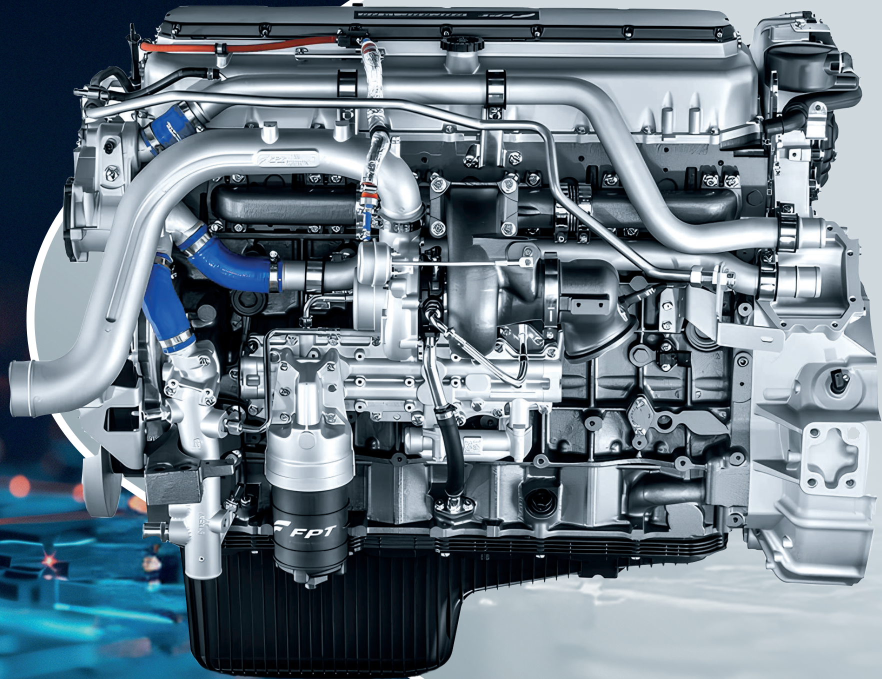
Internal Combustion Engines

Narrative Report

2024



automotive council UK

ADVANCED PROPULSION CENTRE UK

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1 | Introduction

1.1 | Foreword to the 2024 roadmaps

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The UK Automotive Council is well known for producing robust and detailed technology roadmaps that define potential routes for Automotive including Commercial Vehicles and Off-Road machinery and related products to achieve our UK environmental and societal goals. Roadmaps are a function of current knowledge and as new ideas and technologies emerge, must be regularly renewed. This exercise, led by the Advanced Propulsion Centre UK, has generated the fourth generation of these roadmaps.

Whilst many organisations develop roadmaps as part of their product planning process, the Automotive Council roadmaps are unique in providing a consented view from the Automotive sector including Commercial Vehicle and Off-Road Machinery, in the UK. This enables us to define common future challenges and where to focus collaborative R&D and capital resources in developing successful, sustainable, net-zero solutions.

These solutions must also meet future consumer needs and not introduce challenges in experience or limitations in operation. Often, more than one technical approach appears viable to meet future needs. It is important that all of these approaches are explored and introduced to market as the carbon reduction goal becomes more urgent. Ultimately, it is possible that one approach may dominate but we cannot afford to wait for this to emerge.

1.2 The purpose of the 2024 roadmaps

The Automotive Council UK roadmaps outline key themes, trends and drivers in the global automotive industry. This narrative report explains and provides insights to support the roadmap's themes. It helps clarify the reasons behind the roadmap's content and how it should be used.

The report aims to guide research and development (R&D), innovation, and cross-sector collaboration. A list of recommendations for how industry, academia, and government can use this information is shown opposite:

Industry

- Compare in-house R&D priorities with industry trends and drivers in the automotive sector.
- Evaluate supply chain risks and develop strategies for sustainable and circular business models in automotive products.
- Help start-ups by guiding their technology focus, investment choices, and collaboration plans.

Academia

- Address long-term research challenges that need to be solved.
- Align university research, education, and skills development with the automotive industry's needs.
- Strengthen partnerships between academia and industry to apply research to real-world solutions.

Government and policymakers

- Understand key themes and trends in automotive technologies.
- Direct policy and funding to support R&D priorities and innovation for reaching net zero.
- Promote cross-sector collaboration and trade policies that benefit the automotive industry and broader industrial sectors.

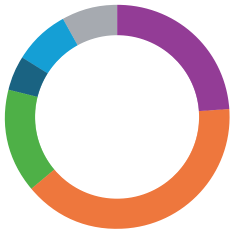
1.3 Building a consensus

This consensus roadmap has been developed through the facilitation of the Advanced Propulsion Centre UK (APC), with contributions from 436 individuals representing 230 organisations, which include government, industry and academia.

Collating the information required for the 2024 roadmaps has only been possible due to the breadth of contribution and valuable feedback from those who have fed into the process, which began in early 2023. The APC would like to thank everyone who gave their time and input across the various webinars, workshops, and surveys conducted.

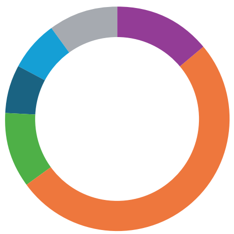
As a result of this consultation across industry and academia the 2024 roadmaps build on previous versions and demonstrate the significant change that is happening across the automotive sector and its supporting industries.

Figure 1: Representation by individual and organisation



436 Individuals

OEM	24%	(104)
Supply chain / SMEs	40%	(176)
RTO	15%	(67)
Academia	5%	(23)
Government	8%	(33)
Other	8%	(33)



230 Organisations

OEM	14%	(32)
Supply chain / SMEs	51%	(117)
RTO	11%	(25)
Academia	7%	(15)
Government	7%	(17)
Other	10%	(24)

Chris Brace
Executive Director
Institute for Advanced Automotive Propulsion Systems (IAAPS)

Internal combustion engines will remain at the forefront of technology to 2040 and beyond, but the fuels that they burn will change radically over this time period. Progress towards net zero means that fuels must be decarbonised rapidly. Reduced carbon fuels for today's fleet remain a critical part of this work. Further progress is possible with radically new sustainable fuels, for which we are already developing new efficient engine and propulsion system technologies. Hydrogen contains no carbon, so allows us to build engines that emit zero CO_2 at the tailpipe. A whole family of fully synthetic hydrocarbons are showing significant potential in the longer term. All of these fuels will be more expensive than the fossil fuels they replace, but they unlock a route to net zero in hard-to-electrify applications that are crucial to our way of life. Almost all of these engines will be part of a hybridised propulsion system that allows the engine itself to be optimised for converting chemical energy into useful work at the highest levels of efficiency and cleanliness by exploiting the flexibility offered by the electrical system. Since we last reviewed this technology roadmap I have become even more optimistic that engineering and science can help us to bring the benefits of clean, sustainable mobility to ever more of the world's population – and that the IC engine will continue to play an essential role in this future.

Professor Colin Garner
APC UK Board Member

Internal combustion engines have fundamental attributes that mean that they will continue to play a crucial role in the future of the automotive industry in meeting sustainability goals. Therefore, APC UK, on behalf of the Automotive Council UK, has led the production of this Internal Combustion Engines (ICE) roadmap which replaces the previous Thermal Propulsion Systems roadmap.

This new roadmap covers a broad range of automotive segments and application requirements including heavy-duty, specialist vehicles and off-highway (including non-road mobile machinery). The roadmap includes critical cross-cutting themes and enablers such as: policy and regulations; energy and infrastructure; materials and manufacturing; digitalisation; and broader lifecycle impact.

The roadmap was developed with inputs from a wide range of industrial and academic experts and given the challenges and complexity of the problem, a remarkable consensus was achieved. We hope that this new ICE roadmap will support the automotive industry and the broader supply chain in guiding the sector in delivering a clean, sustainable future.

1.4 Internal Combustion Engines – overview

In the 2020 roadmap release, this report was named Thermal Propulsion Systems. As part of our 2024 refresh and update, the decision was taken, with industry input, to rename to Internal Combustion Engines (ICE) to more accurately reflect the current state-of-play.

Overview: ICE

ICE have been a pillar of the automotive century for over a century, and will remain an important part of the transport propulsion solution. In 2024 ICE continues with improvements to thermal efficiency, systems integration, hybridisation and the development of new and existing non-fossil fuels to meet stricter emissions regulations.

Thermal efficiency improvements

Energy efficiency, commonly measured as Brake Thermal Efficiency (BTE), has continued to increase marginally since the 2020 Roadmap, however, development activities have instead been more focussed on system level efficiencies.

For both low-duty vehicles (LDV) and heavy-duty vehicles (HDV), BTE figures are expected to reach up to 53% by 2030 and 58% by 2040, dependent on the fuel combusted.

Optimising engine performance

For light-duty applications, there are a number of high-level technology pathways that can be used to reduce the current CO_2-eq output. These include cylinder deactivation, variable valve actuation, automated transmission technology, etc.

For HDV applications, there are additional measures that can be taken to reduce the CO_2-eq output, such as integrated waste heat-recovery systems, engine right-sizing, advanced and integrated cooling.

Innovations for combustion engines continue and include reducing heat loss through coatings and materials; flexible fuel injection systems; waste heat recovery and full hybridisation.

ICE are experiencing a renewed research and development (R&D) focus with manufacturers opting to continue investment in them alongside other options, such as battery electric vehicles (BEVs) and fuel cell electric vehicles (FCEVs). The aim is to accelerate the decarbonisation of the automotive sector by exploring all avenues available, including non-fossil fuel solutions like hydrogen combustion.

Transitioning the supply chain to support net zero

A key benefit of combustion engines is the well-established supply chain, strong recycling capability, a focus on repurposing and remanufacture and mainstream low-carbon manufacturing processes.

Research continues to identify new drop-in and non-drop-in fuels, which could be used in place of existing fossil fuels, with the aim to further reduce carbon emissions and create non-fossil fuel alternatives that can still take advantage of the established supply chain and production systems that belong to combustion engines.

Increasing policy and regulation surrounding end-of-life and recyclability has seen an increased focus on designing for disassembly, reuse and recycling. ICE benefits from well-established recycling practices and recovery of all materials at end-of-life.

