonomy will impact PHEVs, BEVs and FCEVs the most

In the short term there will be a gradual adoption of driver assist functions and features that enable conditional autonomy; defined here as the vehicle managing specific aspects of driving like motorway driving. This could lead to improved real world powertrain efficiency and lower emissions through managing speeds or effectively navigating traffic.

As connected and autonomous vehicles (CAVs) become more advanced, achieving Level 4 and 5 autonomy, new vehicle ownership and usage patterns are likely to emerge which could encourage new design priorities, reflecting the different types of mobility. New operational models could emerge in which passenger vehicles are integrated with mass transit systems, though this would require effective communication between the vehicles and the road infrastructure. Such communication could also enable vehicles to efficiently manage charging and energy recovery, utilising V2X data to optimise driving strategies as well as routes and enforce zero tailpipe emissions zones.

Volvo Electric Bus

4

PRODUCT ROADMAPS

BUS

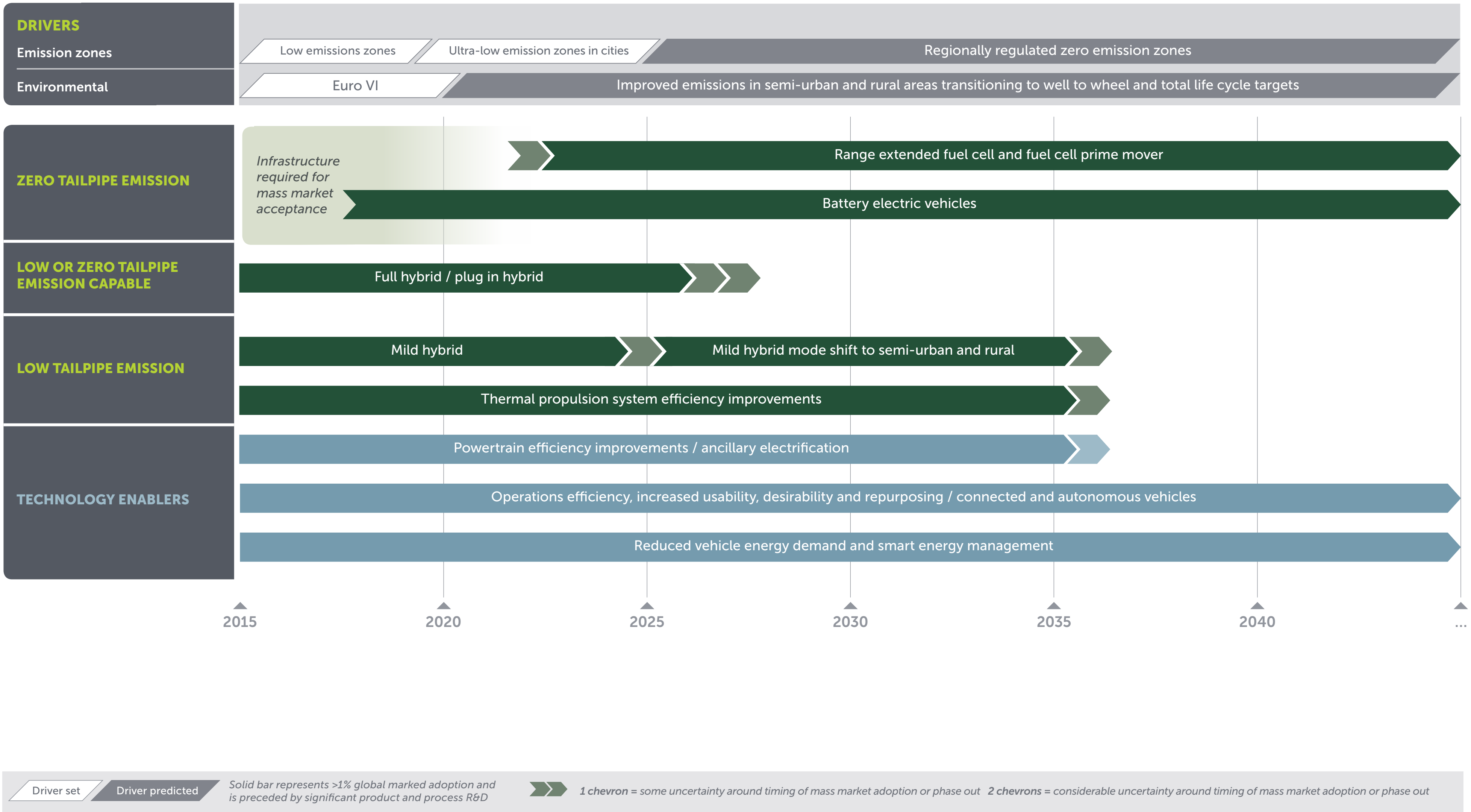
OVERVIEW

The bus roadmap reflects the divergent technology strategies emerging due to the growing influence of air quality and zero tailpipe emissions operating zones. In the short to medium term, bus operators need a cost-effective emissions reduction solution for semi-urban and rural routes and a practical zero emissions bus for city centre and urban operations. In the long term, it is envisaged that the vast majority of new buses will become zero tailpipe emissions, enabled by new powertrain technologies and closer integration with intelligent transport systems.

> *In the long term, its envisaged that the vast majority of new buses will become zero tailpipe emissions enabled by new powertrain technologies and by integration within intelligent transport systems*

Wrightbus Routemaster

BUS


DRIVERS
Emission zones
Environmental
Low emissions zones
Ultra-low emission zones in cities
Regionally regulated zero emission zones
Euro VI
Improved emissions in semi-urban and rural areas transitioning to well to wheel and total life cycle targets
ZERO TAILPIPE EMISSION
Infrastructure required for mass market acceptance
Range extended fuel cell and fuel cell prime mover
Battery electric vehicles
LOW OR ZERO TAILPIPE EMISSION CAPABLE
Full hybrid / plug in hybrid
LOW TAILPIPE EMISSION
Mild hybrid
Mild hybrid mode shift to semi-urban and rural
Thermal propulsion system efficiency improvements
TECHNOLOGY ENABLERS
Powertrain efficiency improvements / ancillary electrification
Operations efficiency, increased usability, desirability and repurposing / connected and autonomous vehicles
Reduced vehicle energy demand and smart energy management
2015
2020
2025
2030
2035
2040
...
Driver set
Driver predicted
Solid bar represents >1% global marked adoption and is preceded by significant product and process R&D
***1 chevron** = some uncertainty around timing of mass market adoption or phase out* ***2 chevrons** = considerable uncertainty around timing of mass market adoption or phase out*

4.1 LOW TAILPIPE EMISSIONS

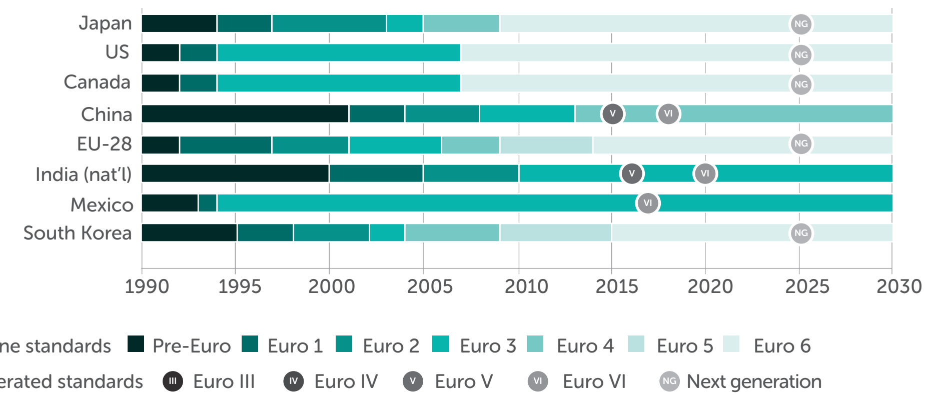
PREDICTION: While Euro VI standards have led to a step change reduction in emissions from diesel buses, the push towards zero tailpipe emissions buses will slow their sales

Historically, developments in TPSs for buses have largely centred on reducing pollutant emissions, with fuel economy and GHG regulation being introduced much later on (see graphs). In Europe, since emissions regulations were introduced for heavy duty vehicles, harmful emissions from buses using TPSs have been significantly reduced. Real-world testing undertaken by the Low Carbon Vehicle Partnership indicates Euro VI diesel buses have achieved around a 95% reduction in NOx from previous Euro V buses and are cleaner than the first generation Euro 6 diesel passenger cars. This is because the heavy duty standards were more comprehensive than the original Euro 6 passenger car requirements, requiring a far more capable and expensive aftertreatment approach. Euro VI heavy duty vehicles, including buses, are therefore fitted with urea seeded selective catalytic reduction and particulate traps to ensure real world emission reductions. More efficient aftertreatment technologies are also likely to deliver further tailpipe emissions reductions in the future.

Despite this step change, more stringent local regulation of toxic emissions is set to change the bus market. For example, the climate leadership group C40 Cities – comprised of the mayors of some of the world's largest cities – has pledged to procure only zero tailpipe emissions buses from 2025 and that only zero tailpipe emissions vehicles will be allowed to operate in some areas of their cities by 2030. Such initiatives will push diesel buses out of cities and eventually out of circulation, though they could still be used in rural and semi-urban areas as an intermediate solution.

In some specific cases, rural routes could utilise lower carbon fuels such as CNG, LNG or bio-methane as a longer term approach to reducing CO2 if the electricity grid is not suitably reinforced or hydrogen stations are too widely dispersed. However, debate is ongoing as to how great a share of these cleaner fuels should be allocated to the bus sector, given the pressing need to decarbonise HGVs, marine operations and air transport. Localised production of sustainable fuels, such as creating bio-methane from farming waste in rural areas, could be one route to satisfy this demand.

HDD vehicle policy timelines (ICCT Bosmal 5/14)



Source: Johnson Matthey, 2015

Estimated implementation timeline for heavy-duty vehicle efficiency standards

	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025
Japan				PHASE 1					PHASE 2					
U.S.			PHASE 1					PHASE 2						
Canada			PHASE 1					PHASE 2						
China	PHASE 1		PHASE 2						PHASE 3					
EU							MONITORING, REPORTING			PHASE 1				
India									PHASE 1					
Mexico									PHASE 1					
S. Korea									PHASE 1					

Hashed areas represent unconfirmed projections of the ICCT.

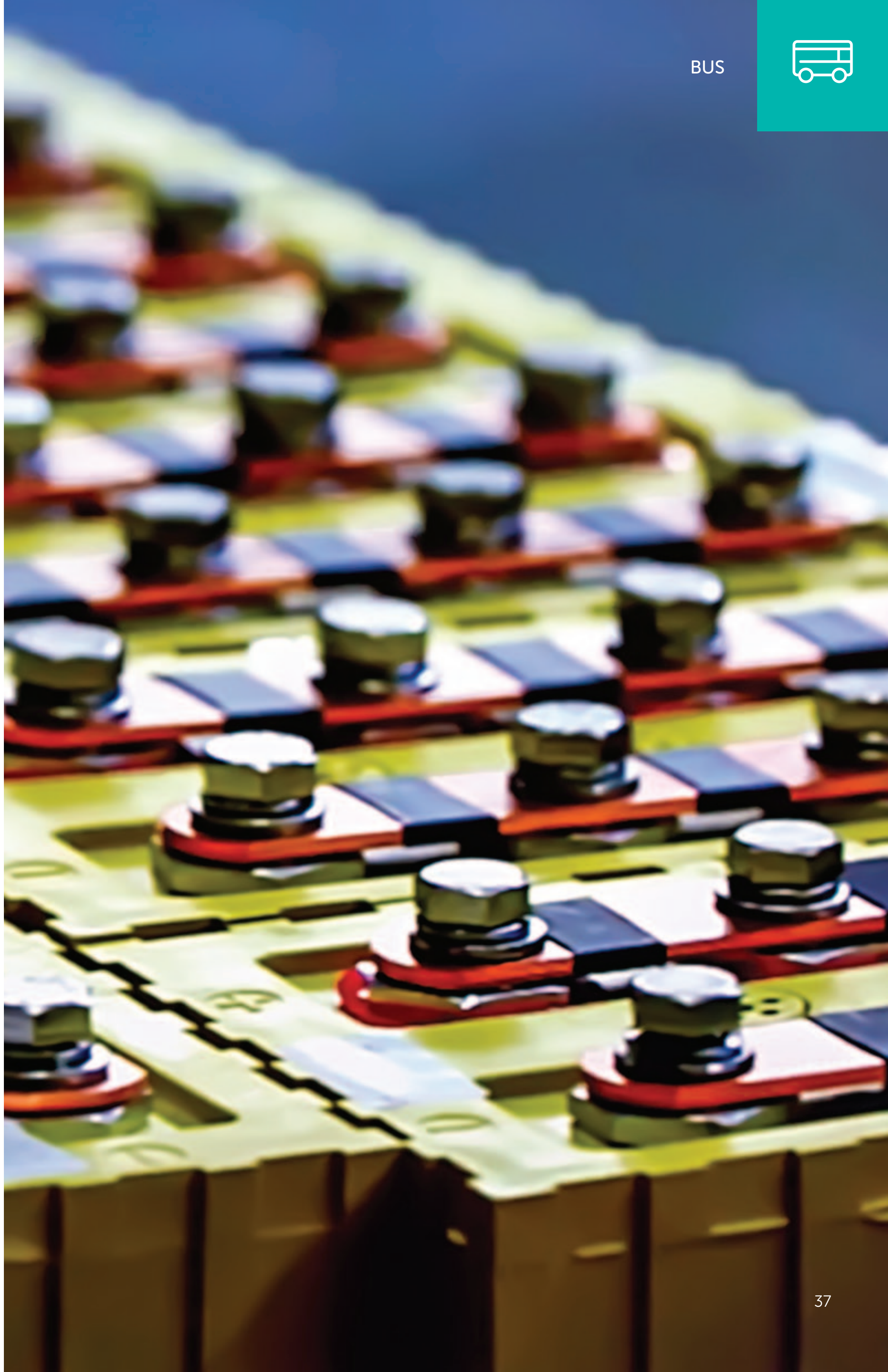
Source: ICCT, 2016b

PREDICTION: Mild hybrid buses will face the same pressures as diesels in urban areas but are a cost effective strategy for reducing CO_2 and emissions on rural and semi-urban routes

Mild hybrids offer a low-cost route to reduced emissions by enhancing existing TPSs through energy recovery devices and higher voltage systems. Power dense batteries, supercapacitors and flywheels, together with torque dense electrical machines, have been common strategies to reduce the emissions from existing diesel powertrains. However, as cities begin to set up zero emissions zones and procure only zero tailpipe emission buses, demand for mild hybrids will fall. The roadmap indicates that mild hybrids may only be relevant in semi-urban and rural areas where there is a limited refuelling infrastructure and operators find it difficult to deploy zero emissions-capable buses.

Looking further ahead, it is expected that mild hybrids will eventually be phased out for two reasons. First, improvements in powertrain technology will enable zero emissions vehicles to operate across a broader area as the energy density of batteries increases and the cost of fuel cells falls, leading to cost-effective vehicles with greater range. Second, it is likely that MaaS could extend to semi-urban and potentially rural areas, reducing the requirement for traditional buses.

It is predicted that intelligent transport systems will be established by 2035, enabling semi-urban communities to become better integrated into existing public transport networks via shared ownership and autonomous vehicles. However, for this to be realised, both the energy and communication infrastructures in these areas need to improve. Bus operators will not only need access to clean, affordable renewable energy (either hydrogen or electricity) but for MaaS to operate effectively advanced connected and autonomous features need to function in rural areas.



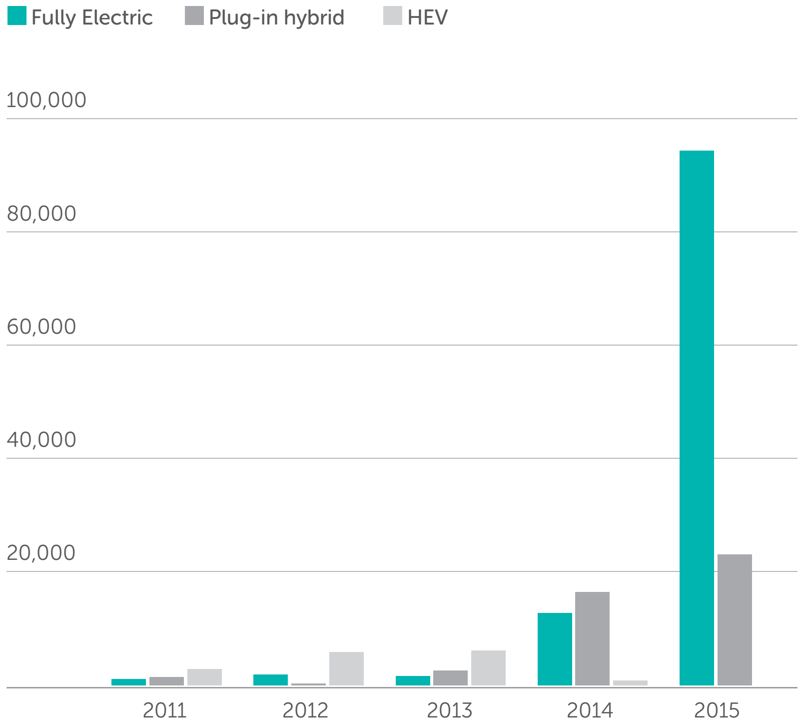
4.2 ZERO TAILPIPE EMISSIONS-CAPABLE

PREDICTION: Full hybrid buses are vulnerable to be phased out quickly as mild hybrids are more cost-effective, while the market for plug-in hybrids will erode as zero emissions options become more viable

Full hybrid and, to a lesser extent, plug-in hybrid buses will be phased out due to competition from better solutions. Improvements in diesel technology mean that full hybrids offer only marginal benefits over Euro VI diesels and mild hybrids, with the latter providing energy capture capability through regenerative braking in a similar way to full hybrids, yet without the cost, weight, complexity and service issues associated with high voltage full hybrid powertrains. Even the most advanced full hybrid heavy buses have insufficient electric range to make them practical for operation in zero emissions zones. On this basis, operators find it difficult to justify the high price premium of a full hybrid. Plug-in hybrids offer a zero emissions tailpipe capability of limited range, causing uncertainty over future demand for this solution.

The expectation is that the bus sector, heavily influenced by substantial subsidies in China and local regulation, could move rapidly towards zero tailpipe emissions vehicles in cities and lower cost mild hybrid vehicles in semi-urban and rural areas. The early signs from the Chinese market support this view; the graphic shows full hybrids were only bought in small quantities then largely phased out by 2015, whereas plug-in hybrids have increased in volume, but their increase is dwarfed by the growth in BEVs. While the uptake in China has been stimulated by subsidies, they provide a useful insight into the largest single market for low carbon buses and provide a helpful indication of the future direction that global demand may follow.

Electrified bus sales in China



Source: CleanTechnica, 2016

The expectation is that the bus sector, heavily influenced by substantial subsidies in China and local regulation, could move rapidly towards zero emissions vehicles in cities and lower cost mild hybrid vehicles in semi-urban and rural areas

4.3 ZERO TAILPIPE EMISSIONS

PREDICTION: The defined operating routines of buses make BEVs an attractive option but to generate significant sales outside China, their weight and cost must be reduced

The roadmap identifies battery electric buses as a long term solution to decarbonising the global bus fleet and improving air quality. A number of cities are already procuring fully electric buses but those on the roads today are mainly used in fleet trials or bought in relatively small volumes, such as Alexander Dennis and BYD jointly operating four BEV routes in London, and Proterra and New Flyer trialling five BEV buses each in New York.

An exception to this trend is in China where sales of BEV buses reached over 94,000 in 2015 and increased to 115,700 in 2016. This fast uptake was instigated by an ambitious bus electrification plan devised by the Chinese central government in 2009 and supported by national and regional subsidies. China's success is a positive sign for battery electric buses, however, the roadmap identifies a number of challenges in trying to reproduce the Chinese model globally without the corresponding subsidies.

A major challenge for fleet operators is the trade-off between vehicle range and weight. Companies can either opt for a larger battery pack that requires charging overnight, or a smaller battery pack that needs to be frequently topped up during the day through rapid and/or 'opportunity' charging. Larger batteries increase up-front cost and kerb weight and decrease passenger capacity due to the maximum axle weight limits imposed on buses. While opting for a smaller battery pack reduces these disadvantages, it introduces significant installation costs due to needing a rapid and/or opportunity charging infrastructure, however, this approach can increase passenger capacity. Whichever strategy a bus operator selects, increasing the uptake of BEV buses depends on improving battery technology and installing the appropriate recharging infrastructure.

If these barriers can be overcome, battery electric buses are likely to displace diesels and hybrids in urban areas. Where electricity costs are lower and routes are shorter, evidence from Bloomberg New Energy Finance's EV Outlook 2018 suggests that by 2019 battery electric buses in almost all charging configurations will have a lower total cost of ownership than conventional diesels. Total cost of ownership is more significant for buses than passenger vehicles because buses have much higher utilisation; in key metrics such as fuel costs, maintenance costs and durability, BEVs perform better than diesels and this has begun to influence fleet operators' purchasing decisions. Nevertheless, despite their promise for urban areas, challenges remain in commercialising BEV buses in rural areas where the lack of grid infrastructure and longer routes mean fewer opportunities for recharging.

BYD and Alexander Dennis electric bus

PREDICTION: Fuel cell buses, though more expensive than battery electric buses, could be more attractive for some operators because of their lower weight, longer range and shorter refuelling times

A number of distinctive benefits have driven the continued development and deployment of fuel cell (FC) buses. The focus of public-private partnerships across the world has shifted from isolated FC bus demonstrator fleets, supplied in small volumes, to delivering significant cost reductions through higher volumes.

In Europe, the proposed JIVE2 initiative aims to deploy 152 FC buses at a capital cost target of €625,000 each, representing a significant cost reduction from earlier models which were estimated at €1.2m to 1.6m each (E4tech, 2017). Despite this progress in market deployment, a number of barriers remain to FC bus uptake including the up-front costs, relatively large fuel tanks and lack of refuelling infrastructure.

Despite these issues, as technical innovation and higher volumes continue to reduce costs, there are opportunities for FC buses in urban areas. Their longer range and shorter refuelling times allow higher utilisation for bus fleet operators. The high initial cost of the refuelling infrastructure means, once installed, it will incentivise the accelerated uptake of FC buses in order to maximise the utilisation of the capital-intensive refilling station. Furthermore, as electrified buses become more popular in cities, FC buses provide the opportunity to reduce the strain on the electricity grid during peak times whereas additional BEV buses would increase the load, given their high charging requirements.

The roadmap therefore identifies BEV and FC buses as complementary technologies; both platforms share many common components and the appropriate technology for individual bus operators will be dependent on the local context and constraints. It is thought that FC powertrains are particularly suited to heavier buses, such as articulated or double-deck vehicles, covering either a high daily mileage or traversing challenging terrain that leads to high energy consumption.

A useful combination identified during the roadmap process was the FC range-extended BEV. This powertrain architecture uses a mid-sized fuel cell coupled with a downsized battery pack to reduce weight compared to a battery electric bus while also reducing cost compared to a normal FC bus, by downsizing the fuel cell and the (currently expensive) hydrogen storage requirement.

Hydrogen bus in London

4.4 ENABLERS

PREDICTION: Local electricity grids will need to manage the high power required for BEV charging; hydrogen refuelling stations will need high utilisation to make them viable

Mass market adoption of the next generation of buses is highly dependent on introducing a refuelling/recharging infrastructure capable of supplying the energy demanded. For both types of electric bus, the siting of the charging infrastructure is less of a challenge than for passenger cars as bus routes are predefined.

The issue for BEV buses is the cost associated with installing higher kW charging and the demand this will place on city infrastructures – especially during peak times and at high demand locations such as bus terminals. For FC buses, a limited number of hydrogen refilling stations are needed but the capital costs of installation are high (in the region of $1 – $5 million depending on the size), making fuel vendors reluctant to invest as the stations need high utilisation levels to make them viable. Clearly, maximising infrastructure utilisation through creating clusters of hydrogen vehicles such as buses, forklifts, delivery vans and HGVs, could accelerate adoption and create a stronger economic case for investment.

Volvo 7900 electric bus recharging

PREDICTION: While weight saving will be desirable to reduce propulsion energy demands, buses have numerous additional energy demands which could be minimised by smart energy management and auxiliary power units

Weight reduction for buses, especially BEVs, will be desirable through design optimisation and selective use of lightweight materials. Wrightbus and Proterra have already used composites in their buses to help compensate for the heavy battery packs. Considerable amounts of energy are used by bus HVAC systems, on-board entertainment features and ancillary power requirements, such as doors and lights. While electrification will allow an increasing range of auxiliary devices to be operated more efficiently, attention needs to be given to how these additional loads will contribute to reduced range in BEV buses. In recent years there have been various proposals for novel auxiliary power units, such as the heat batteries developed by Sunamp, to store and utilise waste heat to reduce the load on the thermal propulsion system or battery.

PREDICTION: Greater emissions reductions will be achieved by integrating buses more closely with existing transport networks to create intelligent transport systems that are more attractive to travellers

Evidence from a study conducted by MRCagney (2017) shows that, even at 20% capacity, a diesel bus produces approximately a third of the CO_2 emissions per passenger kilometre of the equivalent number of private vehicles. By increasing the desirability of buses through better HVAC systems, comfort, Wi-Fi connectivity and enhanced accessibility, a shift in travel habits could be encouraged that would bring significant emissions reductions.

With the advent of CAVs, buses will benefit from powertrain optimisation which is likely to significantly reduce operating costs and enhance the passenger experience. In the longer term, fully autonomous buses integrated into an intelligent transport systems will offer further cost and emissions benefits as operators are able to maximise efficiency as traffic flows can be greatly improved making buses a more attractive travel option.

However the key enablers in unlocking this opportunity will be the development of new business models and stimulating behavioural change. Greater use of buses could be incentivised through more attractive customer options and the ability to move easily from one transport mode to another. Therefore government and industry need greater awareness of customers' willingness to share data, use autonomous transport services and understand what factors will encourage people to forego journeys in personal vehicles.

PREDICTION: Increasingly modular approaches to powertrain and vehicle configuration will accommodate the repurposing of city buses for subsequent rural and semi-urban use, and increase the flexibility offered by BEV buses

Modular bus designs are increasingly being considered in order to accommodate the zero emissions requirements of city operation during 1st life use, followed by refurbishment and a powertrain change for a 2nd life in an inter-urban or rural environment. BEVs with modular powertrains will also enable bus manufacturers to match their products to particular range and duty cycle requirements. BEV manufacturer Proterra use a modular approach to vehicle configuration, offering customers an online simulation tool to select the right battery capacity and charging solutions to meet the needs of specific routes.

