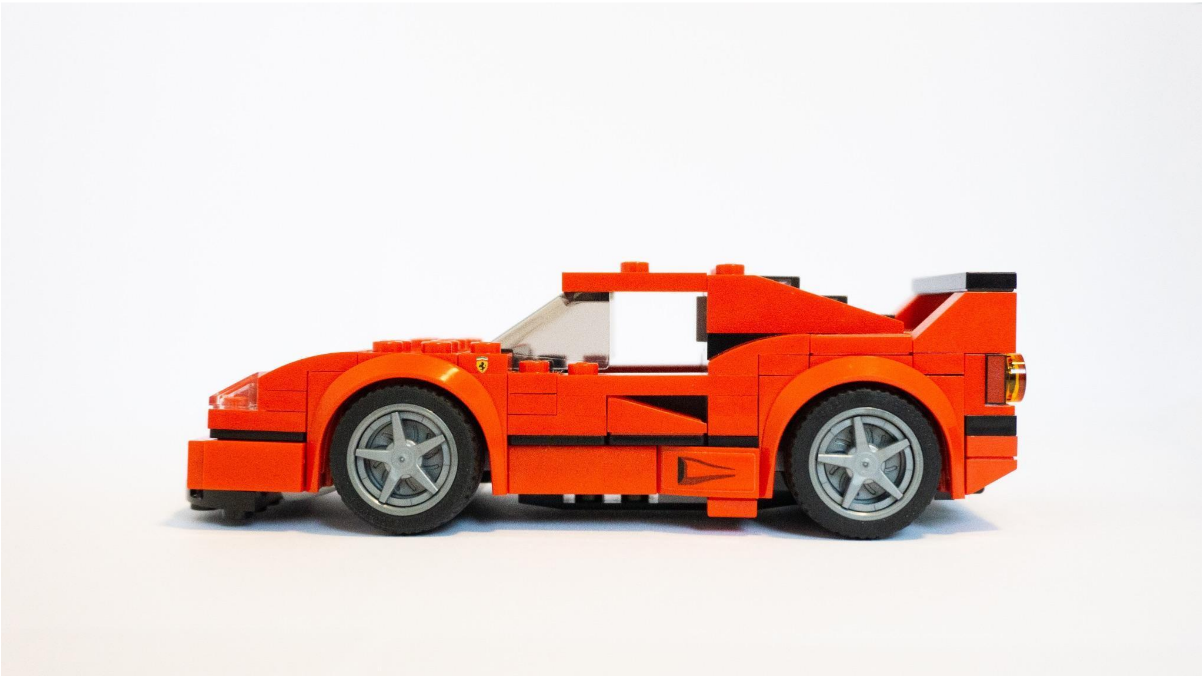
A critical review of plastics and circularity in automotive supply chains



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Summary

Plastics are increasingly used in the automotive sector due to their mechanical properties and light weight. However, the automotive plastic supply chain is characterised by pollution, resource depletion, and high carbon emissions. This critical review provides an understanding of how *transitioning to a circular supply chain can reduce the impact of plastic use in the UK automotive industry?*

The review contains three sections: Section 1 provides an overview of plastic use in the automotive sector and introduces the lifecycle and supply and demand of automotive plastics, in addition to outlining the review methodology and key terms; Section 2 summarises the current state of automotive plastics, focusing on raw material extraction, produce and use, and end of life; and Section 3 discusses options for change to improve the circularity of the automotive plastics supply chain.

Key takeaways identified in this critical review include:

➔ Currently there is a lack of dynamic Material Flow Analysis (MFA) models which specifically track automotive plastic flows in the UK. Therefore, results are inferred from data about material quantities and wider scope MFA studies. Better data collection including detailed breakdowns of plastic types would enable sector specific MFA studies in the future.

➔ There is a lack of granularity of plastic types in Life Cycle Assessment studies and reports of material breakdowns. Plastics are often grouped as one material in Life Cycle Assessment studies and studies that report vehicle material breakdowns. Identification and reporting of specific polymer types in material breakdowns is required.

➔ Current studies are lacking in downstream product use coverage. Information provided in case studies of plastic use from vehicle manufacturers is typically not detailed. Specifically, the quantity of plastics that use circular techniques (e.g., biosourced plastics, recycled plastics in new components) is not specified.

➔ The circularity of automotive plastics can be improved by reducing the number of polymer types, implementing design principles that enable easy disassembly, and using non-petroleum-based materials.

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Section 1: An overview of plastic use in the automotive sector

Plastic is a revered industrial material with advantageous mechanical properties. In vehicles, plastics are used due to their light weight, resistance to corrosion, durability, and design flexibility (Martinez Sanz et al., 2022). However, the automotive plastic supply chain is characterised by pollution, resource depletion, and high carbon emissions. Plastic use accounted for 4.5% of global greenhouse gas emissions in 2015; plastic production is responsible for the majority of these emissions (96%), with smaller contributions from end-of-life processes (Cabernard, Livia, and Pfister, 2022). Despite the sizeable environmental impacts, global demand for plastics has quadrupled over the past four decades and is projected to continue to increase in the future; an estimated 8,300 Mt has been produced to date (Geyer, 2017). Plastic use is however important in modern economies; 2.3% of the global workforce is employed in plastic production which results in 2.6% value added to global GDP (Cabernard, Livia, and Pfister, 2022)

The automotive sector is a large user of plastic, comprising 10% of overall global plastic demand (van Bruggen et al., 2022). Plastics are an important material in the automotive sector due to their low mass and performance-related benefits for lightweighting, which results in fuel and emissions savings (Aguilar Esteva et al., 2021), and the ease with which plastic can be formed into complex shapes. However, automotive plastics are difficult to recycle due to the cost associated with separating the numerous polymer types, as a result of the lack of infrastructure and economic incentives (Wyss et al., 2022). While plastic use can be beneficial in the vehicle use phase, environmental burdens are shifted to the end of life (material disposal) (Miller et al., 2014). At present automotive plastics have a low value for recovery and are not designed to be recycled, hampering efforts to achieve a circular economy in the automotive sector.