This is a new section for the 2024 roadmaps and aims to provide a comprehensive context for issues and drivers that extend beyond vehicular systems and technologies.

Four overarching themes or micro-level drivers that influence all aspects of the technology roadmaps have been pinpointed. The drivers identified are multifaceted, ranging from global to local scales. Global drivers encompass changes and challenges that transcend national boundaries, often beyond the direct influence of UK suppliers. National drivers are those that are unique to the UK's socio-economic and regulatory environment, while local drivers affect specific regions or communities within the UK. The interplay between these cross-cutting themes and drivers impacts the evolution and development of forecasted technology solutions. These drivers interact with each other and with the technology roadmaps – expediting the advancement of certain technologies, while simultaneously necessitating change in others. In this section, we delve into four pivotal drivers that are reshaping the landscape of technology and innovation:

1. Policy and regulations: examining the influence of legislative frameworks on technological progress.
2. Energy and infrastructure: assessing the role of energy availability and infrastructural support in driving innovation.
3. Materials and manufacturing: understanding the impact of manufacturing capabilities and constraints on technology development.
4. Digitalisation: exploring the transformative power of digital technologies across the automotive sector.

2 | Cross-cutting themes

2.1 | Policy and regulations

Global targets for vehicle sales

Global targets to reduce the levels of CO_2 and tailpipe emissions, particularly for light- and heavy-duty vehicles are impacting the ongoing research and development of the ICE that are currently used in mainstream applications. The focus on existing technologies, such as fossil fuels (gasoline / diesel) is shifting with new non-fossil fuels and technologies like hydrogen combustion enjoying the spotlight.

In some regions, for example the UK and Europe, new policies and regulations introduced over the past decade detailing low and zero-emission new vehicle purchases, have encouraged original equipment manufacturers (OEMs) globally to invest heavily in alternative propulsions, for example BEVs and FCEVs. However recent industry discussions point to the need for a technology-agnostic approach to identify the most efficient, best-fit technology for specific applications.

A key example is off-highway, including non-road mobile machinery (NRMM), which has specific requirements that current BEV and FCEV technology cannot easily meet. Here, a non-fossil fuel combustion engine solution is preferred for certain applications, as well as in other use-cases, such as long-distance, HDVs and some specialist passenger cars.

A significant amount of research and industry opinion suggests that a blanket solution across all of the automotive industry is counterproductive in the route to decarbonisation. Non-fossil-fuel powered engines such as hydrogen, or bio-fuels, e.g. bio-methane, are being trialled in a wide range of applications and real-world scenarios.

OEMs and suppliers have expressed that they find the current terminology used in legislation negatively impacts ICE R&D initiatives. For example, in most cases, hydrogen combustion engines cannot be classified as zero emission due to the NOx emitted. Instead, there are discussions about adopting a CO_2-eq reduction target, or net-zero emissions rather than 'at tailpipe', to ensure development can continue, particularly for those applications which may rely on the benefits of an ICE to operate effectively.

Figure 2 below illustrates key global targets to 2040, with some regions opting to focus on one of: CO_2 reduction, zero-emission vehicles (ZEV) or new energy vehicles (NEV).

Smarter systems for regulation management

Across global regions, a smarter road infrastructure is being implemented with camera systems, sensors and connectivity becoming commonplace. Within cities, there are low-emission zones either currently active or in the development phase. UK cities, such as London, have the ultra-low emissions zone (ULEZ), and France has introduced the “Crit’Air” clean-air stickers.

These regulations, as well as efficiency concerns, paired with the advancement in onboard smart technology have made features, such as geofencing and Vehicle to Everything (V2X) powertrain control, more prevalent in vehicle design, particularly vehicles with hybrid powertrains. As a vehicle approaches a clean-air zone, it is expected that geofencing could automatically enable the powertrain to switch to solely electric propulsion to ensure no pollutants are emitted by as soon as 2027.

However, a concern is that if a pre-planned route identifies a clean-air or low-emission zone, the smart systems may decide to ensure the on-board batteries have enough charge to commute through the zone and use excessive engine power to recharge the batteries beforehand. This could result in a net-increase of pollutants across the whole journey, especially if repeated.

Figure 2:
Zero-emission vehicle sales commitments

	2025	2030	2035	2040
EU	• 15% CO_2 reduction across car fleet • 15% CO_2 reduction across HDV fleet	• 55% CO_2 reduction across car fleet (50% for LCV) • 45% CO_2 reduction across HDV fleet	• All new cars zero CO_2 emissions • HDV 65% fleet CO_2 reduction	• HDV 90% fleet CO_2 reduction
UK	• ZEV sales targets 22% cars and 10% vans	• ZEV sales targets 80% cars and 70% vans	• All sales ZEV for cars and vans • All HDV <26 tonnes ZEV	• All HDV ZEV
Rest of the world	• **Canada** 20% ZEV for light and heavy-duty sales (2026)	• **USA** 50% of vehicle sales to be electric • **China** NEV 60% of sales • **Japan** 20% BEV and PHEV passenger car sales • **India** 30% car sales ZEV, 70% commercial vehicles ad 80% two / three-wheelers • **Australia** 30% LDV sales to be ZEV	• **Canada** 100% ZEV for light- and heavy-duty sales • **Japan** 100% EV passenger car sales • **Australia** 100% LDV sales to be ZEV	• **China** 100% NEV for light- and heavy-duty sales

Dates correct at time of publication

2.2 Energy and infrastructure

An existing supply chain and knowledge base

ICE has the advantage over BEVs and FCEVs, as it has an established supply chain.

Challenges remain with BEVs due to continued research in battery chemistries, electric motors and lightweighting measures. FCEV fuel cell stacks come at a significant cost compared to BEV and current ICE, with components such as bipolar plates representing a large portion of that cost.

ICE is a mature technology, however, there are innovation opportunities around the adaptation of the systems to use non-fossil fuels, e.g. green hydrogen.

Certain components require further R&D including new gaseous tanks for future fuels, e.g. hydrogen storage. However, this is not exclusive to hydrogen combustion and is a shared resource cost between fuel-cell and hydrogen combustion engine storage development.

Hydrogen infrastructure (hydrogen combustion)

Similarly to the issues highlighted in the 'Hydrogen Fuel Cells and Storage' roadmap, the growth of hydrogen combustion, as an alternative, is directly impacted by the infrastructure development and struggles for energy requirements (the grid network). As fuel cell and storage development continues to grow, hydrogen combustion will benefit as a result. The refuelling network is expanding and becoming more connected with numerous infrastructure projects on the horizon globally and this is positive for the future of FCEVs, particularly for fleet operations.

The existing infrastructure in most countries is still in early development, although China, Germany and the USA are all investing in hydrogen refuelling. In 2023 alone, 37 new hydrogen stations opened in Europe, 12 in Japan, 29 in South Korea and 7 in North America[1]. Several initiatives and projects globally have been introduced, such as the Hydrogen Mobility Europe initiative, which deployed over 45 stations in the EU between 2015 and 2022 and was co-funded by the Clean Hydrogen Partnership[2].

Additionally, as part of the EU's 'Fit for 55' package, the Alternative Fuel Infrastructure Regulation (AFIR) plays an important role in shaping the future of hydrogen refuelling across the EU, setting specific targets for the deployment of these stations. The key target in this directive is that publicly available hydrogen refuelling stations, serving both cars and lorries, must be deployed from 2030 onwards in all urban nodes and every 200 km along the Trans-European Network for Transport (TEN-T). Investment in the refuelling infrastructure is crucial for growth of these non-fossil fuels alternatives - lack of investment could stifle innovation within these alternative ICE solutions. The energy landscape, or electricity grid capacity, is another infrastructure related aspect that can affect these technologies. The energy landscape plays a pivotal role in shaping the development and adoption of non-fossil fuel combustion engine technologies, and a significant increase in renewable energy sources like wind and solar is essential for sustainable alternative fuel production, e.g. green hydrogen.

The National Grid highlighted that if all heavy goods vehicles (HGVs) in England and Wales were hydrogen fuel-cell powered, the annual energy demand would be around 98 TWh / year, about 30% of 2019's total electricity generation. Adding hydrogen combustion engines to the mix would further increase energy combustion, risking grid instability[3].

1 H2stations.org
2 https://h2me.eu/about/hydrogen-refuelling-infrastructure/
3 https://www.nationalgrid.com/document/146441/download

2.3 Materials and manufacturing

Remanufacture and reconditioning

An important aspect of manufacturing alternative-fuel engines is the possibility of remanufacturing and repurposing ICE at end-of-life for compatibility with fuels like hydrogen. Rather than disposing of older diesel and gasoline engines, part and production lines have the potential to be redesigned and modified enabling non-fossil fuel engine production.

The option for remanufacturing parts, or even entire engines, will likely be more applicable for fleet operators or specialised equipment owners (such as performance vehicles, construction earth-movers, excavators, etc.).

As the initial purchase cost is high, it would prove to be more financially beneficial to replace engine components rather than replace machinery in its entirety. Additionally, depending on the fuel used, the application and the previous engine design, repurposing an engine can range from replacing individual parts, e.g. injectors, through to the entire engine, so it is a flexible approach that can be taken case-by-case.

Material recovery

Material recovery is a high-level focus across other technologies, such as BEV and FCEV, but is already a well-established practice in the ICE market. The focus here is to continue this at scale using existing supply chains and growing networks, with a view to maintain momentum as the industry transitions to sustainable fuel-engine designs, such as hydrogen combustion engines.

Additionally, to achieve true net zero, some non-fossil fuels like hydrogen will still have some form of emission at the tailpipe. Ensuring that all critical materials are recovered at end-of-life, and where possible, reintroduced to the manufacturing line, the overall environmental impact of the engine production is significantly reduced. Conserving natural resources and not relying on new raw materials for engine components will greatly reduce overall pollution and make sustainable combustion engines a viable option for mass decarbonisation.

Hydrogen storage (hydrogen combustion)

For hydrogen combustion, there is an inherent overlap with hydrogen fuel cells when it comes to the storage solution used, as both applications will rely on efficient, lightweight and cost-effective hydrogen storage (Types 3, 4 and 5 tanks) as well as other gaseous storage for non-fossil fuels, other than hydrogen.