JCB E-TEC digger

5

PRODUCT ROADMAPS

COMMERCIAL AND OFF HIGHWAY

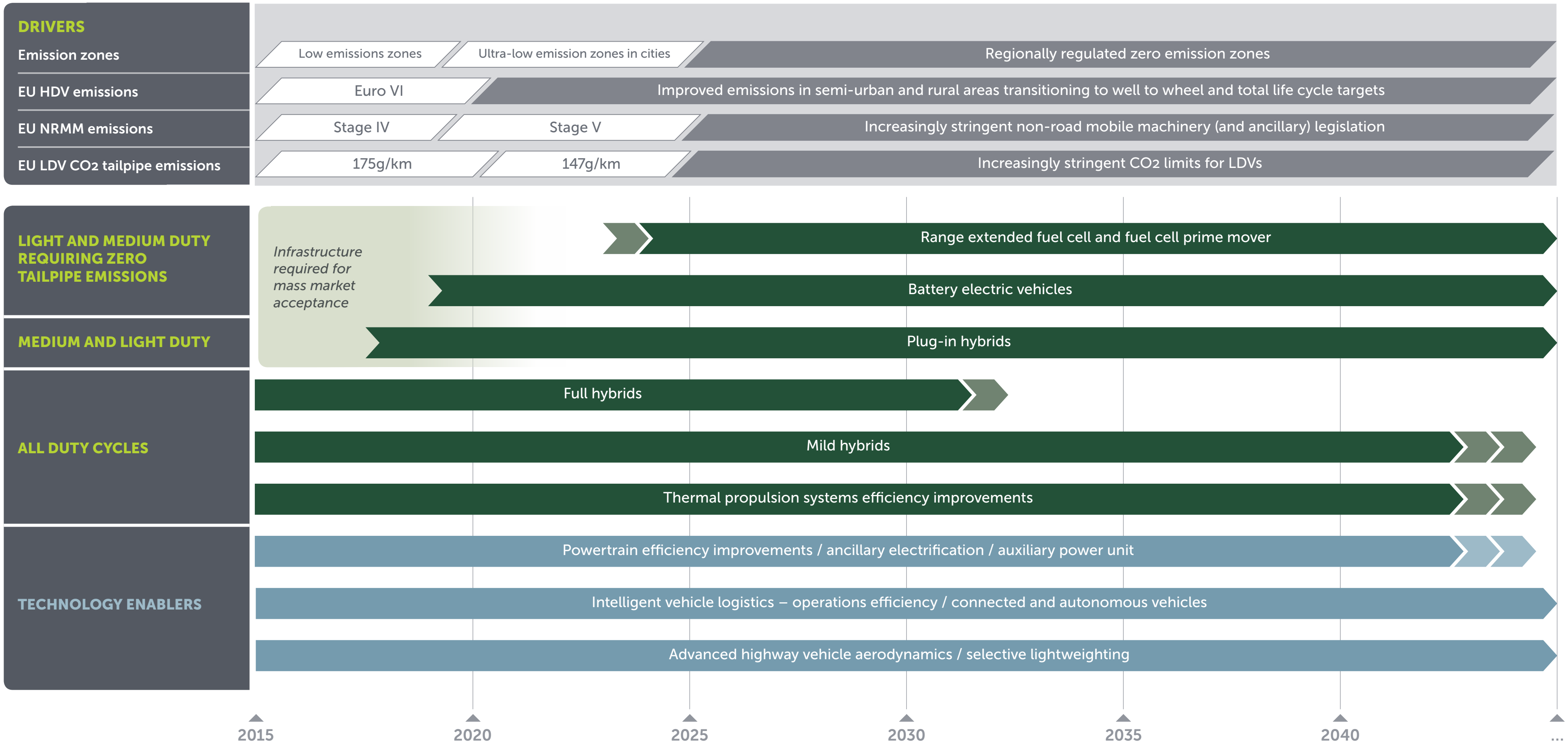
OVERVIEW

The commercial and off-highway roadmap contains a broad spectrum of different vehicle segments, ranging from long distance haulage trucks, mining equipment, forklifts to urban delivery vehicles. Whilst the duty cycles and operating cycles vary greatly, recent advances in hybrid technology, coupled with the growing influence of emissions operating zones, are effecting all commercial vehicle and off-highway technology choices. For heavy duty vehicles, or those operating in rural/semi-urban environments, strategies to fully decarbonise are challenging and expected to require a high efficiency TPS operating on a low carbon fuel with some degree of hybridisation. For smaller vehicles and those operating in urban areas, a zero tailpipe emission capability is required to comply with the expected emission legislation in cities.

> *Recent advances in hybrid technology, coupled with the growing influence of low emissions operating zones, are effecting all commercial vehicle and off-highway technology choices*

DAF LF

COMMERCIAL AND OFF HIGHWAY VEHICLE



Driver set | Driver predicted | *Solid bar represents >1% global marked adoption and is preceded by significant product and process R&D* | ***1 chevron** = some uncertainty around timing of mass market adoption or phase out* ***2 chevrons** = considerable uncertainty around timing of mass market adoption or phase out*

5.1 ALL DUTY CYCLES

PREDICTION: The TPS will continue to be a vital part of a commercial or off-highway vehicle due to its exceptional energy density and cost

Diesel powertrains deliver unrivalled power and performance for a range of medium and heavy duty applications, particularly for vehicles covering long distances or operating in remote zones. The introduction of the VECTO toolset by the European Commission is expected to provide operators with the means to objectively assess fuel saving technologies in this sector, which is heavily driven by total cost of ownership, and is expected to drive the uptake of the most beneficial technologies. Moreover, the European Commission has now published proposals for a 15% reduction in CO_2 emissions by 2025 and a 30% reduction by 2030, all relative to a 2019 baseline which mirrors other jurisdictions such as Japan and the US.

The solutions in the roadmap rely on technologies that reduce both harmful and GHG emissions; these include advanced after treatment systems, waste heat recovery and the electrification of ancillaries with mild hybridisation. 44 tonne heavy duty trucks currently provide the majority of long range haulage and are the most significant energy consumer; electrifying these vehicles using batteries will be difficult technically and commercially even if battery technology continues to improve. Overhead charging, as proposed by Siemens, and fuel cells, as proposed by Toyota, might provide longer term options if the significant infrastructure barriers can be overcome.

The difficulties of fully electrifying long haul trucks and heavy machinery opens up the possibility of commercialising radical thermal propulsion systems that offer a step change in brake thermal efficiency. One example offered was a split cycle combustion system, whereby one cylinder is used for intake and compression, and another for power and exhaust which facilitates efficient exhaust heat recovery and differential compression/expansion.

PREDICTION: Large off-highway machinery must harness the transient energy that would otherwise be wasted during typical operating cycles

Off-highway machinery is of considerable importance to UK manufacturing but has been identified as a significant contributor to pollutant emissions in certain urban areas. This has triggered more stringent legislation covering Non-Road Mobile Machinery (NRMM) emissions. The often heavily transient duty cycles of these machines are not well-suited to diesel and provide significant after-treatment challenges for pollutant control. However this duty cycle does provide significant energy recovery opportunities, therefore, technologies that provide a return on investment, increase productivity and do not negatively impact the residual value are expected to prevail.

PREDICTION: Mild hybrids can cost-effectively reduce fuel consumption and therefore CO_2 through varying degrees of electrification and a range of kinetic energy recovery systems

Heavy and medium duty trucks are technically the most suitable categories for partial electrification, especially as vehicle manufacturers need to meet more challenging decarbonisation targets. It is expected that the cost-effectiveness of mild hybridisation will see it become the standard route to reduced fuel consumption for most trucks; greater depth of electrification, and therefore the degree of torque assist and energy recovery possible, is likely to be determined by the duty cycle in which the vehicle is most frequently operated. Mild hybridisation is particularly effective in reducing the heavy transients that greatly increase both the emissions and fuel consumption of off-highway diesels.

In addition to electric hybrid solutions, mechanical energy recovery using advanced flywheel systems could offer a cost-effective alternative for commercial and off-highway vehicles operating with a repetitive duty cycle.

5.2 MEDIUM AND LIGHT DUTY

PREDICTION: Some medium and light duty vehicles will require a zero tailpipe emissions capability but their diverse drive cycles will require an additional power source

Certain commercial and off-highway vehicles will experience both inner city and long distance operation, requiring two power sources. Coaches and medium duty construction could prove challenging as they cover long distances, or experience sustained periods of work, but will also operate within urban emissions zones. Some light duty vans will also require an additional power source until battery technology reaches a sufficient energy density to cover the required distances. Therefore a plug-in hybrid or range extender seems the most viable option for these vehicles in the short to medium term. To ensure compliance with emissions zones, some form of geo-fencing function will be needed, as seen in the Ford Transit PHEV being trialled in London.

> *To ensure compliance with emission zones, some form of geo-fencing function will be needed, as seen in the Ford Transit PHEV being trialled in London*

Ford Transit PHEV

5.3 MEDIUM AND LIGHT DUTY REQUIRING ZERO TAILPIPE EMISSIONS

PREDICTION: The powertrains used in zero tailpipe emissions light duty commercial vehicles will closely resemble those used in passenger cars

Light duty commercial vehicle technology (below 3.5 tonnes) is driven by EU pollutant emissions standards and fleet average CO_2 standards and is therefore likely to evolve in the same direction as passenger cars. Early market developments indicate that for zero emission vehicles, a number of components will be shared between cars and vans. Nissan and Renault utilise the battery pack and electric drivetrain from the LEAF and ZOE for the e-NV200 and Kangoo Z.E respectively. This commonality enables OEMs to quickly introduce zero emissions van platforms without incurring additional development costs.

LEVC's TX5 being recharged

PREDICTION: Demand for zero tailpipe emissions commercial and off-highway vehicles will be driven by the growth of urban zero emissions areas and the frequency with which vehicles enter such zones

Cities are powerful authorities that can instigate change quickly in response to direct challenges such as air quality; London, Paris and Oslo are good examples of where the need for low or zero tailpipe emissions vehicles drives the market towards a significant uptake of alternative technologies. Cities can also exert influence through various mechanisms including public procurement, incentives, parking charges and emissions charges. Local government activism in this area is encouraging, however, it requires effective management from national and supranational legislatures (see section 1.2).

For commercial vehicles, BEVs and FCEVs are likely to be popular solutions in situations where vehicles will predominately operate in an emissions restriction zone or where the duty cycle is predictable. Their continued uptake will depend on total cost of ownership, vehicle utilisation and easy access to the relevant energy infrastructure.

There is also significant scope for zero tailpipe emissions vehicles in smaller non-road applications that operate in confined spaces (such as underground mines) or in local emissions zones. In response to urbanisation and greater awareness of air quality, JCB has developed a 1.9 tonne fully electric excavator with fast charging capability to work in urban areas and under mines. Warehouses have also been early adopters of hydrogen fuel cell forklift trucks, as they can deliver significant benefits over diesel and electric powertrains when considering the total cost of ownership.

5.4 ENABLERS

PREDICTION: Increased operational efficiency and productivity could be achieved through intelligent vehicle logistics, irrespective of powertrain type

Regardless of powertrain type, managing fleets of vehicles so they consume less energy will be required in order to minimise emissions and reduce fuel costs. Therefore the focus of legislation may shift to g/CO_2 per ton/km which means optimising vehicle loading via advanced logistics so all commercial vehicles operate at close to full capacity.

Improved, smart and connected logistics has the potential to contribute through route optimisation and congestion avoidance, but this has so far not materialised as an emissions reduction tool. Increasing transport costs are expected to stimulate further investigation into these approaches as part of the drive for improved productivity.

Advanced autonomous features are already used in some off-highway vehicles in the agricultural and mining sectors. This has removed the need for humans to work in dangerous environments, improving safety and operational efficiency. Longer term it is expected that CAVs will impact commercial vehicles by improving platooning efficiency, regulating speeds and optimising powertrains for maximum fuel economy. Fleet owners also gain operational benefits if drivers can obtain rest credits when not driving in a platoon.

> *Longer term it is expected that CAVs will impact commercial vehicles by improving platooning efficiency, regulating speeds and optimising powertrains for maximum fuel economy*

PREDICTION: Increasingly stringent local legislation on emissions, safety and noise may influence the size of vehicles

As more stringent local legislation on emissions, safety and noise are introduced, larger vehicles may be slowly phased out of inner city areas to make way for smaller vehicles. Smaller vehicles are not only easier to electrify, but they can improve the safety of pedestrians. For commercial vehicles this could facilitate the creation of new business models with a potential approach being a ‘hub and spoke’ delivery model. In this approach, larger vehicles enter the outskirts of a city at a delivery node and smaller zero tailpipe emissions vehicles deliver goods inside the city limits. However organisations such as Transport for London have identified that the proliferation of many smaller vehicles may increase congestion so the increase in smaller vehicles will need to be managed to minimise congestion. For off-highway vehicles, increasingly localised legislation is driving manufacturers to move away from a one-size-fits-all machine to developing more bespoke vehicles. These bespoke vehicles will typically be low carbon and emissions to meet the new legislative drivers. As more off-highway vehicles become autonomous, driver cabins and comfort features can be eliminated offering further opportunities to create smaller more efficient vehicles.

Arrival T4 Hero

PREDICTION: Improved aerodynamics, selective weight saving and other technologies provide attractive routes to reduce CO_2 emissions in certain vehicle classes

CO_2 emissions and other pollutants from commercial vehicles can be reduced by minimising the energy consumed for propulsion through reducing tyre friction, aerodynamic drag and the effects of vehicle weight. Designing vehicles for platooning, especially for long haulage trucks on selected motorways, deliver some immediate efficiency gains, as demonstrated by recent trials by the UK government.

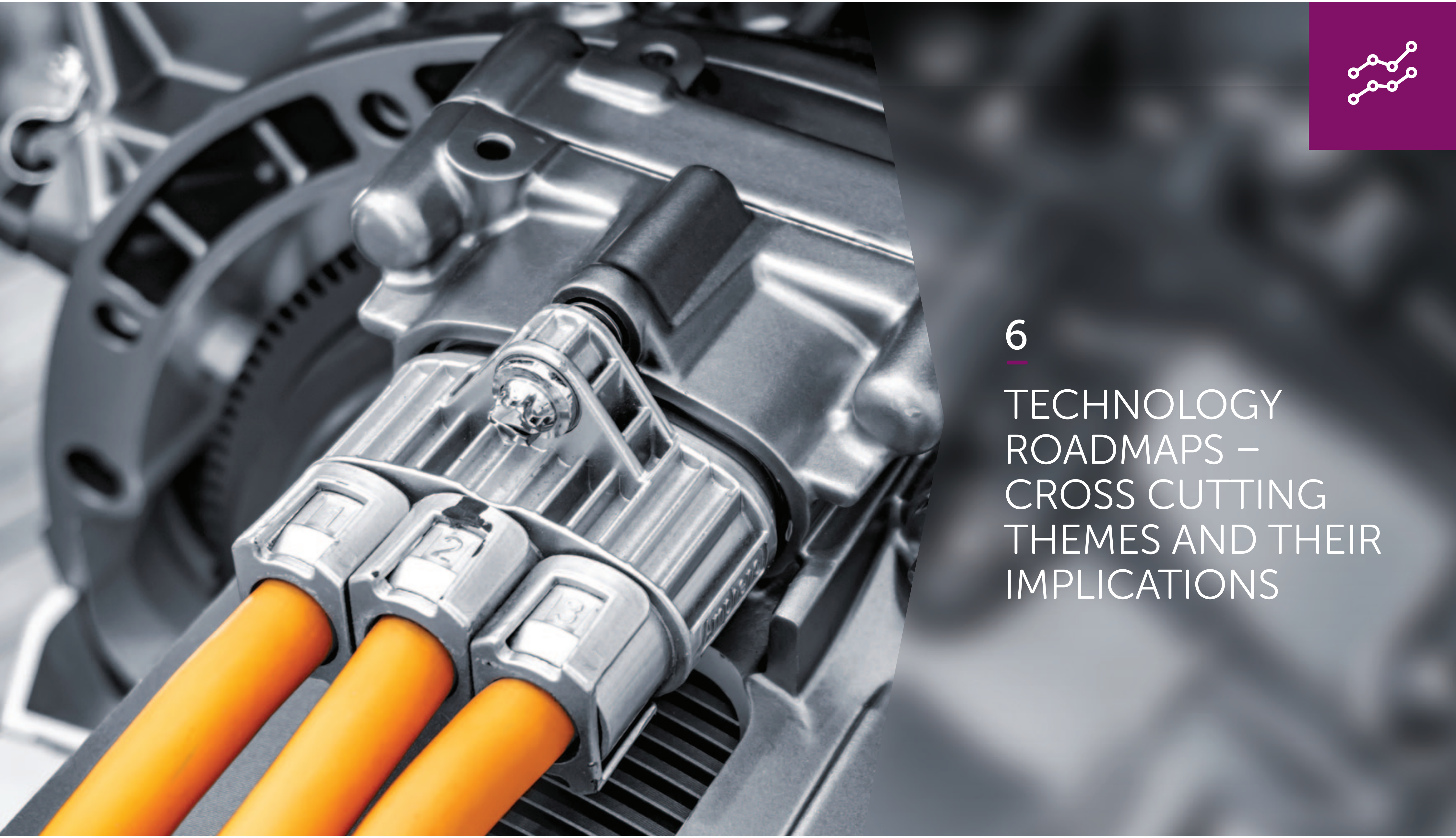
Weight reduction is a promising route for improving fuel consumption but the benefits are not uniform across all commercial and off-highway vehicle platforms. In some instances, customers may profit from increased weight due to enhanced stability, especially in vehicles such large backhoe loaders and excavators. However there is a trend of selective lightweighting of certain components, such as excavator arms, which then allows larger amounts of material to be lifted. The VECTO software toolkit from the European Commission is expected to lead to greater awareness and adoption of the latest technical approaches.

> *Weight reduction is a promising route for improving fuel consumption but the benefits are not uniform across all commercial and off-highway vehicle platforms*

PREDICTION: Apart from propulsion, many heavy duty vehicles have significant auxiliary and ancillary energy demands; managing these more effectively could greatly reduce pollutant and CO_2 emissions

The electrification of ancillary and auxiliary power systems presents a further significant opportunity for improving the energy efficiency of commercial and off-highway vehicles. For many vehicles, these functions represent a substantial energy consumption at relatively low efficiency levels. Heavy duty vehicles could potentially utilise a zero emission auxiliary power unit (APU) allowing the engine to be switched off and ancillaries to still receive power e.g. refrigeration trucks or cement mixers. It is expected that increased electrification will be of most benefit to those vehicles with relatively modest, mostly urban duty cycles, particularly those operating in low emissions zones or at night.

Dearman engine



6

TECHNOLOGY ROADMAPS – CROSS CUTTING THEMES AND THEIR IMPLICATIONS

During the roadmapping process, a number of overarching themes emerged, demonstrating important cross-links between technologies.

6.1 HIGH VOLUME AND LOW VOLUME MANUFACTURING

PREDICTION: Technologies used for high volume passenger car manufacturing will largely take a different route to those for lower volume and bespoke vehicle applications, yet there is considerable potential for knowledge transfer between the sectors

The development of electrified powertrains and weight saving technologies for high volume passenger vehicles will take a different development path to smaller volume vehicles such as performance cars, trucks and buses, where the differing duty cycles, customer requirements and cost sensitivities will drive varied technical solutions.

The technology roadmaps for electrical energy storage, electrical machines, power electronics and lightweighting all contain targets that relate to high volume passenger cars because this sector will be largely responsible for driving cost reductions and manufacturing innovation in these technologies. Away from high volume passenger cars, other attributes are valued more highly (such as peak performance and reliability) and these will drive the technology choices. For example, while a high volume passenger car requires energy-dense batteries and cost-effective electrical machines, luxury passenger vehicles and sports cars will tend towards high-power electrical machines and specialised batteries.

The exception to the low/high volume distinction is the TPS roadmap where the split is based on duty cycles. For light duty cycles, encompassing all passenger cars and buses, the dominant short-medium term solution will be an increasingly hybridised TPS, whereas heavy duty applications, such as long distance trucks and off-highway machinery, will require more thermally efficient TPSs. Nevertheless, there remains the potential for the transfer of technologies, such as advanced battery management systems, from motorsport and performance vehicles into high volume passenger cars.

6.2 INTEGRATING POWERTRAIN TECHNOLOGIES

PREDICTION: Optimising the whole powertrain as a single system will be vital for maximising vehicle-level efficiency improvements

While the individual technology roadmaps provide a commentary on the potential evolution of specific technologies, this approach may overlook nuances and potential synergies between complementary powertrain technologies. Perhaps the strongest theme underlining all of the technology roadmapping workshops was that maximum powertrain and vehicle efficiency will only come from optimising the separate technologies coherently as a whole system.

Certain technologies demonstrate strong interaction, so the specification and performance criteria of one technology will significantly influence another. For example, understanding the optimum calibration for a TPS in a hybrid vehicle requires knowledge of the loads the electrical machine and its interaction with the transmission. This awareness enables the electrical systems to more effectively reduce ancillary engine loads whilst maintaining or improving performance. Fully electric drives also demonstrate great opportunity for closer integration and are being explored by GKN Driveline's ACeDrive project, funded by the APC. The project will integrate the core functions of an e-Drive system, reducing the number of connecting components while using a high frequency inverter, enabling a higher-speed, smaller, lighter motor and advanced cooling, yielding greater system efficiency.

> *The strongest theme underlining all of the technology roadmapping workshops was that maximum powertrain and vehicle efficiency will only come from optimising the separate technologies coherently as a whole system*

6.3 IMPROVED MODELLING, SIMULATION AND TESTING

PREDICTION: Utilising better modelling capability, simulation and virtual testing will improve performance and shorten product cycles

The Virtual Product Engineering roadmap published by the Automotive Council in 2016 described the importance of improved modelling and simulation. The roadmap identified that advances in computing power, increased validation in a virtual environment and reducing the time from initial concept to production are all vital for improving productivity and vehicle energy efficiency.

In each technology area, the use of advanced modelling techniques and design tools could improve existing technologies and accelerate the uptake of new ones. Multi-physics modelling, for example, enables multiple phenomena, such as thermal, electrical and mechanical characteristics, to be simulated together which is crucial in accelerating the development of individual powertrain technologies. Improved virtual design allows better system integration and identifies optimal manufacturing routes as individual technologies can be coupled together in a virtual environment, assessed to better understand the system-level trade-offs, then re-engineered to deliver powertrain-level benefits.

Additive layer manufacturing

6.4 NEW MANUFACTURING PROCESSES

PREDICTION: Utilising new manufacturing techniques could provide a step change in cost reduction through higher levels of automation, or enable more complex designs through techniques such as additive layer manufacturing

New manufacturing processes and advanced manufacturing techniques will be key enablers for both increased productivity and the manufacture of new powertrain technologies. A short term trend is to develop manufacturing innovations alongside products, going beyond the traditional 'design for manufacture' ethos in which product innovation is constrained by existing manufacturing techniques. This approach can apply to both new powertrain component types as well as established products, such as fuel injector systems.

Automation, though already widespread in the automotive industry, could be applied further. For example electrical machine manufacture requires high levels of precision to perform complex procedures, such as coil winding. In the APC HVEMS project, automated manufacturing equipment from the medical industry is being used to achieve the high levels of accuracy required for machine assembly processes.

Additive layer manufacturing was also identified as a key enabler across all of the technology themes, due to its ability to create complex shapes, reduce parts count, integrate functions and reduce manufacturing process steps. However, the technique is currently only used in relatively small volumes such as motorsport; significant cost reductions are needed for it to be used for higher volumes. Other advanced techniques have been identified as promising, such as metal injection moulding, cold forging and tailoring existing steel manufacturing processes to suit other materials.

6.5 LEARNING FROM PARALLEL SECTORS

PREDICTION: Applying expertise, technology or manufacturing processes from parallel sectors could ease the automotive industry's transition to new powertrains

Collaboration with other sectors, such as aerospace, chemical or power generation, could accelerate the commercialisation of many new powertrain technologies. This could include utilising known manufacturing procedures from other industries, using cutting-edge technology from aerospace or motorsport whereby automotive applications serve as a test-bed to reduce costs, or leveraging expertise from the software industry to improve design. A number of specific examples of these points have been identified.

First, the manufacturing processes used to make paint and pigments are relatively similar to those used in battery chemicals so sharing this expertise with the automotive industry could help advance both sectors. Second, next generation power electronics and lightweight materials used in aerospace, motorsport and power generation show massive performance increases over current automotive technology.

The roadmap workshops examined how these advanced technologies could be adapted to fit automotive requirements. The electrical machine workshop recognised that next-generation machines will require materials scientists to help e-machine designers make the best use of unfamiliar materials. Finally, it was identified that the current shortfall in software engineering capability in the automotive sector could be mitigated by collaboration with industries such as gaming; their software expertise and design tools could enable more accurate simulation and the construction of more complex models, with virtual reality already delivering some case study examples.

6.6 LIFE CYCLE ANALYSIS

PREDICTION: Each technology will be subject to greater life cycle analysis, with electrified powertrains facing particular scrutiny

Ensuring the sustainability of all future powertrains and vehicles will be a crucial long term driver for the automotive industry. Even in the short to medium term, well-to-wheels analysis will become more important as consumers become more aware that the energy needed, both to produce and fuel new powertrains, may not be carbon neutral. In the long term, it will be important to ensure powertrain systems are designed for disassembly, manufactured using recyclable materials, manufactured using energy from low carbon sources and have little negative impact on the local environment. In fact, a full life cycle analysis incorporates more than just carbon, including water use, VOC emissions, land degradation and the wider social impacts of a manufacturing site. This may benefit some technology choices over others.

The manufacture of electrified powertrains will result in a greater use of both rare-earth and politically strategic materials. Extracting these materials and manufacturing components such as the batteries and e-machines will generate significant amounts of CO_2 and other pollutants, which impact on their sustainability. This emphasises the need to commercialise cost effective end-of-life recovery processes to ensure a circular economy is established.

Finally, while existing body structures are largely recyclable by established processes, future body structures will increasingly use materials (and intimately mixed combinations of materials) that currently do not have robust recovery and reuse processes. Moreover existing materials such as steel have relatively low environmental impacts in their production, whereas other materials, such as virgin aluminium and carbon fibre, currently have a larger environmental footprint.

