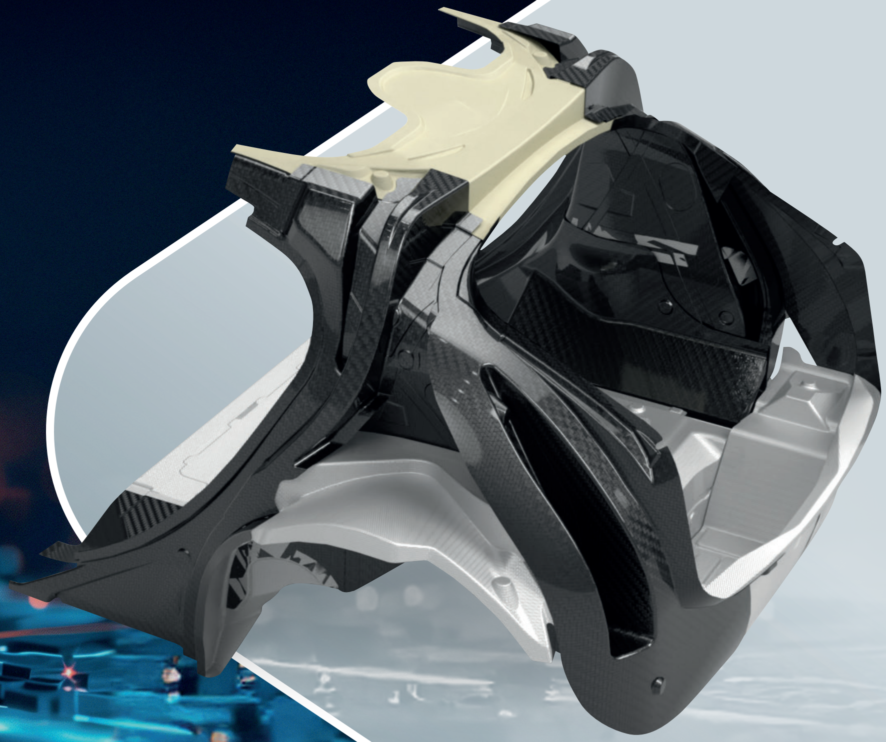
Lightweight Vehicle and Powertrain Structures

Narrative Report

2024



automotive council UK

ADVANCED PROPULSION CENTRE UK

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

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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.

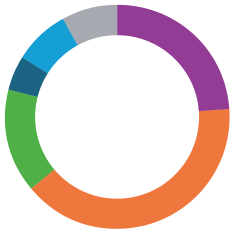
1.3 Building a consensus

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.

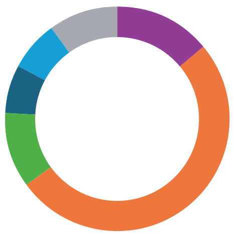
As a result of this consultation across industry and academia the 2024 roadmaps build on previous versions and demonstrate the significant change that is happening across the automotive sector and its supporting industries.

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)

Professor Geoffrey Scamans
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(on behalf of the composites leadership forum vehicular composites group)

Dr Hadi Moztarzadeh
Advanced Propulsion Centre UK

The Automotive Council Lightweight Vehicle and Powertrain Structures Roadmap through its sequential iterations has demonstrated the latest advancements in lightweighting technologies and guided innovation and R&D projects in crucial areas such as development of low embodied carbon aluminium sheet, extrusion and structural casting alloys for applications across different vehicle types.

These capability developments and the resulting future investments in UK materials and manufacturing capabilities provide the opportunity for the supply of low embodied carbon products that meet and, in most cases exceed, the sustainability requirements of all the major automotive Tier1s and OEMs.

We welcome the updated version of the lightweighting roadmap developed by the APC UK, on behalf of industry, and looking forward to working and collaborating with all industry and research and innovation stakeholders to realise the opportunities identified in the roadmap.

The 2024 update of the lightweight vehicle and powertrain structures roadmap reflects the growing importance of whole life environmental impact through electrification and alternatives to fossil fuels. Lightweighting innovation remains a key strategy to enhance both performance and efficiency with forecasts given by vehicle sub-system.

Design, material and manufacturing considerations are detailed, with transitions of emphasis as technologies mature. Key updates include the use of sophisticated analytical tools for optimisation, refinement and the use of AI. Design for disassembly, resource efficiency, additive manufacturing and supply chain resilience are identified as key innovative steps.

Since the last update, sustainability considerations are commonplace for OEMs, Tier 1, academia and beyond. In this revision material circularity through increasing levels of secondary content (including closed loop supply chains) is gaining focus for metals, polymers and composites.

In 2020, the APC on behalf of the Auto Council, published a lightweighting technology roadmap for Automotive industry, covering a range of technology themes and sub-themes around vehicles and powertrain structures, manufacturing processes and materials to reduce weight for more efficiency vehicles systems.

We have covered a broad range of themes with regard to design-led, material-led and manufacturing and processing-led developments and approaches to lightweighting, to improve efficiency, material circularity across the entire vehicle value chain.

Compared to 2020 roadmap, we have expanded the scope of the lifecycle impact and material recovery and included carbon intensity, environmental impacts, resource consumption and recyclability across the automotive supply chain.

We would like to thank industry, academia and the entire automotive ecosystem for their continued support and inputs into the technology roadmap and looking forward to working with the automotive manufacturing supply chain to build and strengthen capabilities and competencies for the future of the automotive sector in the UK, towards a net zero and sustainable automotive and transport industry.

1.4 Lightweight Vehicle and Powertrain Structures – overview

In recent decades, the automotive industry has come to rely on a just-in-time global supply chain. Global events, such as the COVID-19 pandemic and geopolitical conflicts, have impacted the security and reliability of this global supply chain. This has raised concerns about the dependence on lowest-cost sourcing and highlighted the need to address environmental impacts. Governments are reacting to supply-chain vulnerabilities and addressing environmental concerns by introducing legislation, for example on end-of-life to increase recycling and re-use of materials. This is encouraging more local supply chains and changing how materials are sourced and selected.

Overview: Lightweighting

Advanced materials and manufacturing processes

There is a growing demand for recycled materials and sustainable products, driven by consumer preferences for greener goods. This demand is likely to increase regardless of legislation and, as Original Equipment Manufacturers (OEMs) become more environmentally conscious, the transition to lower-embedded CO_2 materials and products will become a necessity.

Within this context, greenhouse gas (GHG) emissions are categorised into three scopes: Scope 1 - direct emissions occurring from sources within an organisation, Scope 2 - indirect emissions associated with energy consumption and Scope 3 - indirect emissions occurring in the value chain of the organisation, upstream and downstream emissions.

Advanced materials, including high-strength steels, aluminium alloys and composites, continue to play an important role depending on the requirements of the sectors. By replacing traditional steel components with lightweight materials, vehicle weight can be reduced, leading to improved fuel efficiency.

For example, large aluminium castings, also known as giga / mega castings, are seen as a way to reduce manufacturing costs. This does not always translate to reduced weight, but does lead to a reduction in the number of parts, which in turn reduces manufacturing complexity and production costs. This move is being welcomed by an increasing number of OEMs. Conversely, large-cast parts present a challenge simply because their size represents higher replacement costs should damage occur when compared to smaller parts.

Mass reduction and efficiency

Lightweight materials play a crucial role in hybrid electric, plug-in hybrid electric and electric vehicles, offsetting the weight of power systems like batteries.

The reduction of vehicle weight generated by lightweight materials can also help with the integration of safety features onto a vehicle, such as improved crashworthiness technologies. The integration of advanced-connectivity, autonomous driving features and related electronics in vehicles necessitates lightweight materials to accommodate the additional components without compromising overall weight.

The rise of shared-mobility services, such as ride-sharing and car-sharing, is expected to increase demand for lightweight materials. Lighter vehicles are more fuel-efficient, reducing operating costs for service providers and minimising environmental impact.

A priority highlighted in the roadmap workshops is the importance of efficiency. In general, vehicle weight is not reducing. Efforts to reduce mass in one component are offset by increases elsewhere. Evolving safety standards and advanced driver-assistance system (ADAS) features are adding extra weight. ADAS technology can require power of up to 3 kW and also involves keeping the equipment clean, which necessitates implementing a 40 litre tank onto a vehicle. Therefore, considering efficiency, e.g. drag and rolling resistance, at the design stage is critical, and even more so for the heavy-duty vehicle (HDV) sector.