Much of the concern and focus surrounding hydrogen storage is linked directly to the adoption and success of hydrogen combustion, such as circularity and material recovery in the tank itself, simplifications of integrated storage designs and the reliability and durability of the hydrogen storage tank.

More information can be found in the ‘Fuel Cell and Hydrogen Storage’ narrative report.

2.4 Digitalisation

Smarter systems, geofencing, V2X and artificial intelligence (AI)

Synergy across onboard powertrain systems is increasingly important for efficiency and safety measures in a combustion engine vehicle. The general trend for industry is to invest heavily into hybridisation, where possible, to increase efficiency and reduce CO_2 emissions. However, there is still ongoing R&D to make the hybrid and engine architectures work more closely together as one unit.

Current technology enables a series hybrid, where the engine serves as a generator; a parallel hybrid, where the engine and motors work simultaneously to power the drivetrain; and a series-parallel system, allowing the engine and motors to have full operational flexibility to ensure efficiency. Smarter onboard systems and increased physical integration can enable the control software to apply these architectures much more efficiently, with series-parallel offering the most flexibility.

An increasing number of cities and localities across the globe, particularly in Europe, are introducing low and zero-emission zones. The aim of these zones is to improve air quality and reduce emissions in densely-populated areas. Geofencing and V2X technologies are being integrated into modern-day vehicles. They can apply external data sources to inform onboard smart-control systems for key decision-making. A use-case example of geofencing is the identification of emission-control zones during a journey enabling a vehicle to auto switch to electric power within the zone or recharge batteries when outside of the zone. V2X allows the vehicle to communicate with infrastructure, other vehicles and the internet. This can then also generate real-time data which, in turn, can be used by the smart systems to improve efficiency.

Geofencing and V2X are not just useful for low-emission zones but can also be implemented in vehicles to map elevation characteristics of a route. The data generated can be used to plan the most efficient engine and motor-drive cycle, such as when to use regenerative braking for recharge. In off-highway, including NRMM, elevation data could map out a new work site or factory design, which could be interpreted by the system to create a navigation plan, further reducing emissions, maximising efficiency, and driving down cost.

Research is in progress on how AI could be introduced into regular powertrain and drivetrain controls, using an array of sensors. The datasets generated in real-time from V2X can maximise the efficiency of a hybrid powertrain. Fully-automated powertrain control could be achieved by implementing AI, with a supporting level of enhanced security to make sure that safety is not compromised.

Component passports

At the end-of-life, to aid in material recovery and recycling, radio frequency identification (RFID) and near field communication (NFC) could be introduced as a unique identifier for components, such as a hydrogen storage tank. This is particularly the case with new components which will be introduced as the industry moves to fossil fuel-free combustion engines. This is to ensure that at end-of-life of any combustion engine system component, the relevant recyclable parts can be disassembled and fed back into production for remanufacture, repurposed for second-life, or responsibly recycled with full accountability of origins and owners.

As with the 2027 battery passport mandate in the EU, fuel cells and hydrogen storage are expected to follow suit with potential regulations for end-of-life and recycling. For hydrogen combustion this will directly affect the system as the storage and balance-of-plant are vital components for the drivetrain.

3 | Narrative to roadmap

3.1 | Internal Combustion Engines (ICE) – technology indicators

Light and heavy-duty applications

Technology indicators

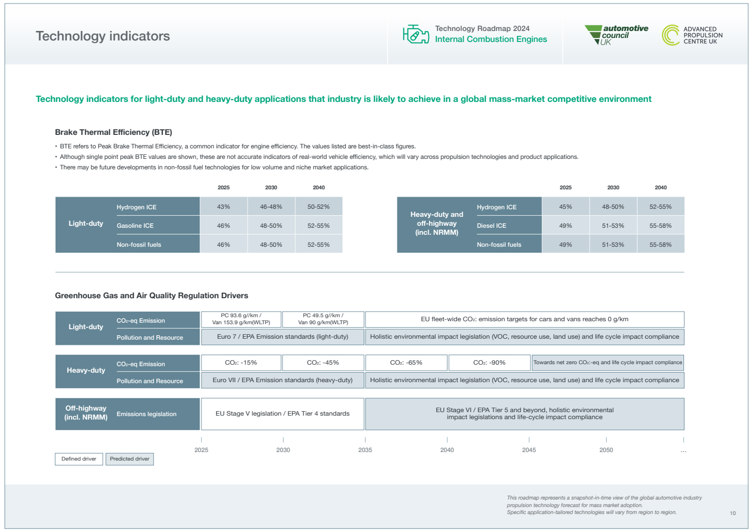
In this 2024 roadmap refresh, the BTE numbers have been retained to provide a general direction of travel for industry, but with further focus on specific fuels for light-duty, heavy-duty and off-highway (including NRMM) applications.

BTE

The indicators for light-duty are provided separately from heavy-duty and off-highway (including NRMM), as their duty cycles and technology selection differ. For 2024, the BTE indicators are further broken down for both categories to include current fuels (gasoline and diesel) and future fuels (hydrogen and other non-fossil fuels).

Regulation drivers

Developing CO_2 emissions, pollution and resources regulations have been updated in this roadmap and directly affect the development of combustion-engine technologies. In addition, this 2024 roadmap includes key emissions legislations influencing off-highway (including NRMM) applications.



Technology indicators

Technology Roadmap 2024
Internal Combustion Engines

Technology indicators for light-duty and heavy-duty applications that industry is likely to achieve in a global mass-market competitive environment

Brake Thermal Efficiency (BTE)

- BTE refers to Peak Brake Thermal Efficiency, a common indicator for engine efficiency. The values listed are best-in-class figures.
- Although single point peak BTE values are shown, these are not accurate indicators of real-world vehicle efficiency, which will vary across propulsion technologies and product applications.
- There may be future developments in non-fossil fuel technologies for low volume and niche market applications.

		2025	2030	2040
Light-duty	Hydrogen ICE	43%	46-48%	50-52%
	Gasoline ICE	46%	48-50%	52-55%
	Non-fossil fuels	46%	48-50%	52-55%

		2025	2030	2040
Heavy-duty and off-highway (incl. NRMM)	Hydrogen ICE	45%	48-50%	52-55%
	Diesel ICE	49%	51-53%	55-58%
	Non-fossil fuels	49%	51-53%	55-58%

Greenhouse Gas and Air Quality Regulation Drivers

Light-duty – CO_2-eq Emission: PC 93.6 g//km / Van 153.9 g/km(WLTP); PC 49.5 g//km / Van 90 g/km(WLTP); EU fleet-wide CO_2: emission targets for cars and vans reaches 0 g/km
Light-duty – Pollution and Resource: Euro 7 / EPA Emission standards (light-duty); Holistic environmental impact legislation (VOC, resource use, land use) and life cycle impact compliance
Heavy-duty – CO_2-eq Emission: CO_2: -15%; CO_2: -45%; CO_2: -65%; CO_2: -90%; Towards net zero CO_2:-eq and life cycle impact compliance
Heavy-duty – Pollution and Resource: Euro VII / EPA Emission standards (heavy-duty); Holistic environmental impact legislation (VOC, resource use, land use) and life cycle impact compliance
Off-highway (incl. NRMM) – Emissions legislation: EU Stage V legislation / EPA Tier 4 standards; EU Stage VI / EPA Tier 5 and beyond, holistic environmental impact legislations and life-cycle impact compliance

2025 2030 2035 2040 2045 2050 ...

Defined driver | Predicted driver

This roadmap represents a snapshot-in-time view of the global automotive industry propulsion technology forecast for mass market adoption.
Specific application-tailored technologies will vary from region to region.

10

Light-duty and heavy-duty BTE

General notes

Higher-peak BTEs than what are currently recorded are achievable by tuning the engine to a single optimisation point. However, it is important to note that this is not representative of a real-word drive-cycle nor does it support the aim of increasing 'net' duty-cycle efficiency.

Averaged drive-cycle BTE values are a preferred way of providing realistic data for real-world applications, however, peak-BTE still provides an ideal indicator for the trajectory of development and innovation.

Light-duty

To achieve proposed fuel-economy requirements, engines must make better use of the available fuel energy. Regardless of how efficient the engine is, there will still be a significant fraction of the fuel energy that is rejected in the exhaust and coolant streams.

In this 2024 roadmap, engine efficiency, commonly measured as BTE, has been expanded to cover three specific fuel-type engines. For light-duty vehicles, these are hydrogen ICE, gasoline ICE and non-fossil fuel ICE. Gasoline ICE continues from the 2020 light-duty BTE indicators and is still increasing. By 2030, gasoline ICE is expected to achieve a 50% peak BTE, increasing to over 52% by 2040.

Heavy-duty

Heavy-duty powertrain efficiency is expected to continue growth with significant advances in technologies, such as engine right-sizing, waste heat-recovery and combustion methods.

Engine efficiency for HDVs has been expanded to cover three specific fuel-type engines, with the aim to meet the Euro VII and EU Stage V emission standards and EPA (Environmental Protection Agency) emission standards, including Tier 4.

Diesel ICE is a continuation from the 2020 roadmap BTE indicators and is initially slightly less optimistic with the 2025 updated figure lower than the 2020 projection. However, the 2040 indicator is expected to reach between 55-58% BTE. BTE. This could be achieved by deploying all thermal-efficiency measures and engine technologies, such as water injection, valve timing, cylinder deactivation, etc.

		2025	2030	2040
Light-duty	Hydrogen ICE	43%	46-48%	50-52%
	Gasoline ICE	46%	48-50%	52-55%
	Non-fossil fuels	46%	48-50%	52-55%

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Heavy-duty and off-highway (incl. NRMM)	Hydrogen ICE	45%	48-50%	52-55%
	Diesel ICE	49%	51-53%	55-58%
	Non-fossil fuels	49%	51-53%	55-58%

Greenhouse gas and air quality regulation drivers

General notes

The defined and predicted drivers for greenhouse gases (GHG) are listed under the CO_2-eq section. For any quantity and type of greenhouse gas, CO_2-eq signifies the amount of CO_2 which would have the equivalent global warming impact.