The circularity of the plastic supply chain in the automotive sector presents an opportunity to transform the sector to be more sustainable and aligned with the wider principles of a circular economy (CE). This critical review analyses the current state of plastics in the automotive sector generally, and in the UK specifically, to identify areas for improvement and end-of-life value opportunities.

1.1 The lifecycle of automotive plastics

This section introduces the use of plastics (thermoplastics and thermosets) in the automotive sector, followed by an overview of the plastic supply chain lifecycle from raw material extraction to end of life.

In the automotive sector, plastics are used for exterior, interior, and under the hood components. Exterior components include bumpers and fenders, light housing and lenses, wheel covers, and trim. Interior components include instrument panels, door panels, and seats. Under the hood components include crash structures, suspension leaf springs, fuel systems, and intake manifolds (Pradeep et al., 2017). Overall, plastics can comprise up to 18% of a vehicle's weight, an average of 350 kg per vehicle (Wyss et al., 2022), and more than 50% of the vehicle's volume (Vieyra et al., 2022).

Plastic automotive components are derived from raw materials (i.e. crude oil, natural gas liquids, or natural alternatives) which are processed into polymers via a series of chemical reactions. These chemical reactions combine one type of monomer or different types of monomers, at elevated temperatures and pressures, to form polymers or plastics. Polymers are mixed with fillers, additives, antioxidants, antistatic agents, pigments, and flame retardants before being made into plastic pellets that can be moulded into different components (Baldassarre et al., 2022; Martinez Sanz et al., 2022). Note that rubbers, which are used in tyres and other automotive components are also derived from similar raw materials. However, as elastomers they are excluded from this review. There are more than 35 types of polymers used in vehicles; the main polymer types include polypropylene (PP), polyurethane (PUR), polyamide (PA), polyethylene (PE), polyvinyl chloride (PVC), acrylonitrile butadiene styrene (ABS), and polyethylene terephthalate (PET) (Baldassarree et al., 2022). The two major classes of polymers are thermoplastics and thermosets. Thermoplastics have high molecular weights from a high degree of polymerisation; the long molecular chains have side chains which are not chemically bonded to other polymer molecules. This allows thermoplastics to be softened by heating, and thus recycled. Conversely, thermosets contain chemically bonded cross links between molecular chains, which form an interconnected network of polymer chains. This cross linking results in mechanically stronger polymers, however, these polymers cannot be softened through heating and therefore cannot normally be recycled (Morici & Dintcheva, 2022).

Once vehicles are produced they remain in the EU market for an average of 17.5 years (Baldassarree et al., 2022). At the end of life, vehicles are depolluted, dismantled, and shredded to recover materials (mainly steel). Recovered plastics contain a mix of polymers and are shredded before being recycled, incinerated for energy-recovery, or landfilled (Baldassarre et al., 2022). Automotive plastic waste contains engineering thermoplastics and thermosets which result in polymer cross-contamination and non-polymer impurities, which make mechanical recycling difficult (Stallkamp et al., 2023). Therefore, landfilling and energy-recovery are the dominant methods for handling end of life automotive plastics (Stallkamp et al., 2023).

At the end of life, plastic parts need to be removed from the vehicle, however some parts are attached with metal fixings which add a layer of complexity to the disassembly process. Manual disassembly allows for accurate plastic removal and sorting; however, it is a time-intensive and expensive process (Martinez Sanz, 2022). Plastic that can be recycled is processed with physical recycling methods or chemical recycling methods. Physical recycling (i.e. mechanical recycling or solvent-based recycling) maintains the polymer structure as temperature is used to change the state of the plastic so that it can be pelletised; mechanical recycling can be used to recycle thermoplastics. Chemical recycling alters the polymer structure of the plastic material. Chemical recycling processes, such as pyrolysis, can be used for materials that are unsuitable for mechanical recycling. Polypropylene (PP; e.g., from bumpers) is the most often recycled plastic from vehicles (Wyss et al., 2022). Depolymerisation breaks down polymers into their monomers, and thermolysis produces oil and gas mixtures which can be used as chemical feedstocks or as an energy supply (Martinez Sanz, 2022). Plastic that cannot be recovered easily is shredded with other light materials (i.e. textiles, paper, leather etc.) and turned into automotive shredder residue (ASR) (Martinez Sanz, 2022). It is difficult to recycle plastic that ends up as ASR, however plastic can be separated by flotation, gravity, or electrostatic techniques, and then recycled, albeit with significant losses of material during the recycling process.

Plastic Type	**Thermoset/thermoplastic**	**Percentage**
Low density polyethylene (LDPE)	Thermoplastic	2.6
High or medium density polyethylene (HDPE/MDPE)	Thermoplastic	6.4
Polypropylene (PP)	Thermoplastic	28.0
Polyvinyl chloride (PVC)	Thermoplastic	2.6
Polyethylene terephthalate (PET)	Thermoplastic	0.0
Polystyrene (PS)	Thermoplastic	1.3
Expanded polystyrene (EPS)	Thermoplastic	0.0
Acrylonitrile butadiene styrene (ABS)	Thermoplastic	5.3
Polyamide (PA)	Thermoplastic	7.6
Polycarbonate (PC)	Thermoplastic	1.3
Poly(methylmethacrylate) (PMMA)	Thermoplastic	0.8
Polyurethane (PUR)	Can be both thermoset and thermoplastic	15.3
Other		28.8

Table 1: Summary of average polymer composition used in the European automotive sector as reported by Plastics Europe under the 'Household, Leisure and Sports' category (Plastics Europe, 2019).