Addressing life cycle impact

In the current landscape, the adoption of advanced lightweight materials is largely influenced by cost considerations. As individual materials approach their performance limits, there is growing interest in combining the strengths of different materials within a single application. These multi-material solutions not only enhance performance, but have the potential to significantly reduce lightweighting costs. Looking ahead, the multi-material approach is expected to dominate, although challenges related to assembly-line joining technology, material separation and recyclability at end-of-life need to be solved. After separating, these materials should be recycled. However, it can be challenging to grade materials for future use, which can lead to down-cycling instead of recycling for automotive use. Simplification and standardisation of material grades would support an increase in secondary-material usage.

With so much choice in materials and ways of producing parts from those materials, it is becoming evermore complex to understand how that will change the life cycle impact of a vehicle.

Design decisions are often based on a limited understanding of the interactions with other sub-systems that will impact the life cycle analysis (LCA). Digital tools are offering greater flexibility in design to optimise on cost and weight. In the era of the fourth industrial revolution (Industry 4.0), artificial intelligence (AI) is playing a major part in vehicle design. Deep learning and generative design technology can help, via algorithms, select the right material in the right place to reduce weight and improve the performance of a vehicle and vehicle components. Additionally, LCA can be included in the first steps of the design process. The carbon footprint (often represented by CO_2 equivalent in tonnes) of a given part can be estimated by using LCA alongside the material selection. This analysis would include the impact of raw-material manufacturing, material transport, production-processing, use-phase and end-of-life.

An emerging trend is designing vehicle-chassis components for greater lifespan and reuse. Trends in ownership of vehicles are changing, shared mobility could see increased usage of vehicles, so durability will be important. Another potential trend is the reuse of certain chassis components to refresh vehicles. If the chassis is durable enough, powertrain components, infotainment systems, and even body panels, could be swapped to refurbish a vehicle before that vehicle sub-system is considered for recycling.

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

Passenger cars and light commercial vehicles (vans) are respectively responsible for around 16% and 3% of total EU emissions of carbon dioxide. To help reduce emissions, the EU introduced Regulation (EU) 2019/63, setting CO_2-emission performance standards for new passenger cars and vans. The amended Regulation (EU) 2019/631 of April 2023, targets a 55% reduction in net greenhouse-gas emissions by 2030 compared with 1990, as well as achieving climate neutrality by 2050, in line with the European Climate Law. This regulation has driven the adoption of lightweight materials and technologies to reduce vehicle weight and improve efficiency. Reduction of vehicle weight also helps reduce the emissions of particles from brake and tyre wear.

The EU directive 2000/53/EC on end-of-life vehicles (ELV Directive) sets clear targets for ELVs and their components. The use of hazardous substances, e.g. lead, mercury, cadmium and hexavalent chromium, is banned during vehicle manufacturing, except in defined exemptions when there are no adequate alternatives. It also stipulates that M1- and N1-category vehicles may be put on the market only if they are reusable and / or recyclable to a minimum of 85% by mass and are reusable and / or recoverable to a minimum of 95% by mass. The EU directive 2005/64/EC addresses the type-approval of motor vehicles with regard to their reusability, recyclability and recoverability.

A UK carbon border adjustment mechanism (CBAM) will be introduced from January 2027. Consultation for this completed in June 2024. There is a risk with decarbonisation that it undermines carbon leakage, which is the movement of production and associated emissions from one country to another due to different levels of decarbonisation effort through carbon pricing and climate. The UK CBAM will be a charge on the emissions embodied in relevant UK imports and will apply to several sectors including aluminium, iron, steel and glass (which includes glass fibres used in the field of polymer composites).

Circular economy principles aim to minimise waste and maximise resource efficiency, with design-for-circularity principles being developed for lightweight materials and components. However circularity can increase weight. An EU circular action plan exists to achieve full circularity for aluminium by 2030.

Efforts have been applied to develop standardisation and certification to ensure safety, consistent quality and performance of lightweight materials, so they can be introduced to existing and new markets. For example, ASTM and ISO standards exist to ensure quality assurance of new materials. ISO 14001 sets the standard for environmental management systems. This certification is for organisations wanting to reduce waste-management costs and show commitment to protecting the environment. Additionally, Composites UK, the trade association for the UK composite industry, published the 'Sustainability Good Practice Guide' in November 2022 to support the industry in adopting sustainable practices. This guide aims to provide comprehensive advice on how to minimise the environmental impact of composite materials throughout their life cycle, from production to end-of-life. The expectation is that polymer composites will face similar requirements to plastics in the EU. Currently, 25% of plastic used to build a vehicle has to come from recycled materials, of which 25% must have originated from end-of-life vehicles.

Future mobility regulations will need to be introduced to address the challenges and opportunities presented by new mobility trends such as ultralight vehicles, in response to the need for sustainable urban developments. For urban mobility and micromobility, regarding shared-mobility services, regulations will focus on regulating ride, bike and scooter-sharing services to ensure they operate safely and efficiently within urban areas.

2.2 | Energy and infrastructure

The automotive industry is increasingly adopting lightweight materials, such as aluminium and polymer composites, to improve fuel efficiency, reduce emissions and enhance performance. This shift necessitates specific energy and infrastructure considerations to support the production and utilisation of these materials.

The production of aluminium is highly energy-intensive, primarily due to the electrolysis process used in refining alumina into aluminium. However, recycling aluminium requires significantly less energy, about 5% of the energy needed for primary production. The production of polymer composites involves processes such as resin-synthesis, fibre-production (glass and carbon fibres) and composite manufacturing (autoclave-cure process and compression moulding). These processes can also be energy-intensive, especially when high-performance materials are involved.

Regarding process optimisation, implementing energy-efficient technologies and process optimisation can reduce energy consumption in the production of aluminium and composites. For example, there are development technologies moving away from standard polyacrylonitrile (PAN) by advancing new precursors to produce carbon fibres. Additionally, using renewable energy sources, such as hydropower for aluminium production and solar or wind energy for composite manufacturing facilities, can significantly lower the carbon footprint.

Aluminium is produced by converting from alumina through the Hall-Héroult process, which involves electrolysis. Smelters are equipped with electrolytic cells (pots) where alumina is dissolved in moulten cryolite and subjected to electric current, reducing the alumina to aluminium. Smelting is highly energy-intensive, requiring a stable and substantial electricity supply. Many smelters are located near power plants, especially hydroelectric plants, to ensure a reliable energy source.

Electric arc furnaces (EAFs) are playing a crucial role in the production of green steel (steel produced with a significantly reduced carbon footprint). This process primarily involves the recycling of scrap-steel and, increasingly, the use of direct reduced iron (DRI) produced with green hydrogen. Green hydrogen refers to hydrogen gas produced through electrolysis, where water is split into hydrogen and oxygen using electricity generated from renewable energy sources such as wind, solar, or hydroelectric power.

For polymer-composite manufacturing, advanced manufacturing processes, such as automated fibre placement (AFP) and resin transfer moulding (RTM), need the right facilities such as freezers for prepregs and ovens for curing or post-curing. All of these demand electric power. These facilities also require the right infrastructure for the collection of composite waste. This waste will be separated, sorted and recycled. Recycling processes for carbon-fibre reinforced plastics (CFRPs) are mainly pyrolysis-based, both in the UK and overseas, and are also energy intensive. Hence, it is crucial to include all of these steps in the life cycle impact of composite-structure manufacturing. In the future, the infrastructures for composite-waste collection will need to be expanded.

There is a focus on achieving net-zero production which is not possible in all regions at this time. This could impact the movement of supply chains to regions able to decarbonise quickly.

2.3 Materials and manufacturing

The manufacture of aluminium is a complex process involving numerous stages and specialised infrastructure. Significant investment in technology and facilities is required. The different steps include mining and refining bauxite, to smelting alumina into aluminium and afterwards there is further processing into finished products.

Continuous advancements in technology and processes aim to improve efficiency, reduce environmental impact and enhance the quality of aluminium products. The manufacture of green aluminium, also known as low-carbon aluminium, aims to significantly reduce the environmental impact of the aluminium-production process. Green-aluminium production includes sustainable raw-material extraction, which entails using advanced mining technologies that minimise land disruption as well as reduce water and energy usage. It also encompasses energy-efficient refining and smelting processes, extensive recycling and the use of renewable energy.