Light-duty

The indicators are taken from the latest European Commission CO_2 emission performance standards for cars and vans regulation documentation (2024 onwards). These standards have been updated since the 2020 roadmap, with specific emission targets for passenger cars and vans for 2025-2030, 2030-2035, and beyond across the world harmonised light-duty vehicles test procedure (WLTP) cycle. Passenger cars are expected to achieve lower than 93.6 g/km of CO_2 by 2025 and under 49.5 g/km by 2030. Vans are expected to achieve 153.9 g/km in 2025 and 90 g/km by 2030, with both vehicle types reaching 0 g/km from 2035 onwards.

Pollution and resource are provided as a separate category to support the range of natural resource considerations becoming increasingly important for automotive manufacturing. This includes air, water, land, biological and raw materials.

Euro 7 is being introduced which builds on the existing Euro 6d standard for light-duty vehicles. Euro 7 has some significant changes and tighter restrictions, including updated limits for exhaust emissions, a focus on tyre and brake emissions, and increased battery durability for electric and hybrid cars and vans. The EPA emission standards for light-duty vehicles were updated in 2024 with the aim to implement more stringent standards to further reduce harmful air pollutant emissions from light- and medium-duty vehicles, model year 2027 onwards. The projected CO_2 targets for light-duty vehicles start at 170 g/mile (approximately 105 g/km) in 2027, and 85 g/mile (approximately 57 g/km) in 2032.

Heavy-duty

A similar approach to GHG and pollution mitigation is demanded for HDVs. VECTO, a simulation tool developed by the European Commission, is still in use to determine CO_2 emissions and fuel consumption for HDVs with a gross vehicle weight above 3.5 tonnes.

In 2023, the European Commission proposed a revision of the CO_2 emission standards, with approval in early 2024. The previous targets for heavy-duty were to reduce 30% of emissions by 2030, and this has been revised to 45%. By 2035, the target reaches 65% and eventually sees a 90% reduction in CO_2 emissions by 2040. The EU's targets are now more closely aligned with other regions, like Japan and the US, which have also opted for fuel economy and CO_2 standards.

Euro 7 regulations now include strict emission regulations for HDVs as well as passenger cars within one stricter legislation. Previously, emission regulations were based on Euro 6 for cars and vans, and Euro VI for trucks and buses, two separate emission limits. Under Euro 7, the regulations set around non-tailpipe emissions, such as evaporative emissions, brake particles, tyre particles and battery durability, will also affect the future of heavy-duty applications. Beyond 2045, heavy-duty CO_2-eq emission targets can expect to be driven towards net zero and pollution legislation will become more stringent for both HDVs and off-highway vehicles.

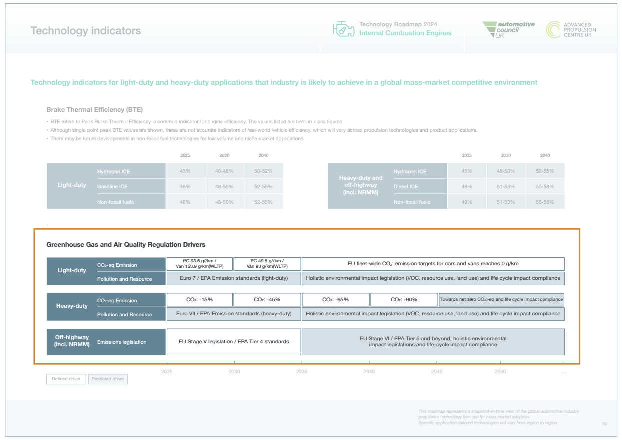
Off-highway (including NRMM)

Off-highway vehicles do not conform to the same standards and regulations as light- or HDVs, and have to meet their own set of emissions legislation.

The Stage V emission standards have been developed by the European Commission and outline stricter emission limits on particulate matter (PM), NOx and CO emissions.

The EPA Tier 4 standards for non-road engines and vehicles also have a dedicated focus to reduce PM and NOx emissions through advanced technologies such as particulate filters, and are in place to improve air quality by reducing pollutants that contribute to smog and respiratory problems.

It is expected that beyond 2035, there could be updates to these legislations, forming EU Stage VI and EPA Tier 5, as well as a focus on life-cycle impact and a focus on system level emissions, in place of engine level.



WLTP: The world harmonised light-duty vehicles test procedure is a global, harmonised standard for determining the levels of pollutants, CO_2 emissions and fuel consumption of traditional and hybrid cars, and the range of fully electric vehicles.

Technology pathways for CO_2-eq reduction in light-duty vehicles

Light-duty pathways for CO_2-eq reduction

Air quality regulations and pollution-control measures are directly shaping the future of the combustion engine, with engine and component manufacturers tasked with increasing efficiencies whilst reducing CO_2-eq output. For light-duty vehicles, there are some key technologies which can contribute to reducing the present baseline figures of CO_2-eq g/km, across engine, transmission and system levels.

Engine level

At the engine level for light-duty vehicles, there are some technologies which are either already in production or in development. These technologies could also be used for heavy-duty applications but would see more gains in efficiency in light-duty. These are specific technologies to improve the thermal efficiencies of a light-duty combustion engine. Here are some examples of the technologies listed:

- Cylinder deactivation is a technique where a combination of cylinders is systematically shut down, reducing engine displacement, improving engine efficiency and fuel economy. This helps reduce the overall consumption of fuel and allows the engine to maintain a high temperature during low load operations.
- Advanced turbocharging includes innovative solutions such as e-turbo systems, which can use electric motors and electric compressors instead of a traditional small turbine, resulting in a faster response time and enabling better fuel economy.
- Variable valve timing (VVT) provides precise control over the engine valve operations, enhancing performance and efficiency. The core principle of VVT is to dynamically alter the timing of the valve-lift event. This allows the engine to benefit from more power and torque across a wider range of engine speeds.
- Fuel injection methods can also help increase thermal efficiency by using direct injection where possible to maximise fuel economy, although this is dependent on fuel, such as hydrogen where initial costs may be of concern, so port injection could prove to be an interim solution.

Transmission level

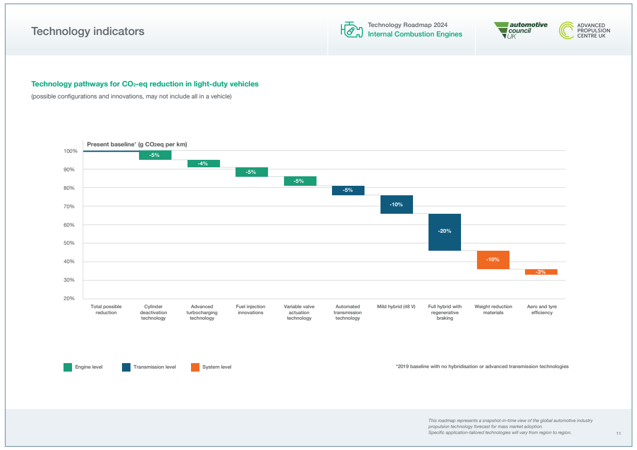
Automated transmissions and dual-clutch technologies will help improve overall efficiency and reduce the friction and material wastage from traditional manual and clutch transmissions. Additionally, smarter onboard systems can take advantage of a fully-automated transmission with smarter gear selection and engine braking to ensure greater efficiencies.

Hybridisation can help to increase engine efficiencies by sharing loads between onboard motors and engines, allowing sections of a journey to offer zero emission. This could be particularly useful in travel that enters low- or zero-emission zones (refer to section 3.8).

System level

Weight-reduction technologies, using advanced materials, could reduce the overall fuel consumption by 6-8%. Replacing cast iron and traditional steel components could directly aid the overall efficiency, as well as using high-strength steel, advanced 3D printing and CAD modelling in the manufacturing process to reduce weight.

Aerodynamics efficiency and advancements in key computational fluid dynamic (CFD) technologies and simulation techniques will be crucial to reduce drag coefficient figures for vehicles, directly improving the overall fuel consumption through reduced drag.



Technology pathways for CO_2-eq reduction in heavy-duty vehicles

Heavy-duty pathways for CO_2-eq reduction

Air quality regulations and pollution-control measures are directly shaping the future of the combustion engine, with engine and component manufacturers tasked with increasing efficiencies whilst reducing CO_2-eq output. For HDVs, there are also varying specific technologies across the engine, transmission and system levels to reduce from the present baseline figures of CO_2-eq g/km.

Engine level

There are some engine-level technologies which would be more suited to heavy-duty applications rather than light-duty ones, but could still apply to both. The technologies aim to improve the thermal efficiencies of a heavy-duty combustion engine, which is subject to higher and longer load times and many more drive cycles than an average light-duty vehicle.

State-of-the-art engines currently focus on lean burn engines, which provide a lower fuel consumption than rich burn by having a higher air-to-fuel combustion process. Lean burn engines can achieve a higher power for a given displacement, and result in lower exhaust temperatures, leading to lower NOx and CO_2 emissions.

Waste heat recovery can also help reduce the overall fuel consumption of an engine by providing additional power from hot exhaust gases / thermal energy. This would normally be exhausted to atmosphere and therefore wasted. Turbo-compounding and organic rankine cycle (ORC) engines are examples of heat-recovery systems.

Engine design is also beginning to implement right-sizing measures instead of down-sizing, as ensuring the engine is optimal for its application can be much more efficient and effective at reducing fuel consumption and emissions than a blanket down-sizing effort. Either reducing or increasing engine displacement can be combined with other thermal efficiencies to create a well-balanced engine design, purpose-built for applications and will require industry-wide collaboration.

Transmission level

Automated transmissions and dual-clutch technologies will help improve the overall efficiency and reduce the friction and material wastage from traditional manual and clutch transmissions. Additionally, smarter onboard systems can take advantage of a fully-automated transmission with smarter gear selection and engine braking to ensure a greater efficiency.