Automotive plastic components have limited recyclability. Overall, the global use of plastic products generates an estimated 6,300 Mt of plastic waste in 2015 (Geyer et al., 2017). Geyer et al. (2017) indicates that of this waste, 9% was recycled, 12% was incinerated and 79% accumulated in landfills and the natural environment. In contrast, Baldassarre et al. (2022) suggest that in the European Union only 19% of automotive plastics are recycled at end-of-life, with 41% combusted in incinerators and 40% landfilled. In recent years, original equipment manufacturers (OEM; i.e., car manufacturers) have increased their demand for recycled plastic due to the cost-savings potential and consumer pressure for improved environmental sustainability. Baldassarre et al. (2022) state that recycled plastics in new vehicles range from 5% to 15% of the total plastic mass; the majority (80%) is obtained from the mechanical recycling of pre-consumer waste from other sectors (non-automotive), with 20% from other post-consumer sources.

This section reviewed the life cycle of automotive plastics and identified that the low rates of recycling for automotive plastics is a gap to achieve a circular economy in the automotive sector. The next section introduces the supply and demand factors for automotive plastics.

1.2 The supply and demand of automotive plastics in globally and in the UK

With the global growth of plastic value chains, plastic use and the locations of production tend to be different (Tukker et al., 2014). Missing, conflicting, and inconsistent data, make it difficult to generate reliable maps for plastic stocks and flows to accurately determine supply and demand (Wang et al., 2021; Cullen et al., 2022). This section provides an overview of the available information to provide an estimate of the factors affecting automotive plastic supply and demand.

What is the global supply and demand for automotive plastics?

In recent decades plastic used in vehicles has increased to approximately 10% to 15% of the total weight of a new vehicle (Pradeep et al., 2017; Nissan Motor Corporation, 2020). Cabernard, Livia, and Pfister (2022) identified that the automotive industry consumes approximately 14% of all end use plastics globally. Plastic use is increasing due to the material properties that make plastic a suitable replacement for heavier materials. The contribution of plastics to increased fuel efficiency has partially offset the weight increases from the growth in the average size of new cars and the development of enhanced features (British Plastics Federation, n.d.; Council, 2023). For example, the Mark 1 Volkswagen Golf, first produced in 1976, weighed 830kg, with a fuel consumption of 7.8 l/100km and contained 48.4 kg of plastic. In contrast, the Mark 6 Volkswagen Golf, first produced in 2008, weighed 1215kg, with a fuel consumption of 6.4 l/100km and contained 127.2kg of plastic (Danilecki et al., 2017). To meet this increasing demand, OEMs use 4.4 Mt of plastic annually in the European Union (Baldassarre et al., 2022).

What is the UK supply and demand for automotive plastics?

At the end of 2022, there were approximately 33 million vehicles registered in the UK; vehicle ownership in the UK is increasing, with 1.4 million new vehicle registrations in 2022 (Department for Transport & Driver and Vehicle Licensing Agency, 2023). The typical service life of a vehicle is approximately 15 years, thus annually about 2 million vehicles reach the end of their service life (Raugei et al., 2021). In the UK, end-of- service life vehicles are either exported and enter second hand markets in other countries or are disposed of.

The UK is home to seven major premium and sports car manufacturers, five commercial vehicle manufacturers, eight bus and coach manufacturers, 5 mainstream car manufacturers, 10 engine manufacturers, and over 2,500 automotive suppliers (Society of Motor Manufacturers and Traders, 2022). Major car manufacturers include Jaguar Land Rover, Nissan, BMW group, Toyota, Honda, and Stellantis (Society of Motor Manufacturers and Traders, 2022). The UK automotive industry had a turnover of £67 billion in 2021 and employs nearly 800,000 people (Society of Motor Manufacturers and Traders, 2022). In 2021 over 850,000 cars were manufactured in the UK, adding £14.1 billion to the economy (Society of Motor Manufacturers and Traders, 2022). The automotive industry exports 8 out of 10 cars manufactured in the UK to many destinations including the EU, USA, and China (Society of Motor Manufacturers and Traders, 2022).

Drewniok et al. (2023) measured the flows of plastic in the UK and identified that 6.3 Mt of plastics were consumed in the UK in 2017, of which 1.0 Mt were consumed by the automotive sector. Drewniok et al. (2023) estimate that plastic stock in vehicles accounts for 21% (9 Mt) of UK plastic stock in service. 58% of the UK plastic demand is for PP, PE, PET, and PVC polymers all of which are used in vehicle manufacturing. However, Plastics Europe (2022) estimates that the UK comprises 6.9% (3.5 Mt) of Europe's converters' plastics demand (not including recycled or bio-based plastics), with 8.6% used by the automotive sector. Recycling for all plastics increased by 175% in the UK from 2006 to 2020, energy recovery increased by 657%, and landfilling decreased by 72%; a total of 37% of UK plastics are recycled, 44% are used for energy recovery, and 19% are landfilled (Plastics Europe, 2022).

Rodrigues et al. (2022) determined that the UK vehicle material stock efficiency (including plastic) declined by 32% from 1960 to 2015, and the waste generated per unit of passenger-kilometre decreased by 12%. The shift away from steel towards plastic and aluminium (i.e. trans-materialism) resulted in a 51% increase in energy efficiency of UK vehicle stock from 1960 to 2015 (Rodrigues et al., 2022). However, Rodrigues et al. (2022) highlight that increasing vehicle material complexity results in additional environmental harms at the raw material extraction and end of life phases. For vehicles to be environmentally sustainable they must be resource efficient, not just fuel efficient.

1.3 Circular supply chain concepts and automotive plastic use

The concept of circular economy (CE) is proposed as a solution to problems caused by waste generation and resource scarcity and as a method to maintain economic prosperity (Leider 2016). In a CE, resources are recovered from end-of-life products through recycling or remanufacturing; in contrast, a linear economy/supply chain considers end of life products waste which can only be incinerated or landfilled (Amir et al., 2023). CE concepts centre around systemic changes to reduce finite resource extraction and waste generation, and the reuse of resources contained in products at the end of the product lifetime, thus achieving economic prosperity without damaging environmental quality (Kirchherr et al., 2017). The European Commission postulates that in a CE the value of products and materials is maintained for as long as possible, waste and resource use are minimised, and resources are kept within the economy when a product has reached the end of its life to be used again and again to create further value (European Commission, 2015).