By investing in advanced technologies, renewable energy sources and sustainable practices, the aluminium industry can significantly reduce its environmental impact and contribute to a more sustainable future. Additionally, the manufacture processes for aluminium include mega- and giga-casting, which refers to advanced manufacturing techniques involving the production of very large aluminium components in a single-casting process. These techniques are disrupting automotive manufacturing by improving efficiency, reducing production costs and enhancing the structural integrity of components.

Arc furnaces, specifically EAFs, are critical in the production of low-carbon aluminium. While EAFs are traditionally used in steelmaking, they can also be adapted for aluminium production, offering significant environmental benefits, especially when combined with renewable energy sources. Additionally, high-strength metal composites, e.g. net-shape technology, are also being developed.

Polymer composites are composed of a polymer matrix (thermoset resins or thermoplastic polymers) reinforced by fibres (carbon, glass, aramid or natural fibres) to tailor materials with enhanced mechanical properties, such as strength, stiffness and durability. There is more and more emphasis on sustainable materials.

Bio-resins such as bio-epoxies and polyfurfuryl alcohol (PFA) are increasingly used in the composite field. The latter is derived from sugar-cane waste. Regarding fibres, more commercial applications promoting flax-fibre composites are appearing. One issue regarding flax fibres is the supply chain, since they are not grown in enough quantities in the UK. To improve the sustainability aspect of composite manufacturing, it is key to understand and improve the UK-based supply chain for bio-based matrices and fibres. Additionally, life cycle assessment of polymer composites can show that material systems offering the greatest mass reduction may not offer the best sustainable option since the global-warming potential (calculated CO_2-eq) from cradle-to-cradle of the composite part may be higher than that of a composite part weighing more. An example would be to compare a carbon fibre / epoxy composite with a glass fibre / bio-epoxy composite.

One way to determine what aspects of composite-structure manufacturing a Tier 1 supplier or an OEM wants to focus on would be to run a Pareto-front study. This analytical approach is used to identify the most efficient solutions in multi-objective optimisation problems. It focuses on finding a set of solutions where no other solution is better in all objectives, known as Pareto-optimal solutions or the Pareto front, e.g. mass reduction versus global-warming potential versus performance.

The technologies used to manufacture polymer composites can vary depending on the application. The technology spectrum ranges from hand lay-up using a bucket and a brush, to advanced depositing technologies such as AFP. Other technologies (non-exhaustive list) are RTM, compression moulding (sheet-moulding compounds (SMCs) or prepregs), vacuum infusion with liquid resin, vacuum bagging using prepregs (cure cycle in an oven or an autoclave), filament winding, automated tape laying (ATL) and pultrusion. After curing of the composite part, other processes take place such as trimming and cutting, using computer-controlled machines such as CNCs and water jets.

Most composite structures require protective coatings and painting for aesthetics. One of these coating processes is called e-coating, also known as electrocoating or electrophoretic painting, and is widely used in the automotive industry. It is a method of applying a protective and decorative coating using an electrical current, which provides a uniform, durable and corrosion-resistant finish. The process includes oven-curing, which takes place between 180°C and 220°C (depending on an OEM's e-coat parameters). This can be challenging for some composite materials since they must display a high enough glass transition temperature (T_g). Joining techniques for composite parts include adhesive bonding, mechanical fastening and welding. Non-destructive testing is often applied for quality control. For example, ultrasonic testing inspects internal structures without damaging the part. For circularity purposes, waste-management, including systems for collecting, sorting and recycling waste materials to minimise environmental impact, should be paramount. The development and use of net-shape manufacturing processes also enable reduction of waste production. End-of-life (EOL) processes for polymer composites are essential for managing the environmental impact of these materials. Given the complexity and variety of polymer composites, these processes aim to recover valuable materials, reduce waste and minimise environmental damage. While mechanical and thermal-recycling are currently the most widely used methods, chemical recycling and the development of biodegradable composites offer promising solutions.

2.4 | Digitalisation

Digitalisation in the field of lightweight materials involves integrating digital technologies to enhance efficiency, productivity and sustainability throughout the production process. This involves advanced tools such as the internet of things (IoT), sensor technology, big data analytics, AI, machine learning (ML), automation and robotics, digital-twin technology, and supply-chain integration to optimise operations, reduce costs and improve product quality.

Analysis-led design (ALD) focuses on using engineering analysis and simulation throughout the design process to guide and inform design decisions. It enables the development of high-performance, cost-effective and innovative structures. This approach entails the integration of analysis early and continuously, ensuring that the design is validated and optimised from the beginning. Finite element analysis (FEA), computational fluid dynamics (CFD) and multi-body dynamics (MBD) are implemented to evaluate design performance. They focus on critical aspects such as stress, thermal performance and aerodynamics. These methods can help reduce the mass of a vehicle body-in-white (BIW), optimise the vehicle aerodynamics and its crash safety. These approaches not only enhance vehicle quality, but also contribute to sustainable and efficient manufacturing processes.

Material tracking and passports will take on a greater level of importance in Industry 4.0 manufacturing and supply chain management. They ensure transparency, traceability, and compliance throughout the life cycle of materials and products. A material passport is a comprehensive digital record of materials used in a component, detailing its characteristics, origin and life cycle information. It serves as a 'passport' that travels with the material, providing essential data for the supply chain across countries or within the same country. It can enable better decision-making and promote a circular economy. As the automotive industry keeps prioritising sustainability and regulatory compliance, the adoption of material tracking and passports is expected to grow, driving innovation and enhancing overall operational management.

ML is transforming manufacturing automation by enabling systems to learn from data, adapt to new conditions and optimise processes in ways that traditional automation cannot. ML algorithms analyse historical and real-time data enabling improvements in automotive manufacturing processes as well as generating cost savings. Throughout constant iterative learning, the manufacturing equipment, e.g. joining robot using adhesive, can determine if the manufacturing step is a pass or a fail, hence, quality control can be improved. ML models analyse product images or sensor data to detect defects and ensure quality control. ML can also optimise manufacturing processes.

Different vendors of vehicle parts may use different data formats, which could cause a significant challenge when it comes to feeding the data into a model for process control. Integrating data from different vendors into a cohesive format suitable for feeding into a process-control model involves several critical steps: data collection, integration, preprocessing, validation, storage and feeding. Ensuring that appropriate tools and technologies are implemented at each step enables data quality and consistency as well as the effective use of ML for manufacturing process control.

Additionally, there is a growing trend for collecting increasing levels of data from a vehicle, including monitoring the lifetime or fatigue of its components. Data management needs to be scalable to implement data checks enabling automated processing and integration via interoperable systems that adapt to changing data needs.

3 | Narrative to roadmap

3.1 | Lightweight Vehicle and Powertrain Structures – technology indicators

Light- and heavy-duty vehicles

These technology indicators represent opportunities to reduce mass across vehicle sub-systems with the recognition that this is part of managing a weight budget and trade-offs are made across the vehicle depending on application, performance needs, cost, and the addition of new features. These technology indicators represent an industry consensus, from application to application there could be significant deviation. Fuel cell powertrain is not included due to its relative maturity in lightweighting compared to BEV and ICE powertrains.

Overall vehicle mass may increase to meet performance, cost and life cycle targets.

Manufacturing emissions targets

The indicators represent CO_2-eq reduction targets for vehicle manufacturing (Scopes 1 and 2), these targets do not include vehicle use or end-of-life.