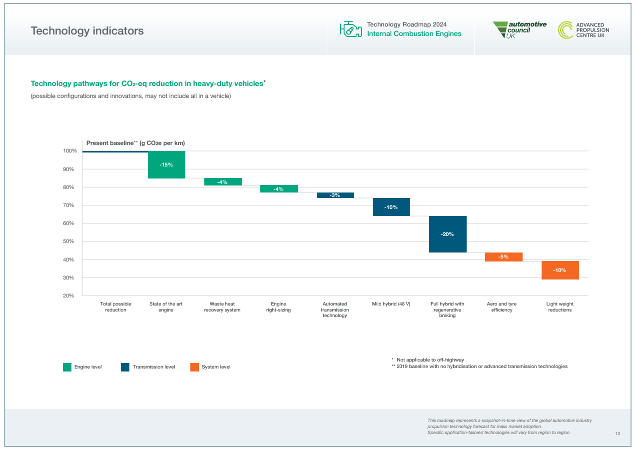
With HDVs there is the consideration of automated transmissions being smart enough to dynamically adapt depending on load, as well as certain applications still using torque converters to reduce strain on the engine and transmission components.

Hybridisation can help increase engine efficiencies by sharing loads between onboard motors and engines, allowing for some parts of a journey to offer zero emission. This could be particularly useful in journeys which enter low- or zero-emission zones (refer to section 3.8). Additionally, for use-cases in HDVs like coasting downhill, hybridisation with regenerative braking could help power an onboard battery for power and auxiliary systems, particularly when fully loaded.

System level

Weight-reduction technologies, using advanced materials, could reduce the overall fuel consumption by 6-8%. Replacing cast iron and traditional steel components could directly aid the overall efficiency, as well as using high-strength steel, advanced 3D printing and CAD modelling in the manufacturing process to reduce weight.

Aerodynamics efficiency and advancements in key CFD technologies as well as simulation techniques will be crucial to reduce drag coefficient figures for vehicles, directly improving the overall fuel consumption.



3.2 | Internal Combustion Engines (ICE) – technology themes

The next few pages take an in-depth look at each section of the ICE Executive Roadmap document. It is recommended that you have the executive roadmap to hand, however, for ease of reference, the relevant page is pictured here.

Roadmap technology themes

(Click underlined links to jump to sections)

Thermal efficiency

Thermal efficiency discusses the trends seen in both light-and heavy-duty vehicle combustion technologies, as well as advancements in design of system architectures to lower emissions and improve fuel economy figures across a wide range of applications.

Technology pathways

Technology pathways identify the key directions industry is moving towards for two key segments: car and van; and heavy-duty, specialist and off-highway vehicles.

Systems integration

Fuel and emissions control systems detail the technology changes and trajectories seen for onboard fuel delivery, as well as CO_2 and pollutant-mitigating after-treatments. New for 2024, there are specific mentions for hydrogen-fuel delivery and after-treatment requirements.

Engine systems and control covers efficiency improvements through boost devices, smarter onboard systems and electrical hybrid system architecture.

Drivetrain and hydraulic systems are continuously improving and provide ICE with significant efficiency and emission improvements with trends in transmission design and system architectures being the main focus.

Life cycle

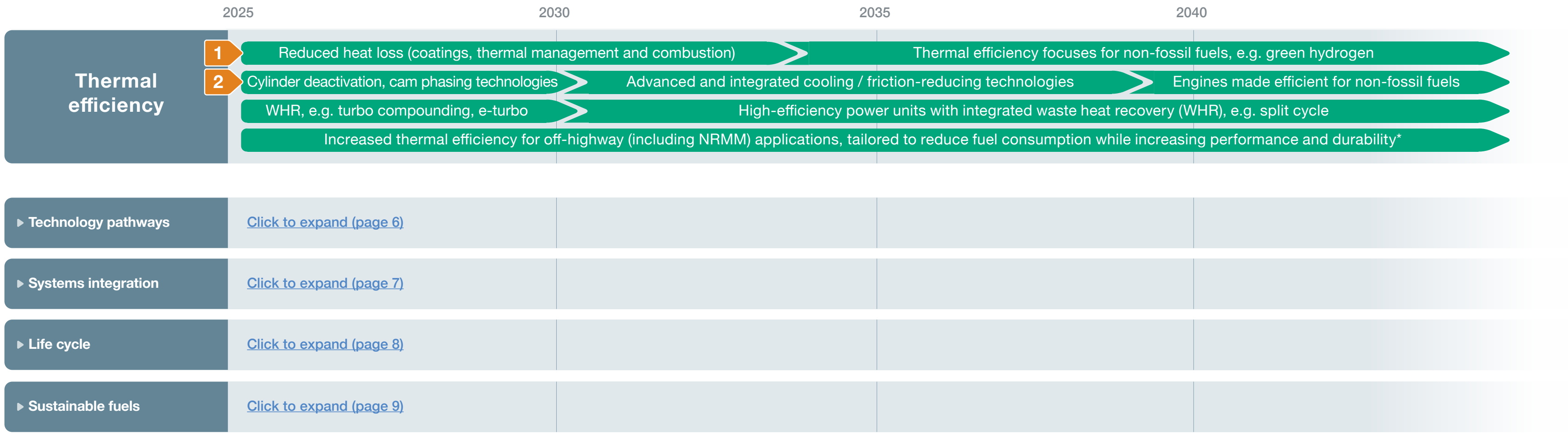
Life cycle impact includes the transition to net-zero CO_2 production systems for ICE and design requirements to achieve circularity across the supply chain.

Material recovery is a new sub-section with key themes focussing on recovery and recycling of all materials at end-of-life, as well as using component passports across the supply chain.

Sustainable fuels

Sustainable fuels is a continued section from the previous roadmaps, as the design, development and manufacture of ICE are dependent on the fuel that is used, as well as the subsequent emissions of the drive cycle. For this roadmap refresh, the themes covered are drop-in, non-drop-in (including hydrogen) and future fuels.

This section looks in detail at the line-by-line activity on the Internal Combustion Engines Roadmap. The numbers will direct you to the line being discussed here in detail.



Thermal efficiency

1 Controlling heat loss and a focus on sustainable fuels

A common trend in engine development is to reduce this heat loss through a number of options which can include moving to more advanced coatings and materials, such as ceramic and silicone-based. The alternative materials still need to have the same properties, such as high adhesion at high temperatures, durability, corrosion resistance and high-load capacity.

Thermal-efficiency research and development will change as industry begins to modify engine architecture design for non-fossil fuels, such as hydrogen, which will have different combustion characteristics and would directly influence the thermal efficiency measures used.

For example, hydrogen operates on a much leaner burn, as well as higher flame velocity, when compared to diesel or gasoline engines. BTE for hydrogen combustion engines is generally lower than diesel, but continued research and development into thermal efficiency measures for hydrogen could reverse this, meaning hydrogen could be more efficient in the future than diesel or gasoline.

2 Efficient ICE systems and reducing fossil fuels

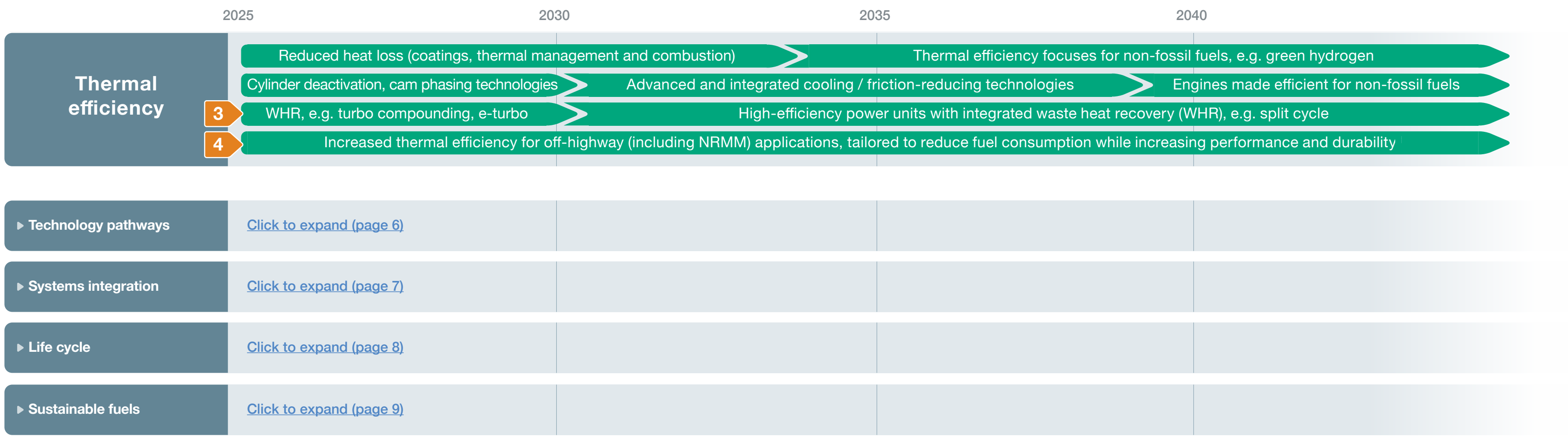
Efficient ICE systems, which are optimised for newer non-drop-in fuels, such as sustainable fuels and non-fossil-fuels, include the combustion of specific items such as lean burn, water injection for wet compression and flexible valve events for cylinder deactivation.

Lean burn refers to the engine operating at a higher air-to-fuel mixture, which can reduce the combustion temperature, directly reducing heat loss. As a result, the NOx output from the engine is reduced significantly.

In wet compression, water is injected at an inlet providing continuous cooling due to the evaporation of water droplets in the air compression process, offering a high efficiency and lower pollutant emissions.

Flexible valve events can also enable increased efficiency measures such as cylinder deactivation, variable valve timing, and further design optimisations.

Fossil fuel reduction will become a primary R&D focus from 2030 and beyond. However, there will still need to be a significant amount of thermal efficiency development, particularly for those applications which will still use ICE as the main technology.



Thermal efficiency (continued)

3 Efficiency through waste-heat recovery

A significant amount of the combusted fuel energy is lost as heat in engine systems. The waste heat can be recovered and re-used as heat power, or converted into electricity, e.g. charging onboard batteries. This is relevant now more than ever, as hybrid powertrains become increasingly commonplace in mass-market applications.

The use of waste-heat recovery (WHR) increases the power output and efficiency of the system whilst reducing emissions. Current examples of WHR systems are turbo-compounding and ORC.