Despite the extensive discourse concerning the implementation of CE strategies, CE as a concept remains the subject of debate. Firstly, there is no commonly accepted coherent definition of CE, leading to inconsistent conceptualisations across the literature (Kirchherr et al., 2017). Secondly, there are often unclear connections between CE and other aspects of sustainable development, such as environmental and social sustainability (Corvellec et al., 2022). Finally, a fully circular system of resource flows (i.e., 100% circularity) is in practice impossible, due to resource dissipation and entropy creation as materials flow through circular loops (Cullen, 2017).

There is a growing body of literature which aims to address the problem of sustainability in supply chains. Sustainable supply chain management is the management of upstream and downstream relationships with suppliers and customers to deliver superior customer value at less cost to the supply chain (Christopher, 2023). Circular economy concepts can be integrated within supply chain management to form circular supply chains (De Angelis et al., 2018). Circular supply chains refer to the 'embodiment of circular economy principles within supply chain management' (De Angelis et al., 2018, p. 425). More specifically, circular supply chains can be defined as closed loops where value is created from products/services, by-products and useful waste flows through prolonged life cycles that improve the economic, social and environmental sustainability of organisations (Batista et al., 2018). De Angelis et al. (2018) identify circular supply chains as focusing on zero landfill and a cascade of use from repair, reuse, refurbish, to recycle.

1.4 Review methodology

This section introduced the lifecycle, supply and demand factors for automotive plastics globally and in the UK, and circular supply chain concepts applicable to the automotive industry. The purpose of this critical review is to provide a knowledge basis for an industry workshop for the Circular Economy Network + in Transportation Systems (CENTS) funded research project on 'Decarbonised and circular automotive plastics supply chain'. The workshop and research project aim to aid the transformation of the UK's automotive industry's plastic supply chain, to become sustainable, environmentally friendly, and aligned with the principles of a circular economy. Therefore, this review focuses on finding answers to the the question:

How can transitioning to a circular supply chain reduce the impact of plastic use in the UK automotive industry?

To answer this question, the literature was subdivided into three streams: plastics, automotive, and circularity (Figure 1) with corresponding search terms (Table 2). The search criteria were applied to two major sources of academic literature, GoogleScholar and Scopus, as well as to industry specific, grey literature, sources such as PlasticsEurope and British Plastics Federation. Sources were selected for inclusion based on relevance to the research question, full-text availability, and publication in English. The critical review does not provide a systematic review on the topic of circularity of automotive plastics, but rather overviews the current state of the sector and identifies areas of opportunity to serve as the basis of a white paper (or special issue) following the CENTS workshop.

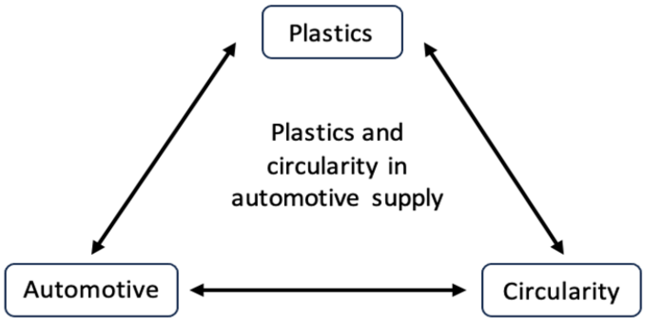

Figure 1: Literature streams

Plastics	**Automotive**	**Circularity**
'Plastic*'	'Automotive'	'Circular economy'
'Polymer*'	'Automobile'	'Recycl*'
'Bioplastic*'	'Car'	'Remanufactur*'
'Bio-feedstock*'	'Passenger vehicle'	'Material efficiency'
		'End of life'
		'Supply chain*'
		'Upcycle'
		'reuse'

Table 2: Search terms

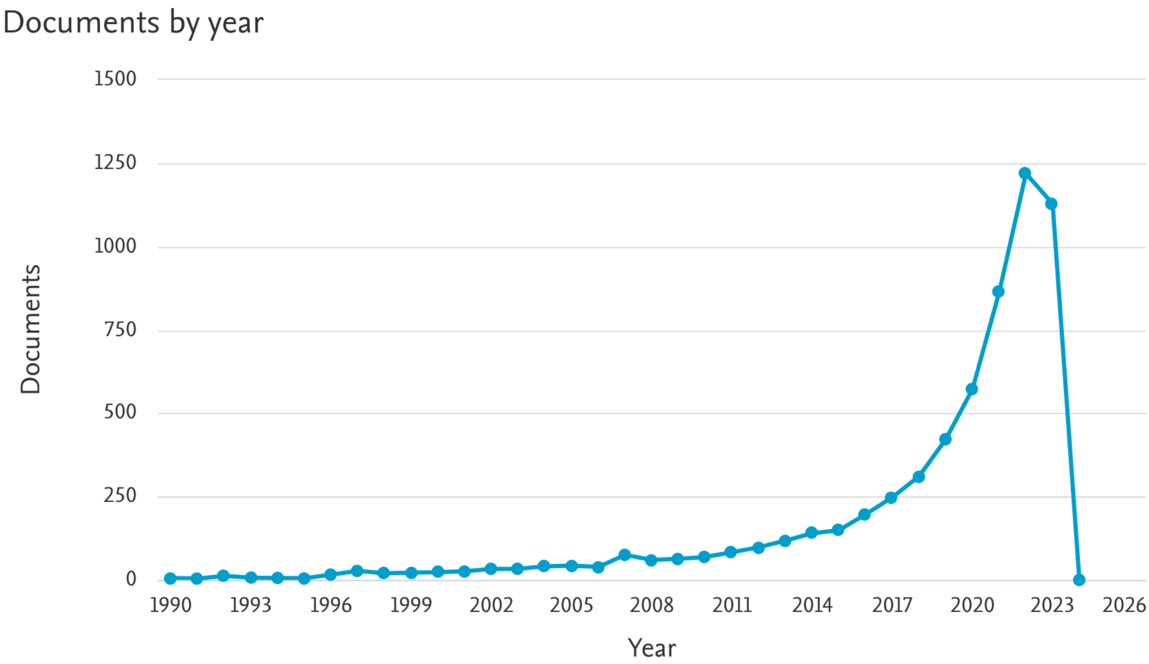

Figure 2: Number of documents published between 1990 and 2024 and available on Scopus for search terms 'plastic' AND 'automotive' AND 'circular'*