		2025	2030	2040
Light-Duty Vehicles	Body (% change)	BASELINE	-15 to 0	-35 to -10
	Chassis (% change)	BASELINE	-10 to 0	-25 to -10
	Interior (% change)	BASELINE	-5 to 0	-15 to -5
	ICE powertrain (% change)	BASELINE	-5 to 0	-10 to -5
	BEV powertrain (% change)	BASELINE	-10 to +10	-20 to -10

		2025	2030	2040
Heavy-Duty Vehicles	Body (% change)	BASELINE	-10 to 0	-20 to -5
	Chassis (% change)	BASELINE	-5 to 0	-10 to -5
	Interior (% change)	BASELINE	-5 to 0	-10 to -5
	ICE powertrain (% change)	BASELINE	-3 to 0	-5 to 0
	BEV powertrain (% change)	BASELINE	-5 to +10	-15 to 0

	2025	2030	2035	2040
Manufacturing emissions targets	BASELINE	> 20% reduction	> 50% reduction	> 90% reduction

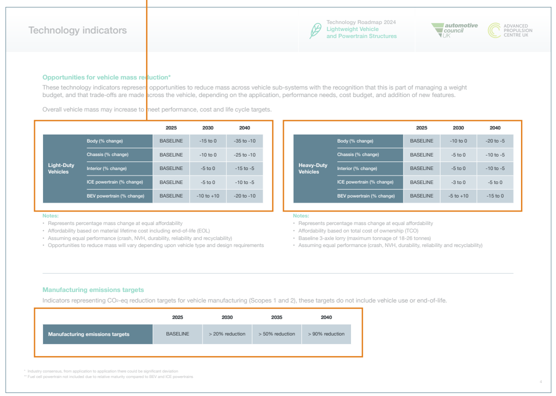
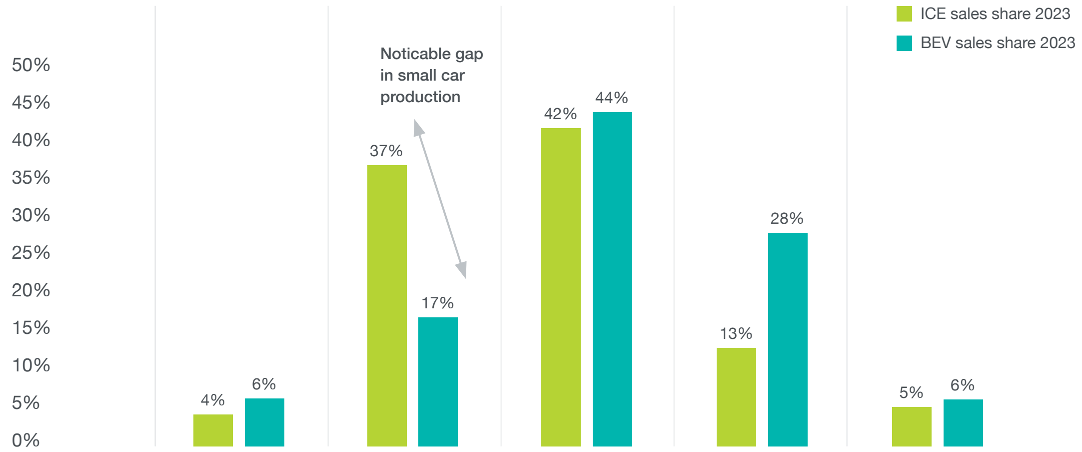


Figure 2 shows the current differences in vehicle size and where there are gaps. Some vehicles are not being produced with battery-electric powertrains because they are not yet cost-effective. However, the manufacturing of battery-electric segment B vehicles is increasing. This is because manufacturing and battery costs are decreasing thanks to the implementation of modular platforms.

Figure 2 : ICE and BEV sales based in vehicle sales segment for UK and EU



Segment	A	B	C	D	E
Existing vehicle model examples					

Source: https://www.transportenvironment.org/articles/carmakers-are-failing-to-deliver-affordable-electric-cars-holding-back-ev-adoption-analysis

3.2 | Lightweight Vehicle and Powertrain Structures – technology themes

The next few pages of this report will look in-depth at each section of the Lightweight Vehicle and Powertrain Structures Technology Roadmap so it is recommended you have the document to hand. However, for ease of reference the relevant page of the roadmap is pictured.

Roadmap technology themes

(Click underlined links to jump to sections)

Design-led

Design-led approaches cover vehicle architectures and new mobility concepts with change being driven by new manufacturing concepts and advances in the application of simulation and AI.

Material-led

Body, chassis, closures and glazing make up the majority of the traditional lightweighting approach for mainstream manufacture. High-strength materials, increasing mixed-material structures, new joining methods and increasing adoption of composite materials for high-volume production are the areas expected to provide the greatest benefits.

Powertrain systems for internal combustion engine (ICE), battery electric and fuel cell vehicles have the potential for reduced weight. These include design concepts that reduce material usage such as further integration of batteries into vehicle structures and further usage of materials offering weight savings.

Electrical architectures can contribute up to 5% of the vehicle mass. This is an area starting to see greater focus with cost opportunities aligning with weight opportunities.

Interior structures represent a wide-range of lightweighting opportunities and additionally provide a customer-facing. point of difference. These include material selection and new design paradigms.

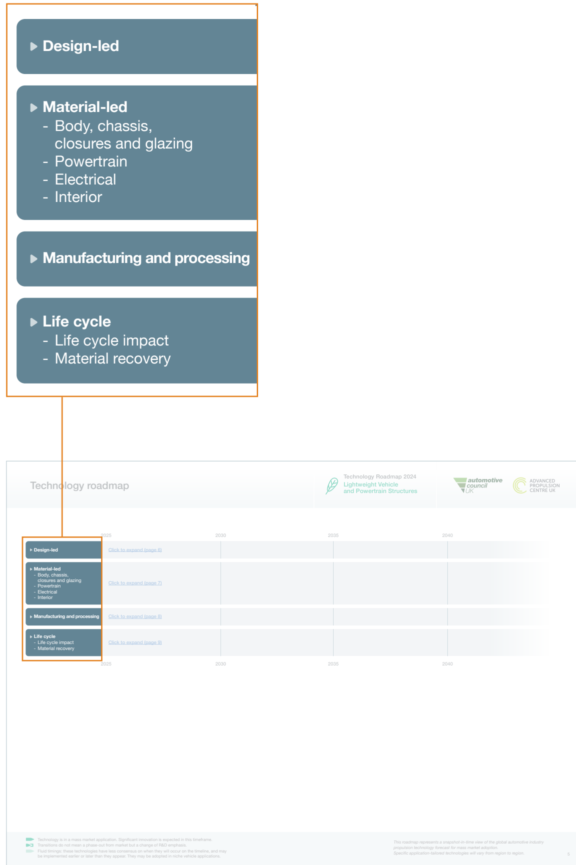
Manufacturing and processing

Manufacturing and processing developments are key to making many lightweighting strategies become a reality at scale. The implementation of digital tools and AI to optimise design and manufacturing processes is a key development.

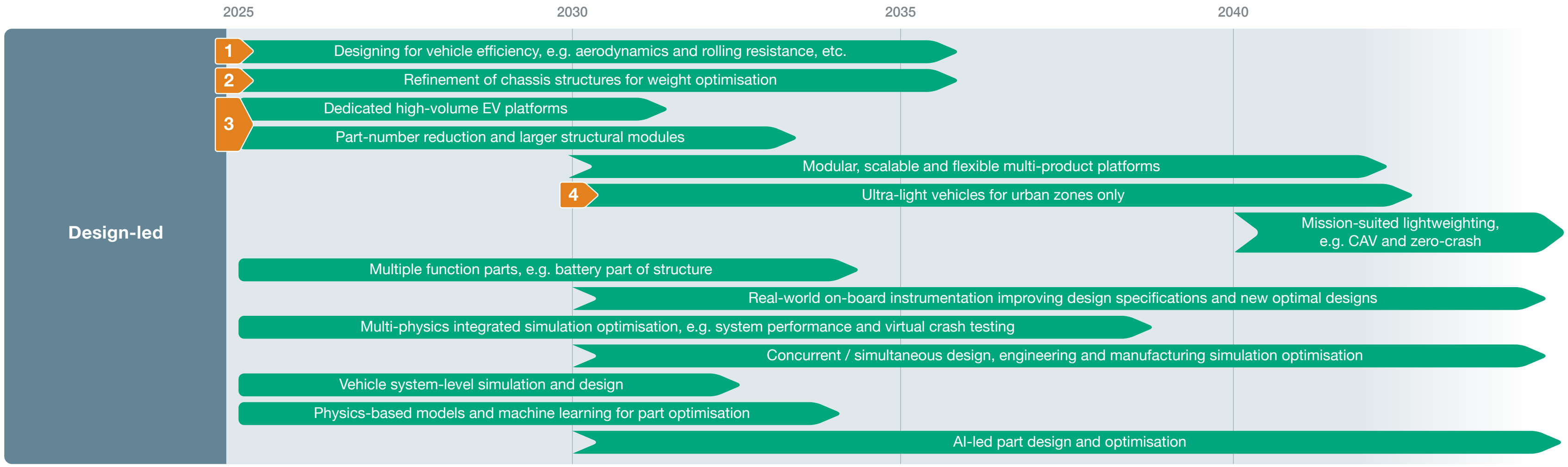
Life cycle

Life cycle impact includes the carbon intensity, environmental impact, resource consumption and recyclability of electric-vehicle structures and their supply chains.