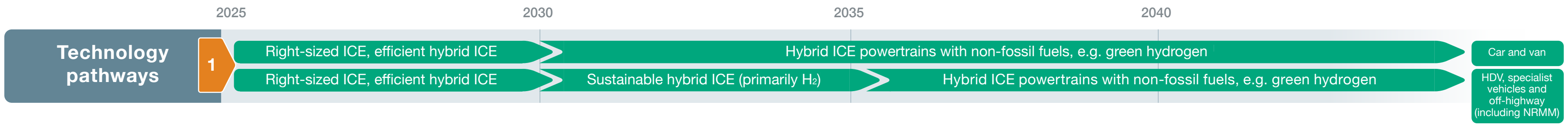
In the future we could see integrated WHR systems become more common, such as split-cycle engines, utilising half of the available cylinders for intake and compression, with the other half for power and exhaust.

4 Thermal efficiency measures for off-highway (including NRMM)

Emissions targets for off-highway and NRMM applications are not as strict as on-highway, particularly with NOx and PM figures. Because of this, R&D emphasis is on primarily reducing fuel consumption while increasing performance and durability, with a reduced focus on lowering emissions.

It is expected that this trend will continue until off-highway and NRMM legislations are updated to make them more stringent and in-line with emissions reductions for on-highway.

Currently, off-highway and NRMM applications conform to specific legislations such as European Commission Stage V non-road emission standards and EPA emissions standards for Nonroad Vehicles and Engines.



Technology pathways

1 Technology pathways (‘car and van’, and ‘HDV, specialist-vehicle and NRMM’)

The automotive industry will see legislation coming into effect globally over the next decade that will impact on the technology pathways shaping future R&D.

These pathways will differ slightly but can be categorised into two main streams of focus: ‘car and van’, and ‘HDVs and specialist and NRMM’.

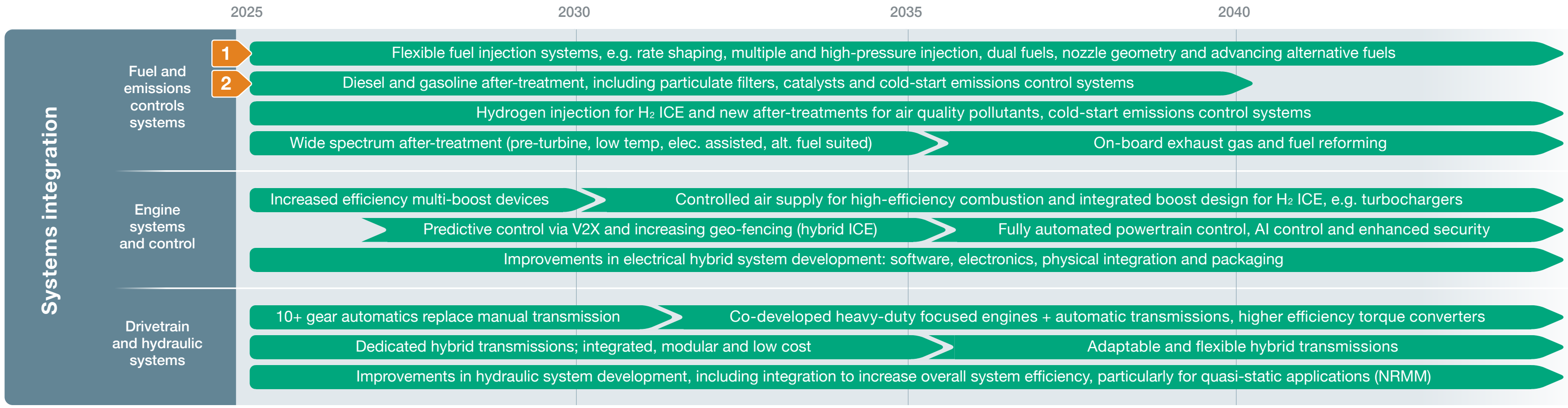
From now until 2030, the general trend seen in engine design is ‘right-sizing’. Simply just down-sizing may not be the right path for all. This applies to both streams and is paired with increasing hybridisation and efficiency in the ICE engine design.

The car and van stream beyond 2030 highlights a focus for hybrid ICE powertrains and an increasing usage of sustainable fuels, such as hydrogen ICE. The ‘sustainable fuels’ section of the accompanying roadmap document details further potential alternatives to fossil fuels that could be used in the future of automotive applications.

The HDV, specialist-vehicle and NRMM stream follows a similar path. However, until 2035 these applications could see a focus on ICE primarily with hydrogen fuel, and limited applications using other sustainable fuels. This is mainly due to current projects already championing hydrogen ICE and development focuses landing elsewhere in this timeframe (engine design, aerodynamics, tyres, etc.).

From 2035, however, this stream realigns with the car and van stream to focus solely on any engine and fuel combination achieving zero emissions.

Hydrogen storage is expected to become a widely used fuel in ICE. The Hydrogen Fuel Cell and System and Hydrogen Storage Roadmap reflects this change with next generation technologies projected to become used in mass-market applications from 2030 onwards, in-line with the timings on the ICE roadmap.



Systems integration

1 Fuel injection systems

As combustion cycles change, new fuels are introduced, high-efficiency gains are targeted and injection systems will continue to develop. Several examples are listed.

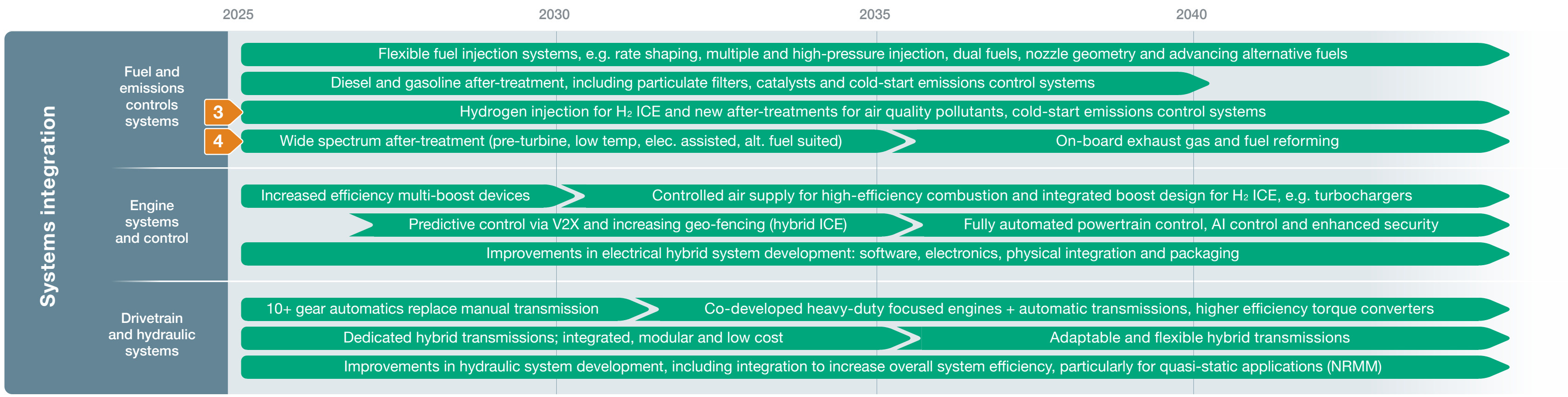
Flexible fuel-injection systems can contribute significantly to the overall performance, efficiency, and environmental impact of an engine, making the technology a crucial component in modern engine design and development.

2 After-treatment for diesel and gasoline engines

For both diesel and gasoline, exhaust gas after-treatments are a priority focus to reduce NOx output at the tailpipe to meet PM and particulate number (PN) regulations. As emission reduction target dates come into force across the globe, it is expected there will be a focus on new, low-carbon and non-fossil-fuel engines, which will heavily reduce R&D efforts around diesel and gasoline after-treatment.

Some examples of diesel after-treatments include diesel particulate filters (DPFs), lean NOx trap and diesel oxidation catalysts.

For gasoline-fuelled engines, potential after-treatments could include active catalytic coating, which reduces gaseous emissions through gasoline particulate filters, three-way catalysts (TWCs) and electrically heated catalysts.



Systems integration (continued)

3 Hydrogen specific injection and after-treatments

Hydrogen is becoming more widely considered as an alternative fuel for engines in light- and heavy-duty applications, but predominantly for off-highway, including NRMM where other technologies, for example, BEVs or FCEVs, may struggle to meet requirements.

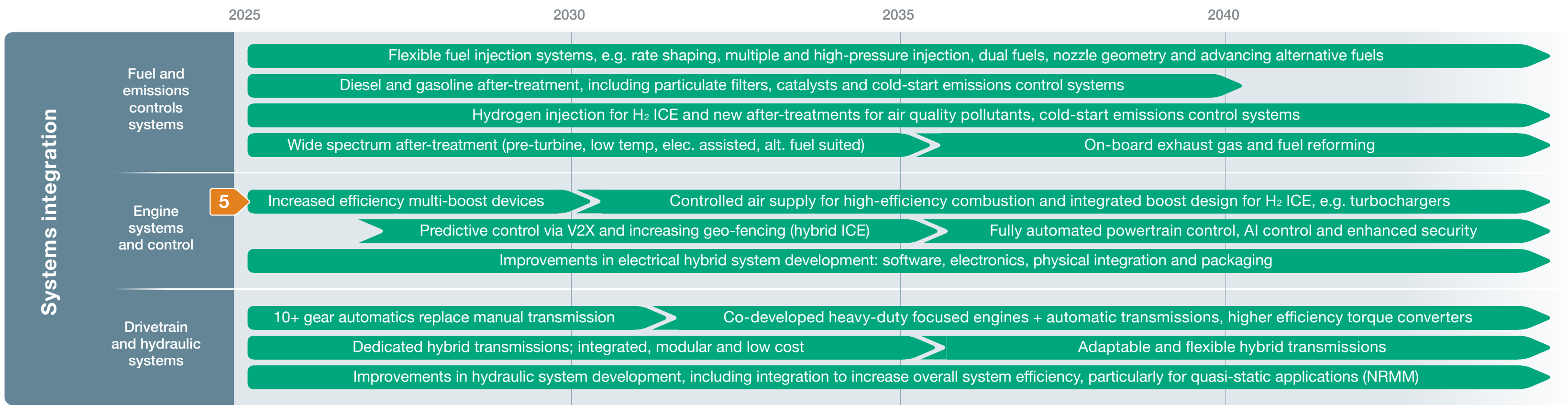
Hydrogen injection in an engine differs from diesel or gasoline injection in many ways, such as in fuel density, suffering from pre-ignition, injection timing and the after-treatments from the NOx emissions left behind post-ignition. The air-fuel ratio is much higher for hydrogen at 34.3:1, compared to diesel at 14.5:1, it runs much leaner, meaning it takes more energy to output a similar amount of energy to diesel.