Cross-section of a Nissan Leaf

MTC automated machine

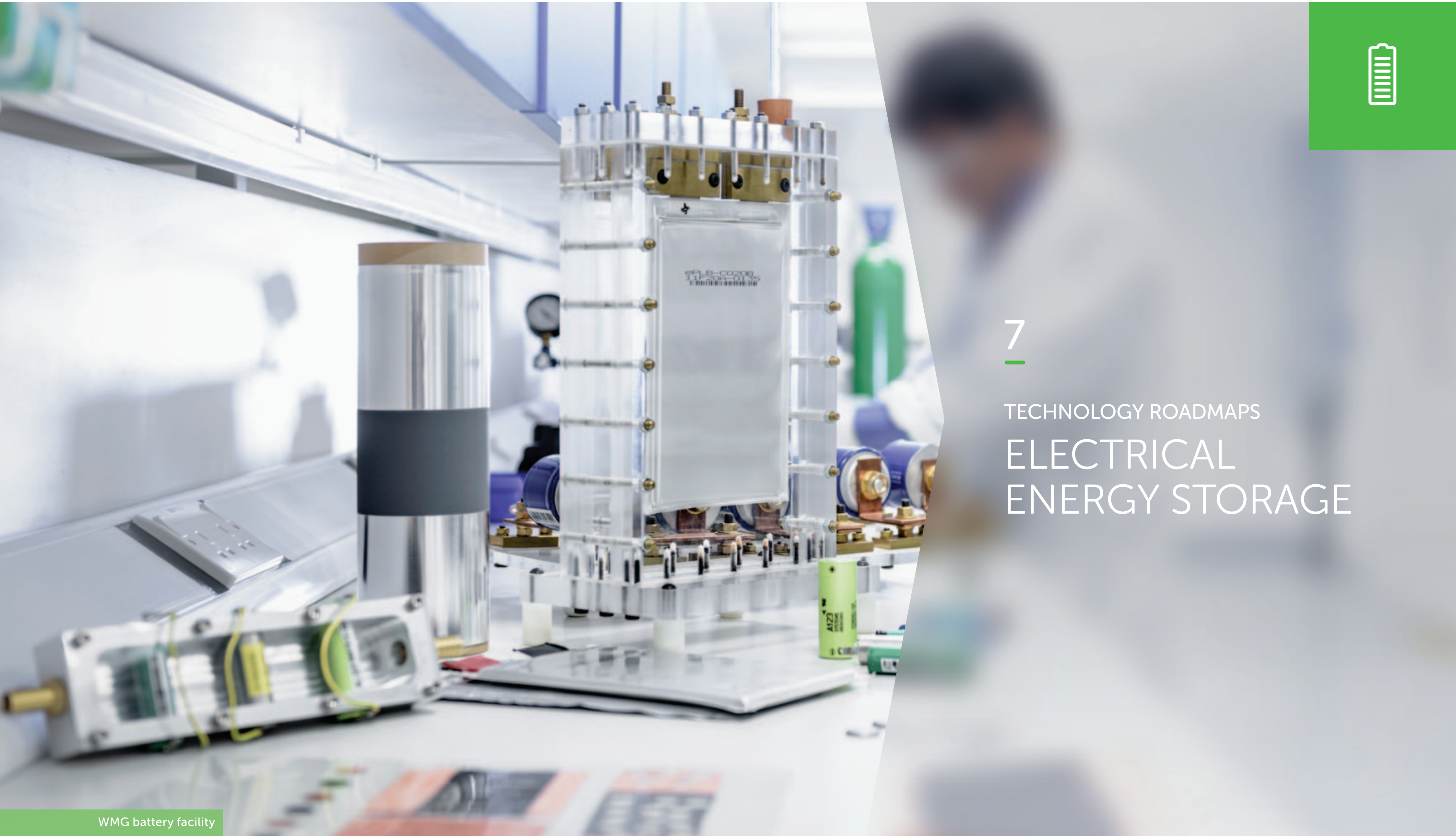
6.7 FLEXIBLE AND CONNECTED SUPPLY CHAINS

PREDICTION: Mobilising a UK supply chain that can deliver competitive costs and higher productivity for electrified powertrains will require significant manufacturing innovation

While technology innovation creates new opportunities, it also threatens the existing supply chain. To ensure sustainable economic growth, today's strong UK automotive technology supply chain must adapt quickly. Numerous workshops articulated the risks associated with scaling up new technologies where market demand is currently low but predicted to sharply rise. Reference was made both to the ability of companies to push technology development so it's ready to be integrated into a vehicle platform as well as the capability of new supply chains to meet future demand.

A recurring theme, offered as a potential solution to the problem, is the need for flexible, low volume manufacturing facilities that can manufacture new technologies for trials and low-volume production vehicles, allowing in-field experience and process validation prior to integration with a high volume vehicles. As innovation in manufacturing is key to both productivity and product performance, ensuring that a high degree of expertise is developed and maintained in the UK will be vital to the delivery of next-generation products. Without this, the UK risks constant reliance on imported tooling and processes, continually having to adapt to other nations' manufacturing methods and unable to stay ahead of developments.

> *As innovation in manufacturing is key to both productivity and product performance, ensuring that a high degree of expertise is developed and maintained in the UK will be vital to the delivery of next-generation products*



WMG battery facility

7

TECHNOLOGY ROADMAPS

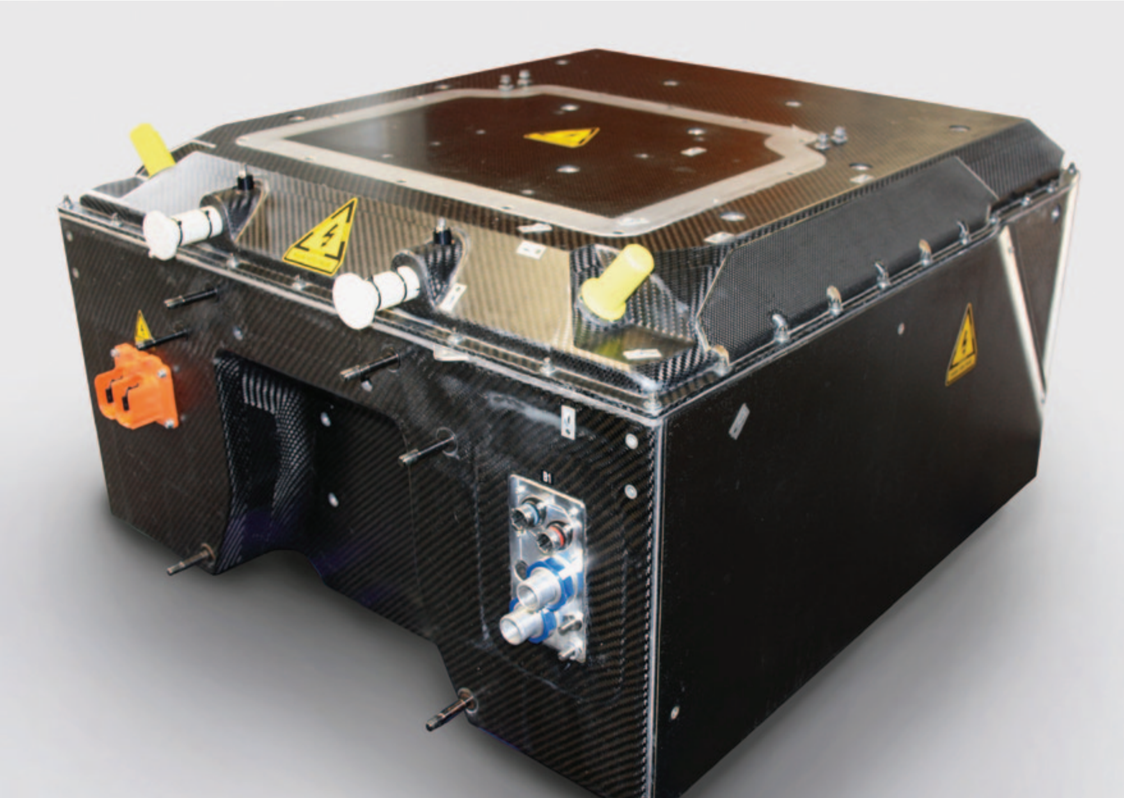
ELECTRICAL ENERGY STORAGE

OVERVIEW

Existing lithium-ion (Li-ion) batteries* are likely to dominate the market throughout the current vehicle cycle and the next. In order to reach the challenging roadmap targets set for 2035, better cell chemistry, battery management and manufacturing processes will have to be developed and commercialised to improve energy density, power density and cost.

Whether the cells are traditional Li-ion or next-generation chemistries, they need to be assembled into modules and packs to make them usable for OEMs, so pack-level innovations are equally important for the industry to progress. Manufacturers will also need to develop packs that can accept the higher charging rates being developed, without considerably degrading pack performance.

One of the biggest long term challenges in establishing a sustainable battery supply chain is minimising the life cycle impact of battery manufacturing. A key risk identified in the roadmap is the current absence of a sustainable, high volume solution for end-of-life recycling.



Formula E Battery – Williams Advanced Engineering

* The importance of both capacitors and batteries is recognised when considering electrical energy storage for automotive propulsion. The roadmap focusses mainly on energy storage devices as these are initially required to provide zero-emissions capability potentially supported by capacitors under transient driving conditions.

ELECTRICAL ENERGY STORAGE

DRIVERS

- xEV uptake, CO_2 limits, air quality regulation, ULEZs, charging access
- Very low CO2, zero emission zones, LCA, materials security, rapid/opportunity charging infrastructure

TARGETS*	Current status	2025 targets	2035 targets
Cost ($/kWh)	280 $/kWh	150 $/kWh	100 $/kWh
Energy Density (Wh/l)	280 Wh/l	550 Wh/l	1000 Wh/l
Power Density (kW/kg)	3 kW/kg	7.5 kW/kg	12 kW/kg

EVOLUTIONARY TECHNOLOGY

- Advanced lead battery and NiMh solutions

CELLS

Electrolytes, separators, binders and solvents

- Optimised liquid electrolytes for Li-ion (e.g. additives and high voltage) → Liquid electrolytes for new chemistries (e.g. Na-ion, Mg-ion, Li-S)
- Room temperature solid state electrolytes with good conductivity
- Separators with reduced thickness and cost, oxidation resistance, heat dissipation → Next gen. separators (e.g. phase change, auxetic structures)
- Solvent replacements for NMP (e.g. N-Acetyl-P) → Next gen. binders (e.g. hybrid, self-healing) → Binderless systems

Anodes and cathodes

- Optimised Li-ion anode materials and structures (e.g. Silicon,LTO, hard carbon)
- Next gen. anodes (e.g. transition metal oxides, metallic anodes and novel additives)
- Optimised Li-ion cathode materials and structures (e.g. LFP, NMC, NCA, LMO)
- Cathode materials for new chemistries (e.g. Na-ion, Mg-ion, Li-S)

Formats and casings

- Embedded sensors in cells → Cells that eliminate thermal runaway
- Cross-OEM standardisation of cell formats

MODULES, PACKS AND BATTERY MANAGEMENT SYSTEMS

- Advanced pack designs for performance and manf. → Mixed cell packs (high energy and power) → New cell-module-pack concepts
- Smart and connected BMS enabling accurate SOC and SOH monitoring and life prediction → Distributed BMS enabling individual cell monitoring
- Advanced thermal management strategies (e.g. integrated with vehicle cooling) → Passive thermal management (e.g. phase change materials)

RECYCLING AND LIFE CYCLE MANAGEMENT

- Pack designs that extend 1st life and enable 2nd life → Deployment of 2nd life batteries with flexible applicability
- Processes for end-of-life recovery of cell material/electrode → Industrial scale up of high efficiency recycling processes

2015 | 2020 | 2025 | 2030 | 2035 | ...

Driver set | Driver predicted

Solid bar represents >1% global marked adoption and is preceded by significant product and process R&D

1 chevron = some uncertainty around timing of mass market adoption or phase out 2 chevrons = considerable uncertainty around timing of mass market adoption or phase out

7.1 TARGETS

In order to meet future mainstream automotive demands, significant improvements in cost, energy density and recyclability are required and the ambitious long term targets reflect this. Storage system targets may be considered as energy-led, typified by the range requirements of a BEV, or power-led, exemplified by PHEV or bus applications.

The targets on the roadmap are defined at pack level as vehicle manufacturers and battery pack suppliers take cells and assemble them into modules and packs for more effective integration into the vehicle. While cell level metrics are informative (and are included in this report), they do not communicate the final cost or the required packaging space to the OEM. Therefore showing battery pack targets on the roadmap performs the dual function of reflecting the vehicle manufacturers' requirements while simultaneously encouraging research in areas other than just battery cells.

	Energy-led [1]	Power-led [1]	2017	2025	2035
Pack Targets					
Cost ($/kWh) [2]	•		280	150	100
Energy Density (Wh/l)	•		280	550	1000
Power Density (kW/kg)		•	3	7.5	12
Pack Life (Years)	•	•	8	10	15
Recyclability (%)	•	•	10 -> 50	75	95
Cell Targets					
Cost ($/kWh) [2]	•		130	80	50
Energy Density (Wh/l)	•		750	1000	1400
Energy Density (Wh/kg)	•		250	350	500
Operating Temperature range (°C) [3]	•	•	-20 -> 60	-30 -> 70	-40 -> 80

1. Energy-led applications typified by BEV, power-led by PHEV or bus
2. Cost targets relate to EV passenger car volume production
3. Temperature range: bottom end is limit of charge acceptance, top end where de-rating required

7.2 EVOLUTIONARY TECHNOLOGY

PREDICTION: Rapid advances in lithium-ion technology could displace some existing battery chemistries but are also stimulating research into lead acid batteries

Lead acid batteries will provide the most cost-effective solution for 12V applications for the immediate future because the rapidly reducing cost of Li-ion has stimulated additional research into their performance. Organisations such as the Advanced Lead Acid Battery Consortium, are now enhancing lead acid batteries, keeping them technically competitive and upgrading their performance for conventional and mild hybrid vehicles.

However, if the cost of Li-ion batteries falls rapidly enough, or if 48V becomes the standard voltage level, Li-ion could challenge traditional lead acid batteries; Hyundai have dispensed with the lead acid battery in their Ioniq hybrid in favour of an isolated 12V Li-ion starter embedded in the traction battery pack.

Despite the large production volume of nickel metal hydride (NiMH) batteries in both Japan and China, it is expected that this chemistry will be slowly phased out. This is because it's one of the only battery chemistries to contain rare earth elements and existing Li-ion exhibit enhanced performance. In fact Toyota now offer a Li-ion variant of the Prius alongside the existing NiMH chemistry.

> *If the cost of Li-ion batteries falls rapidly enough, or if 48V becomes the standard voltage level, Li-ion could challenge traditional lead acid batteries*

7.3 CELL MATERIALS

PREDICTION: Optimising current graphite anode technology will complement enhancements in lithium-based cathodes, but as new chemistries are developed and charging rates increase new anode technologies will be needed

Graphite has been the state-of-the-art anode material for the last 25 years, but the automotive sector's demand for higher energy densities and faster charging rates is stimulating research into improved anode technology. A number of short term incremental improvements are possible, such as adding silicon (which is Panasonic's approach) or exploring the use of hard carbon, however there is a limit to the concentrations of silicon that can be added due to volumetric expansion and reduced lifetime.

New anodes will also be required to enable new cathode materials to work effectively. For example, sodium-ion cannot intercalate into graphite very well due to the unfavourable thermodynamics; new anode materials such as tin, antimony or metal oxides need to be commercialised for sodium-ion batteries to operate more effectively. Similarly for solid state batteries to be successfully commercialised, new lithium metal anodes need to be developed in conjunction with the solid electrolyte.

Faradion sodium ion battery

PREDICTION: Lithium-based cathodes will predominate in the short term but new cathode materials are required to deliver cost reductions, better energy/power densities and greater recyclability

Optimising cathode materials and structures in existing Li-ion cells will be an important strategy to improve automotive battery packs in the short term. The public workshops identified altering the chemical composition of cathodes as a promising route to reduce costs or improve energy density. For example, increasing the nickel and cobalt content offers improved energy density, but raises costs significantly and leaves OEMs exposed to raw material price increases. If reducing cost is the priority, then more abundant materials such as iron could be utilised, but at the expense of lower energy density.

High power Li-ion cathodes are predicted to take a different development path to that of energy dense cathodes, due to their higher currents and lower nominal voltages. In the short term this is expected to increase overall pack costs due to more sophisticated cell designs, advanced thermal management strategies and techniques to minimise lithium plating.

Regardless of whether the priority is lower cost, better energy density or greater power density, achieving the 2035 targets will require new cathode structures and materials. For high energy density batteries, cathode development will be required to commercialise new chemistries such as lithium sulfur, metal-air and multi-valent chemistries, whereas for the lower cost chemistries, such as sodium-ion or calcium ion, completely different cathode materials and manufacturing processes will be needed.

PREDICTION: The content of binders, solvents and additives required to create the anode and cathode will be reduced

Manufacturing battery electrodes requires the use of binders, solvents and additives to form a slurry so the active material binds to the current collector (typically copper foil in the anode and aluminium foil in the cathode). These materials are called inactive or indirect materials because, though needed for the production of battery cells, their inclusion contributes nothing to cell performance.

Reducing content of these materials could reduce manufacturing process steps and improve performance whilst also reducing costs. The roadmap process highlighted that using more sustainable and cheaper materials, as well as removing harmful solvents such N-Methyl-2-pyrrolidone (NMP), are effective short term measures. Longer term, transitioning the binder material from a liquid additive to a dry particle coating would significantly enhance performance and improve the proportion of active material in the cell.

WMG employee mixing battery slurry

PREDICTION: Liquid electrolytes have provided a relatively low cost route to rapid commercialisation of automotive Li-ion cells, but solid-state electrolytes could offer a step change in cell performance

In a Li-ion cell, the electrolyte transports positive lithium ions between the cathode and anode. The performance of the electrolyte strongly influences the battery's current density and reliability. In the short term, higher purity, more stable and higher voltage electrolytes are key to improving the conductivity (which influences efficiency), thermal performance and robustness of Li-ion cells.

For new anode and cathode materials, next-generation liquid electrolytes (e.g. ionic liquid electrolytes) will be required that operate at much higher temperatures, that are self-healing and which exhibit very high conductivity.

If commercialised successfully, solid-state electrolytes will offer greater stability than liquid-based electrolytes, increased battery life and greater energy densities, but early incarnations of the technology have tended to weigh more and do not currently match the ionic conductivity of liquid electrolytes at higher voltages. For solid state batteries to compete with traditional Li-ion in the future, they need considerable manufacturing innovation as the technology has only been demonstrated scientifically and has not been manufactured at scale.

PREDICTION: Separators currently fulfil a safety-critical role but the next generation will need to work with new electrolyte concepts

Separators in existing Li-ion cells fulfil two important functions: provision of a physical barrier for the anode and cathode, preventing thermal runaway, and holding an electrolyte reservoir that allows ions to move between the anode and the cathode. A separator must be highly porous, a good electronic insulator and a good ionic conductor.

As manufacturers increase cell current densities, maintaining the safety of Li-ion battery packs requires separators that are thinner, dissipate heat quicker and are resilient to chemical breakdown in the more challenging operating conditions. In the longer term, as the industry moves to alternative battery chemistries, separators will need to evolve further, with new materials also providing increased functionality; for example, advanced chemistries such as Li-S may require separators to help prevent a build-up of ions between the cathode and the separator as this could lead to capacity fades.

Multifunctional separators could also be developed to enhance performance, for example through auxetic structures (separators that become thicker perpendicular to the applied force), advanced thermal management strategies (i.e. phase change materials that store heat) or fire resistant materials that improve safety.

> *As manufacturers increase cell current densities, maintaining the safety of Li-ion battery packs requires separators that are thinner, dissipate heat more quickly and are resistant to chemical breakdown in the more challenging operating conditions*

7.4 MODULES, PACKS AND BATTERY MANAGEMENT SYSTEMS

PREDICTION: The desire for improved range, reduced cost and faster charging rates will stimulate innovative battery pack designs, increased packing densities and innovative cell-module-pack concepts

As the number of PHEVs and BEVs increase, battery packs will need to be manufactured in much higher volumes. Assembling battery packs cost-effectively at high volume has been identified as a key challenge. Current manufacturing facilities require high levels of cleanliness and have high 'work in progress' costs due to conditioning requirements.

In light of the manufacturing challenges, maximising the efficiency of existing manufacturing processes is deemed crucial in reducing costs in the short term. Leveraging help from adjacent sectors was viewed as a key enabler, as other sectors could assist with critical processes such as: cell assembly, cell formation, module/cell welding, in-line and end-of-line testing. Another short term focus is identifying areas where existing battery packs have been over-engineered, especially in early products. This could reduce the percentage of inactive pack material and assist the industry in moving to higher volumes.

In the longer term, it is envisaged that battery packs will need to cater for mixed cell types (i.e. a blend of high power and high energy density) or include super capacitors with the possibility of new concepts that blur the boundary between cells and modules. These may use existing manufacturing processes or require new ones to realise these new concepts.

> *Current manufacturing facilities require high levels of cleanliness and have high 'work in progress' costs due to conditioning requirements. Maximising the efficiency of existing manufacturing processes is therefore deemed crucial in reducing costs in the short term.*

PREDICTION: Advances in battery management, most notably to deliver improved thermal management strategies, will be required before battery performance can be extended.

Battery cells, whether traditional Li-ion or next generation chemistries, need pack-level management to ensure they can operate with maximised efficiency. Developments in battery management systems (BMS), and especially thermal management strategies, will make a significant contribution to improving safety and extending battery lifetime

In time it's expected the BMS could transition from passively sensing at the module level to actively predicting performance and self parameterising. This can be achieved either through data from embedded sensors within each cell or leveraging 'virtual sensors' which uses simpler measures to predict cell characteristics but needs advanced modelling capability to understand cell chemistry. An advanced BMS also enables more targeted thermal management strategies, controlling the temperature of each cell so it can be individually optimised based on its condition. In the short term, it is predicted that tab and surface cooling strategies will be optimised using either air, water or glycol, but as cell chemistry advances, passive cooling systems could be utilised in which the battery is inherently thermally stable.

7.5 RECYCLING AND LIFE CYCLE MANAGEMENT

PREDICTION: Mobilising numerous industries to collaborate with the automotive sector to appropriately recycle or re-use batteries will determine their credibility as a long term powertrain solution

Two main possibilities have emerged for automotive battery packs when the vehicle has reached the end of its life. The first of these is to reuse the battery for second life applications such as home energy storage or grid balancing. Data from Bloomberg New Energy Finance (2017) suggests that an estimated 95GWh of batteries will come from cars between now and 2025, of which 26GWh would be suitable for stationary storage.

The second option is to recycle xEV battery packs and reuse the materials in the manufacture of new batteries. Irrespective of whether older automotive batteries are successfully commercialised for second life applications, the repurposed batteries will eventually need to be recycled, as will those not suitable for second life applications. There are broadly two approaches to battery recycling: early stage standardisation leading to volume-driven recovery, or dedicated processes for differing battery chemistries. Current market trends suggest that OEMs are using several variations of Li-ion and will continue to do so. The implication is that dedicated recycling processes will be required for each variation, incurring significant extra costs. Therefore designing cells for remanufacture will be crucial in minimising the cost of recycling processes.

> *Irrespective of whether older automotive batteries are successfully commercialised for second life applications, the repurposed batteries will eventually need to be recycled, as will those not suitable for second life applications*

7.6 RESEARCH AND DEVELOPMENT CHALLENGES FOR THE SHORT, MEDIUM AND LONG TERM

Professor Dave Greenwood
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Batteries are a defining component of an electrified vehicle and will need to halve in cost and double in energy density in the next two decades without using unsustainable materials or manufacturing processes. The fourteen research themes outlined in the following table include a broad range of technology innovations, manufacturing processes and design approaches that help deliver the challenging targets identified on the roadmap. Developed by the Electrical Energy Storage Spoke community, they represent the pressing challenges our community need to address.

The short term focus centres on optimising existing lithium ion cells and pack technologies to meet the imminent demand for electrified vehicles. Hence the challenges listed in the short term are largely manufacturing ones, with incremental technical innovations such as fine tuning the chemical composition of anodes and cathodes as well as managing the health of battery packs.

As time progresses, and the potential pathways for satisfying future performance requirements diverge, more profound technical and manufacturing challenges arise. Perhaps the most important long term change is that future improvements in battery packs will shift from improving in-use performance to the total life cycle impact of battery manufacturing. This will not only drive the automotive industry to scale-up recycling facilities but also ensure the chemicals used in batteries are sustainably sourced and manufactured.

What's clear is that for the automotive industry to address these battery challenges, we need help from adjacent industries. We hope that these research and development challenges will help facilitate discussions between interested companies and aid those organisations in other sectors wishing to navigate the automotive battery landscape.