Material recovery details the development of closed-loop material recycling from new recycling methods through to adoption.



This section looks in detail at the line-by-line activity on the Lightweight Vehicle and Powertrain Structures Executive Roadmap. The numbers will direct you to the line being discussed here in detail.



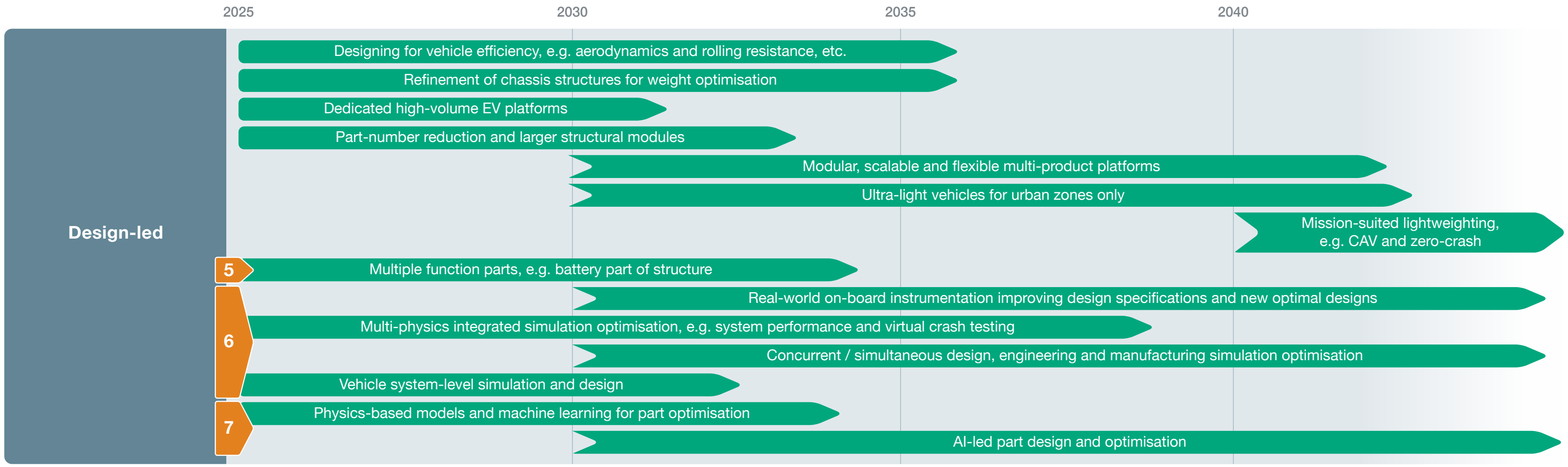
Design-led

1 While not relating to lightweighting, this is important with regard to air-particulate regulations, especially HDV applications. Designing vehicles for efficiency is essential for addressing environmental challenges, achieving economic benefits, complying with regulations, driving technological innovation and enhancing consumer satisfaction. As the automotive industry continues to evolve, prioritising vehicle efficiency will remain a key factor in ensuring long-term success and sustainability.

2 Optimising weight does not always mean reducing weight, particularly when thinking about HDVs and non-road mobile machinery (NRMM). New materials and material combinations allow for design refinements in the chassis structure and optimise the vehicle weight. This may lead to weight savings, but it can also be moving weight to where it is needed.

3 OEMs are moving to dedicated EV platforms, or skateboard models, which allow for reduced parts, and weight. Large structural modules, e.g. mega- and giga-castings, are growing in use. However, it does not always mean weight reduction is achieved. Part and cost-manufacturing reductions are nonetheless obtained, although there is a risk of increased in-use costs of repair. There is an argument that recyclability is improved by having large single-material / monolithic parts. This would enable more efficient design for disassembly. In the near future, some flexible multi-product platforms will allow easier switching between models being produced on the same line. These platforms would enable switching from battery electric vehicles (BEVs) to fuel cell electric vehicles (FCEVs).

4 Higher uptake of urban-zone-only vehicles will increase demand for lightweight materials. Autonomous zones, where only lightweight autonomous vehicles are allowed, should see reduced crash-performance requirements enabling further mass-reduction of those vehicles and more novel designs.



Design-led (continued)

5 There is an increased use of parts to meet multiple functional requirements. The integration of multiple functional parts into single components, for example, if the battery were to be integrated in the main body of the vehicle, represents a significant advancement in vehicle design. It entails challenges in material development, safety, manufacturing complexity and cost. However, the potential benefits in terms of weight reduction, performance improvement, cost efficiency and environmental impact are significant. An example is integrating cooling systems with those of heating, ventilation, and air conditioning (HVAC).

6 The combination of simulation and real-world data from embedded sensors will be used to optimise designs and shorten time to market. Currently, this is mostly achieved at a part or sub-system level. More complex simulation and modelling allow for vehicle system-level design optimisation. When simulation is combined with data from available manufacturing techniques, it enables full-vehicle manufacturing optimisation to be carried out. Niche / high-performance OEMs are able to do this sooner as they can be more flexible in their manufacturing.

7 Part-design and material choices are driven by physics-based models and ML using a combination of tools. From 2030 AI will be leveraged to create new designs beyond those possible using ML models only. However, the energy consumption of using sensors on a vehicle would need to be considered. Also, heat is generated by these sensors, hence an adequate thermal management needs to be in place.

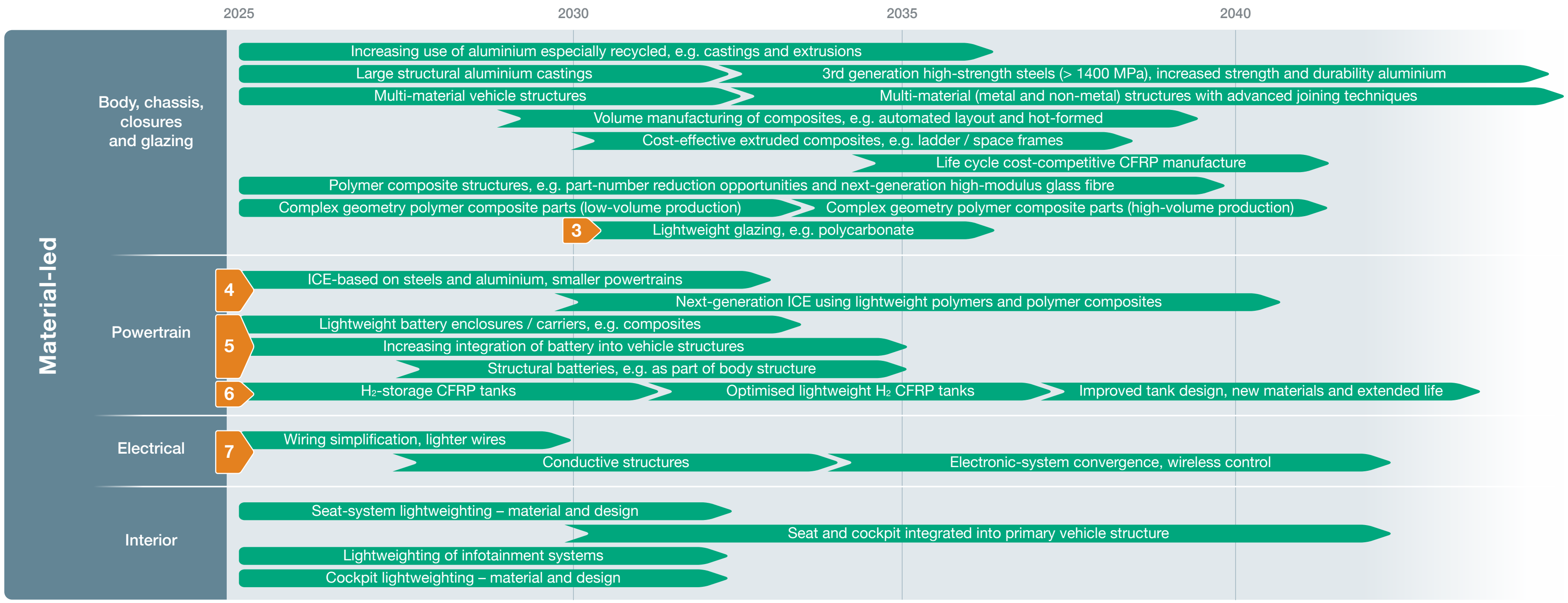
Material-led

1 Large structural castings are the mega- and giga-castings, which are typically applied to aluminium. There is also an increased use of recycled aluminium throughout the structure. New advanced high-strength steels continue to be developed as a way to maintain strength where needed. However, it still allows for a reduction in mass and cost.