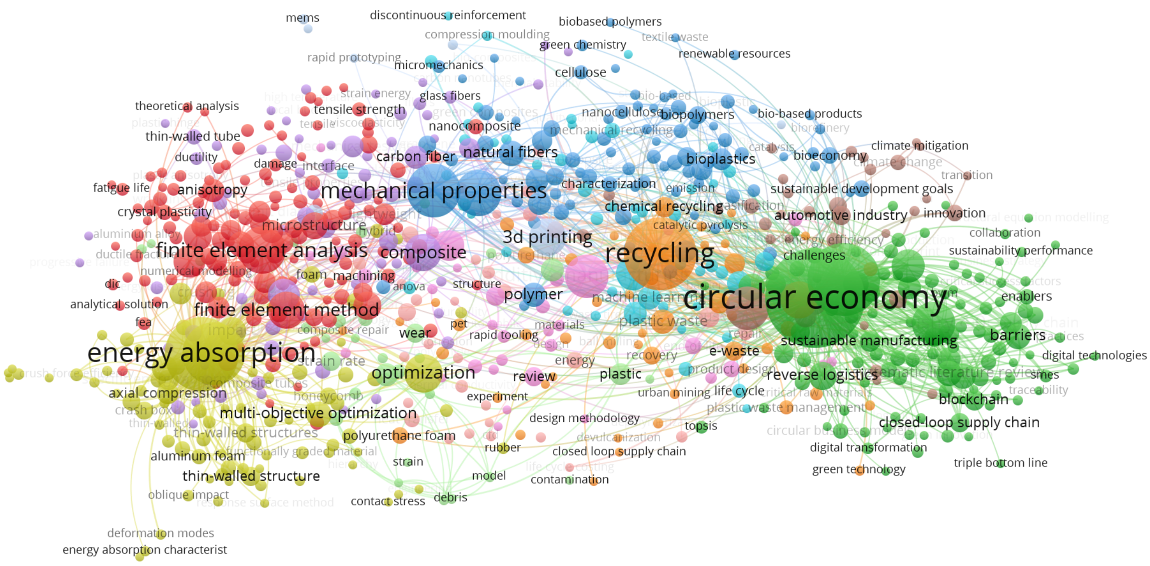

Figure 3: VOSviewer network visualisation for Scopus results for search terms 'plastic' AND 'automotive' AND 'circular'*

Definitions of key terms:

- ➔ *Automotive*: relating to motor vehicles
- ➔ *Plastics*: a synthetic material made from a wide range of organic polymers such as polyethylene, PVC, nylon, etc., that can be moulded into shape while soft, and then set into a rigid or slightly elastic form (Google).
- ➔ *Circular economy*: no widely accepted definition (see Section 1.3.). However, in this review circular economy refers to production systems where automotive components and plastic materials remain in the market through reuse and regeneration in an environmentally sustainable way.
- ➔ *Circular supply chains*: the 'embodiment of circular economy principles within supply chain management' (De Angelis et al., 2018, p. 425)

The remainder of the critical review sets out to review the current state of automotive plastics (Section 2), before identifying areas of opportunity to improve the circularity of automotive plastics (Section 3).

Section 2: The Current State of Automotive Plastics

The current flows of plastics through society are mostly linear with low amounts of plastic passing back into production and use at the end of life. The circularity index is a method of quantifying the level of circularity of a material in production-consumption systems. The circularity index metric (Cullen 2017) combines metrics representing both the *quantity* of material recovered and the *quality* of material in terms of the ration between the energy requirements for material recovery and energy requirements for primary production. The quantity and quality fractions are multiplied together to give a combined circularity index, with the value of 1 representing a perfect circular material flow and a value of 0 indicating a completely linear material flow. Plastic is estimated to have a circularity index of 0.07, compared to 0.14 for steel and 0.20 for aluminium (Cullen 2017). The low circularity index for plastic indicates the practical challenges of collecting, sorting and recycling plastic waste (quantity) and the mixed nature of plastic waste which requires additional energy to return to pure feedstock (quality).

The previous section introduced the life cycle, and supply and demand of automotive plastics globally and in the UK. This section will assess the current state of automotive plastics including the types and quantities of plastics, and their uses in the automotive sector. This section also covers the current state of raw material extraction, production and use, and end of life for automotive plastics to provide context for identifying areas for sustainability improvement.

2.1 Raw material extraction

To understand the potential for transitioning towards circular supply chains and decarbonising plastics in the automotive industry, the current feedstocks used to produce plastics must be assessed. In this section, we review the literature quantifying the main feedstocks used to produce plastics used in the automotive industry.

What is the origin of plastics used in the automotive industry?

The automotive sector's demand for plastics accounts for 9.6% of all plastic use in Europe (Plastics Europe, 2020). Thermoplastics used in the automotive sector are primarily derived from fossil fuel feedstocks (natural gas and natural gas liquids, liquid oil products, refinery-sourced olefins, and aromatics) (Levi & Cullen, 2018). Thermoplastics refer to plastics that are reversible, they can be melted when heated and hardened when cooled, which allows them to be mechanically recyclable (Cullen et al., 2022). The production of plastics is an energy and emissions intensive process; in 2019 540 Mt of CO_{2e} emissions were released from the production of thermoplastics (Cullen et al., 2022). The production of thermoplastics and thermosets from ethylene and propylene intermediates is the most emissions intensive process in the plastic life cycle resulting in 0.8% of global carbon emissions (Tullo, 2021).