To enable efficient hydrogen engine designs, research suggests that effective hydrogen injection into the engine will reach mass-market by 2030 onwards. This may vary from port fuel injection (PFI) to direct injection (DI), depending on application and cost specifics. The general trend seen in industry is that there will be more applications using PFI as a cost-saving measure in the short-term, moving initially to low pressure DI, followed by higher pressure DI.

The after-treatments are still highly relevant for hydrogen as, although a more sustainable option than fossil fuels, there are still NOx emissions and other air quality pollutants which can be reduced significantly by applying existing measures, such as exhaust gas recirculation (EGR) or catalytic converters and newer solutions, such as bespoke catalysts for sustainable fuels. Much of the hydrogen ICE after-treatments and emission control is very dependent on local regulations and will be simpler or more complex depending on what they entail.

4 Wide spectrum after-treatments

This refers to the systems which can offer a wider spectrum performance as waste heat declines in the future due to other fuel specific treatments (see lines 2 and 3). Longer-term and very novel technologies are still prevalent in R&D, such as onboard exhaust gas reforming, CO_2 capture and emission management across narrower engine operating ranges, particularly for light-duty applications. Some examples are listed in line 4 of the diagram above.



Systems integration (continued)

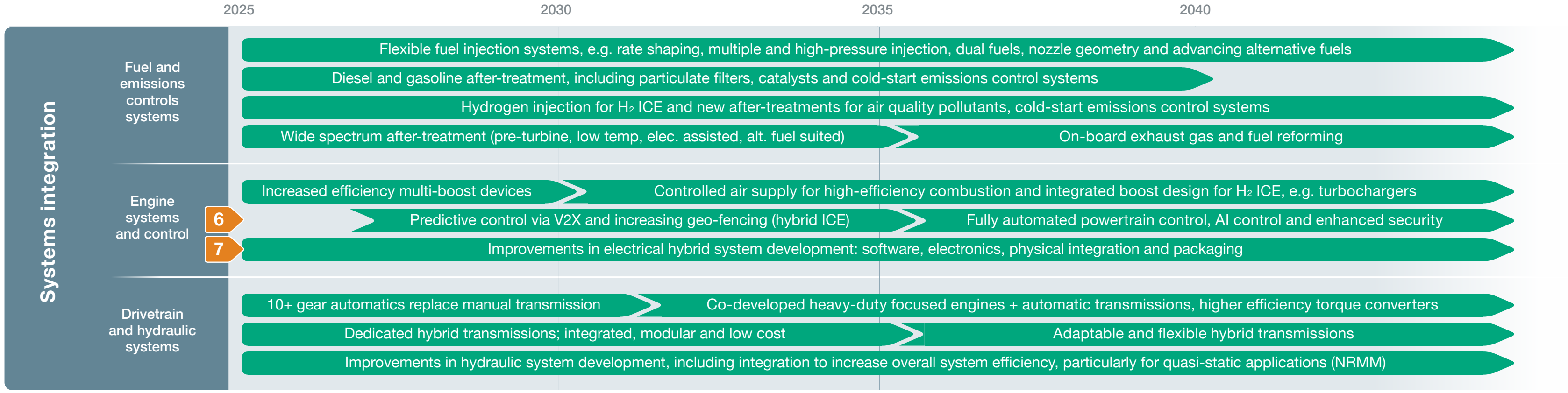
5 Boost devices and technologies

Boost systems provide a wide range of effective operations through combining devices. These devices continue to improve through material and bearing developments (higher temperatures, lower friction).

Boost systems are key for efficiency gains and drivetrain simplification and include multiple boost devices, such as turbochargers and superchargers, or a combination of a few. These devices are continuously being improved, through material and bearing developments, e.g. higher temperatures and lower friction, and this is the primary development focus up to 2030.

E-boosting is a technology being mass-introduced into industry and is enabled with higher voltages (48 V +), complementing the multi-device approach.

Hydrogen-fuelled engines run at lean burn, meaning they have a high air / fuel ratio. The benefit is increased efficiency and better NOx control, however, this requires high- and efficient-boost systems to ensure that the engine receives enough air to ignite the fuel mixture.



Systems integration (continued)

6 Control systems (powertrain, predictive, AI-embedded)

Smart powertrain control is already well implemented within vehicles and is key to improving fuel consumption, particularly with hybrid powertrain setups. V2X allows the vehicle to communicate with various infrastructure components, other vehicles and the internet to identify key information, which is applied to journey planning.

For on-highway, this could include the mapping-out of geographical elevations. This data could then be used, depending on the vehicle architecture, to maximise efficiency. For example, when approaching an upcoming incline, a plug-in hybrid powertrain may opt to use the engine rather than its batteries. For off-highway, including NRMM, when arriving at a site for the first time, the vehicle could capture data of the landscape and use this to generate a plan for optimal engine performance, reducing emissions in daily applications.

Increased levels of geofencing and stricter onboard control will ensure that vehicles with the ability to turn off their engines can do so when approaching low- or zero-emission zones within cities.

Additionally, using forward route planning, the onboard systems could estimate the duration of usage and battery consumption required within the city, ensuring the vehicle has enough charge to accommodate the emissions zone. Adversely, this can also result in a higher emission output before entering the zone as the engine is being run at a higher RPM to generate more electricity. Connected autonomous vehicles, especially level 4[4] and beyond, can make fully-automated powertrain control systems possible, with full harmony across the vehicle, all managed onboard and via V2X.

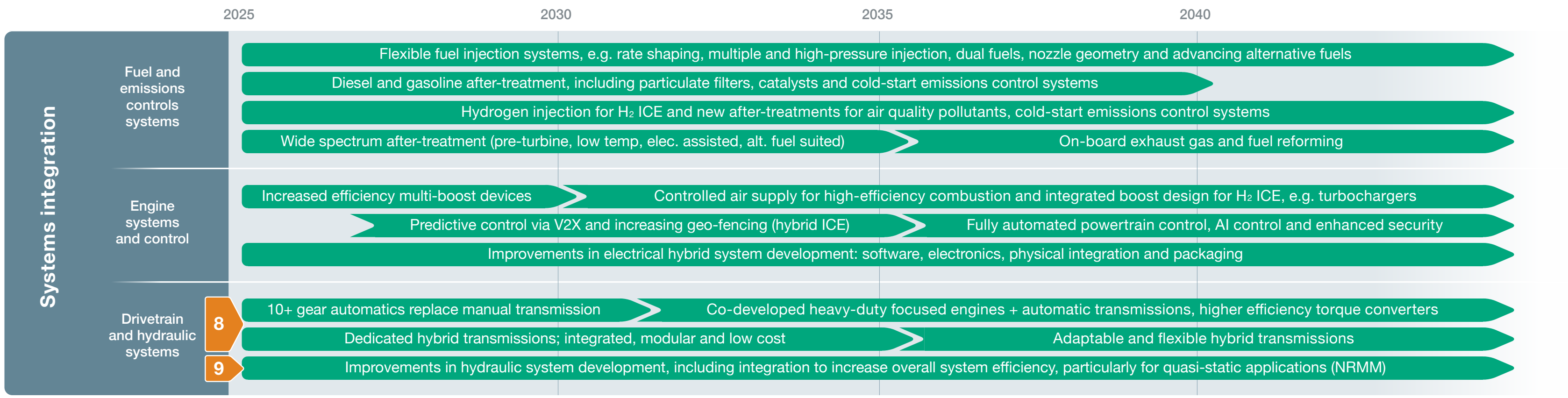
7 Electrical hybrid systems

As hybrid systems become more common in mass-market applications, for light- and heavy-duty applications and NRMM, there is an expectation that there will be continuous collaboration in electrical hybrid system development.

Software, electronics, physical integration and packaging are all crucial elements which can contribute to simplified and harmonised control systems in the future.

Navigating from 2025 through to 2040 and beyond, in a hybrid engine, the overall integration of the ICE and onboard electric powertrain will become increasingly synonymous.

4 https://www.sae.org/blog/sae-j3016-update



Systems integration (continued)

8 Transmissions, torque converters and hybrid transmissions

Transmissions enable optimum engine operations, particularly when moving towards 10+ gear smarter automatic transmissions replacing existing manual transmissions. These new transmissions should operate more closely with the smarter onboard systems, for example, using V2X and powertrain control to manage gear selection.

In light-duty vehicles, these smart transmissions could be multi- and variable-speed transmissions, i.e. continuously variable transmissions (CVTs). For heavy-duty applications, we expect to sees powertrains co-developed by OEMs in collaboration with the specialist heavy-duty engine and transmission supply chain to create an optimal solution.

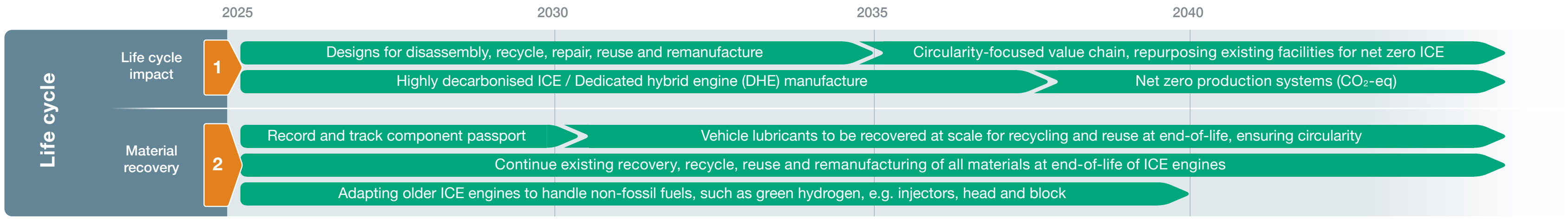
However, certain heavy-duty, off-highway and NRMM applications will continue to have a need for higher efficiency torque converters rather than co-developed transmission and engine combinations.