2 The technologies used to manufacture polymer composites can vary depending on the production volume and targeted market. The technology spectrum ranges from hand lay-up using a bucket and a brush, to advanced depositing technologies, such as automated fibre placement (AFP). For example, extruded polymer composites offer a cost-effective solution for various applications due to their enhanced mechanical properties, durability, and versatility. The development and use of net-shape manufacturing processes, such as AFP and ATL, enable reduction of waste products. However, advanced automated lay-up techniques are not yet cost-effective enough for low-production volumes. Resin transfer moulding (RTM), compression moulding, e.g. using SMCs or prepregs and 3D printing are examples of processes which can be used to manufacture complex geometry polymer-composites parts.

For higher volumes, ATL, ATP, compression moulding and high-pressure resin transfer moulding (HP-RTM) are the preferred processes. Polymers used in these processes are required to display fast cure-cycles. Thermoplastic stamping, where thermoplastic composite sheets are heated and then stamped into shape using a press, is also increasingly common. Thermoplastic composites offer advantages at the recycling stage of a structure as it can be remelted, reshaped and / or blended with another polymer. There is more emphasis on multi-material structures. This is based on the concept of using the right material in the right place. However, this could lead to life cycle impact challenges due to the need to separate different materials at end-of-life.

Joining techniques for composite and multi-material parts include adhesive bonding, mechanical fastening and welding. The use of adhesive helps reduce weight on a body structure and aids the disassembly process. However, it is important to understand and take into account the environmental impact of using such adhesive resins when designing the vehicle in the first place. Welding technologies for polymer composites, such as ultrasonic or laser welding, are essential for creating strong, durable joints, without the need for adhesives or mechanical fasteners.



Material-led (continued)

3 For glazing application, glass can be replaced by other transparent and resilient materials, such as polycarbonates. These materials can help reduce weight during the design stage. Vehicle headlights can be manufactured from polycarbonate polymer. For bigger glazing surfaces, they are more likely to be used in high-performance and ultra-light vehicles.

4 Next-generation ICEs will have adaptations for e-fuels. Regulations still need to be clearly defined in Europe. Outside of Europe there is potential, e.g. Brazil is already using bio-derived fuels. However, NRMMs and agriculture applications will still have ICE in this timeline.

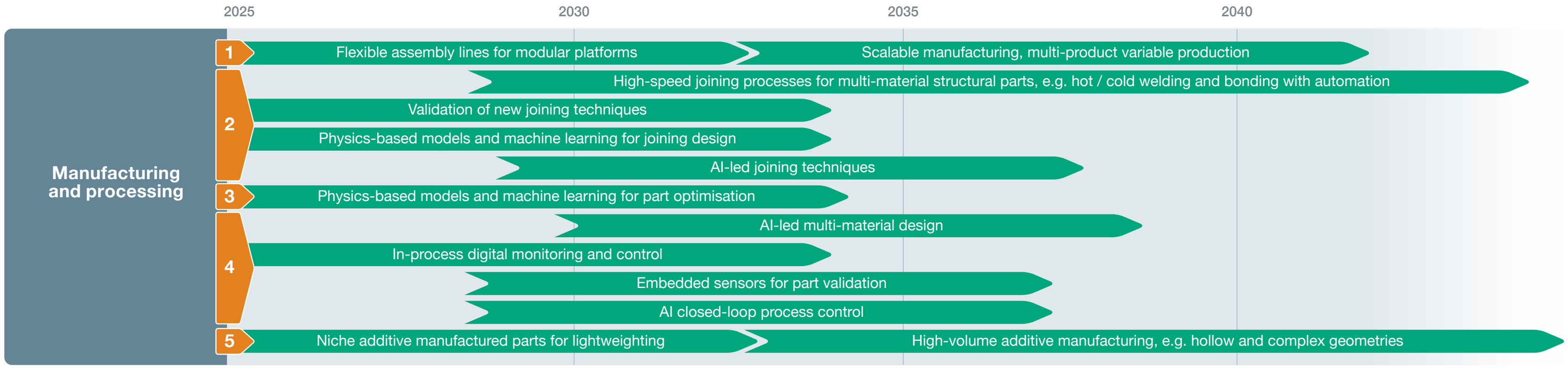
5 Composites are being more widely adopted for battery-pack enclosures to reduce weight. For example, bio-based composites composed of PFA are developed for these applications. There is a growing trend of further integrating battery modules and cells directly into a vehicle to reduce part numbers and, therefore, weight. However, this is not suitable for all applications and has end-of-life implications.

6 CFRPs are key materials used in the production of hydrogen tanks due to their exceptional strength-to-weight ratio, durability and resistance to high pressures. Hydrogen tanks are critical components in fuel cell vehicles and CFRPs offer significant advantages over traditional materials like steel or aluminium. Type III and IV tanks use CFRPs (refer to the Hydrogen Fuel Cell System and Hydrogen Storage Technology Roadmap).

7 As more electrical components are added, particularly with a growing move towards greater autonomy in vehicles, wiring mass tends to increase. To counteract this increase, alternative materials and designs are being deployed. These include conductive structures, e.g. embedded strips, functional integration of different systems and further adoption of wireless systems. Wiring accounts for around 5% of the vehicle mass and, with a trend increasing wiring mass due to additional features, there is definite opportunity in rationalising wiring harness designs.

Material-led (continued)

8 A primary driver for interiors is sustainability rather than lightweighting. There is a trend to select more natural-based solutions, moving away from leather. However, material and design choices can reduce weight. CFRPs can be used for interiors, which can account for 5% of the mass, so there are opportunities, e.g. trends in electronics miniaturisation. Additionally, the integration of seat and cockpit structures into the BIW structure for new vehicle architectures, particularly for ultra-light vehicles, is occurring. This reduces part count, improves manufacturability and reduces weight.



Manufacturing and processing

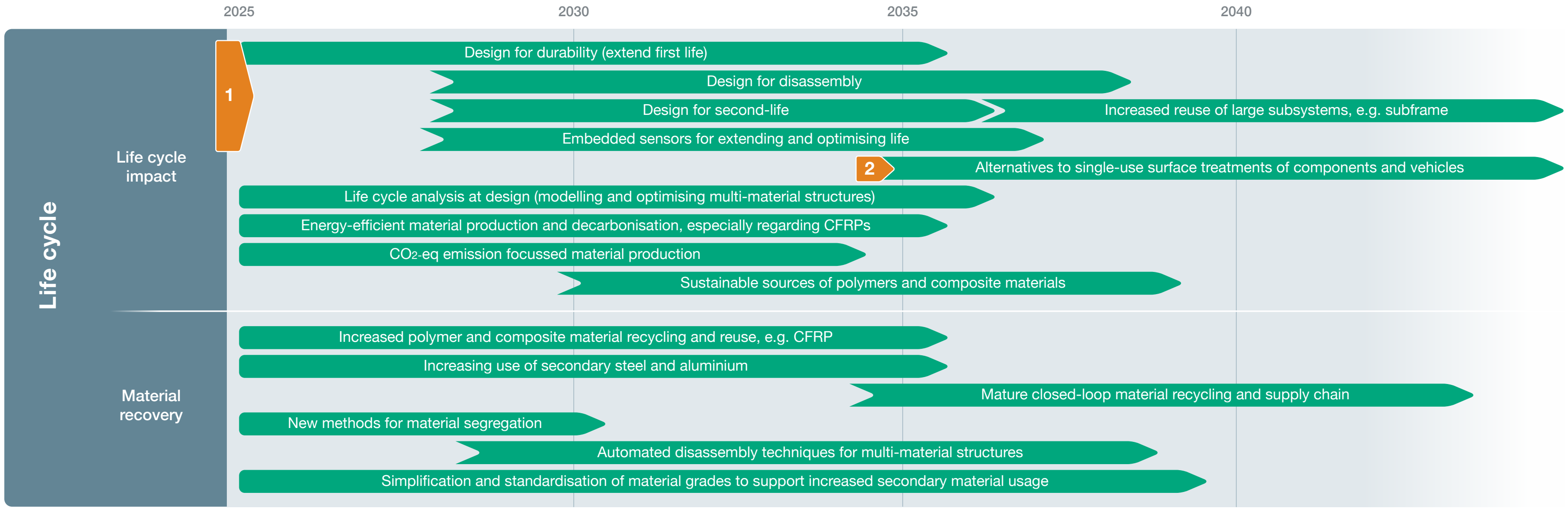
1 Modular designs require a modular manufacturing method, which is the most complex part of achieving this goal. Coming up with the design is one step, however creating a cost-effective multi-product modular production line is very difficult. This approach has been successfully demonstrated in China.