Globally, fossil fuel feedstocks are still used for the majority of applications, with minor contributions from bio-based plastics and post-consumer recycled plastics. In 2019, 352 Mt of fossil-based plastics were produced, compared with 32.5 Mt of post-consumer recycled plastics and 5.9 Mt of bio-based plastics. In Europe, 3.2% (106kt) of automotive plastic production is derived from post-consumer recycled plastics, which is below the average for European plastics production across all sectors. Overall, 9.9% of the European plastic supply is from post-consumer plastic feedstocks, with high recycled plastic use rates in the agriculture (25.4%) and construction sectors (18.1%) (Plastics Europe, 2022). OEM's report using non-petroleum plastics for specific applications: bio-plastics are used in the UK automotive industry by Nissan to make seat coverings for the Nissan LEAF (Nissan Motor Corporation, 2020); plastic collected from the ocean is used as a constituent material to make car seats(Stellantis, 2020); recycled fishing nets are used to make trim parts using plastic injection moulding (BMW Brilliance automotive, 2021); and Polyethylene terephthalate (PET) bottles are used to make seat textiles (Volkswagen Group, 2022).

2.2 Production and use

Vehicle weight directly affects energy consumption and thus vehicle emissions; a 10% reduction in vehicle weight can improve fuel economy by approximately 7% (Lyu & Choi, 2015). Given the benefit of reducing vehicle weight, polymers have frequently been used to replace ferrous and non-ferrous metals in vehicles (Lyu & Choi, 2015). Furthermore, given their versatility, plastics can be used as high-performance polymers, polymers for weight reduction, reinforced polymer composites, polymer sandwich panels, and polymer/metal hybrid systems (Lyu & Choi, 2015).

Vehicles produced by the automotive industry can generally be categorised as either light-duty vehicles or heavy-duty vehicles. The United Nations Economic Commission for Europe provides vehicle categorisations used for regulatory purposes (Economic Commission for Europe, 2017): light-duty vehicles (cars and vans) are typically referred to as vehicles with at least 4 wheels and either intended for carrying passengers with a maximum of 8 seats or intended for carrying goods and with a mass of less than 3.5 tonnes; heavy-duty vehicles (buses, coaches, lorries) typically refers to vehicles with at least 4 wheels intended for carrying passengers with a minimum of 8 seats or for carrying goods and with a mass of more than 3.5 tonnes (Economic Commission for Europe, 2017). In this section we identify and quantify the uses of plastic in light-duty, battery electric, and heavy-duty vehicles.

2.2.1 Light-duty vehicles

In 2021, there were 35 million cars registered in the UK and 4.6 million light commercial vehicles (vans) (Society of Motor Manufacturers and Traders, 2022). Plastics typically comprise around 50% of a car's volume and around 10% of a car's mass (Isenstadt et al., 2016). However, to fully assess the extent of plastic use in the automotive industry it is useful to understand the composition and quantities of plastic types in vehicle components.

How much plastic is currently used in light-duty vehicles?

Plastics are used in a range of car components and subsystems, such as car bodies, chassis components, powertrain components, interiors, and body panels which make up the majority of a car's mass, as shown in Figure 4. The quantity reported in material breakdowns is typically given in terms of the overall plastic share. The International Council on Clean Transportation assumes approximately 10% the mass of a contemporary car to be plastic, without reporting further detail on the quantities in which different plastic types are used (Isenstadt et al., 2016). Davis and Boundy provide a similar estimate, reporting that the share of plastic in light-duty vehicles built in North America was 8.6% in 2017 (Davis & Boundy, 2021).

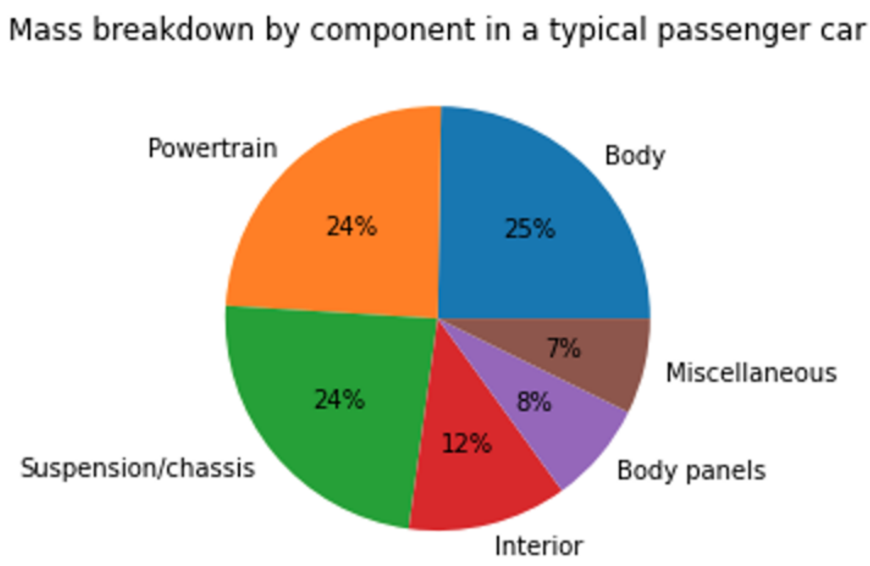

Figure 4: Breakdown of vehicle weight by component group (Isenstadt et al., 2016)

What types of plastics are used in light-duty vehicles?

To assess the prospects for increasing circularity in automotive supply chains, it is necessary to understand which specific materials are currently used. Knowledge of the material used is imperative to identify the correct recycling strategies and suitable alternative feedstocks to reduce the demand for virgin plastics. In this section, we assess the sources that provide a detailed breakdown of the types of plastics used in light-duty vehicles.