> *Batteries will need to halve in cost and double in energy density in the next two decades without using unsustainable materials or manufacturing processes*

Identification of key research and pre-competitive development challenges to help facilitate academic / industrial collaboration on longer term product and manufacturing research and development

Research Challenge	**SHORT TERM** (5-7 years to mass market)	**MEDIUM TERM** (7-15 years to mass market)	**LONG TERM** (10-20 years to mass market)
1 Cost effective battery packs	All research challenges listed below imply efforts to reduce cost wherever possible, or, demonstrate an improvement in performance that mitigates the increase in cost		
2 Improve safety	• Safer cells and packs, with improved cell-level fault containment	• Cell level solutions to make fault conditions benign, including thermal shut-down separators and sensors integrated into the cell	• Eliminating thermal runaway at a pack level by using electro-chemistries that are inherently stable
3 Fast charging capability for BEV's	• Pack charge rate capability to 1.5-2C	• Pack and cell charge rate capability to 2.5-5C	• Pack and cell charge rate capability to 5+ C
4 Increase power density for high power applications	• Combining hybrid Li-Ion and/or ultracap cells in a pack • Utilise current materials and approaches to create cells tolerant to high power densities (i.e. carbon anodes)	• Reducing interconnect resistance • Mixed lithium ion cells that mix high power and high energy performance • Advanced cooling strategies in operation to achieve high power densities	• New materials (including graphene morphologies) for higher power and higher energy density capacitors (I.e. supercapacitors, pseudo capacitors)
5 Increase energy density in existing lithium-ion chemistry	• Improving existing electrolytes, electrode structure and cell packaging in known chemistries • Introducing elements into lithium based cathodes that enhance energy density	• Higher voltage (5V) electrolytes • Developing safety concepts for high voltage modules and packs	

Research Challenge	SHORT TERM (5-7 years to mass market)	MEDIUM TERM (7-15 years to mass market)	LONG TERM (10-20 years to mass market)
6 Better battery pack design through improved predictability of performance, durability and ageing via modelling, simulation and testing	• Predictive modelling tools with greater accuracy <5% margin of error (e.g. prediction of life models) • System engineering solutions to improve pack robustness to >8 years (1st life) • Better understand response of cell structures to mechanical stimuli (bending, impact, vibration, crush) and the effect on health • Better modelling of battery lifetime requirements of applications with heavier duty cycles (e.g. trucks, off- highway machinery)	• Testing techniques for accurately predicting life and performance degradation in 1st and 2nd life applications • Better modelling and understanding of battery lifetime requirements for CAVs	• Holistic predictive modelling tools with <1% margin of error • In-situ electrochemical analysis techniques leading to improved fundamental understanding and predictive modelling capabilities encompassing electrochemical, electrical, mechanical and thermal properties • Improved understanding of degradation mechanisms to enable more radical materials and engineering solutions to increase pack durability to 15 years (1st life), including self-healing binders, separators and electrolyte
7 Reduce mass and volumes overheads at vehicle level	• Utilising multi-material solutions, plus integrating structures to increase the % of active materials in battery packs (45% active material)	• New multi-material approaches to increase the % of active materials in battery packs (55% active materials)	• Structural batteries with novel structure and form • New concepts for integration of the cell, module and pack to increase the % of active materials in battery packs (65% active materials)
8 Increase operating temperature range and efficiency of thermal management systems	• Battery packs with -30°C / +70°C capability • Higher temperature capable electrolyte • Reducing the power consumption of thermal management systems	• Thermal management systems fully integrated with vehicle thermal management systems that leverage new technologies (such as phase change materials) to improve efficiency and reduce parasitic loss	• Battery packs with -40°C / +80°C capability • Cells with passive cooling capability

Research Challenge	SHORT TERM (5-7 years to mass market)	MEDIUM TERM (7-15 years to mass market)	LONG TERM (10-20 years to mass market)
9 Improve BMS systems	• Embedding accurate real time cell models into BMS • In-situ diagnostic techniques	• Cell level monitoring systems • Real-time prognosis and active SOH management	• Predict failures with >95% reliability • On board machine learning to self-parameterise and self mitigate in event of degradation and failure
10 Increase the speed, improve the quality, reduce the cost and improve the sustainability of manufacturing	• High volume automotive standard production and quality assurance processes • Improved cell to busbar joining technology • Production variability and process control • Improved electrode processing methods and structures at higher volumes • Develop low cost high speed deposition processes and evaluate in larger footprint and alternative cell formats • Understand and validate life cycle impact analysis	• More consistent processes to improve the homogeneity of cells • Lower cost formation processes • Actively reduce lifecycle impact of manufacturing • Mass manufacturing processes for new chemistries • New production process and equipment reducing cell manufacturing times • Material solutions to increase cell durability and improved cell joining technologies	• Developing chemistries and processes to reduce formation time and speed up conditioning • Standardisation of formats for vehicle applications • Better integration of pack and vehicle manufacturing • Creating a circular economy for automotive battery packs
11 Identifying the next-generation chemistry to displace existing Li-Ion		• Example: Lithium-Sulfur (Li-S) as an automotive technology capable of delivering > 25% improvement in energy density at equivalent cost relative to contemporary lithium ion • Example: Sodium-ion (Na-ion) as an automotive technology capable of delivering similar performance levels at >25% cost reduction relative to contemporary lithium ion • Developing room temperature solid state electrolytes with high ionic conductivity	• Breakthrough concepts such as: lithium-air and alternation metal-ion chemistries, higher energy capacitors and more sustainable cells • Anodes for higher energy density (e.g. lithium metal) and higher power density (e.g. graphene) • Exploring whether multi-valent chemistries such as Zn, Al and Mg can tolerate higher voltage levels (5V+)

Research Challenge	SHORT TERM (5-7 years to mass market)	MEDIUM TERM (7-15 years to mass market)	LONG TERM (10-20 years to mass market)
12 Mobilising a UK supply chain that demonstrates cost competitiveness and higher productivity	• Develop flexible pilot and high volume manufacturing capability to capitalise on future cell technologies • Leveraging and adapting manufacturing processes and materials used in adjacent sectors (e.g. chemicals industry) to improve UK battery manufacturing capability	• Manufacturing capabilities that are automated and flexible enough to capitalise upon different potential technology paths (e.g. cylinder vs. pouch vs. prismatic, liquid vs. solid electrolyte etc.) • Aligning manufacturing processes with next generation chemistries (see medium term challenge 11) • Flexible rapid prototyping / proof-of-concept capabilities for new module & pack concepts • Flexible rapid digital prototyping / proof-of-concept capabilities for new materials and cell concepts • Large volume (i.e GWh) manufacturing capability and capacity	• 3D printed, multipolar formats, conformable cells, electrochemically functionalised materials • Aligning manufacturing processes with next generation +1 chemistries (see long term challenge 11)
13 Develop an economically viable value chain for 2nd life reuse	• 1st life design systems that meet 2nd life End-of-life diagnostic tools • Model and test aggregation of aged batteries for energy storage applications	• Scaling up of repurposing facilities to enable roll-out • Design packs for 2nd life to enable easy interoperability • Predictive performance and life models for 2nd life applications	• Understanding the economic case of using 2nd life batteries compared to virgin materials • Techniques for post-crash health diagnostics, remanufacturing cell components and processed materials (e.g. cathode powder) into new cells
14 Develop and scale up of cell and pack recycling processes	• Define and develop processes for material recovery from cells (including value modelling) • Design methodologies and cost models for design for disassembly of modules and packs • Understanding the logistical and economics implications of recycling	• Interconnects that enable removal of individual cells • High throughput end of life testing and recycling processes (including automation) • Increased use of recycled materials in battery packs	• Methods to recycle 100% of a cell and pull materials back into new material streams • Develop a circular economy for battery packs

YASA motor

8

TECHNOLOGY ROADMAPS

ELECTRIC MACHINES

Saietta brushed motor

OVERVIEW

The roadmap illustrates how developments in e-machines will broadly focus on three main areas:

1. Achieving a step change in performance (power density or efficiency) for high-end applications
2. Reducing cost for mass market applications
3. Minimising the environmental impact of manufacture and end of life recycling.

As a result, the automotive industry has pursued a wide variety of e-machine architectures to meet various performances requirements.

Existing e-machine designs can be optimised to either reduce costs or improve performance but a number of technology evolutions that reduce this compromise are shown from 2025, reflecting the immaturity of the current e-machine automotive mass market and the need for targeted R&D on future applications. To ensure the effective integration of e-machines into the wider powertrain, closer collaboration with the power electronics and engine communities will be needed to understand the benefits and trade-offs at system level.

To reach the long term performance and cost targets identified in the roadmap, the e-machine community will have to explore new materials and manufacturing processes. This will require motor designers to work closely alongside adjacent sectors, such as metallurgists and manufacturing equipment suppliers, in order to achieve the ambitious technical targets.

As it stands today, the majority of e-machines are made using materials and manufacturing processes that currently have a negative impact upon the environment. Therefore innovative processes are needed to recover and recycle them with the aim of establishing a circular economy.

To ensure the effective integration of e-machines into the wider powertrain, closer collaboration with the power electronics and engine communities will be needed to understand the benefits and trade-offs at system level

ELECTRIC MACHINES

DRIVERS

- xEV uptake, CO_2 limits, air quality regulation, ULEZs, charging access
- Very low CO2, zero emission zones, LCA, materials security, rapid/opportunity charging infrastructure

TARGETS*	Current status	2025 targets	2035 targets
Cost ($/kW)	**10** $/kW	**5.8** $/kW	**4.5** $/kW
Power Density (kW/kg)	**2.5** kW/kg	**7** kW/kg	**9** kW/kg
Power Density (kW/l)	**7** kW/l	**25** kW/l	**30** kW/l

MACHINE ARCHITECTURE

- Evolution of existing high performance architectures (e.g. higher speeds, targeted cooling, improved materials)
- Adv. architectures (e.g. in-wheel, axial flux, transverse flux) → Radical architectures enabling a step change in performance
- Lower cost architectures (e.g. induction wound rotor and switched reluctance motors)
- Radical architectures enabling a step change in cost reduction
- Safety and fault tolerance mechanisms for electric machines (e.g. for CAVs)

MACHINE INTEGRATION

- Close coupling with transmissions and TPS (i.e. xHEV) → Co-developed machine, TPS and transmissions (i.e. xHEV)
- Integrated xEV drives (motor, PE, control and transmission) → Motors with fully embedded PE

MATERIALS & MANUFACTURING

Windings and insulation

- Optimised winding techniques (e.g. increase material fill, hairpin windings) → Elimination of winding process (e.g. additive layer manu.)
- Alternative low cost windings (e.g. aluminium)
- Higher performance windings (e.g. carbon, HTS, nanomaterials)

Soft magnetics

- Optimised e-steels (e.g. 6.5% Si steel, better bonding/coating, thinner laminations) → Next gen. e-steels (e.g. improved alloys, localised properties)
- Optimised SMCs (e.g. lower losses, reduced saturation) → Enhanced SMCs (e.g. improved materials, smaller grain size)

Permanent magnets

- Eliminate heavy rare earths (e.g. Dy) → Eliminate rare earth content (e.g. other magnetic materials or magnet free)
- Refine manu. processes for consistent PM magnet attributes → Increased use of recycled rare earths (e.g. Nd)

ENABLERS

- Advanced control software developed in collaboration with power electronics community → Self learning software optimised for drive cycle
- Improved electric machine assembly processes with new manufacturing methods
- Adv. designs for reuse/recycling (e.g. easy extraction of PMs/conductors) → Design for LCA

2015 | 2020 | 2025 | 2030 | 2035 | ...

Driver set | Driver predicted

Solid bar represents >1% global marked adoption and is preceded by significant product and process R&D

***1 chevron** = some uncertainty around timing of mass market adoption or phase out* ***2 chevrons** = considerable uncertainty around timing of mass market adoption or phase out*

8.1 TARGETS

The performance targets set by the Electric Machine roadmap are expressed in kW/kg for gravimetric power density and kW/l for volumetric power density; cost is shown in $/kW. While sustainability and design for recycling has no defined metric, reducing the negative environmental impact of e-machine production and improving end of life recycling feature prominently in the drivers and the visual roadmap.

Different targets have been set for passenger cars and heavy duty applications because each vehicle type has particular drive cycles requiring different e-machine designs. However for consistency, all the targets on the roadmap assume the same input voltages, material price mark-up and efficiencies based on the Worldwide Harmonised Light Vehicle Test Procedure (WLTP).

For the passenger car targets the cost, power density and drive cycle efficiency metrics represent expected improvements for a C-segment BEV traction machine and should be all read together. All power density targets are based on continuous power output rather than peak power as this is a fairer representation of real-life operation than a transient peak figure. Nevertheless, the roadmap acknowledges that greater power densities could be achieved for higher performance applications.

	2017	2025	2035
Passenger Car Traction Motor [1]			
Cost ($/kW) [2]	10	5.8	4.5
Continuous power density (kW/kg)	2.5	7	9
Continuous power density (kW/l)	7	25	30
Drive cycle efficiency (%) [3]	86.5	92.5	93
Truck and Bus Traction Motor [1]			
Cost ($/kW) [2]	60	15	12
Continuous power density (kW/kg)	1.5	2	2.5
Continuous power density (kW/l)	4.5	6	7
Drive cycle efficiency (%) [3]	83	88	90

8.2 MACHINE ARCHITECTURE

PREDICTION: In the short term a number of strategies will be used to optimise existing machines, with reducing costs and improving performance within established machine architectures the two primary goals

Existing e-machines can be redesigned for higher performance through high fidelity thermal modelling that can precisely simulate temperature distribution in the machine. Understanding the key hotspots in a machine allows more targeted thermal management such as internal rotor cooling or the targeted cooling of printed stators. Performance can be further optimised through operating at higher speed, with novel bearings (e.g. ceramic and/or air bearings), more compact motors and faster inverter switching frequencies being potential options.

Lower cost e-machines require more effective utilisation of existing materials, reducing copper losses through better winding designs and reducing iron losses. An emerging trend is the use of lower cost topologies for mild hybrid applications. For example Renault have opted to use a Continental induction motor for their 48V mild hybrid Scenic and Controlled Power Technologies (now Federal Mogul) are aiming their switched reluctance motors initially at 48V applications.

1. All assume 350V / 450Amps @ 65°C inlet
2. Prices are 300% mark-up on material costs
3. Drive cycle based on WLTP

PREDICTION: Advanced high performance motor designs will soon reach the market, but new materials and manufacturing techniques could enable lower cost designs in the longer term

Advanced architectures, not traditionally used in automotive applications, are being explored and are close to mass market launch. These new e-machine designs are for specialist applications such as heavy duty vehicles or high performance passenger cars. The architectures can be defined by their method of integration into the vehicle (e.g. distributed such as wheel-hub motors) or their novel magnetic/mechanical design (i.e. axial, radial and transverse flux motors). The increased performance of power electronics will further enhance the performance of a number of motor architectures, making them suitable for higher performance applications. For example the performance of switched reluctance motors can be greatly enhanced through the higher switching frequencies attained by wide band gap power electronics.

In the longer term, lower cost e-machines could be achieved through both technology and manufacturing innovations. One technology innovation is ironless machine topologies which eliminate costly laminated steel from the stator (removing iron losses) and iron from the rotor which could instead use low cost plastics to secure the magnetic materials. Manufacturing innovations include the proliferation of high precision, automated manufacturing equipment which will increase production efficiency, with additive layer manufacturing providing the opportunity to reduce manufacturing steps enabling further cost reductions.

Equipmake facility

8.3 MACHINE INTEGRATION

PREDICTION: Electric machines will become better integrated into existing powertrain architectures to achieve short term emissions and CO_2 reduction

Existing full hybrid architectures such as the Toyota Prius have achieved mature levels of integration of the thermal propulsion system (TPS) and e-machine. In order for mild hybrids to more effectively meet near term emissions legislation, their e-machines will require closer coupling with the transmission and TPS to deliver the optimum performance.

In the short term, 48V e-machines will replace existing 12V alternators, providing attractive fuel consumption improvements to meet the imminent CO_2 targets under the new driving cycles and test procedures. However, in the medium term, the e-machines of mild hybrids will need to be co-developed with the TPS and transmission to enable engine rightsizing and utilisation of novel combustion strategies, which will require a larger, or potentially multiple, e-machines integrated at different points in the drivetrain. In these more advanced mild hybrid applications, vehicles will be able to operate with the TPS off under defined conditions (e.g. coasting, parking and 'e-creep'). However a challenge with integrating power dense, high speed machines into the transmission is that the gear reduction drive becomes more complex which can create losses.

For heavy duty applications, e-machines may also require closer integration with other energy storage mechanisms such as flywheels and hydraulic systems, especially in the off-highway sector.

PREDICTION: As BEV and PHEV platforms become more sophisticated, closer integration of motor and power electronics is expected

Integrating both the e-machine and power electronics into a single unit is one potential route for OEMs to reduce costs and packaging requirements. For 48V architectures, the inverters and e-machines can already be integrated into one housing which reduces the cost and weight of external cables. This enables integrated drives to be packaged between the TPS and transmission where space is constrained.

However, integrated drives with higher power outputs for EVs present a number of challenges. First, managing the thermal differences between the inverter and motor proves challenging, as both can often run at different temperatures, especially if wide band gap materials are used. Second, ensuring integrated drives for EVs can be manufactured cost effectively at higher volumes was cited as a key concern during the workshop process. In the long term, the potential exists for a combined manufacturing processes for integrated drives where the power electronics and e-machine are fabricated together. This could be enabled by reducing the costs of additive layer manufacturing processes in conjunction with developing sophisticated, multi-physics modelling tools that can design fully integrated electric drives.

> *In the long term, the potential exists for a combined manufacturing processes for integrated drives where the power electronics and e-machine are fabricated together*

8.4 MATERIALS AND MANUFACTURING

PREDICTION: Alternative winding materials and different manufacturing techniques could deliver e-machines with improved performance at lower cost

Losses in copper windings are one of the major sources of efficiency loss in e-machines, so development is intensely focused on reducing these losses wherever possible. Both different winding techniques and replacing copper with other materials are being investigated and have the potential to significantly reduce costs or radically improve performance.

For lower cost applications, aluminium windings have been identified as a cheaper, lighter alternative that is more readily recyclable than copper. Significant research has been conducted into aluminium windings in the UK within the Innovate UK Evoque_e project, exploring the use of aluminium windings for traction machines.

Higher performance materials were also identified as being attractive for luxury and performance vehicles, as well as heavy duty vehicles. These applications need high power densities, greater torque densities and ultra-high efficiencies, which cannot be attained using existing approaches. Materials offering higher conductivity and lower losses compared to copper include: carbon nanotubes (embedded in copper or on the surface), graphene, nano-materials or high temperature superconductors. However these advanced materials are currently in the research stage and command a price premium.

Alternative winding strategies, including distributed, concentrated and hairpin, also offer the potential to maximise performance and reduce machine losses. However, each approach must dissipate heat effectively while delivering increased material fill factors. In the long term, the use of advanced additive layer manufacturing may be promising as it could remove the requirement for dedicated winding processes, eliminating a costly manufacturing step. However this will only become feasible if the complex e-machine designs possible with additive layer manufacturing can be scaled up to sufficient volumes.

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PREDICTION: Breakthroughs in metallurgy and manufacturing processes could enable the commercialisation of advanced electrical steels and soft magnetic composites

Iron losses are another major source of loss in e-machines so advances in soft magnetics are identified as a crucial area of further research. Two soft magnetic materials highlighted in the roadmap are electrical steels and soft magnetic composites.

Electrical steels are currently the most popular approach for automotive applications, so improving their magnetic and chemical properties is deemed crucial to reducing eddy and hysteresis losses. In the short term, development is underway using thinner laminations (0.1-0.2mm) and optimising the crystal structure of grain-orientated steels, to improve electrical steel properties. In addition, better electrical steel coatings are recognised as a promising area of research and can help in minimising losses and mechanical stress. Potentially useful areas of long term research include the cost effective introduction of additional materials such as silicon, cobalt, manganese, vanadium or chromium into electrical steels, and tailoring the properties to deliver performance in specific areas in order to more effectively manage flux paths.

Soft magnetic composites (SMCs) are less commonly used in automotive applications than electrical steels, but allow more complex shapes to be produced through net-shape manufacturing. As a result, machines can be designed where the magnetic flux can travel freely in the e-machine, allowing radically different topologies to be used for higher performance applications. Using SMCs has also been recognised as easier to manufacture than thin laminated electrical steels, offering the potential for more cost effective volume manufacturing. This is because the iron cores and parts can be die-pressed to the desired shape and dimensions, minimising machining and processing steps. From a performance perspective, the surface coating and adhesives used to bond the powder reduce the eddy current losses compared to steel (especially at higher frequencies) however the hysteresis losses in SMCs are more pronounced.

PREDICTION: The automotive sector must reduce its reliance on rare earth permanent magnets in future traction machines in order to achieve a sustainable supply chain

The short term priority is the removal of heavy rare earth materials such as Dysprosium and Terbium, added to improve the temperature resistance of Neodymium. These are expensive and mined mainly in China, so eliminating them not only reduces cost but shields many e-machine manufacturers from potential prices rises and supply issues.

Many automakers are currently trying to reduce the content of rare earth magnets in automotive e-machines, but the roadmap recognises that in the longer term the focus will shift to reducing the content of light rare earth magnets (e.g. Neodymium), which also represent a significant cost in current e-machines.

Continuously optimising the properties of magnetic materials to allow thinner laminations, reduce eddy current losses and improve the strength, durability and high temperature capability was identified by the roadmap as a development priority. Utilising alternative magnetic materials, such as ferrite magnets, is also seen as a potential alternative to rare earth materials.

Designing e-machine architectures that reduce magnet use (such as the motors in the BMW i3 and i8) and using machine topologies that do not use permanent magnets (i.e. induction and switched reluctance) have been identified as promising routes to reducing the automotive sector's use of rare earths. However removing permanent magnets from the machine may introduce additional costs in the power electronics, which occurs in switched reluctance motors in order to achieve the equivalent peak power and torque densities of permanent magnet machines. Finally, reducing the environmental impact of NdFeB magnet refining and manufacturing by reusing magnetic materials was highlighted as being a crucial development for permanent magnets.

8.5 ENABLERS

PREDICTION: System performance could be improved by developing motor control software in conjunction with the power electronics community

Innovative control strategies will help improve noise, vibration and harshness (NVH) with the potential for wireless and/or sensorless control. The introduction of advanced data analytics, vehicle-to-vehicle communications and self-learning software could enable e-machines to self-adapt for high efficiency, peak power or reliability based on driving styles.

PREDICTION: Advanced manufacturing techniques could help reduce costs or enhance performance through higher levels of automation, including additive layer manufacturing

Automotive e-machines (especially traction machines) will require significant manufacturing innovation in order to cost-effectively scale up to the desired volumes. Refinement of existing manufacturing techniques will deliver short term improvements in performance, but utilising experience from adjacent sectors that have expertise in manufacturing e-machines in large volumes will be crucial.

Increased levels of automation with higher precision tooling will support advanced manufacturing techniques, such as additive layer manufacturing, by reducing process steps and enable more complex e-machine designs not possible with conventional manufacturing processes. Another crucial challenge identified in the roadmap process is a viable route for manufacturing integrated drives as the complexity and tooling equipment is currently not available for high volume production.

PREDICTION: Life cycle management and design for recycling will help ensure that e-machines deliver environmental benefits over a TPS

The development of e-machines that are less harmful for the environment is key to ensuring that electrified powertrains remain a viable solution for the automotive industry. To satisfy end-of-life requirements, two routes exist for improving their sustainability: designing machines that do not contain rare earth materials, or creating a closed loop supply chain whereby rare earth materials (and all other materials) are recycled and re-used within the supply chain.

Current e-machine designs, such as interior permanent magnet machines, are difficult to recycle as the magnets are embedded inside the rotor and bonded with strong adhesives, making extraction difficult. Furthermore e-machine windings are currently designed with significant copper content to maximise performance. These windings are fixed in place by strong adhesives, ensuring optimal performance making recycling more challenging. Once extracted, recycling copper is costly because different recycling processes are required for electrical steels, copper and rare earth magnets.

In light of these challenges, the roadmap recognises that e-machines need to be designed for remanufacture. In addition, new recycling processes to enable sensing, sorting, separation, purification and reprocessing of materials is required in order to improve the environmental and economic sustainability of e-machines.

Current e-machine designs, such as interior permanent magnet machines, are difficult to recycle as the magnets are embedded inside the rotor and bonded with strong adhesives, making extraction difficult

8.7 RESEARCH AND DEVELOPMENT CHALLENGES FOR THE SHORT, MEDIUM AND LONG TERM

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The electrification of road transport is facilitating an unprecedented level of innovation in electric machines. Novel architectures, better materials and advanced manufacturing processes are all being explored in response to the diverse and demanding requirements of the automotive sector.

As the number of electrified cars, buses and heavy duty vehicle increases, electric machines will play an ever greater role in creating and safeguarding jobs, as the manufacture of conventional powertrains begins to plateau and eventually decline. Therefore electric machines provide an attractive opportunity to ensure national industries can continue to export powertrain components.

The exciting thing is companies and academics from many different disciplines can contribute to the development of electric machines, from material scientists right through to manufacturing equipment providers, system integrators and computer modellers. In light of this opportunity the APC, in collaboration with the Electric Machine Spoke community, has identified nine broad research themes that capture a range of innovation areas.

The Spoke community quickly recognised that for the UK to be internationally leading, we need to harness the broadest range of skills possible. This isn't limited to just technology innovations but also the manufacturing technologies used to make electric machines. For us to be innovation leaders, we need to develop electric machines and manufacturing technologies in tandem to reap the greatest benefits. In light of this, manufacturing innovations feature strongly in the following research and development challenges.

> *As the number of electrified cars, buses and heavy duty vehicle increases, electric machines will play an ever greater role in creating and safeguarding jobs*

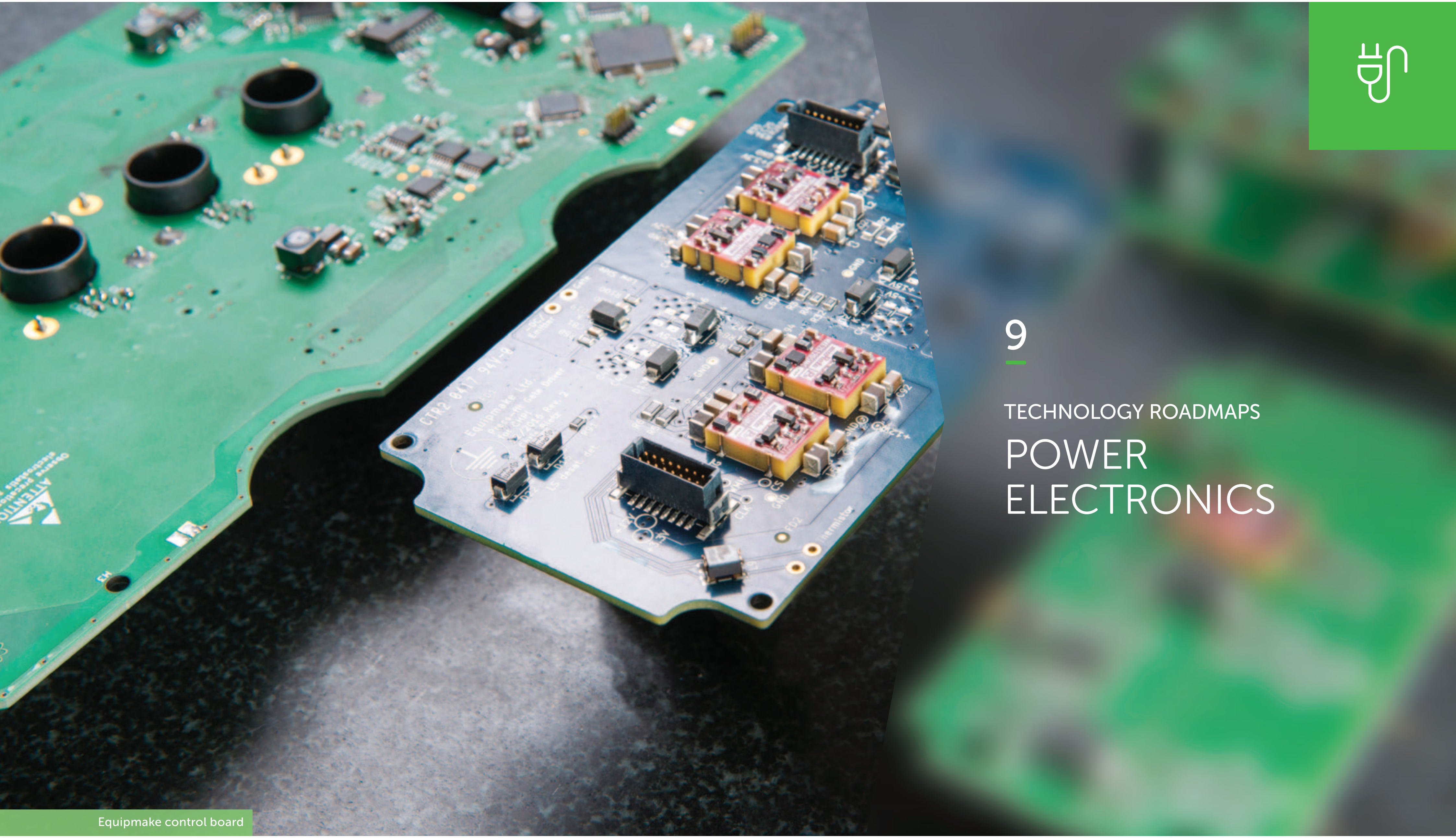
Identification of key research and pre-competitive development challenges to facilitate academic / industrial collaboration on longer term product and manufacturing research and development