2 Joining stands out as a major focus area to enable multi-material structural and functional parts. This will require new techniques to be developed and validated, which will be achieved with the use of digital tools and AI. There is more focus in mainstream automotive applications on welding techniques (laser welding) for metallic and multi-material (metal / polymer composite) structures.

3 Analysis-led design of composite materials is an approach enabling advanced computational tools and methodologies to optimise the design and performance of composite structures. This approach is crucial for maximising the benefits of composite materials, such as tailored mechanical properties. Additionally, there are opportunities to generate greater implementation of multi-material solutions via the use of physics-based models and AI.

4 Manufacturing efficiency can be improved via the use of in-line process monitoring and control. Sensors embedded into parts during manufacture can provide additional data. In addition, non-destructive sensing techniques, e.g. Eddy-current and infrared systems, deployed on-line in real-time, are important for monitoring the health and integrity of structures and components. AI can provide full closed-loop control leveraging all these data.

5 Additive manufacturing is already used in niche applications and for some small parts in mass-volume manufacturing. It is expected that cost barriers can be overcome to realise high-volume additive manufacturing applications. For example, hollow structures, which can be metallic lattice structures produced by laser-sintered additive manufacturing, can offer mass savings on a vehicle component.

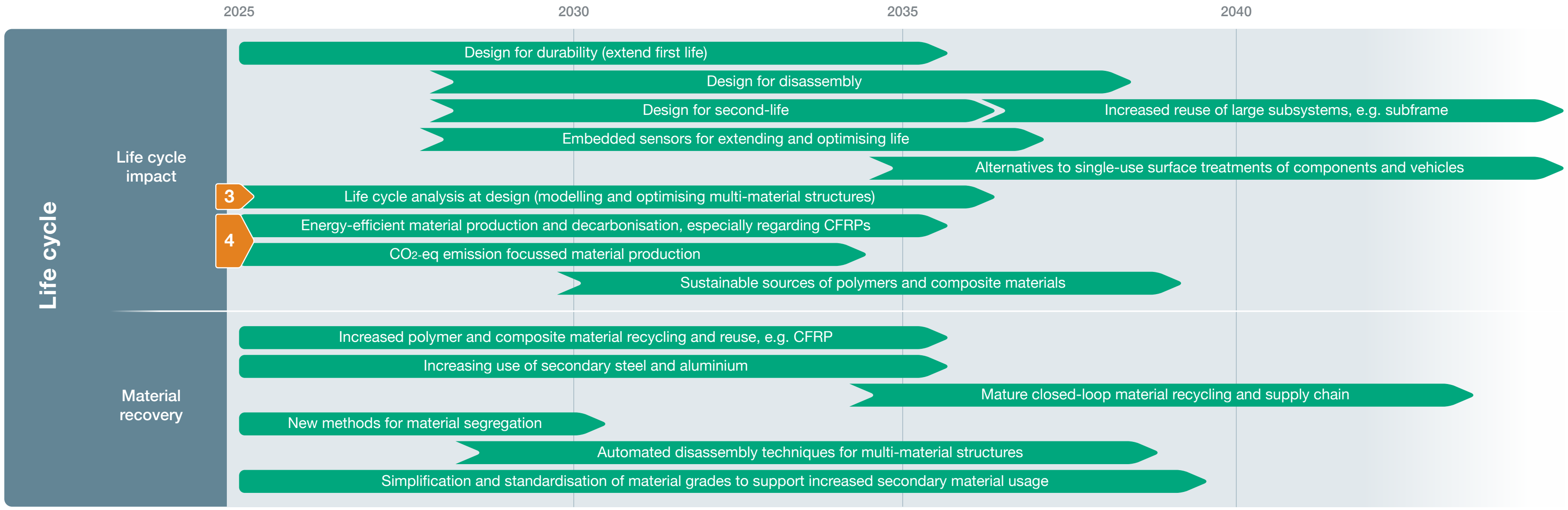


Life cycle

1 Due to the growing emphasis on regulations, cost-efficiency and sustainability, designing for durability, disassembly and reuse is increasingly critical for vehicles. Reducing the need for new vehicles and extending the lifespan of current vehicles helps lower the environmental impact associated with manufacturing and disposal. To enable a vehicle to be taken apart at the end of its life cycle is crucial for efficient recycling, repair, and maintenance. Designing for easy disassembly from the start of the process facilitates the separation and recycling of materials, reducing waste and the need for virgin materials. Reusing sub-systems and materials reduces the demand for new raw materials, which in turn enables savings in natural resources and energy. These steps enable the transition to a circular economy. Additionally, these design principles help manufacturers comply with increasingly strict environmental regulations and standards, such as the European Union's ELV Directive.

Embedded sensors in vehicles extend and optimise their product lifespan by providing real-time data on various systems and components. This information enables predictive maintenance, improved performance, enhanced safety and efficient operation. However, as highlighted earlier in this narrative report, the sensors require energy to function and generate heat, which can be contrapositive.

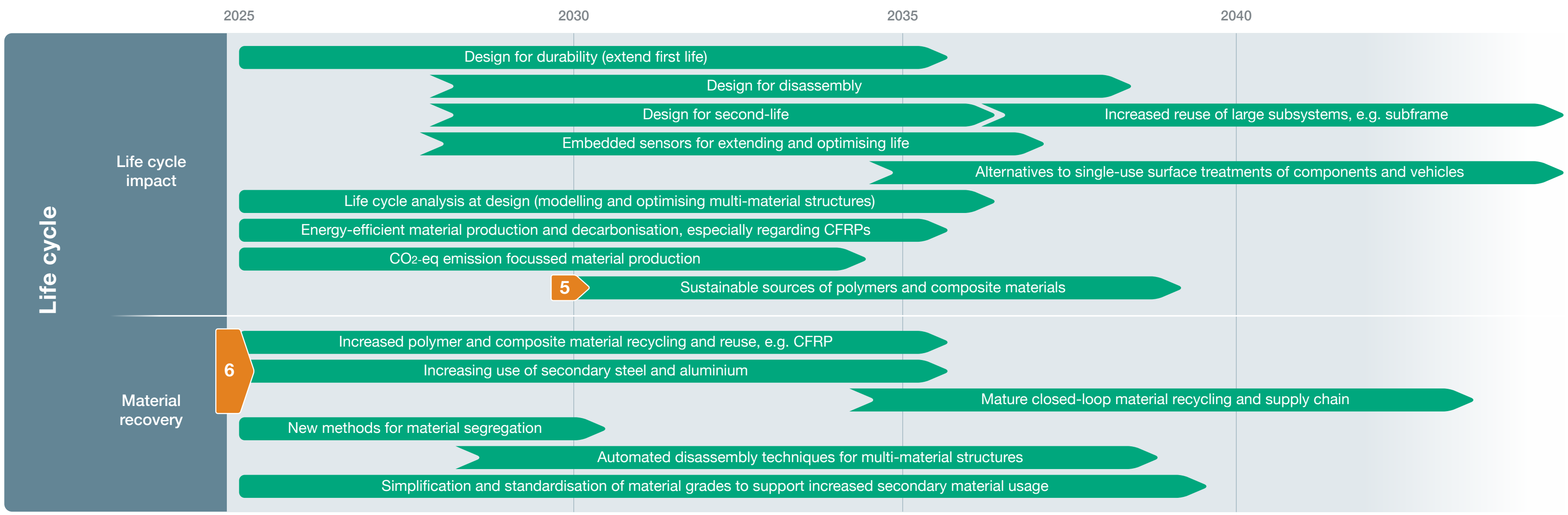
2 Paint is a major contributor to the life cycle impact of vehicle production. The painting process in vehicle manufacturing significantly impacts the carbon footprint due to the energy-intensive nature of paint application and curing, e.g. electrocoating / e-coat process. Addressing these challenges involves optimising processes, adopting sustainable materials, e.g. bio-based solvents and integrating advanced technologies. Potential alternatives to single-use surface treatment like paint, such as powder-coating, physical vapour deposition (PVD) and self-healing coating, are being developed.