The GREET model maintained by the Argonne National Laboratory uses a discrete plastics category to report the quantity of plastics in cars; some detail is also provided on the types of plastic used. The quantity of all materials is calculated by aggregating the material composition of major components and weighting by the component's contribution to total vehicle weight. The model assumes that around half the plastics used in vehicle components consist of 3 plastic types: polypropylene (PP; 24%), polyethylene terephthalate (PET; 14%) and high-density polyethylene (HD-PE; 10%). Vehicle dismantling tests confirm that this assumption is reasonable (Burnham et al., 2006).

Sullivan et al. (1998) provide a more detailed breakdown of 16 different plastic types used in an average North American sedan car (Figure 5). The mass, composition, and material type for each part/component was generated by dividing the vehicle into three sections of roughly equal weight; the first section was modelled on a Chevrolet Lumina, the second section was modelled on a Dodge Intrepid, and the third was modelled on a Ford Taurus (Sullivan et al., 1998). The generic vehicle is found to contain 9.3% plastic by weight (Sawyer-Beaulieu, 2009), which is in line with more recent assumptions on the overall contribution of plastic to a car's total mass: 10% (Isenstadt 2016) and 9-11% (Elgowainy et al., 2016). This breakdown is used by Elgowainy et al. (2016) and Sawyer-Beaulieu (2009) in life cycle assessment analyses.

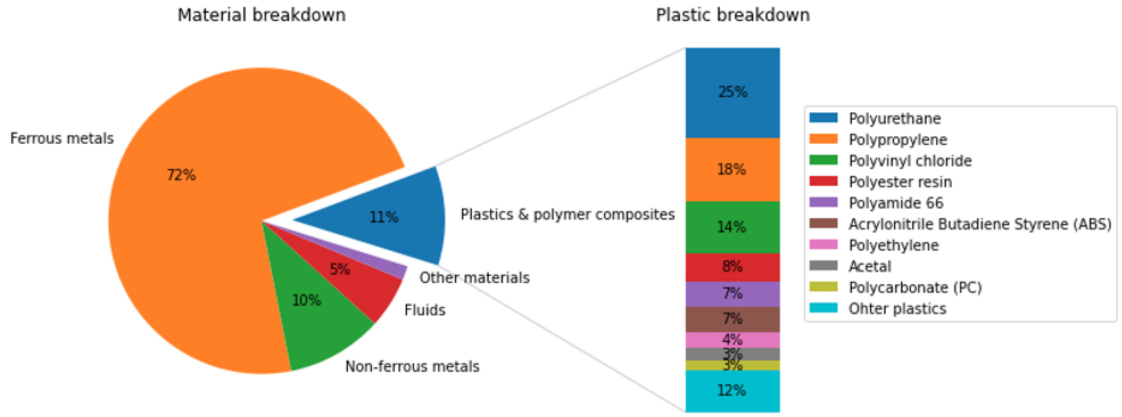

Figure 5: Breakdown of plastic use in cars (Sullivan et al., 1998).

Another analysis by the American Chemistry Council calculates a breakdown of the materials used in typical North American cars, using data from industry sources such as the American Chemistry Council's Plastics Industry Producers Statistics Group and the International Organization of Motor Vehicle Manufacturers (Council, 2023). The material breakdown is shown in Figure 6, and includes the amount of different plastic types.

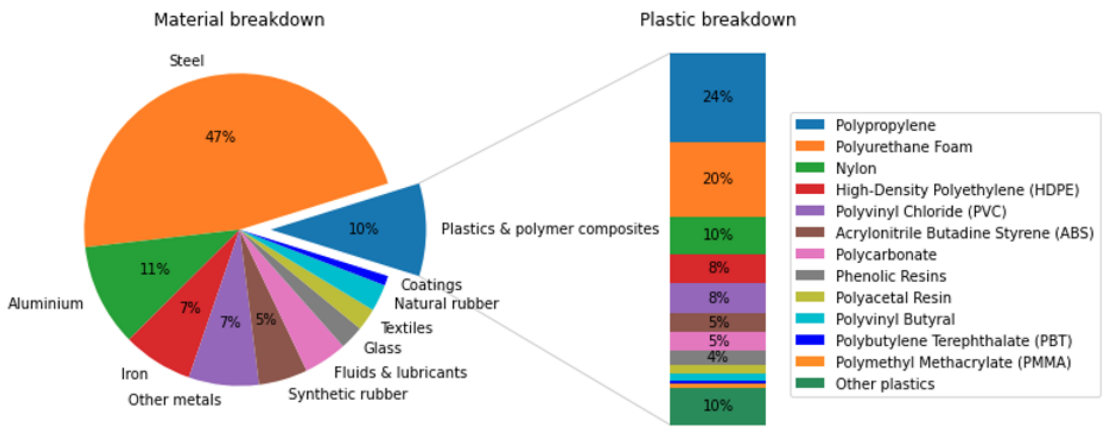

Figure 6: Breakdown of material and plastic content of a typical car (American Chemistry Council 2023)

How has plastic use in cars evolved?

OEM's have used plastic and aluminium to replace steel and other metals to reduce vehicle weight and increase fuel efficiency (Council, 2023). The proportion of vehicle weight attributed to plastic has steadily increased over the past 30 years (Isenstadt et al., 2016). Danilecki et al., (2017) indicates that compared to steel, using plastic or aluminium can reduce the weight of a vehicle by up to 40%. Thus, plastic has been used to replace other heavier materials to reduce fuel and emissions.

The increase of plastic is illustrated by Danilecki et al. (2017). The authors report the material breakdown, including a breakdown by 11 different plastic types of 6 different Volkswagen Golf models produced over 36 years (Figure 7). The Volkswagen Golf was the 6th best-selling car model in the UK in 2021, with over 30,000 new vehicles sold (Society of Motor Manufacturers and Traders, 2022).