Hybrid powertrain systems used more frequently in a variety of applications will be more common in the future. To support this, dedicated hybrid transmissions, which are integrated, modular and low-cost, are key in the transition to using hybrids in the majority of applications. Through electrical and mechanical storage, hybrid systems provide greater energy recovery and can offer propulsion assistance to ICE. Similarly to co-developed heavy-duty transmissions, engine and hybrid systems will be developed collaboratively for optimum engine operation enabling low emissions and high efficiency.

9 Hydraulic systems development

To increase systems efficiency in off-highway and NRMM, particularly quasistatic applications, improvements in hydraulic system development must be considered as part of the solution to increasing overall systems efficiency.

Hydraulic systems in off-highway and NRMM often have direct connections with the engine and drivetrain, such as hydraulic pumps powered by the engine, motors integrated into the drivetrain and, in some cases, hydrostatic transmissions, using hydraulic pumps and motors in place of traditional mechanical gearboxes.



Life cycle

1 Life cycle impact

End-of-life in engines, particularly recycling and reuse of parts, is well-established in the automotive supply chain. Ensuring that further engine designs allow for easy disassembly, recycling and remanufacture is crucial, particularly as designs develop and change for new technologies and fuels.

An example is gaseous hydrogen combustion, where fundamental design changes in the block, head and other components, could prevent hydrogen gas leakage. These new designs must continue to consider what happens at end-of-life. Hence, the entire combustion engine value chain can further close the loop on circularity, ensuring that as many parts and as much repurposed material can be fed directly back into the manufacturing process.

Additionally, existing ICE manufacturing plants are expected to repurpose existing facilities to manufacture net-zero combustion and non-fossil fuel engines by 2035 and beyond.

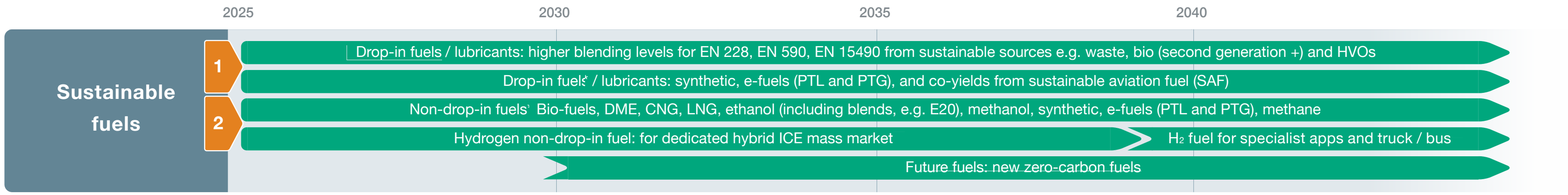
Manufacturing processes and production systems for ICE and dedicated hybrid engines are expected to have significant decarbonisation to further support net-zero emission targets, with the aim for full net-zero CO_2-eq production systems achieved between 2035 and 2040.

Within automotive decarbonisation, powertrain production must also be considered, not just at the tailpipe. The energy consumption of manufacturing plants has a linked carbon footprint and is a priority focus for most OEMs.

2 Material recovery

Recovering materials at end-of-life is crucial to enable a circularity-focused value chain, ensuring there is enough recycled supply returned to the manufacturing process, reducing wastage and maximising net-zero capability. As with all material recovery, there is a shared responsibility for engine design to plan for disassembly and for recyclers at end-of-life to disassemble correctly, for materials and parts to be recycled, reconditioned for second-life, or disposed of in an environmentally-friendly process.

Additionally, at the end-of-life for certain applications and use-cases, it may be more cost effective to adapt older fossil-fuel combustion engines to handle non-fossil fuels, such as hydrogen and fuels with a higher biofuel mix, e.g. E20, E30, rather than manufacturing entire new powertrains. This could range from single components being repurposed, to entire engine systems. Particularly for hydrogen, this will likely be more common in fleets and specialist applications where a new purchase, single or multiple, comes at a significant cost. Vehicle lubricants also must be recovered at end-of-life, ensuring full circularity.



Sustainable fuels

1 Drop-in fuels

Drop-in fuel solutions are an industry focus for the nearer term, with the aim to decarbonise the current global fleet of over 1.2 billion ICE passenger cars. These are low-, net-zero carbon and non-fossil fuels and can be added to or replace existing fuels and work in existing engine systems. Some examples are listed, such as e-fuels, which are generated from electricity-use, to fuels from living waste materials. Bio-fuels can be used for agricultural vehicles, but currently come from a biomass source, meaning a sustainable fuel and heat supply need to be developed.

Production scale-up is a key issue needing to be addressed as some drop-in fuels which could be used today are either expensive to produce and source, or the quantity produced in not sufficient for automotive demand. Synthetic fuels and e-fuels are a viable alternative, however industry must use renewable energy in its production to ensure a net-zero carbon, or non-fossil fuel is produced.

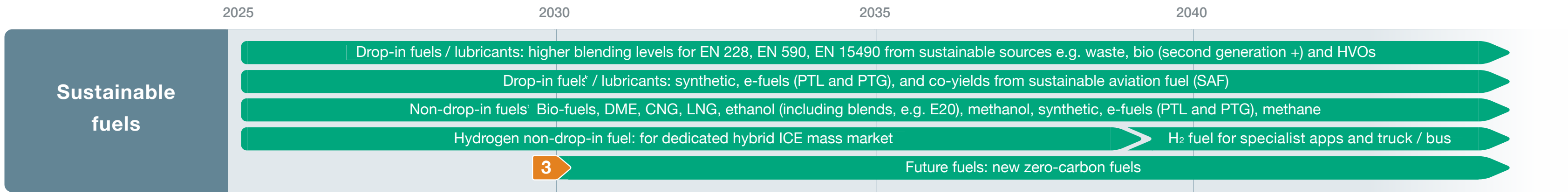
Additionally, sustainable non-polluting lubricants, which may also be known as 'bio-lubricants', are required to support the combustion engine becoming net zero. Some key drivers for these sustainable lubricants are an overall reduced carbon footprint of engine production and use, regulatory compliance and an increased energy efficiency, saving running costs in the long-term. There may also be co-yields from the manufacture of fuels for other industries, such as sustainable aviation fuel (SAF), which would otherwise be wasted. These fuels could be used as drop-in alternatives, to assist in decarbonising existing global fleets.

2 Hydrogen and other non-drop-in fuels

Non-drop-in fuels will be more suitable for niche applications and low-volume markets, and these fuels will be suitable for new specification engines designed today and in the future. These cannot be directly substituted into current ICE systems as they need equipment modification. This can range from a simple modification to the storage tank or injection systems, to a full change to the combustion engine components.

A key non-fossil fuel which is being developed at a much faster pace than other non-drop-in fuels is hydrogen. Hydrogen is usable in two primary applications for automotive: hydrogen combustion and fuel cells. This, coupled with the fact it is a proven fuel in these applications via trials and existing products, enables a much higher level of activity surrounding the fuel, making it a viable alternative to current fossil fuels today.

Low-carbon and net-zero fuels offer a further range of fuel options, including dimethyl ether (DME), a gaseous fuel made from methanol, and several other synthetic or e-fuels. Some non-drop-in-fuels, such as ammonia, are not commercially viable for use today for safety reasons in automotive applications. However, in the near-term, these fuels may be suitable for other applications, such as marine or aerospace, where safety development will take place, making these fuels potentially viable for the future.



Sustainable fuels (continued)

3 Future fuels

These are new fuels that can provide zero-carbon emissions in their operation, but are not currently in widespread use, are not proven to be viable, or are simply not discovered yet.

The automotive industry is still searching to find new combustion-engine fuels, with some OEMs declaring that a BEV-only approach is not realistic. Instead a technology agnostic approach to decarbonisation is more likely, with non-fossil-fuel combustion engines being a part of that future.

Significant research is underway to find alternatives to fossil fuels, which could be introduced with little modification, to benefit from the already well-established supply chain.

Glossary

AFIR	Alternative fuel infrastructure regulation
AI	Artificial intelligence
BEV	Battery electric vehicle
BTE	Brake thermal efficiency
CAD	Computer aided development
CFD	Computational fluid dynamics
CO_2	Carbon dioxide
CO_2-eq	Carbon dioxide equivalent
CVT	Continuously variable transmission
DI	Direct injection
DME	Dimethyl ether
DPF	Diesel particulate filter
EGR	Exhaust gas recirculation
EPA	Environmental Protection Agency
EU	European Union
FCEV	Fuel cell electric vehicle
GHG	Greenhouse gases
HDV	Heavy-duty vehicle
HGV	Heavy goods vehicle
ICE	Internal combustion engines
NEV	New energy vehicle
NFC	Near field communication
NOX	Nitrogen oxides
NRMM	Non-road mobile machinery
ORC	Organic rankine cycle
PFI	Port fuel injection
PM	Particulate matter
R&D	Research and development
RFID	Radio frequency identification
RPM	Revolutions per minute
SAF	Sustainable aviation fuel
TEN-T	Trans-European Network for Transport
TWC	Three-way catalysts
UK	United Kingdom
ULEZ	Ultra-low emission zone
V2X	Vehicle-to-everything
VVT	Variable valve timing
WHR	Waste heat recovery
WLTP	World harmonised light-duty vehicles test procedure
ZEV	Zero emission vehicle

System-Level Roadmaps

Mobility of People

Mobility of Goods

Technology Roadmaps

Electric Machines

Power Electronics

Electrical Energy Storage

Lightweight Vehicle and Powertrain Structures

Internal Combustion Engines

Hydrogen Fuel Cell System and Storage

Find all the roadmaps at

www.apcuk.co.uk/technology-roadmaps

automotive council UK

ADVANCED PROPULSION CENTRE UK

Established in 2013, the Advanced Propulsion Centre UK (APC), with the backing of the UK Government's Department for Business and Trade (DBT), has facilitated funding for 304 low-carbon and zero-emission projects involving 538 partners. Working with companies of all sizes, this funding is estimated to have helped to create or safeguard over 59,000 jobs in the UK. The technologies and products that result from these projects are projected to save over 425 million tonnes of CO_2.

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