Life cycle (continued)

3 LCA is a method for assessing the environmental impacts associated with all stages of a product life, from cradle-to-grave or even from cradle-to-cradle. Integrating LCA at the design phase will help optimise material choices and design. In general, LCA is focused on production, however, it will continue to develop to encompass a more holistic approach to the full life cycle. The carbon footprint (often represented by CO_2 in tonnes) of a given part can be estimated by using LCA alongside the material selection. This analysis would include the impact of raw-material manufacturing, material transport, production processing, use phase and end-of-life.

4 Decarbonisation of material production and improving the energy efficiency are paramount for improving the sustainability around part manufacturing. Decarbonisation of material production through the use of microgrids is a promising approach to reduce GHG emissions and improve energy efficiency. Microgrids are localised grids that can operate independently or in conjunction with the main power grid. They integrate various distributed energy resources (DERs), such as renewable energy sources, e.g. solar and wind, energy storage systems, and advanced control systems to produce reliable and sustainable power. There is a focus on achieving net-zero production which is not possible in all regions at this time and this may see some movement of supply chains to regions that can decarbonise quicker.

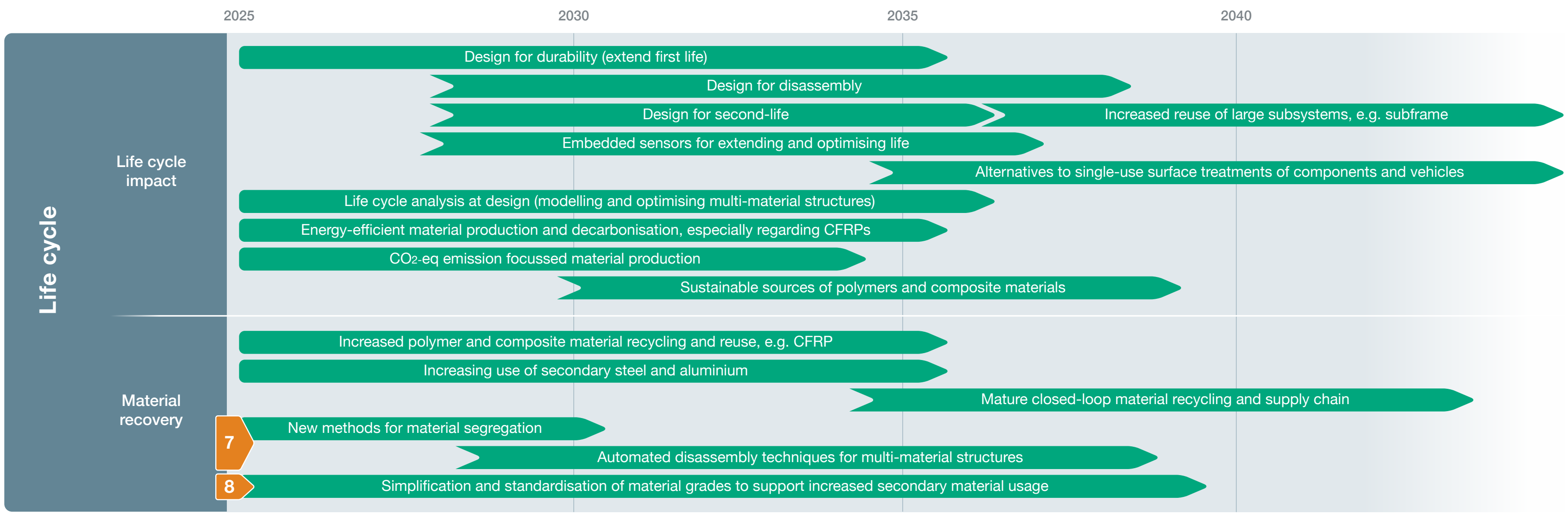


Life cycle (continued)

5 There is more and more emphasis on sustainable materials. Bio-resins such as bio-epoxies and PFAs are increasingly used in the composite field. The latter is derived from sugar-cane waste. Regarding fibres, more commercial applications promoting flax-fibre composites are appearing. One issue regarding flax fibres is the supply chain since they are not grown in big enough quantities in the UK. To improve the sustainability aspect of composite manufacturing, it is key to understand and improve the UK-based supply chain for bio-based matrices and fibres. Additionally, LCA of polymer composites can show that material systems offering the greatest mass reduction may not offer the best sustainable option since the global-warming potential (calculated CO_2-eq) from cradle-to-cradle of the composite part may be higher than that of a composite part weighing more. An example would be to compare a carbon fibre / epoxy composite with a glass fibre / bio-epoxy composite.

6 Increasing the recycling and reuse of polymer and composite materials in the automotive industry is essential for achieving sustainability and reducing the environmental impact of vehicle production and disposal. Materials, such as fibres and fabrics, can be reclaimed, recovered and reused in their original state, e.g. virgin carbon-fibres recovered from dry fabric. Materials can also be recycled and undergo a recycling process (mechanical or thermal). Thermal recycling technologies, e.g. pyrolysis, water solvolysis and fluidised-bed process for CFRP components, enable the automotive industry to move towards a more circular economy. Recycled fibres can be used in a different format, e.g. long discontinuous carbon fibres integrated in a non-crimp fabric. There is however, a need to have consistent and reliable composite recycling processes in the UK to ensure continuity in the supply chain.

Many OEMs have committed to increase their use of secondary steel and aluminium in vehicle production. The recycling process for aluminium involves several key steps such as shredding, densification, cleaning and melting. Material recycling not only offers benefits for the environment, but it also provides economic advantages and helps manufacturers comply with regulatory requirements. More recycling and more use of recycled material leads to a closed-loop supply chain. Closed-loop recycling, where reusing recycled materials within the same manufacturing process or product line, is becoming more common. The challenge here will be achieving cost competitiveness but this is expected as the recycling becomes compulsory. It is paramount that the waste from one industry will be the feedstock for another with some raw material always needed to feed the loop.



Life cycle (continued)

7 The increased use of multi-material structures, methods to segregate different materials, has become paramount. These technologies need to be energy-efficient without impacting too heavily on Scope 3 of a component, especially at end-of-life. There is a counter-intuitive end-of-life penalty to reducing weight using multiple materials.

8 Closed-loop circularity in manufacturing requires the use of fewer grades of material. When recycling is done via a spoke and hub model, vehicles are broken down with parts sent to a hub for recycling, these grades become mixed. Therefore, they become unusable in a new product without extra effort to regenerate a suitable grade. Simplifying grades to enable recyclers to produce material grades that multiple manufacturers could buy with confidence, would improve the economics of recycling and using recycled materials.

Glossary

ADAS	Advanced driver-assistance system
AFP	Automated fibre placement
AI	Artificial intelligence
ALD	Analysis-led design
ATL	Automated tape laying
BEV	Battery electric vehicle
BIW	Body-in-white
CBAM	Carbon border adjustment mechanism
CFD	Computational fluid dynamics
CFRP	Carbon-fibre reinforced plastic
CNC	Computer numerical control
CO_2	Carbon dioxide
CO_2-eq	Carbon dioxide equivalent
DER	Distributed energy resource
DRI	Direct reduced iron
EAF	Electric arc furnace
ELV	End-of-life vehicle
EOL	End-of-life
EV	Electric vehicle
EU	European Union
FCEV	Fuel cell electric vehicle
FEA	Finite element analysis
GHG	Greenhouse gas
HDV	Heavy-duty vehicle
HP-RTM	High-pressure resin transfer moulding
HVAC	Heating, ventilation, and air conditioning
ICE	Internal combustion engine
IoT	Internet of things
LCA	Life cycle analysis / assessment
LDV	Light-duty vehicle
MBD	Multi-body dynamics
ML	Machine learning
NDT	Non-destructive testing
NRMM	Non-road mobile machinery
NVH	Noise, vibration, and harshness
OEM	Original equipment manufacturer
PAN	Polyacrylonitrile
PFA	Polyfurfuryl alcohol
PVD	Physical vapour deposition
R&D	Research and development
RTM	Resin transfer moulding
SMC	Sheet moulding compound
T_g	Glass transition temperature

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

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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.

The APC would like to acknowledge the extensive support provided by industry and academia in developing and publishing the roadmaps.

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