Research Challenge	**SHORT TERM** (5-7 years to mass market)	**MEDIUM TERM** (7-15 years to mass market)	**LONG TERM** (10-20 years to mass market)
1 More efficient, higher speed power-dense machines	• Safer and higher speed capable (up to 30,000rpm) bearings and magnet retention systems • Effectively integrating machines: understanding the implications of different bearing types (aerofoil, hydrodynamic, hydrostatic etc.) and chosen gearbox/transmission arrangements • Developing higher speed machines that: minimise AC and iron losses, do not compromise NVH and maintain efficiency	• Machines that are optimised for higher switching frequencies enabled via innovations in wide band gap materials • Mechanisms for managing rotor losses at extreme speeds (i.e. how to alleviate gas friction on rotor)	• Low cost, novel bearing types (e.g. air, composite or magnetic) • Active NVH management • Machines designed in conjunction with ultra-wide band gap materials
2 Effective and efficient thermal management systems fully integrated with vehicle thermal management systems	• Machines capable of running on 85-105°C cooling circuits shared with ICE and transmission • Targeted cooling strategies in the machine i.e. cooling of rotor to allow lower grade magnets, or, better magnet temperature distribution to enable removal of Dysprosium	• Electric machine and power electronics thermal management systems fully integrated with vehicle thermal management systems that leverage new technologies (such as phase change materials) to improve efficiency & reduce parasitic loss • Advanced low cost insulations materials with ultra low film thickness • Accurate modelling of temperatures that can enable the machine to run as close as possible to its thermal threshold • High surface area AM heat exchanger	• New motor structures and materials to maximise heat rejection • Windings with integrated cooling channels • Heat pipe technology in conductors • Ceramic coatings for higher temperature capabilities

Research Challenge	SHORT TERM (5-7 years to mass market)	MEDIUM TERM (7-15 years to mass market)	LONG TERM (10-20 years to mass market)
3 Improved materials and processing technologies	• Effective winding insulation materials that deliver higher temperature operations (300°C) with shorter cycle manufacturing processes • Wire insulation that doesn't degrade with various cooling strategies (e.g. oil spray and jet cooling) • Lower cost machines with aluminium windings that maintain the weight, size and power density as copper wound machines, including their manufacturability and termination challenges for aluminium windings • Net (or near net) shape manufacturing techniques for PM magnets (i.e. metal injection moulding, casting rotor magnets onto rotor shaft) • Moving high fill density (i.e. 80% of stator slot) automated winding technology from prototype to higher volumes	• Cost effective multi stranding (e.g. Litz) and lamination of windings • Practical and affordable, high strength non-oriented electrical steel laminations • Alternative solutions to coil winding • Permanent magnets improved strength, durability, electrical resistivity and higher temperature capability • New techniques to create laminated (rolled) permanent magnets <2mm thickness without machining losses and grains <1micron • Optimising SMC designs for higher frequency operations • Cost effective manufacturing processes capable of stamping of 6.5% silicon steel quickly • Faster lamination cuttings without impairment on material properties • Treatment of laminations to modify permeability and saturation	• Developing room temperature superconductors, carbon-based conductors and replacements for electrical steels with non-magnetic steels to radically improve machine performance • Alternatives to rare earth magnets to improve sustainability, reduce cost and reduce the risk of price volatility • Improved thermal conductivity (20W/mK) insulation materials • Deposition techniques to 3D print magnets • Coreless/ironless machines eliminating electrical steels/SMCs
4 Holistic multi-physics modelling capability to improve the performance of integrated systems	• Validated models compliant with auto industry safety standards/processes • Accurate electric machine datasets (materials, electrical, mechanical thermal etc.) as well as the platforms to share this data openly and securely across industry • Improvements in simulation of NVH and CFD • Modelling tools that accurately predict high frequency effects • Full specification material data (beyond 50Hz) to enable better designs • Improved condition monitoring systems with <10% margin of error	• Digital twins of machine and inverters to optimise system level designs • Design tools which allow designers to make system level trade-offs (i.e. increase in costs of x provides y amount of efficiency) • Cloud based system level multi-physics models to enable faster collaboration across industry (and between organisations not co-located)	• Real time modelling of in motor stresses and losses • High fidelity modelling looking at vehicle level trade offs and interaction with environment • Multi-physics modelling of machines and power electronics with <1% margin of error

Research Challenge	SHORT TERM (5-7 years to mass market)	MEDIUM TERM (7-15 years to mass market)	LONG TERM (10-20 years to mass market)
5 Improved sensing and monitoring technology to improve performance and facilitate predictive maintenance	• Improved rotor temperature sensors to allow operation closer to the thermal limit • Data gathering and sharing to facilitate an open knowledge base	• Systems leveraging 'virtual sensing' techniques and big data analysis to enable predictive maintenance with a margin of error <5% • Sensors modifying machine control (i.e. to extend life in certain operations) • Multi-purpose sensors which do numerous jobs	• Systems leveraging 'virtual sensing' techniques and big data analysis to enable predictive maintenance with a margin of error <1%
6 Machines that leverage advances in manufacturing technology	• Additive layer manufacturing for prototype and low volume production motors • Laser cutting electrical steels to improve processing speed an enable production (with a need to investigate effect on laminations) • Modularity of sub-components and machines to promote interchangeability and recyclability	• Additive layer manufacturing of stator and rotor with high bulk resistivity utilising new materials such as SMCs to create more complex geometries • Fully automated machine assembly processes	• Additive manufactured printed higher power density drives • Collaborative manufacturing utilising machine learning to optimise motor designs (Industry 4.0) • Higher utilisation of sintered and compacted components • Injection moulding of windings in machine
7 Mobilising a UK supply chain that demonstrates cost competitiveness and higher productivity	• Develop flexible prototyping and high volume pilot manufacturing capability to capitalise on future machine topologies • High volume automotive standard production and quality assurance processes • Understanding the key performance variations and challenges associated with scaling from prototype to production • Leveraging and adapting manufacturing processes and materials used in adjacent sectors for electric machine manufacturing capability • Develop new manufacturing technologies for automotive traction machines	• Integrated manufacturing of e-machine, power electronics and transmission	• Automated prototyping facilities (informed by models) that have iterative design loops to auto- optimise machine designs

Research Challenge	SHORT TERM (5-7 years to mass market)	MEDIUM TERM (7-15 years to mass market)	LONG TERM (10-20 years to mass market)
8 Improved materials, machine design and processes to facilitate a sustainable and economically viable value chain for end-of-life recovery, re-use and recycling	• Scaling up recycling technologies to sense, sort, separate, purify and reprocess small sub-components with uniform design • Prototype facilities capable of cost effectively extracting rare earths from IPM and SPM machines without breaking or demagnetising the magnets • Design for recycling: optimised machine designs (including encapsulating materials, coatings and housings) to aid recycling of magnetic materials, soft magnetics and windings • Pilot facilities for use of recycled magnets from adjacent sectors (i.e. consumer electronics)	• Cost effective processes for recycling net shape magnets which are harder and more expensive to recycle • Recycle 50% of all PM magnets contained in automotive electric drive trains • Increased use of recycled materials in electric machines • Processes that can recycle integrated drives (power electronics and electrical machines)	• Achieve >95% economically viable end-of-life recycling rates via material selection and design for recycling • Removal of rare earth materials and copper to create more streamlined recycling processes • Cost effective recycling technologies to sense, sort, separate, purify and reprocess different machines sizes with different topologies
9 Design verification plan and validation facilities	• Address national infrastructure limitations in terms of automotive electric machine testing • New test equipment concepts • Clear standards and targets for e-machine testing and verification	• Development of future testing capacity informed by the agreed standards	



Equipmake control board

9

TECHNOLOGY ROADMAPS

POWER ELECTRONICS

OVERVIEW

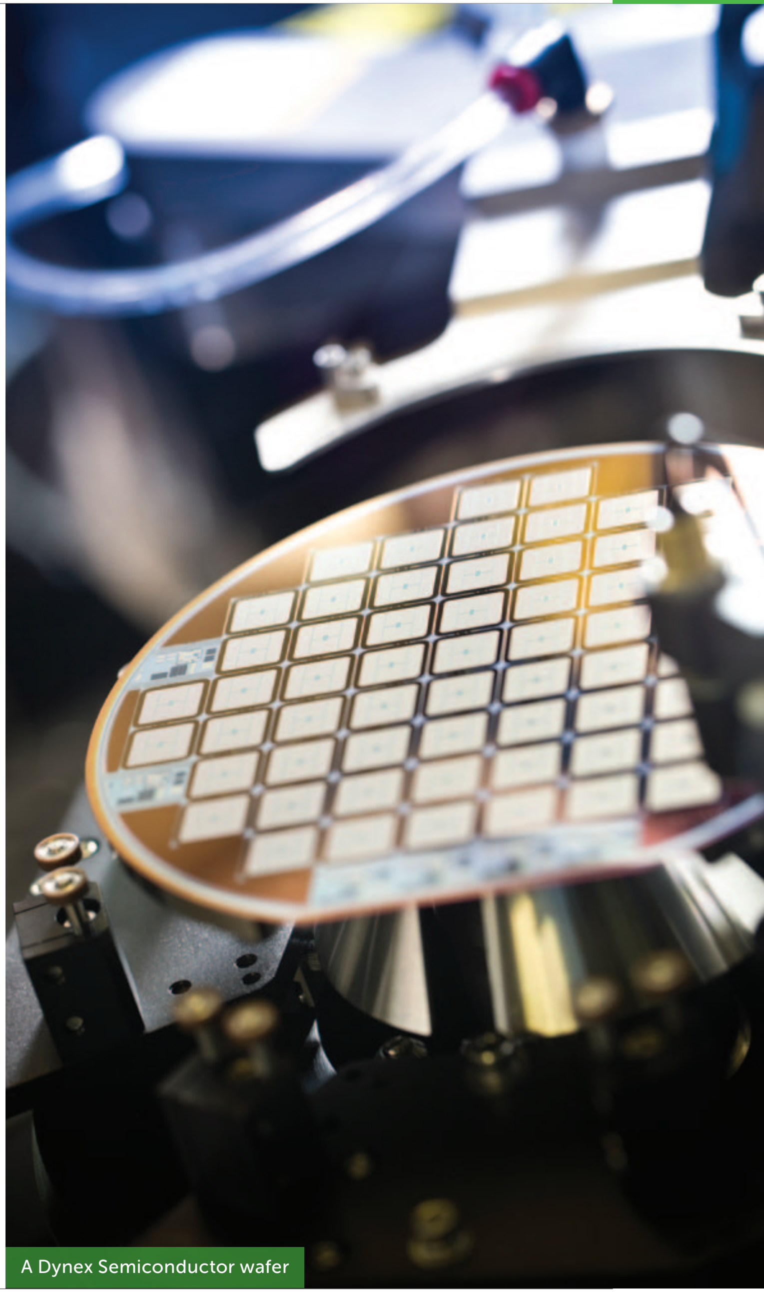
Power electronics play a crucial role in regulating the voltage levels, controlling power flow to the electric traction motor and enabling plug-in vehicles to charge from the electricity grid. As the number of electrified vehicles on the road increases, more sophisticated power electronic solutions will be needed to reduce electrical losses, system weight and cost.

Silicon-based semiconductor devices will continue to play an important role in the automotive sector, due to their manufacturability, established supply chain and suitability for lower voltage applications. However, the roadmap recognises that new wide bandgap* semiconductor materials, such as silicon carbide and gallium nitride, will soon enter the automotive market, especially for high-power traction applications.

These new devices will offer improved thermal and electrical performance over traditional silicon devices, but bring challenges around their manufacturability, integration and cost.

To maximise the potential benefits of wide bandgap materials, advanced components, converter topologies and techniques for circuit integration will need to be co-developed alongside them.

Future strategies for the integration of power electronics present a number of opportunities for the supply chain. The roadmap identifies two such paths; fully integrated drives, where motor and power electronics are co-developed, or a single power management converter able to manage power across the vehicle.

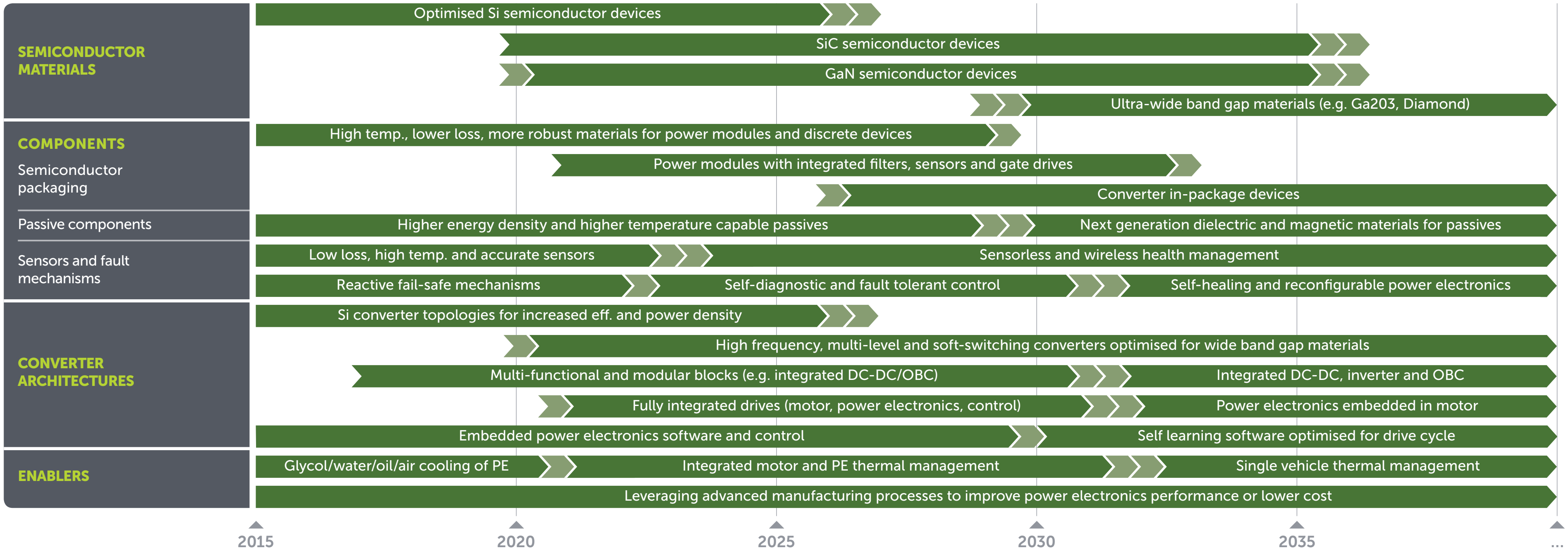


A Dynex Semiconductor wafer

* A bandgap refers to the energy needed to excite electrons from a material's valence band into the conduction band. Materials with larger bandgaps such as silicon carbide (SiC) and gallium nitride (GaN) are able to operate more efficiently at higher voltages and can withstand higher temperatures compared to silicon.

POWER ELECTRONICS

DRIVERS	xEV uptake, CO_2 limits, air quality regulation, ULEZs, charging access	Very low CO2, zero emission zones, LCA, materials security, rapid/opportunity charging infrastructure	
TARGETS*	Current status	2025 targets	2035 targets
Cost ($/kW)	5 $/kW	4 $/kW	3 $/kW
Power Density (kW/kg)	15 kW/kg	22 kW/kg	50 kW/kg
Power Density (kW/l)	12 kW/l	15 kW/l	60 kW/l



Driver set | Driver predicted | *Solid bar represents >1% global marked adoption and is preceded by significant product and process R&D* | ***1 chevron** = some uncertainty around timing of mass market adoption or phase out* ***2 chevrons** = considerable uncertainty around timing of mass market adoption or phase out*

9.1 TARGETS

Power electronics are required by all xEV formats, becoming increasingly sophisticated in BEV and PHEV applications. The future roadmap targets cannot be attained with existing technologies and architectures. Meeting mainstream automotive demands will therefore require higher efficiencies, improved power densities and lower system costs. In response to these challenges, ambitious power electronics targets have been set to drive innovation in inverters, DC-DC converters and integrated chargers/DC-DC converters: the key power electronics components for BEVs and PHEVs.

Cost and power density targets should be read independently from one another as different OEMs will prioritise different targets based on their product requirements.

	Cost effective applications	Specialist applications	2017	2025	2035
Inverter [1]					
Cost ($/kW)	•		5	4	3
Power Density (kW/kg)		•	15	22	50
Power Density (kW/l)		•	12	15	60
Efficiency (%)	•	•	96	97	98
DC-DC Converter (2-port) [2]					
Cost ($/kW)	•		15	10	6
Power Density (kW/kg)		•	8	15	50
Power Density (kW/l)		•	6	12	60
Efficiency (%)	•	•	97	98	99
Integrated Charger/DC-DC Converter [3]					
Cost ($/kW)	•		30	15	8
Power Density (kW/kg)		•	3	6	12
Power Density (kW/l)		•	2	4	15
Efficiency (%)	•	•	94	96	97

1. 3-phase with dc-link and controls
2. 2-port non isolated, bidirectional buck-boost
3. PFC front-end, isolated DC-DC with HV and LV battery outputs, bidirectional by 2030 (or earlier depending on V2G introduction)

9.2 SEMICONDUCTOR MATERIALS

PREDICTION: The low cost and embedded manufacturing capacity of silicon-based devices will maintain their attraction for automotive applications

Silicon-based power semiconductors currently dominate automotive power electronics due to their low cost, suitability for high volume manufacturing and reasonably high efficiencies. In the short term, performance gains can still be achieved in silicon-based semiconductors through smaller chip sizes, thinner wafers and innovative insulated-gate bipolar transistor (GBT) and metal-oxide-semiconductor field effect transistor (MOSFET) designs (e.g. fast IGBTs; reverse blocking and conducting IGBTs). Longer term, silicon could still remain popular as wide bandgap materials may not provide sufficient efficiency improvements to justify a cost premium in applications such as 48V mild hybrids.

Silicon wafers will still be required in a future of wide bandgap materials because a cost effective way of commercialising gallium nitride (GaN) is using silicon wafers to grow it.

PREDICTION: Silicon carbide and gallium nitride, though offering significant performance improvements over silicon, will initially emerge for high performance and specialist applications

New wide bandgap devices are smaller, faster, and more efficient than silicon, with greater tolerance to high temperatures, making SiC and GaN power semiconductors key enablers for more efficient electro-mobility.

Currently, SiC and GaN technologies are both relatively immature. SiC based semiconductor devices are being used in the Formula E series, with ROHM supplying the devices to a number of Formula E teams. Other manufacturers, such as Mitsubishi, Wolfspeed and Infineon, are producing SiC-based devices for mainstream automotive applications which are anticipated to enter the market in the next few years. SiC is likely to be introduced into the traction inverter market before GaN as its better suited to higher power and high temperature applications. Notable challenges with SiC include: accelerating the speed of wafer growth; increasing the production rate while reducing the cost of growing different wafer types; and making reliable and higher temperature devices suitable for automotive standards.

The roadmap identifies GaN as more being suitable for lower voltage and power applications that require higher switching frequencies (above 100 kHz which strains the comfortable operating limit of silicon). Therefore initial applications of GaN semiconductors are likely to occur in on-board chargers and DC-DC converters where the power requirements are lower but the higher switching frequency is desirable to increase efficiency. GaN could also be attractive for lower voltage applications such as mild hybrids if the costs can be reduced. Challenges associated with GaN include: growing substrates in bulk; lattice mismatch with silicon; and the reduced thermal performance of GaN on Si. Currently, the optimum voltage operation of GaN is below 600V, but this may be extended in future devices, potentially displacing SiC.

PREDICTION: Ultra-wide bandgap materials such as gallium oxide or diamond, though offering further improvements over today's wide bandgap materials, require significant additional development before use in automotive applications

The roadmap identifies numerous next-generation semiconductor materials called 'ultra-wide' bandgap materials that could, in the long term, displace SiC and GaN. Frontrunner technologies identified include diamond, gallium oxide and aluminium nitride. While these materials offer a step change in performance they are still only at a fundamental level of research and require significant technical improvement and cost reduction to satisfy automotive requirements.

9.3 COMPONENTS

PREDICTION: Methods of packaging semiconductor devices will be re-evaluated as increasingly compact solutions are required with greater power density

The packaging of semiconductor devices is crucial in managing their thermal and electrical performance, as well as mechanical stability. In the short term, material improvements are needed to increase their temperature range; this includes better thermal interface materials, novel substrate concepts and improved encapsulation technologies. There is also a need for alternative materials to provide better mechanical stability and robustness, as well as improved bonding mechanisms for each level of component assembly, to better withstand repeated power and temperature cycling.

In the longer term, existing methods of packaging semiconductor devices need to be revaluated; the benefits of SiC and GaN power electronics devices cannot be realised if they are treated as drop-in replacements for silicon devices. New packaging techniques and circuit designs are required that take full advantage of their properties, in turn reducing the size of cooling and auxiliary circuit components. For example, the introduction of wide bandgap materials reduces the need for some passive components, enabling more highly integrated solutions with sensing, gate drivers and filters incorporated within the semiconductor.

A potential opportunity exists to use converter-in-package technologies by replacing single and multi-chip modules, housing just semiconductor components, with fully integrated power modules. This new semiconductor topology could accept higher currents and temperatures, contain fewer interfaces and incorporate multifunctional sub-components and materials (e.g. multi-functional PCBs). However more complex designs will create new manufacturing challenges. Therefore new design concepts need to consider the impact on manufacturing technologies from the outset and may leverage new production processes such as additive layer manufacturing.

PREDICTION: Passive components will need to be optimised to work alongside new semiconductor materials and converter architectures

Passive components, such as capacitors and inductors, are crucial in building functioning circuits but are often limiting factors in terms of the achievable levels of operating temperature and power density. A key short term requirement identified in the roadmap is for passive components to be co-developed alongside the new wide bandgap semiconductors. For example, as frequency increases the required capacitance and inductance values decrease allowing smaller components to be employed.

Capacitors and other passive components that remain in the circuit must, however, operate satisfactorily at the same high temperatures and high frequencies to the new semiconductor materials. In the longer term, this requires new materials for passive components. Candidates include carbon nanotube windings for inductors, high temperature ceramic capacitors and improved magnetic and dielectric materials to achieve higher energy storage densities.

> *A key short term requirement identified in the roadmap is for passive components to be co-developed alongside new wide bandgap semiconductors*

PREDICTION: Sensors and fault tolerance mechanisms will need to evolve to deliver multi-functional prognostics and health management

Sensing and fault tolerance are important in ensuring safety, improving performance and overall system health management. In the short term, the roadmap identifies that sensors will need to become tolerant to higher temperatures and generate lower losses while maintaining accuracy. However, as wide bandgap materials start to proliferate, sensors will also need to become smaller to fit within the reduced package sizes and operate at higher frequencies. Multifunctional sensors may be employed to reduce cost, packaging space while improving functionality.

In the long term, the roadmap anticipates that more wireless sensors will be used to reduce weight, wiring as well as to simplify packaging. Advances in sensing technology will support the transition of reactive fail-safe mechanisms into predictive health management, enabled by in-field data collection, and potentially extending into self-healing and reconfigurable power electronics enabled by AI/ machine learning. Turning captured data into value will require advanced data analytics to be commercialised.

9.4 CONVERTER ARCHITECTURES

PREDICTION: Converter architectures using silicon can be further optimised but the introduction of wide bandgap materials will encourage a wider range of enhanced converter topologies

In the short term, existing silicon-based converter topologies will dominate in many applications until the additional cost of wide band gap materials can be absorbed and the system level benefits realised. Therefore innovations in silicon-based technologies are expected to continue in order to maximise efficiency. Strategies are likely to include the use of SiC diodes and Si switches, more efficient circuit topologies, distributed architectures (with many small converters paralleled) and parallel/interleaving systems.

The full potential of advanced converter topologies will be unlocked when wide bandgap materials are introduced. These may include soft-switching topologies for high frequency applications; adaptive power inverters; higher frequency modulation schemes; resonant converters and multi-level converters.

In the short term, existing silicon-based converter topologies will dominate in many applications until the additional cost of wide band gap materials can be absorbed and the system level benefits realised

PREDICTION: As BEV and PHEV platforms become more sophisticated, there will be a closer integration of motor and power electronics

The trend towards smaller electrical drives with higher power density, to meet the performance needs and evolving packaging requirements of OEMs, has led researchers to consider integrated drives that could offer a more efficient and power dense solution. This allows interconnections to be deleted, a move from cables to busbars for motor phases and common cooling circuits. However the physical integration of the converter and the e-machine requires careful mechanical, structural and thermal optimisation in order to manage the temperature differentials between different components. The introduction of wide bandgap semiconductors could make integrated drives more attractive because they are smaller, more efficient and capable of operation at higher temperatures.

Some specialists anticipate that advances in manufacturing technologies will enable more radical integrated drives in the longer term; specifically there is potential for motors and power electronics to be fabricated together using additive layer manufacturing which would create a truly multifunctional, light weight electric drive.

PREDICTION: In a move to reduce complexity and costs, there could be an integration of power electronics where a single converter is able to manage power across the vehicle

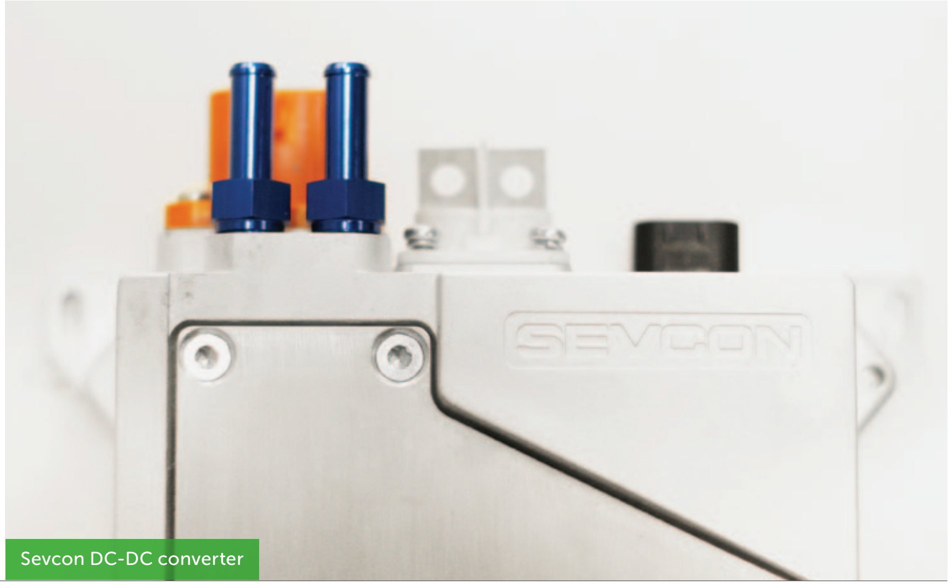
Multifunctional converter topologies reduce complexity and hardware, freeing up packaging space while reducing weight and cost. This approach is already implemented on the Nissan LEAF where the DC-DC converter and on-board charger have been merged to provide enhanced functionality and a more compact power electronics solution. A similar approach has been used in the Renault ZOE whereby the motor inverter is used to charge the vehicle. This approach enables the ZOE to charge from numerous charging stations and eliminates the need for a separate on-board charger.

The use of modular blocks is also an attractive approach; as the volumes of electrified vehicles increase, modularity enables higher volume manufacturing with greater commonality. In the long term, to meet the requirements of vehicle-to-grid, ultra-compact power electronics solutions may be required that can be redeployed to provide other on-vehicle functions. A single power electronics block that can provide all functions is one possible route to achieving this.

> *To meet the requirements of vehicle-to-grid, ultra-compact power electronics solutions may be required that can be redeployed to provide other on-vehicle functions*

PREDICTION: More powerful control hardware will be needed to complement new convertor architectures, with the potential for adaptive control functionality as connected vehicles become more widespread

Advanced control software provides significant opportunities for product differentiation as hardware costs fall. Wide bandgap power electronics will require faster controls and more powerful control hardware. As control technology advances, advanced data analytics, vehicle-to-vehicle and self-learning software could enable converters to adapt for high efficiency, peak power or reliability, based on driving styles.



Sevcon DC-DC converter

9.5 ENABLERS

PREDICTION: Despite the higher operating temperatures of new semiconductor materials, system level thermal management strategies will still be needed to provide effective cooling

Currently the emphasis is on simplifying the cooling arrangements across the vehicle platform, e.g. by applying a single cooling loop. More advanced cooling strategies may emerge in response to demands for deeper integration of power electronics with other components such as e-machines and batteries. This could entail the operation of power electronics at higher or lower temperatures, with the possibility of using the heat generated to bring the battery up to optimum temperature.

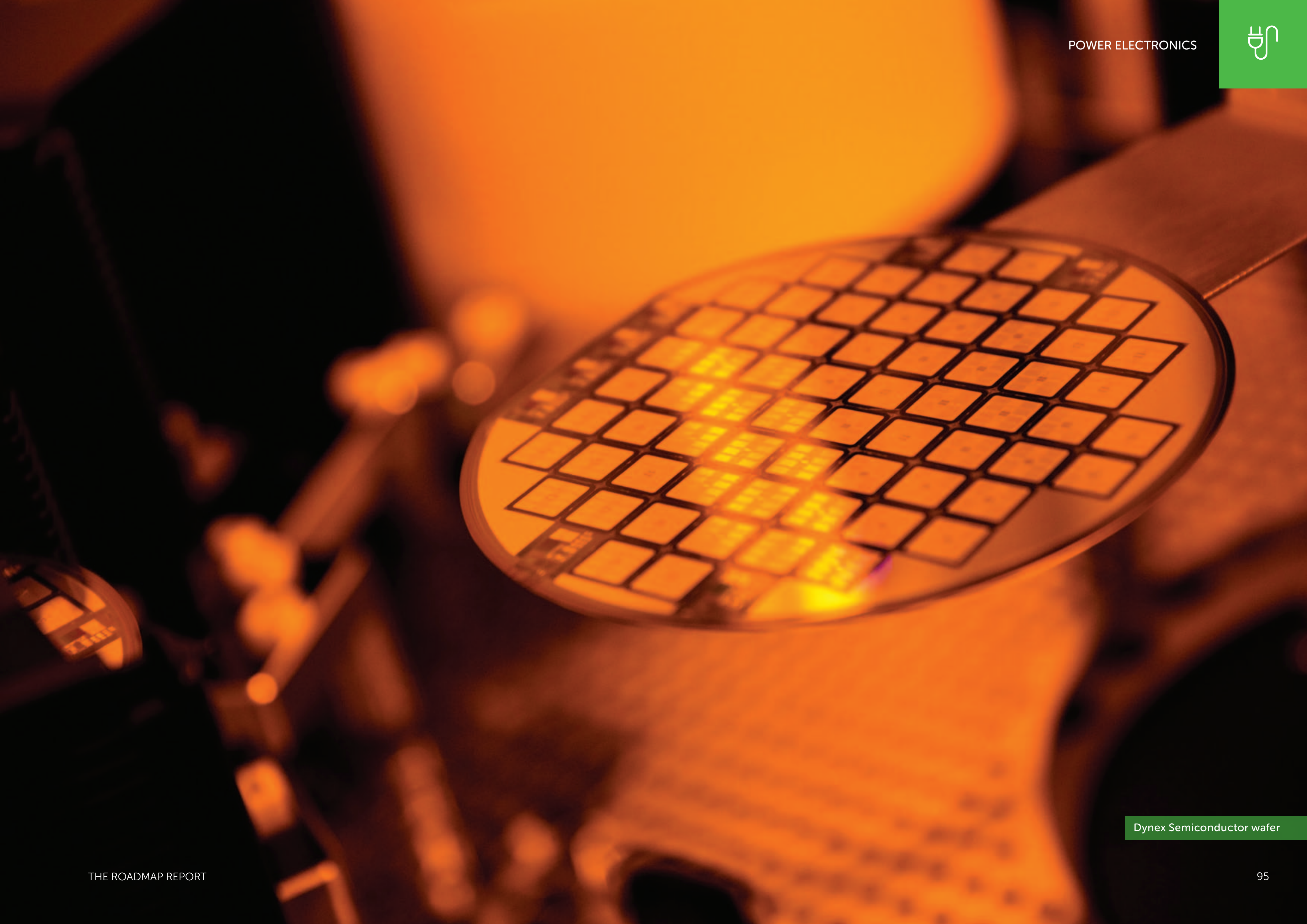
The absence of a thermal propulsion system (TPS) will require BEVs to implement new thermal management strategies to support vehicle-wide comfort and operational requirements. Oil cooling, shared with the TPS and transmission, may still be prominent in hybrid vehicles but as BEVs become more abundant, a number of strategies prove attractive. Air cooling, either passively or forced, may be a popular solution for mass market BEVs or those not experiencing high power operation. Cooling by submerging the electronics, or by circulation of water based coolant through passages in the converter, may be better suited to higher performance applications where high amounts of heat are generated and manufacturers are less sensitive to cost.

In the long term, it is envisaged that power electronics cooling may become part of single vehicle-wide loop including waste heat recovery and storage.

PREDICTION: Advanced manufacturing techniques could reduce costs through higher levels of automation and new design for manufacturing options enabled by additive layer manufacturing

The roadmap identifies that time-to-market for new products could be accelerated through the use of advanced manufacturing technologies such as additive layer manufacturing to produce complex prototypes, or by automation to reduce costs. As additive layer manufacturing becomes increasingly attractive for high volume manufacturing, this offers significant cost savings by reducing process steps and improving the consistency of manufacturing resulting in less variations.

Newport Wafer Fab



Dynex Semiconductor wafer

9.6 RESEARCH AND DEVELOPMENT CHALLENGES FOR THE SHORT, MEDIUM AND LONG TERM

Mark Johnson
Professor of Power Electronics

APC Power Electronics Spoke

ADVANCED PROPULSION CENTRE UK
POWER ELECTRONICS SPOKE

Existing approaches in power electronics have served the automotive sector well, but with the advent of electric vehicles, silicon based devices and converter topologies are reaching their performance limitations. The wide range of requirements in the automotive sector is driving demand for higher temperature materials, higher switching frequencies, improved reliability and more power dense solutions. More importantly, new, promising technologies need scaling up to meet the demands of the automotive sector, which creates both technical and manufacturing challenges.

Developed through the APC's Power Electronics Spoke community, the twelve research themes identified below articulate a host of challenges facing the automotive power electronics community. A key message across the research themes is that the progressive introduction of wide bandgap materials will impact the whole supply chain, from semiconductor device manufacturers through to companies integrating power electronics into a vehicle platform.

It is clear that to get the best out of these new materials, collaboration between different disciplines within power electronics is essential.

For the UK supply chain the window of opportunity is narrowing. Strong competitors from Europe, Asia and the United States are amassing considerable capability in automotive power electronics and the UK must build upon its strengths and protect areas where considerable value can be created. The research themes identified below therefore act as a blueprint to aid organisations seeking to understand how they can help overcome the future challenges in automotive power electronics.

> *The wide range of requirements in the automotive sector is driving demand for higher temperature materials, higher switching frequencies, improved reliability and more power dense solutions*

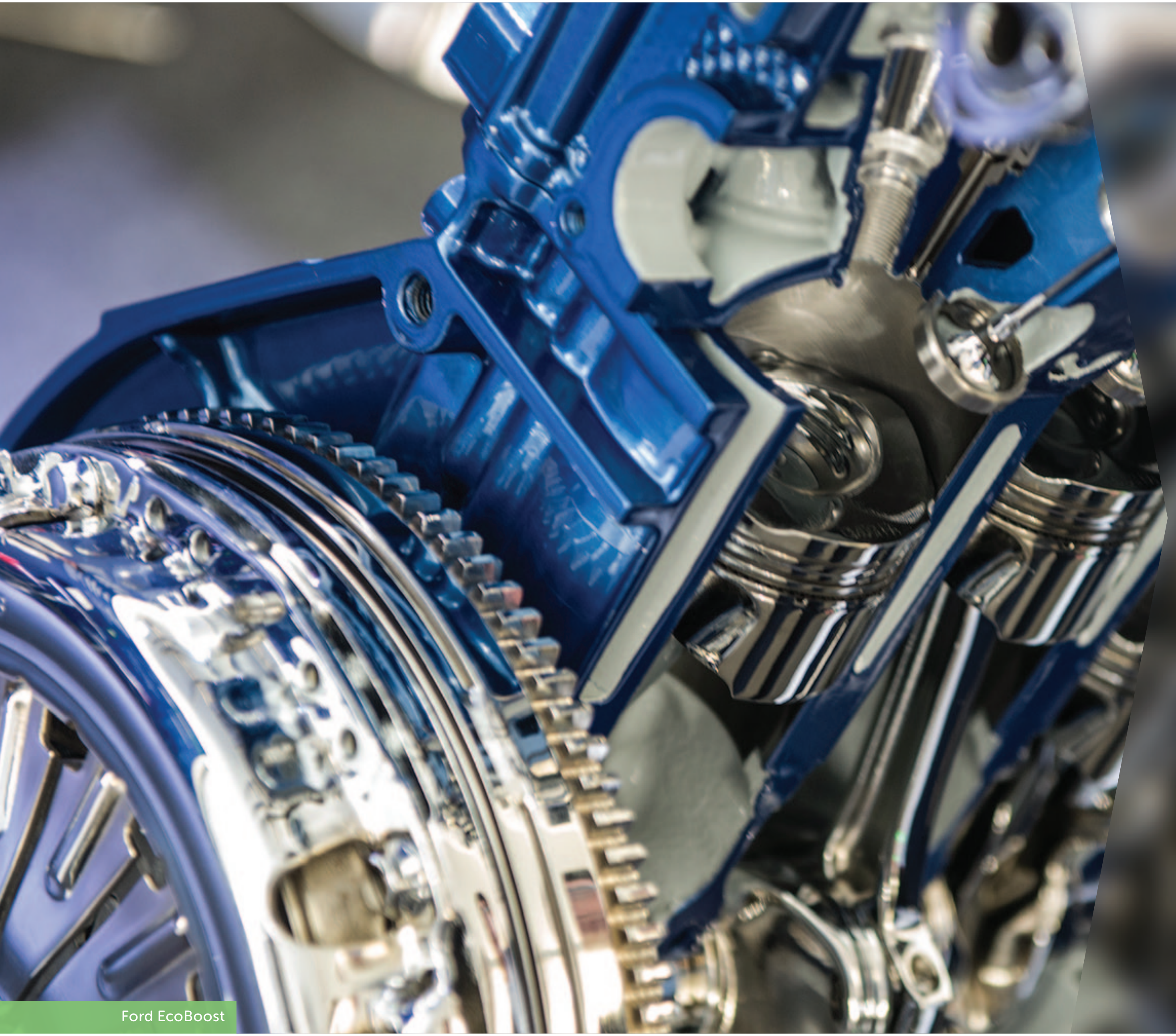
Identification of key research and pre-competitive development challenges to help facilitate academic / industrial collaboration on longer term product and manufacturing research and development

Research Challenge	**SHORT TERM** (5-7 years to mass market)	**MEDIUM TERM** (7-15 years to mass market)	**LONG TERM** (10-20 years to mass market)
1 Improved power semiconductor materials and devices	• Continued improvement of Si device designs: IGBTs, MOSFETs, Power ICs • Reducing cost and improving quality of SiC and GaN epitaxy and substrates • Alternative substrate materials e.g. GaN and SiC on Si • Identifying commonality in Si and wide band gap device manufacturing and adjusting processes to create reduced cost manufacturing capability for wide band gap devices	• SiC and GaN devices with enhanced reliability operating to >250°C • SiC on Si substrate scale-up and reduced cost • GaN Power ICs • GaN devices with improved stability	• Cost effective, higher voltage >1500V GaN and SiC • Large area, low-cost GaN substrates • GaN vertical devices • Diamond & Gallium Oxide materials and device processes • Exploring new materials and/or devices that radically improve breakdown fields, thermal conductivity & electron velocity of semiconductors
2 Improved power semiconductor packaging technology	• Development of standard interfaces to allow multisourcing-manufacturers • Embedded chip and planar interconnect for low-inductance • High reliability joining and interconnect technologies • Modules with integrated passive components • Low-cost integrated cooling (e.g. double sided cooling for flip chip) • Materials and assembly processes for wide temperature range cycling and power cycling with rapid transients	• Integration of gate drives, filters, controls and sensors • Embedded power and control elements • Integrated EMI suppression • Converter-in-package for increased power density • Materials and assembly processes for 250°C capability including wide temperature range cycling and power cycling with rapid transients	• Easy to design and manufacture power modules with elementary bricks, pre-packaged chips • High volume, low-cost manufacturing platform • 3D integrated hetrogenous assemblies • Low-cost substrate & laminate materials with low CTE (<16ppm) and high thermal conductivity (>20W/(mK)) • Reconfigurable, multi-functional Converter-in-Package • Materials and assembly processes for >250°C capability including wide temperature range cycling and power cycling with rapid transients

Research Challenge	SHORT TERM (5-7 years to mass market)	MEDIUM TERM (7-15 years to mass market)	LONG TERM (10-20 years to mass market)
3 Integrated control functionality within power semiconductors		• Monolithic gate drives and power transistors (SiC and GaN) • Stable, reliable on-chip current sensing with wide bandwidth • GaN/SiC devices with intelligent gate drives • Integrated multi-functional sensors for health check and control	• GaN/SiC half bridge on-chip with current/temperature sensing @ 1000V, 400A • Integrated direct optical control
4 Higher performance passive components	• Higher energy density (>0.01J/cm^3) wound components through improved thermal management • Higher temperature (200°C) passive components • Low-cost, high-performance and higher frequency capacitors for >125°C • Connectors with higher current, temperature and voltage capability	• Magnetic and dielectric materials with higher energy density and lower losses • Magnetic and dielectric materials with higher temperature (>250°C) capability • Higher temperature (250°C) passive component • Magnetic component designs for improved flux confinement and lower loss	• Super capacitors with high temperature (>200°C) capability • Higher temperature (>250°C) passive components • Smart/multi-functional materials for passive components • Peltier technology for active cooling • Integrated, multi-functional passive components
5 Improved driving, sensing and monitoring technology	• Compatibility of gate drivers with range of WBG semi conductors • Better sensor technology (e.g. stable, reliable, low-cost current sensing with wide bandwidth; high temperature sensors; low loss sensors) • Semiconductor temperature estimation and/or monitoring • Algorithms to improve the interpretation, management and analysis of sensor data	• Alternative approaches for sensing e.g. embedded and/or wireless sensors for condition monitoring • Condition monitoring of mechanical stress, displacement, electrical resistance and thermal resistance	• Sensor-less drivetrain monitoring and control based on system-level observations • Utilising data from vehicle fleets (enabled through wireless networks and CAVs) to better manage PE performance • Understanding and mitigating the effects of interactions between CAV sensors and power electronics (e.g. EMC aspects)

Research Challenge	**SHORT TERM** (5-7 years to mass market)	**MEDIUM TERM** (7-15 years to mass market)	**LONG TERM** (10-20 years to mass market)
6 Advanced converter topologies	• Multi-level & modular topologies suited to >800V using Si MOSFET, IGBT and WBG devices • Multi-functional, reconfigurable converters (Inverter, DC-DC, OBC combinations)	• Soft-switching ultra-high frequency topologies for inverter, DC-DC and OBC employing WBG devices • Converter-in-Package integration leading to power densities > 60kW/litre • Submersible converters • Structural materials for building WBG based converters that can withstand higher temperatures, EMC etc.	• Multi-level & modular topologies for 1500V to 25kV • Converter-in-Package integration leading to power densities > 120kW/litre • Reconfigurable, fault-tolerant & self-healing converters
7 Closer integration of power electronics into vehicle powertrain	• Integrated drives with thermal separation (12kW/l) • High temperature capable power electronics (>105°C coolant) • Multiphase and modular inverters for better integration	• Integrated drives with common thermal management (30kW/l) • Modular inverter topologies that can be used with different motor topologies	• Low-cost, high-volume integrated drives supported by common manufacturing platform (>30kW/l) • Cost effective fabrication (i.e. additive layer manufacturing) of power electronics into motors
8 Improved system level thermal management	• Active thermal control of PE • Merging of ICE/PE cooling loops using >105°C water/glycol • Two-phase cooling for high heat flux and high power density	• Common heat transfer loop for BEVs (battery, e-machine, PE, HVAC)	• Removal of dedicated power electronics cooling, integrated into the powertrain • Optimised vehicle level thermal management for BEVs with active thermal control (battery, e-machine, PE, HVAC) • Integrating advanced heat recovery (i.e. phase change materials) into a system wide thermal management system to deploy heat effectively
9 Improved control software	• Software & control for high-speed (>50 kHz) switching • Thermal and power management using adaptive modulation strategies	• Software and control for ultra-high-speed (>1MHz) switching • Condition and load-adaptive control algorithms • Spread spectrum loss optimising control for soft switched converters • Higher performance integrated control hardware	• Reconfigurable, fault-tolerant, self healing control algorithms • Utilising advancements in vehicle-to-vehicle and vehicle-to-infrastructure technology to understand vehicles situation and location to modify power electronics performance

Research Challenge	SHORT TERM (5-7 years to mass market)	MEDIUM TERM (7-15 years to mass market)	LONG TERM (10-20 years to mass market)
10 Improved fault tolerance mechanisms and overall system reliability	• Understanding PE degradation and failure mechanisms and FIT • Condition monitoring for key PE components (power semiconductors, modules, capacitors)	• In-service prognostic and health management for PE converters • Machine learning based prognostics • In-service life consumption estimation and predictive maintenance • Fault tolerant control systems	• Reconfigurable, fault-tolerant, self healing PE systems
11 Improve predictability of performance and reliability through modelling, simulation, testing and analysis techniques and facilities	• Predictive modelling tools with <5% margin of error • EMI testing for high power wide band gap materials • Improved physics-based reliability models for PE (e.g. SiC and GaN devices) • Improved modelling of specific phenomena (e.g. better EMI modelling, improved thermo-mechanical modelling) • Use of NDE to characterise PE degradation • Accelerated test methods • Open-access powertrain-level HiL evaluation facility for PE & integrated drives • Life-time estimation through modelling during the design phase	• Multi-domain virtual prototyping environment (electrical, thermal, mechanical, reliability) • Accelerated test methods for advanced packaging • Design for sustainability • Cloud based system level multi-physics models to enable faster collaboration across industry (and between organisations not co-located)	• Holistic, through-life predictive design tools with <1% margin of error • Tools for multi-domain, multi-time-scale rapid design optimisation
12 Mobilising a UK supply chain that can demonstrate cost competitiveness and higher productivity	**Leveraging advanced manufacturing techniques and establishing rapid prototype facilities are both key in mobilising a UK supply chain**		
	• Open-access prototyping and scale-up facility for PE manufacturing • Open-access powertrain-level HiL evaluation facility for PE • Open-access reliability test and characterisation facility for PE • High-density 3D circuit-board technologies • Scaling PE manufacturing to high volumes • Automation of manufacturing processes for low-cost & high-volume • Leveraging capability and previous learning from adjacent industries (i.e. aerospace, military, rail) to improve automotive power electronics • Establishing recycling technologies to sense, sort, separate and reprocess small sub-components with uniform design	• Open-access prototyping and scale-up facility for embedded 3D PE on common manufacturing platform • Extended evaluation and validation facilities for 3D PE manufacturing • 3D integrated manufacturing technologies for PE converters to 100kW+ • Manufacturing of embedded component technologies and Converter-in-Package • Open-access facilities that can test power electronics to 250kW and above • Fully recyclable power electronics taking into consideration new materials	• Open-access prototyping and scale-up facility for integrated drives on common manufacturing platform • Transition to low-cost 3D automated manufacturing • Additive layer and printed 3D manufacturing of PE • Flexible, automated manufacturing facilities (informed by models) that auto-optimise power electronics designs based on requirements • Establish and scale up processes that can disassemble and recycle integrated drives (power electronics and electrical machines)


Ford EcoBoost

10

TECHNOLOGY ROADMAPS

THERMAL PROPULSION SYSTEMS

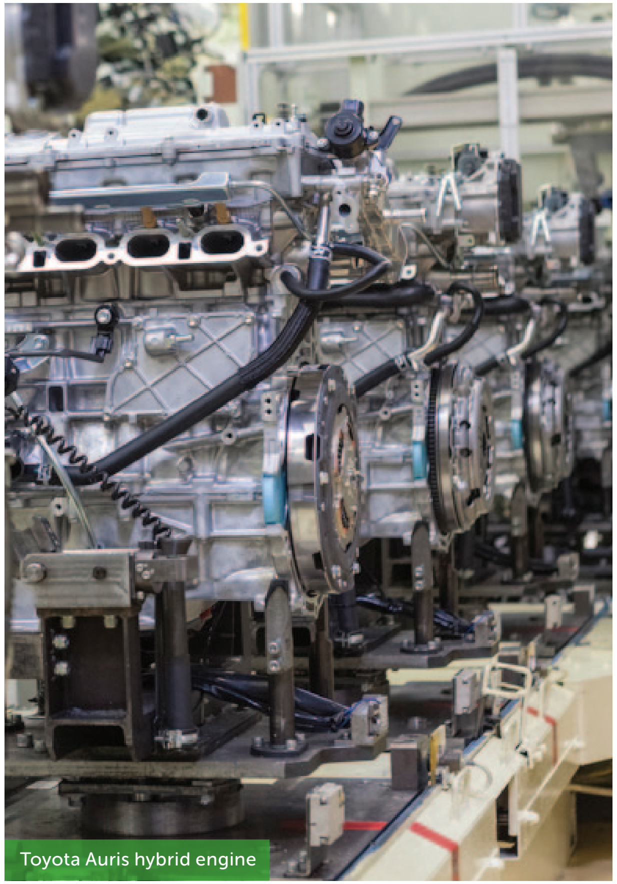
OVERVIEW

Despite the high expectations for electrification, thermal propulsion systems (TPS) will continue to have a significant role to play to 2035 and beyond, especially in heavy duty vehicles. It is recognised that this requires further improvements in real world efficiency and emissions in order to stay relevant.

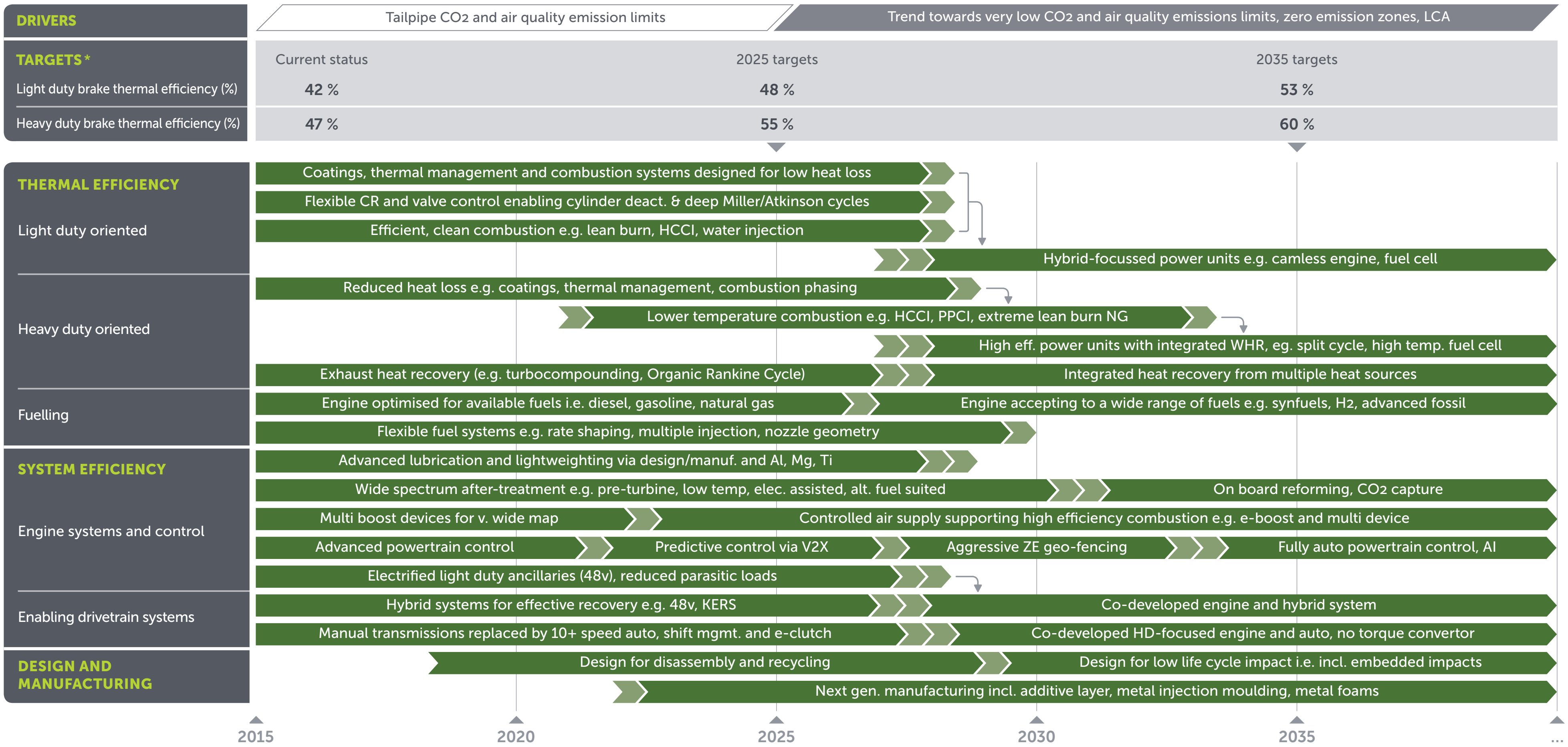
Improved system efficiency means doing the basics better despite it becoming harder; this includes reducing friction, minimising weight through improved system design and utilising novel materials and production processes. It is assumed that these measures will be implemented in parallel with the other changes identified in the roadmap.

In the short to medium term, light duty vehicles are expected to focus on combining the best elements of the TPS with electrification to cost-effectively improve system efficiency. The roadmap reflects this, indicating that the evolving duty cycle of the TPS may lead to a reduced operating window, which will allow further simplification and efficiency gains. Therefore it is expected that the engine will be progressively simplified while becoming more sophisticated in its design and more closely integrated within the propulsion system. This will range from 48V mild hybridisation where the TPS remains the heart of the overall system to a fully serial hybrid where the TPS provides power to an energy storage device via a generator.

Electrification of heavy duty propulsion systems will likely be limited to short distance vehicles with pre-determined journeys. The roadmap therefore suggests significant focus on thermal efficiency improvements to the base engine, supported by improvements in the complete system, including the electrification of some functions. It is envisaged that sustainable, low-carbon fuels will be required to further reduce the CO_2 emissions of these vehicles. This is expected to be driven by an increased use of lifecycle emission approaches sometime after 2030.


Toyota Auris hybrid engine

THERMAL PROPULSION SYSTEMS



Driver set | Driver predicted | *Solid bar represents >1% global marked adoption and is preceded by significant product and process R&D* | ***1 chevron** = some uncertainty around timing of mass market adoption or phase out* ***2 chevrons** = considerable uncertainty around timing of mass market adoption or phase out*

10.1 TARGETS

Despite the significant real-world improvements made by TPSs in both CO_2 and pollutant emissions over the last 20 years, public confidence has been severely damaged by news stories about the growing gap between certified test results and real world emissions. This has led to a reaction from policy makers at local, national and international level leading to divergence in requirements. Real World Driving Emissions (RDE) testing procedures will be at the heart of any new legislation. Heavy duty vehicles in particular have shown that meeting stringent limits under RDE are achievable. The aggressive TPS targets in the roadmap for both efficiency and tailpipe emissions reflect the need to do more to improve pollutant and CO_2 emissions from both light and heavy duty vehicles.

The efficiency values quoted in each case represent a mid-point between diesel and gasoline efficiencies. Peak values are shown but the roadmap recognises the increasing importance of achieving high efficiencies across the reduced operating ranges in which the TPS will function as part of a hybrid powertrain that is designed as a single, highly integrated hybrid solution.

	2017	2025	2035
Light Duty			
Engine System Brake Thermal Efficiency (%)[1,2]	42	48	53
Tailpipe NOx & Particulates (Mass & Number)	In line with legislated limits	Zero impact in emissions controlled zones[3]	
Heavy Duty			
Engine System Brake Thermal Efficiency (%)[1,2]	47	55	60
Tailpipe NOx & Particulates (Mass & Number)	In line with legislated limits	Zero impact in emissions controlled zones[3]	

1. Peak efficiency values shown. Increasingly important to achieve high efficiency across a wider operating range, in keeping with testing cycles based on real world performance
2. Values reflect mid point between diesel and gasoline efficiency (current difference ~5%)
3. Below measureable limits or below ambient (background) levels

10.2 THERMAL EFFICIENCY

PREDICTION: Light duty TPSs are expected to increasingly form part of the wider propulsion system, allowing substantial changes in combustion strategy

Efficiency improvements for light duty vehicles are expected to come from increasingly integrating the TPS into the wider propulsion system and leveraging the synergies between the TPS and the e-machine. This permits further optimisation of the engine through novel cycles, improved combustion regimes and improved thermal management. Downsizing the TPS had been a popular approach over the past couple of years, but it was observed by a number of OEMs that ‘rightsizing’ the TPS presents a strong alternative to ensure improvements are delivered under real world driving conditions.

In the short to medium term, novel valve control is a key enabling technology for improving thermodynamic cycles, offering higher thermal efficiency and fuel-saving strategies. One route being explored by companies is cylinder de-activation. Ford’s approach has been to implement cylinder deactivation in their downsized three cylinder engine whereas Delphi Technology’s system, developed in partnership with Tula, adopts a ‘skip fire’ cylinder deactivation control strategy that determines which cylinders to fire on each cycle.

Other combustion strategies enabled through more flexible valve control include: variable compression ratio systems (now being used by Nissan), and advanced Miller/Atkinson cycles, exploited by Toyota in the Prius and now being advanced by other OEMs. Nissan’s variable compression ratio system, launched in 2017 for their Infiniti brand, adjusts its compression ratio via a multi-link system. The link system continuously raises or lowers the pistons’ reach to adjust compression ratio – offering both power and efficiency.

As electrification provides the greatest opportunities for improvement, including zero tailpipe emissions capability, it is expected that in the longer term the TPS will increasingly be designed with this function in mind, leading to simpler, more cost-effective architectures but with more sophisticated combustion systems and controls. The Toyota Prius and BMW i3 (ReX) demonstrate this trend in an early form while Mazda has announced that it will bring its HCCI engine to market in 2019.

PREDICTION: Further thermal efficiency improvements are expected for heavy duty TPSs, initially through highly efficient low temperature combustion processes and heat recovery then, potentially, novel combustion cycles

It is expected that efficiency improvements will be largely incremental, focusing initially on exhaust heat recovery and improved combustion systems, as indicated by improvements demonstrated on the US Supertruck programme. In order to meet the aggressive targets set in this roadmap, more significant changes to the combustion systems will be required. These are likely to include a low temperature combustion regime, such as HCCI, PPCI or very lean burn, which combines high efficiency with low levels of engine-out pollutants. These systems currently operate well in controlled conditions; the challenge is to ensure satisfactory operation under wide ranging real-world conditions.

Longer term the roadmap recognises that fuel cells - both Solid Oxide Fuel Cells (SOFC) and Polymer Electrolyte Membrane Fuel Cells (PEMFC) - are the ultimate in low temperature oxidation that could lead to further efficiency and emission improvements. Novel power units could also be commercialised to reach the 2035 target but are currently in the early stages of research. Examples cited in the public workshop were split cycle concepts, integrating the heat recovery function within the thermal propulsion system and linear piston generators.

10.3 SYSTEM EFFICIENCY

PREDICTION: The development of sustainable fuels could take two directions, fuels tailored for specific TPS designs or fuels that work in numerous TPS designs

In the short term, it's recognised that reducing the carbon intensity of conventional fuels whilst retaining current fuel quality standards would deliver a substantial reduction in CO_2 emissions. This remains an attractive strategy and has now been adopted as a primary objective for the fuels industry in Europe.

Long term, in order to achieve deeper reductions in the carbon footprint of heavy duty vehicles, traditional diesel fuel is likely to be displaced by lower carbon fuels. Two pathways were identified for how the TPS could evolve alongside next generation fuels. The first route is to develop a TPS that is tolerant to a wide variety of fuels. The second pathway identified, which is the approach used today with diesel is to optimise the TPS for one fuel type.

Various alternative fuels are in different stages of development and commercialisation; LNG/CNG/LPG seem attractive short term alternatives assuming methane slip across the life cycle can be significantly reduced and enhanced combustion techniques, such as HPDI, can be commercialised. In the longer term, increasing competition for fuel resources could drive the development of novel TPS approaches that are tolerant to a wider range of fuels while maintaining high levels of efficiency.

PREDICTION: Further integration will be required to improve whole-system efficiency across the wide-ranging operating conditions

Further reductions in pollutant emissions during real-world use, even on a very efficient low temperature TPS, will require significant further development of after treatment systems. This is expected to lead to a combination of devices in the exhaust system that provide cover across a wide spectrum of operating conditions. These might have to be supplemented by further systems for vehicles operated outside even this wide spectrum, such as when using particular alternative fuels or for extensive operation at low ambient temperatures.

In the longer term, on-board reforming and CO_2 capture could be feasible for very heavy duty applications; light duty systems are expected to follow the opposite trend with aftertreatment systems only having to work with a TPS operating within a restricted band, due to increased levels of electrification.

A similar divergence between light and heavy duty is likely for air supply systems. Initially wider operating envelopes are likely to be required, especially for light duty thermal propulsions systems, requiring multiple devices and electrically driven boosters. Increasing the level of electrification will present both opportunities and challenges. Multiple boosting systems, linked to 48V architectures, could enable greater energy recovery capability in both light and heavy duty system. However for light duty applications, the TPS will potentially require more precisely controlled air delivery across a smaller operating window, relying on better control of the energy available within the system.

In the short term, the powertrain control unit will assume additional responsibilities, allowing it to deliver the high levels of control integration that ensure maximum efficiency of the complete system. In the longer term, additional data from outside the vehicle will enable further efficiency improvements, ranging from actively taking account of road and traffic situations to being fully integrated into an automated transport system.

Significant system efficiency improvements can also be achieved through the electrification of ancillaries. This route is recognised as a cost-effective way to reduce CO_2 emissions, especially in light duty vehicles, where 48V is expected to be the new standard for mild hybridisation. Beyond 2025 it is uncertain which development path non plug in hybrids will take. While some believe higher-voltage 'full' hybrids will displace 48V hybridisation in the mid-term, others have plotted a roadmap that shows growing complexity and integration of 48V system architectures. Initially, this path shows the integration of a single e-machine into the engine or transmission, followed by the application of multiple or higher powered e-machines, for example to provide energy capture and torque control for each wheel.

PREDICTION: Electrification and transmissions are the key enabling technologies to further improve thermal propulsion systems

Brake energy recovery offers significantly improved vehicle efficiency. Although the energy can be recovered by a number of means, partial electrification of the propulsion system is thought to be the most attractive for light duty vehicles because it also provides zero tailpipe emissions capability. For heavy duty vehicles, electric, hydraulic, mechanical and pneumatic energy recovery systems have been explored due to the diverse range of applications and ease of which they can be integrated.

Improved transmissions and increasing levels of electrification will allow the TPS to be optimised for further efficiency improvements, with automatic transmissions expected to become dominant and to work with the TPS to optimise the operating requirement.

10.4 DESIGN AND MANUFACTURING

PREDICTION: Enhanced modelling and simulation tools, coupled with advanced manufacturing techniques, will reduce the required number of manufacturing steps for a TPS and reduce complexity

End-of-life recycling requirements for vehicles are expected to become increasingly demanding, leading to improved designs in terms of disassembly and part count. In the longer term, emissions assessment based on life cycle impact is expected to drive further design and manufacturing improvements, including novel manufacturing processes such as additive layer, metal injection and metal foam technologies, enabling the use of innovative design techniques.

Whilst not explicitly pulled out in the roadmap, enhanced modelling and simulation tools are crucial to unlocking new TPS designs and manufacturing routes. Utilising real world performance data, leveraging virtual prototyping and testing as well as simulating manufacturing processes will enable more sophisticated, lightweight products. This will accelerate new products time to market and enable manufacturers to reduce CO_2 and emissions earlier.

Utilising real world performance data, leveraging virtual prototyping and testing as well as simulating manufacturing processes will enable more sophisticated, lightweight products

10.5 RESEARCH AND DEVELOPMENT CHALLENGES FOR THE SHORT, MEDIUM AND LONG TERM

Dr Robert Morgan
Reader University of Brighton

APC TPS Thermal Efficiency Spoke

Professor Chris Brace
Professor of Automotive Propulsion

APC TPS System Efficiency Spoke

ADVANCED PROPULSION CENTRE UK
TPS THERMAL EFFICIENCY SPOKE

ADVANCED PROPULSION CENTRE UK
TPS SYSTEM EFFICIENCY SPOKE

Thermal propulsion systems will continue to be essential for our future transport systems. The exceptionally high energy density of liquid hydrocarbons offer unparalleled utility and versatility that's critical for many applications and geographical areas. It is important that as we move to a more sustainable future we continue to improve the efficiency and cleanliness of thermal propulsion systems as these will constitute a significant part of the installed capacity for many decades to come.

The research and development challenges, identified by the Thermal and System Efficiency Spoke communities, illustrate the greatest challenges facing thermal propulsion systems. In the short term, opportunities centre on optimising existing approaches to combustion systems, after treatment systems, control strategy and boosting, to name a few. Longer term, the table articulates the challenges in achieving achieve clean, ultra-low carbon combustion systems in tandem with sustainable fuels. This offers consumers the prospect of a cost-effective, high utility propulsion future that combines the best aspects of thermal propulsion and electrified systems.

> *It is important that as we move to a more sustainable future we continue to improve the efficiency and cleanliness of thermal propulsion systems as these will constitute a significant part of the installed capacity for many decades to come*

Identification of key research and pre-competitive development challenges to facilitate academic / industrial collaboration on longer term product and manufacturing research and development. As identified in the roadmap, research priorities will differ depending on whether an application is for lighter or heavier duty cycles.

<table>
<tr><th>Research Challenge</th><th>SHORT TERM (5-7 years to mass market)</th><th>MEDIUM TERM (7-15 years to mass market)</th><th>LONG TERM (10-20 years to mass market)</th></tr>
<tr><td rowspan="2">1
Reduced air quality impact</td><td colspan="3">The implications of improving air quality both in cylinder and post-combustion need to be considered together and not taken in isolation</td></tr>
<tr><td>In-cylinder approaches
• Novel ignition systems for dilute operation
• Multiple/split injection strategies to overcome the NOx/soot trade-off (inc. including understanding problems such as cavitation associated with new injection methods)
• Fast cycle – cycle control of homogenous compression ignition
• On board water recovery for water injection
• Dilute homogenous combustion (both CI and SI)

After treatment approaches
• Develop more efficient approaches for reducing NOx, and oxidizing PM, HC, and CO in low temperature exhaust (150°C).
• Portable emissions measurement systems (PEMS) for future requirements (e.g. particulate numbers, future EU-7 and gaseous vehicles)
• Improved DPF and GPF efficiency for smaller particles (below >23nm)
• Low temperature (below 350°C) oxidation catalysts for CH4</td><td colspan="2">Technologies that achieve zero emission impact thermal propulsion systems
• Zero emission combustion systems / architectures compatible with carbon neutral fuels (e.g. nitrogen scrubbing, full cycle HCCI, catalytic combustion)
• Radical near 100% efficient after treatment systems that convert over the whole operating cycle
• Low cost, mass manufacturable and recyclable fuel cells (both high and low temperature)
• Cost effective technology for on vehicle hydrogen storage</td></tr>
</table>

Research Challenge	**SHORT TERM** (5-7 years to mass market)	**MEDIUM TERM** (7-15 years to mass market)	**LONG TERM** (10-20 years to mass market)
2 Improved thermal propulsion system efficiency and real world fuel consumption/GHG reduction	**Challenges in improving real world fuel consumption / reducing GHG emissions occur during combustion and systems that operate around the TPS**		
	Optimising current combustion cycles • Improving conventional combustion cycles (i.e. through better valve control, deeper Miller/Atkinson cycles, altering combustion cycles depending on load) to improve thermal efficiency • Cascading technologies and principles from lighter duty (i.e. cylinder deactivation and downsizing) into heavier duty cycles **Improving existing techniques for thermal management and friction loss** • Cost effective surface treatments for friction and heat loss (e.g. thermal barrier coatings and new lubricant formulas) • Lower cost WHR systems and components (i.e. turbo-compound, thermoelectric, thermo-acoustic) **Optimising current air handling strategies** • Improved turbocharger efficiency over wide map, including down speeding (e.g. better twin scroll, e-boost)	**Advanced combustion strategies to achieve higher engine efficiencies** • Advanced efficient combustion systems such as ultra lean and SACI • Geometric variable compression ratio concepts **New concepts for thermal management and friction loss** • Novel thermal barrier coatings (e.g. temperature swing) • Fast warm up systems (e.g. on board thermal storage, low thermal inertia systems) • WHR combining high grade and low grade heat, including direct powertrain cooling • High efficiency expander that can operate over a wide turn-down ratio • Novel fluids for high efficiency WHR **Advanced air handling strategies integrated with other systems** • Integrated WHR (thermoelectric) and electric turbocharger (e-boost, e-turbine) and integration (e.g. water recovery) **Fuel injection systems** • High flexibility FIE (including injection rate and nozzle geometry	**Technologies that achieve carbon neutral thermal propulsion systems** • Thermodynamic cycles with integrated waste heat recovery (e.g. split cycles, on board fuel reformation) • Multi fuel combustion systems that deliver ultra-low life cycle CO_2 • On board CO_2 capture (pre and post combustion) • Low cost, mass manufacture fuel cells (high and low temperature) with advanced WHR systems

Research Challenge	SHORT TERM (5-7 years to mass market)	MEDIUM TERM (7-15 years to mass market)	LONG TERM (10-20 years to mass market)
3 Reducing the cost and complexity / attribute trade-off of electrified thermal propulsion systems	• Modifying current engine architectures and platforms to operate as part of a hybrid system	• New, flexible and modular thermal propulsion system for hybrid applications applicable across vehicle platforms	• New architectures for low cost and complexity PHEV / REEV thermal propulsion systems
4 Improved powertrain control and operation using approaches such as machine learning or connected data	• Utilising connected vehicle data for improved powertrain control • Advanced model based control with reduced reliance on base maps • Improved sensor technologies (e.g. better accuracy, more parameters, lower cost)	• Design systems for cyber security • Prognostics – improved software capability to better sustain health of engine and powertrain • E-horizon enabled powertrain control considering V2V interactions, geo-fencing and optimising vehicle level energy management. • Application of machine learning to powertrain control, calibration, validation and OBD	• AI led, adaptive and collaborative control schemes, fully connected with city infrastructure • Low power consumption control, sensing and processing • Human-like autonomous control focussed on customer experience
5 Decarbonising thermal propulsion systems via co-developed engines and de-carbonised fuels	**Two possible research pathways: TPS fully optimised with fuels or TPS that is flexible and accepts a wide range of alternative fuels**		
	• Higher efficiency engines for lower GHG-intensity fuels (i.e. bi and duel fuel concepts, lean burn DI CNG/LNG combustion systems with negligible methane slip) • Novel concepts to extend the utility of low grade or renewable fuels and/or reduce the need for high grade fuels • Global energy system analysis tools to inform fuel pathway choices and engine development	• Mass production of fuels tailored for clean, efficient TPS e.g. on vehicle fuel reforming, lean homogenous combustion, high temperature fuel cells • TPS tolerant to wider fuel specification (higher bio content, fuels from recycled waste) • Drop-in low carbon fuels to decarbonise existing fuel content • Mass production of paraffinic fuels (e.g. Fischer–Tropsch, HVO) • On board fuel conversion from a low cost liquid source	• Alternative thermodynamic cycles for ultra high efficiency (inc. fuel cells) using sustainable, low cost drop in 'sun-to-liquid' fuels and /or tailored bio-fuels • Co-developed engines and tailored 'sun-to-liquid' fuels for near zero emissions • Sustainable fuel production processes from recycled waste with zero emissions TPS tolerant to variable fuel specifications • Offering electrical network system resilience via TPS in V2G mode

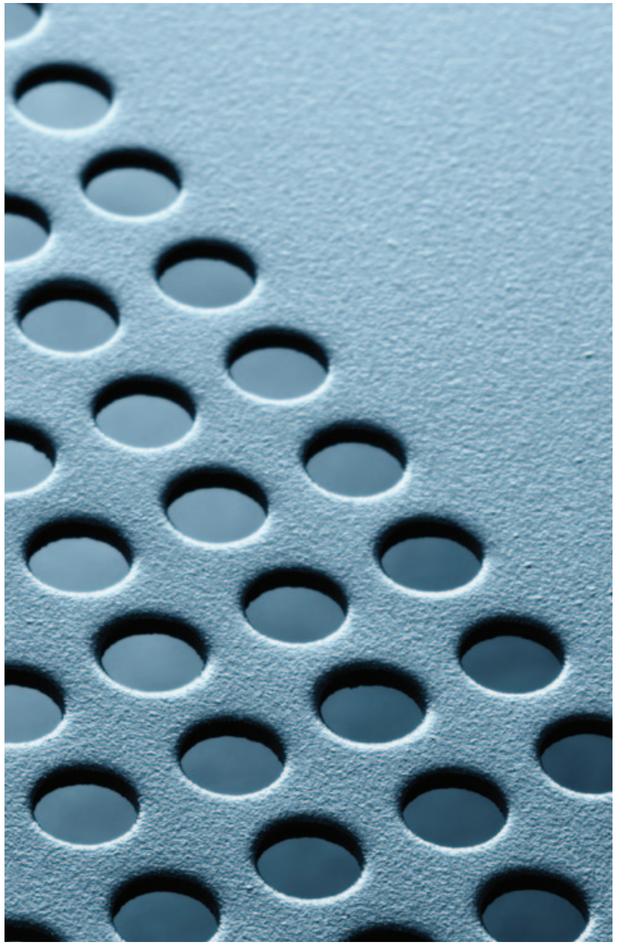
Research Challenge	SHORT TERM (5-7 years to mass market)	MEDIUM TERM (7-15 years to mass market)	LONG TERM (10-20 years to mass market)
6 Manufacturing and materials for improved attributes, recyclability or life cycle impact	• Engines designed for serviceability and manufacture • In-engine lightweight technology with mid and end of life in mind • Additive manufacturing for niche applications • Low cost thermoelectric materials • Develop deeper LCA insights into powertrain materials, their manufacture and end of life	• Cost effective next generation surface treatments such as temperature swing coatings or ceramics for exhaust • Mass production additive manufacturing techniques and associated evolution in component design • Greater use of bio materials and recycled materials in TPS components	• Chemical heat storage materials • Lubricant free materials • Low cost, volume production using additive layer manufacturing (i.e. fully printed powertrains) • Fully automated manufacturing tools that auto optimise and self regulate • Low LCA and environmental impact of TPS materials and manufacturing processes
7 Minimising time to market, efficiency of development and product attributes via improved methods and toolchains	• Virtual calibration based on improved representation of physics in engine models • Use of big data for harnessing in-service data to inform engine design, control and OBD • Models that can effectively simulate engine combustion and in-cylinder emission formation processes through to the performance degradation of after treatment systems for existing and new combustion cycles	• Multi-physics system level modelling to understand powertrain level trade-offs and optimise powertrain architectures • Predictive simulation tools for industry to design advanced thermal propulsion systems • 70% virtual testing and verification for thermal propulsion systems	• AI led deign and optimisation techniques • 95% virtual testing and verification for thermal propulsion systems

Williams Advanced Engineering EV chassis

11

TECHNOLOGY ROADMAPS

LIGHTWEIGHT VEHICLE AND POWERTRAIN STRUCTURES



OVERVIEW

Historically, vehicle weight has increased through the addition of more content such as passive and active safety features and more sophisticated comfort and convenience features. Efforts to offset these increases have ensured vehicle weight has remained stable across most classes whilst still improving performance and fuel economy.

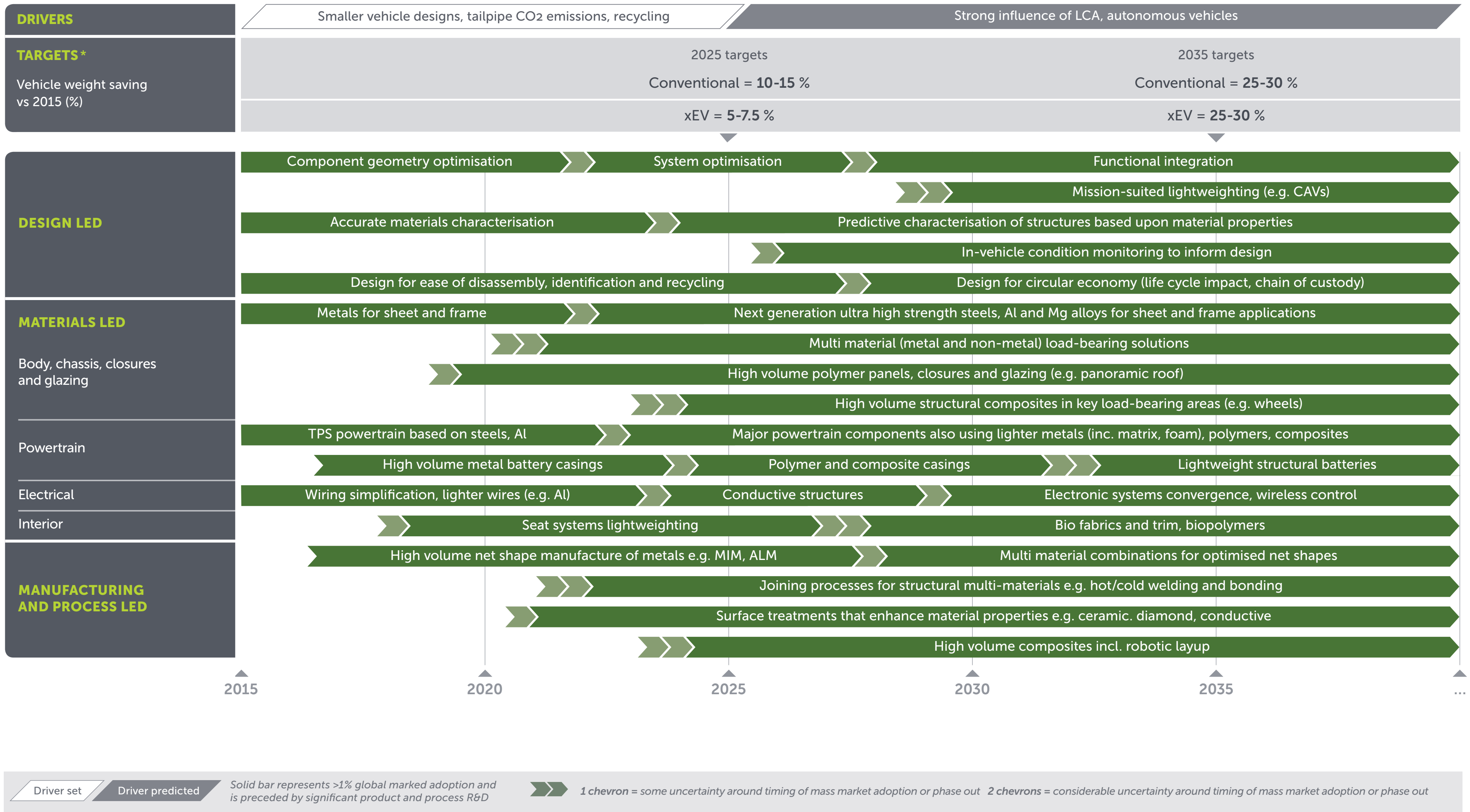
The increasing influence of tailpipe emission regulation combined with the increased sales of electrified vehicles has sharpened the industry's focus on reducing vehicle weight. For conventional vehicles the reduced energy requirement for propulsion results in lower CO_2 emissions as well as improved performance and fuel economy. For electrified vehicles the challenges of reducing vehicle weight are more pronounced due to the heavy battery pack but reductions in weight can contribute to an extended range. In both conventional and electrified powertrains, weight reduction can also create a virtuous circle, whereby the weight saved in one area permits further savings in other areas, such as the brakes or suspension in conventional vehicles, or the battery in electric vehicles.

The roadmap identifies developments in design, materials and manufacturing as being the key routes to lower weight. High volume vehicles are predicted to take a different development path to premium vehicles produced in lower volumes, where different approaches to materials specification and manufacturing processes can be employed.

Individual short term weight reduction targets have been provided for conventional vehicles and for xEVs, as the weight of the battery pack makes weight reduction harder for the latter in the short term. In the longer term, improvements in electrified powertrain technologies will enable weight reductions but the effect of CAVs in conjunction with a change in ownership models is predicted to radically alter vehicle duty cycles, eliminating the extremes of manual operation and enabling lighter designs.

All developments in lightweight technology will be subject to increasing sustainability constraints, requiring due consideration of cost effective end-of-life recyclability before implementation.

LIGHTWEIGHT VEHICLE AND POWERTRAIN STRUCTURES



11.1 TARGETS

In order to meet future CO2 targets, incremental reductions in weight are not sufficient, so ambitious long term targets have been set to drive innovation. The short term targets recognise that electrification poses additional challenges for vehicle weight; for PHEVs and BEVs especially, the larger batteries and electrified propulsion components make these vehicles heavier than conventional vehicles. It is assumed that no adverse effect on vehicle cost, safety or emissions will be accepted as a consequence of weight saving.

	2015	2025	2035
Passenger Car			
Conventional vehicle weight decrease (%)[1]	Baseline	10 -> 15%[2]	25 -> 30%[2]
xEV vehicle weight decrease[3]	Baseline	5 -> 7.5%	25 -> 30%
Recyclability of material (%)	85%	85%[4]	95%

1. Some components will be untouched during this period, so those which are redesigned must have a higher % saving than the vehicle % saving required
2. Future vehicle weight reductions will need to counter weight gains from e.g. ADAS, infotainment, NVH, safety systems, refinement solutions (weight gain estimated to be around 5% in 2025 and up to 10% by 2035)
3. The target for 2025 is lower than conventional ICE because larger batteries will increase the weight of next generation xEVs. However the improved energy density of batteries, as well lighter motor and power electronics solutions, are keeping weight increases as small as possible.
4. Number remains the same to reflect the inclusion of battery packs in end of life regulations

11.2 DESIGN-LED WEIGHT SAVING

PREDICTION: Improved simulation and design tools will enable greater optimisation of components and, in the longer term, could enable functional integration of key components

Increasingly accurate material datasets that inform design and simulation tools will enable component weight reduction through geometry optimisation.

In the short term, creating open access material databases that provide an accurate understanding of real life performance characteristics could enable designers to utilise existing modelling tools to reduce material usage and choose more suitable materials, or combinations of materials, to optimise component design. Examples of this approach include hollow structures and the use of multi-materials with the stronger material deployed only where most needed.

As modelling tools evolve and encompass more elements of analysis (potentially including whole-life aspects such as second life usage), functional integration to reduce system level complexity was identified as an attractive option for further weight reduction. An example of this approach can be seen in Renault’s DTI 5 engine which achieved a 25% weight reduction using a novel metal additive manufacturing processes. The prototype engine Renault demonstrated a reduced part count compared to existing models and eliminated a number of manufacturing processes, all enabled by 3D modelling.

PREDICTION: Vehicles will become increasingly tailored for specific applications as CAVs become more widespread, leading to different designs depending on use case and driving environment

The majority of vehicles are designed for personal ownership so must satisfy a number of different requirements such as large luggage capacity, five or more occupants, and the corresponding crash and safety regulations that all add significant weight. Designing vehicles specifically for certain applications, such as smaller vehicles for urban environments, would dramatically reduce vehicle weight through more appropriate design.

Vehicles such as Daimler's Smart car range, Renault's Twizy and the many Japanese Kei cars are already designed along such lines, however the impact of CAVs combined with shifting mobility business models could spur on the development of smaller, lighter concepts such as autonomous pods. An initial design benefit of CAVs will be the elimination of over-engineered components that are usually designed to cope with user-induced peak loads and performance demands. This will enable smaller and lighter components that do not need to accommodate a wide variety of performance extremes. Understanding what will incentivise consumers to adopt personalised mobility services will further drive demand for these services and encourage the production of these vehicles.

In the long term, as vehicle ownership declines in favour of using autonomous and shared services, and primary safety can be improved by geo-fenced environments for CAVs, the level of crash protection needed could be reduced, enabling the use of new designs and innovative material choices. However the impact of CAVs on weight reduction could be diminished by additional sensors, actuators and computer processors, especially if duplication occurs due to safety requirements.

Nevertheless the automotive industry is already investigating these possibilities, with UK company Westfield trialling autonomous pods in Greenwich and Toyota announcing their 'e-palette' concept at the CES 2018 event. For CAVs, it is expected there will be a trade-off between the level of weight reduction possible and the increasing weight of systems required for enhanced CAV operation and on-vehicle entertainment systems.

PREDICTION: Increasing data collection from vehicles will enable live condition monitoring and enable designers to optimise vehicles based on real-world data

In-situ data gathering using embedded sensors is essential for informing next-generation vehicle designs and managing the health of existing fleets. Immediate applications for this technology are most appropriate in vehicles that experience very high utilisation such as buses, trucks and delivery vans. For such applications, in-service reliability and longevity is crucial to maximising commercial return, so actively managing vehicle health and using the data to schedule preventive maintenance could prevent failures, reduce vehicle downtime and improve traffic flows to avoid congestion. High performance passenger cars could utilise this technology by leveraging advanced data analytics used in the motorsport sector to inform next generation vehicle design. For example, since 2012 Mercedes AMG has been leveraging advanced data analytics to improve TPS design, reduce validation times and improve manufacturing efficiency. It's envisaged that this approach could extend beyond TPS analytics and encompass the whole vehicle.

In the longer term, growing volumes of real-life data can be used to inform modelling tools, helping to optimise designs and improve vehicle efficiency. As embedded sensors are increasingly adopted in commercial vehicles, the technology is likely to migrate into passenger cars as the ownership model changes towards shared and autonomous vehicles with higher utilisation.

As embedded sensors are increasingly adopted in commercial vehicles, the technology is likely to migrate into passenger cars as the ownership model changes towards shared and autonomous vehicles with higher utilisation

PREDICTION: Though many vehicles are already designed for disassembly and recycling, as powertrains evolve vehicles need to be designed for a circular economy that captures and reuses valuable materials

Legislation for passenger cars already includes end-of-life requirements, such as the EU End-of-Life Directive which defines how recyclable they should be and the recovery rate of materials by mass. However, as the emphasis shifts towards total life cycle analysis, the embedded impacts of a vehicle's materials and manufacturing processes will become increasingly important, profoundly affecting the types of materials and processes used by the automotive industry.

Weight-saving materials that bring benefits during a vehicle's use will be less attractive if they produce detrimental environmental impacts during their production or recycling phase, for example multi-materials may deliver impressive vehicle weight savings but create significant challenges for recycling. Separating dissimilar materials during recycling has been identified as a significant challenge as the processes which currently exist can damage the materials, making them less desirable for reuse.

> *As the emphasis shifts towards total life cycle analysis, the embedded impacts of a vehicle's materials and manufacturing processes will become increasingly important, profoundly affecting the types of materials and processes used by the automotive industry*

11.3 MATERIALS-LED WEIGHT SAVING

PREDICTION: Advanced steels will dominate in key load-bearing and body structures for high and medium volumes, but alternative metals and polymers could be used in structures that are less integral to vehicle safety and in lower volume or niche applications

In the short to medium term, high strength steel is seen as the lowest risk option for high volume applications involving important load bearing structures. Divergence from steel is seen largely in low and medium volume applications or on selected models with sufficiently high margins to absorb the added material costs. Ford and Jaguar Land Rover in particular use aluminium body structures, with Ford's largest selling product, the F-150, transitioning from steel to aluminium bodies in 2014 and Jaguar Land Rover's Castle Bromwich plant exclusively producing cars with aluminium body structures.

Audi and BMW have opted for a multi-material approach; the new Audi A8 uses four different materials (steel, aluminium, magnesium and carbon fibre reinforced polymers) for its weight-bearing body structure and the BMW i3 uses carbon fibre body panels joined to an aluminium frame.

In some heavy duty applications, such as buses, carbon fibre and aluminium are more commonplace; Proterra use carbon fibre body panels in their Catalyst buses and Wrightbus used composites in the body structure to help minimise the weight of their hybrid buses.

The automotive sector's interest in alternative materials for integral crash structures has triggered the steel industry to develop more innovative products to protect its market share. Advanced ultra-high strength steels that are not only lighter but have improved mechanical properties are being continuously developed by the steel industry to meet future weight reduction requirements. The aluminium industry is also investing in new grades and especially in improved manufacturing techniques that extend the range of applications while also reducing costs. Ensuring a closed-loop material value chain, to reduce the reliance on expensive and energy-intensive virgin aluminium, is crucial before such material can be applied in higher volumes.

Low-cost thermoplastics are promising for areas such as panoramic roofs, bumpers and selected closures but carbon composites would need a dramatic improvement in manufacturing processes, reducing the takt time to seconds rather than minutes, to suit high volume applications (see section 11.4).

PREDICTION: TPS-based powertrains will continue to be constructed largely from metals but the use of alternative materials is becoming more widespread

For TPS-based powertrains, metals will continue to dominate due to the high temperatures experienced and the pre-existing high volume manufacturing capability. To reduce weight in the short to medium term, more exotic materials for the TPS such as foams, titanium springs, magnesium alloy castings and metal matrix composites could be used. Driveline components offer good potential for weight reduction, for example thermoplastic differential and e-machine casings and carbon fibre reinforced polymer prop shafts are actively being researched and developed.

As the powertrain becomes increasingly electrified, opportunities will arise to use lighter materials, particularly for the battery pack which comprises a significant percentage of weight in PHEVs and BEVs. Most battery casings and internal support structures are metal, in part due to simplicity but also to provide some structural support and heat transfer. However, to reduce the weight of batteries, the roadmap identifies the potential to use polymers and composites casings, enabling OEMs to consolidate parts and integrate functions into fewer, lighter components. Longer term, the potential exists for batteries to be more thoroughly integrated into the vehicle, with the active chemistry embedded within the floor or body structure.

PREDICTION: As vehicle electrical systems increase in complexity, through infotainment systems, connected features and electrified powertrains, the weight of these systems must be reduced

The volume of electrical systems in vehicles is set to increase through electrified powertrains, infotainment systems, connected and autonomous features and safety equipment. Without substantial effort from OEMs to reduce the weight of wiring, terminals and connectors, these additional systems will contribute significant additional weight.

In the short term, copper wiring could be replaced with lighter alternatives such as aluminium (providing the oxidation challenge is overcome) or copper-clad aluminium. Rationalisation of key circuits and the integration of some components may reduce the number of wiring harnesses and control units in the vehicle. The next step is to commercialise conductive body structures through embedded strips, or data and power transfer in composite materials. In the longer term, it is envisaged that functional integration of electrical architectures and wireless control should be employed in order to radically reduce the complexity and weight of vehicle electrical systems.

The Automotive Council’s Electrical and Electronic Architectures roadmap also highlights the move from distributed to more centralised control, driven by the dramatic escalation in power and communication requirements for CAVs, as another key driver for electrical systems convergence.

> *The volume of electrical systems in vehicles is set to increase through electrified powertrains, infotainment systems, connected and autonomous features and safety equipment*

Interior of Nissan LEAF

PREDICTION: Vehicle interiors, predominately seats in the short term, show great potential for weight reduction

Seating systems are the largest weight contributor in a vehicle interior because of the growing number of comfort and safety features included, making lightweight seating systems an attractive short term path for interior weight reductions. A range of materials have been identified that could be utilised in seats, ranging from next generation ultra-high strength steels developed by Tata, to thermoplastic seats developed by Brose for Jaguar Land Rover. Opportunities exist for multi-material approaches to cut the weight of seats even further, with Adient using magnesium, glass and carbon fibre reinforced plastics as well as aluminium in their seating range.

In the long term, as life cycle analysis becomes a prominent driver, sustainable bio-fabrics and bio-materials for interior applications will become more relevant, not only for seating systems but for interior trim, with the potential for bio-polymers and bio-composites to be used in structural applications. For this to become feasible, improvement is required in the technical performance of bio-composites and more cost-effective methods of creating the organic materials are needed.

Seating systems are the largest weight contributor in a vehicle interior because of the growing number of comfort and safety features included, making lightweight seating systems an attractive short term path for interior weight reductions

11.4 MANUFACTURING AND PROCESS-LED WEIGHT SAVING

PREDICTION: Advanced forming technologies will be key in creating near net shapes with the possibility of manufacturing multi-material components in one process step

The roadmap process identified a number of potentially attractive forming techniques, particularly net shape forming which could, in the short term, improve existing metalworking processes by reducing the need for machining and enable the fast, low cost production of accurate parts. Examples of this approach include metal injection moulding, cold forming to enable plastics to undergo the same processes as metals, and additive layer manufacturing for some applications. In time it is envisaged that highly automated processes may enable multi-material net shape manufacturing to achieve maximum component performance with minimum cost and weight.

PREDICTION: Existing joining processes for similar materials will be adopted for dissimilar materials but new techniques will be required to improve joint quality and simplify end-of-life disassembly

Currently, the lack of suitable joining processes for dissimilar materials is one of the biggest barriers to reducing the weight of vehicle platforms. The immediate focus is on enhancing current mono-material processes that utilise existing manufacturing tooling. While various joining options exist for new materials, there is limited application knowledge or experience. This illustrates the need for more accurate material databases and creates issues in using more advanced lightweight materials as the joint is often thought of as the weak link in the whole vehicle structure. Therefore better understanding of joint technology will be pivotal in accelerating the uptake of lighter materials.

Processes for joining multi-materials that have been actively researched include: multi-point joining (e.g. remote laser welding, hot, cold and thermoplastic welding), bonding (e.g. quick cold cure resins), mechanical joining (e.g. self-piercing rivets, fasteners and friction bit joining). While these techniques can provide mechanically strong joints, further research into the disassembly of multi-materials is required, such as that conducted at Michigan University on disassembly techniques for plastic joints using reversible adhesives.

Advances in joining technology are becoming an enabler for new materials applications, with the highly focussed properties of some new materials requiring a combination of techniques. For example, very thin materials, specified for weight reduction, will require a higher joined surface area to spread the load, yet bonding may not provide the resistance to peel that this requires. A solution increasingly employed is to complement bonding with mechanical fastening.

PREDICTION: New surface treatments will be needed to enhance material properties

Surface treatment technologies are traditionally employed to enable materials to be formed or joined together, or to achieve a desired surface property. However, advances in materials science are producing a wide range of new materials and processes that, when applied to the surface of other materials, can improve the properties or enable dual functionality. Properties that can be modified include conductivity, thermal performance, hardness, friction and aesthetics.

PREDICTION: High levels of automation will be crucial in scaling up composite manufacture to higher volumes suitable for mainstream automotive applications

Carbon fibre reinforced polymers have been identified as materials that can be used to save weight across the vehicle structure, powertrain and interior. Early adopters of carbon fibre include McLaren Automotive, who used carbon fibre in their hybrid McLaren P1, and BMW who used body panels for the electric i3. However to encourage carbon fibre's adoption in other vehicle segments, a significant reduction in the manufacturing cycle time must occur so it aligns with high volume vehicle assembly processes. The roadmap explicitly highlights this as a critical barrier to the commercialisation of carbon fibre reinforced polymers, requiring manufacturing innovations such as robotic automated fibre placement to increase speed, accuracy, reduce waste and enable full automation of pressing and curing steps.

High volume application of carbon fibre reinforced polymers will also require improved end-of-life recovery and re-use of the costly carbon component. Recycling facilities have already been established in the UK, such as ELG Carbon Fibre's factory in the West Midlands, but these are currently processing low volumes of materials, predominately from aerospace, rail and low volume automotive applications.

> *High volume application of carbon fibre reinforced polymers will also require improved end-of-life recovery and re-use of the costly carbon component*


McLaren P1

ELG Carbon Fibre facility

11.5 RESEARCH AND DEVELOPMENT CHALLENGES FOR THE SHORT, MEDIUM AND LONG TERM

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Increasing vehicle weight, driven by additional safety features, enhancing passenger comfort and electrified powertrains, has stimulated intense research to reduce overall vehicle mass. From material designers exploring advanced steels, aluminium and more exotic hybrid materials, to reimagining vehicle designs to exploit autonomous capability, the suite of options today's engineers have at their disposal is broad. An immediate challenge is the initial adoption of modularised technology which will lead to deeper product integration, where interfaces are removed and supporting operational systems shared.

The eight research themes identified through a public workshop and an expert Steering Committee highlight the pressing need for research in better design tools, improved materials and more efficient manufacturing processes. However a consistent message throughout the update process was that improvements in these three areas strongly overlap and shouldn't be taken in isolation.

The short term challenges reflect the fact that optimising future components will increasingly utilise advanced design tools that will successfully leverage new material datasets and require complex multi physics simulation to determine optimum system solutions. This approach could lead designers to using new materials, or combinations thereof, to cost effectively reduce weight. Therefore material suppliers are not only required to continuously improve existing and new materials, but, to understand how materials will perform and interact within a multi-material or hybrid structure. Once this is understood, new manufacturing methods that reduce process steps, reduce wastage from forming and effectively join multi-material structures need to be established. More importantly, these manufacturing processes need to deliver on both automotive quality standards and takt times.

Longer term the challenges reflect the expected impact of CAVs and shared mobility on vehicle design, the growing influence of life cycle analysis on both material selection and manufacturing processes as well as higher levels of automation and cost effective additive layer manufacturing processes. These challenges should not be seen as an exhaustive list of all the exciting development in design, materials and manufacturing, but, indicate those areas that respondents expected to see considerable technical innovation.

Identification of key research and pre-competitive development challenges to help facilitate academic / industrial collaboration on longer term product and manufacturing research and development

Research Challenge	SHORT TERM (5-7 years to mass market)	MEDIUM TERM (7-15 years to mass market)	LONG TERM (10-20 years to mass market)
1 Enhancing modelling and design tools capability	• Open access datasets to inform models (i.e. standards, interoperability, reuse, openness) • Component level digital twins (i.e. chassis, body structures) to optimise subcomponents and reduce costs associated with real life testing • Better modelling and understanding of: distinct phenomena (i.e. NVH, thermal performance, crash properties); less familiar materials (i.e. composites, Mg, multi-materials/ hybrid materials) and; manufacturing processes (e.g. joining, forming) • Improving the processing speed of simulations (e.g. days to hours) • Low cost simulation technologies incorporating simple user interfaces and highly parallel simulation on high performance computer networks • Integration of augmented and virtual reality into design and development	• Vehicle level digital twins to model system interactions and improve overall vehicle design • Integrated multi-scalar modelling of crash, stiffness, electromagnetic characteristics • AI driven structural optimisation techniques • Highly optimised high performance computer network simulation codes to minimise development timeframes (e.g. hours to minutes)	• AI driven digital twin that incorporates: through life cost, detailed material datasets, simulated manufacturing processes, in vehicle use data and vehicle end of life/second life. • Advanced supercomputing capability to generate complex simulations rapidly (e.g. minutes to seconds)
2 Leveraging advanced digital and sensing technologies	• Embedding sensors into current vehicle structures to inform next generation vehicle design • Through process sensing to reduce scrap • Glass fibre sensors embedded in composite materials	• Wireless sensing systems to assess structural health of critical components • Embedded real time material property data and traceability (e.g. RFID) from pre-form to second life. • Prognosis and health management techniques	• Ultra low cost, low energy wireless sensors to address the increased monitoring required for CAVs and shared vehicles • Low energy wireless communication standards • Localised power systems to reduce complexity • Develop multifunctional materials with self-diagnostics using dielectric material properties (i.e., the material itself provides sensing)

Research Challenge	SHORT TERM (5-7 years to mass market)	MEDIUM TERM (7-15 years to mass market)	LONG TERM (10-20 years to mass market)
3 Improved surface treatments	• Low cost, innovative chromate free surface treatment of aluminium through environmental friendly reagents and processes • Lowering steel hardening and coating temperatures to enabling plastics to undergo electro-coating processes • Laser hardening and surface treatment • Improved traditional surface treatments such as carburising and nitriding • Low cost, environmentally friendly surface treatments to prevent Mg corrosion	• In process laser hardening and surface treatment to reduce manufacturing steps • Advancements in chemical etching processes • Surface treatment of materials to allow 'reversible' bonds making separation of multi-materials easier	• Coatings and surface finishing that allow multiple functionalities (e.g. tailored friction, self-cleaning, data transfer etc)
4 Improving the material characteristics of metals, polymers, hybrid and multifunctional materials	• Steels that can achieve a tensile strength of 2000MPa without compromising formability • Reduced cost improved formability and weldability AHSS with strength 1000 - 1500 MPa • Aluminium alloys that achieve a tensile strength of more than 500MPa without compromising formability and recyclability • Tailoring the material properties of metals/polymers to enable injection moulded components • Cost effective metal/composite fibre mixed weave materials for powertrain applications (i.e. for high temperature operations, components susceptible to wear etc.)	• Development of particulate and nano-materials to improve performance of existing materials • Increase of scandium alloy aluminium • Alternatives to problematic elements (Lead and Beryllium) for free machining metals • Aluminium alloys that achieve a tensile strength of more than 750MPa without compromising formability and recyclability • Higher Tg polymers at lower cost (e.g. for engine and drivetrain components) • Cost effective high stiffness, high strength, high elongation polymers (e.g wishbones + wheels) • Polycarbonate with hard surface (scratch resistant) for glazing • Multi-structural and multi-powder components	• Advanced grain structures of UHSS to enable cold forming • Aluminium alloys that achieve a tensile strength of more than 1000Mpa without compromising formability and recyclability • New materials and structures for super capacitors that can enable regeneration into body structures • Lightweight smart glass (e.g. energy harvesting, HVAC, embedded electronics, better structural characteristics) • Memory shape alloys and polymers for vehicle structures • Multi-material blanks • Data transfer through materials • Leveraging AI to explore new material compositions • Structural battery – energy storage and power storage in the body structures.

Research Challenge	**SHORT TERM** (5-7 years to mass market)	**MEDIUM TERM** (7-15 years to mass market)	**LONG TERM** (10-20 years to mass market)
5 Improving forming technologies	• Elimination of defects and repeatability of ultra-thin wall net shape casting • Zero waste, reduced steps and reduced tooling requirement of forming using existing processes • Energy efficient warm/hot formed sheet metals with complex cooled tooling geometries (AM tooling) • Improved blank utilisation on stamped metal parts • Improved material utilisation for composite forming • Develop new extrusion methods for Mg that do not rely on rare earth elements for its strength, ductility and energy absorption properties	• Lower temperature forming technologies that improve environmental impact • Localised magnetic pulse welding • Microwave induction heat • Low cost, higher volume Mg extrusion techniques for appropriate components (i.e. bumper beams, crush tips and intrusion beams) • Improved 3D roll forming with high D/t ratios • Improved hydroforming for high strength thin wall high D/t tubes	• Complete 3D printed vehicles
6 Efficient joining processes	• Joining without surface activation technologies • Zero waste, reduced steps and reduced tooling requirement of joining using existing processes • Fasteners capable of joining metals and polymers • Rivetless cold joining • High speed laser spot welding • Remote/distributed laser welding of sub-assemblies	• Low cost joining technologies for dissimilar materials that have zero impact on material properties • Fixtureless joining on the assembly line • Adhesive inkjet printing • Unjoining and de-bonding processes to facilitate improved material recovery	• Complete 3D printed vehicles

Research Challenge	SHORT TERM (5-7 years to mass market)	MEDIUM TERM (7-15 years to mass market)	LONG TERM (10-20 years to mass market)
7 Improving the environmental impact of vehicles in their production, use and end of life	• Aluminium automotive alloys made from at least 50% process scrap and 25% end of life vehicle scrap • Harmonised industry standards for life cycle analysis • Utilisation of green energy for energy intensive processes • Hydrogen capture and cleaning technologies • Industrial fuel cell integration • Closed loop recycling and higher utilisation of scrap in the material production process • High speed continuous casting of metals	• Scale up of carbon fibre recycling processes e.g. pyrolysis and solvolysis without impairing material properties • Reduce manufacturing energy use of high volume composite manufacture • Aluminium automotive alloys made from at least 50% process scrap and 50% end of life scrap • Utilising waste materials from other sectors for use in automotive whilst maintaining (or enhancing) material properties • Direct raw materials conversion processes • Technologies to reduce manufacturing energy and environmental impact (i.e. carbon capture and storage technologies, waste heat capture)	• Fully circular economy for vehicle manufacturing • 100% manufacturing energy from renewable or carbon neutral sources (i.e. CCS)
8 Developing new manufacturing methods to reduce takt time, enable more complex geometries and reduce manufacturing steps	• Develop faster oxidation processes to remove the bottleneck of carbon fibre conversion to further lower the cost of carbon fibre • Composite in process qualification to reduce takt time. • Net shape metal injection moulded steel components • Complex geometry hollow forging • Combining joining and forming to minimise process steps	• Machine learning additive layer manufacturing components to improve component functionality and reduce overall system complexity • Automated in-line inspection utilising Industry 4.0 techniques • Larger scale metal injection molding with hollow section • Hybrid machined and additive layer manufacturing part development • In process laser heat treatment • New tool materials for increased machining speeds • Tailor forged blank • Thin wall hollow forging • 'Smart Manufacturing' proactively responding to variations in input parameters on a part by part basis to minimise scrap, tool wear and energy use • Single stage production processes for powder metal production	• Reconfigurable manufacturing processes • Low cost high volume/large scale additive layer manufacturing processes • Fully automated vehicle assembly processes that are sensitive to demand

12

WORKING TOGETHER TO COMMERCIALISE THE PRODUCTS AND TECHNOLOGIES IDENTIFIED IN THE ROADMAPS

12.1 NEW OPPORTUNITIES TO CONNECT, COLLABORATE AND GROW

The roadmaps clearly demonstrate emerging societal needs and how these will lead to changes in propulsion technology requirements. There is now a clear and rapidly growing market pull for new low carbon technologies globally, underpinned by more local policies such as the UK's 'Road to Zero' strategy. Traditionally the automotive industry has responded to changing market requirements through incremental technology steps mainly led by OEMs and their first tier suppliers. The scale and speed of the change is unprecedented and requires a systems approach to introducing new technology into the market. This provides an opportunity for a more collaborative approach to overcome significant technical challenges and bring new low carbon products to market quicker. In parallel, rapid growth in the capability and capacity of the complete supply chain is required to deliver this new technology in sufficient volumes and cost-effectively.

The APC is built on a collaborative approach having originated from the UK's Automotive Council. The enormity of the challenge calls for organisations and individuals from around the globe to collaborate to bring about the required change. The APC, together with our spokes, academia, policy makers and industry are here to actively support the development, industrialisation and manufacturing of new technology in order to support this required change.

> *The enormity of the challenge calls for organisations and individuals from around the globe to collaborate to bring about the required change*

ADVANCED PROPULSION CENTRE UK

APC networking event

12.2 CONCLUSION

IAN CONSTANCE – CEO, THE ADVANCED PROPULSION CENTRE

This report is intended to be a catalyst for further dialogue between industry, academia and government regarding the future technology pathways for zero and low emission vehicles and propulsion technologies. The true value of the roadmaps will only be realised if organisations work collaboratively to deliver the technologies the community have identified.

The roadmaps provide a consensus view of the main challenges in commercialising technology. These challenges represent a significant opportunity for those who embrace change and are willing and able to work closely with other sectors in new areas. For example, how can the UK's impressive chemical sector progress automotive battery development? How can our steel industry metallurgists help progress advanced traction motors? These are the types of questions that the roadmapping process has raised while helping to form the view that extending the automotive supply chain will significantly accelerate technology delivery.

In a period of unprecedented change in the automotive industry, we expect these roadmaps to facilitate activity between the key organisations operating in these fields as well as helping those businesses and researchers in adjacent sectors to understand and engage with the automotive industry challenges.

The roadmaps provide a consensus view of the main challenges in commercialising technology. These challenges represent a significant opportunity for those who embrace change and are willing and able to work closely with other sectors in new areas.

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