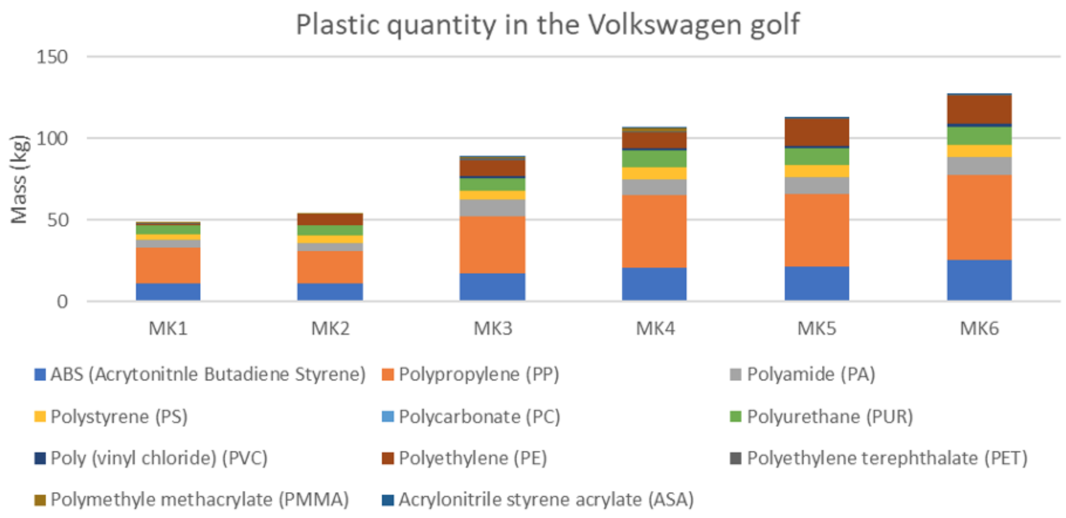

Figure 7: Plastic quantity and type in the Volkswagen Golf (Danilecki et al., 2017)

Which components contain plastics and why?

The potential to reduce the impacts of plastic use in the automotive industry depends on whether plastic components can feasibly be changed without compromising the component performance. Therefore, in this section we identify the uses of automotive plastic types, as well as the quantities and properties that make plastics suitable for use in specific automotive components.

Table 3 summarises the results of the work of Pradeep et al. (2017) and Elgowainy et al. (2016) for the plastic use in cars: Pradeep et al. (2017) provide a summary of plastics used in different vehicle components; Elgowainy et al. (2016) provide a breakdown of the proportion of plastic in different vehicle components, based on personal communications, vehicle dismantling reports and assumptions.

Component	**Component purpose**	**Required properties**	**Typical plastic/plastic composites used**
Bumper and fenders	*Outer fascia* Control airflow and aesthetic purposes. *Energy absorbing material* Reduce forces acting upon rest of car body *Reinforcement bar* Protect rest of car and occupants in a collision.	High corrosion resistance, light weight, good shock energy absorption, ease of manufacture by injection moulding for high volume production.	*Outer fascia* Polypropylene (PP), Polyurethane (PUR), Polycarbonate (PC). *Mechanical energy absorber* Polypropylene, polyurethane, low density polyethylene (LDPE), thermoplastic polyolefins (TPOs). *Reinforcement bar* Glass fibre reinforced polyester (GFRP), carbon fibre reinforced polymer (CFRP).
Wheel cover	Protect wheel bearing from dirt, dust and moisture, protect wheel nuts and bolts from corrosion, aesthetic purposes.	Lightweight, high corrosion resistance, high dimensional stability, easily paintable.	Acrylonitrile butadiene styrene (ABS), acrylonitrile styrene acrylate (ASA), thermoplastic polyolefins (TPOs), mineral filled polyamide 6 (PA6).
Headlight / rear lights housing	Protect the lighting component from dust, dirt and moisture.	Heat resistance, high strength, fracture toughness, good thermal stability, good luminous transmittance properties.	Poly (methyl methacrylate) (PMMA), Polycarbonate (PC), polyetherimide (PEI), poly(p-phenylene sulfide) (PPS), acrylonitrile butadiene styrene (ABS).

Component	**Component purpose**	**Required properties**	**Typical plastic/plastic composites used**
Car body (chassis/ monocoque)	Main structural component. House all other components.	High strength, lightweight.	Carbon fibre reinforced polymer (CFRP)
Instrument panel	House interior components and controls.	High heat resistance, good manufacturability, high impact resistance.	Polypropylene (PP), Thermoplastic olefin (TPO), acrylonitrile butadiene styrene (ABS), polyvinyl chloride (PVC), styrene-maleic anhydride copolymers (SMA), polyurethane.
Door panels	Interface between car interior and door components. Protect the occupants in a collision.	High impact resistance.	Glass fibre-polyurethane (PUR), glass fibre reinforced-polypropylene (PP), cellulosic fibre-polyurethane (PUR), cellulosic fibre-polypropylene(PP), thermoplastic olefin (TPO).
Pillar covers	Support the roof and provide a frame for the windows.	High collapse strength, good shock energy absorption.	Polypropylene (PP), Polyethylene terephthalate (PET), Polyamide (PA).
Seats	Provide protection for the occupants.	High impact strength, good shock energy absorption.	Polyurethane (PU), glass fibre reinforced polyamide (PA), glass mat reinforced thermoplastic (GMT), polypropylene (PP).
Seat covers and cushioning	Provide comfort for the occupants.	Soft, shock absorption, low density for cushions	Polyurethane (PUR),

Component	Component purpose	Required properties	Typical plastic/plastic composites used
Seatbelts	Provide protection for occupants in a collision.	High impact strength, low friction, high wear resistance.	Polyester fibre, nylon.
Crash structures	Provide protection for occupants in a collision.	High impact strength, good shock energy absorption.	Glas fibre-vinyl ester, glass fibre-polyester, glass fibre-epoxy, carbon fibre-epoxy, carbon fibre-polyetherether ketone (PEEK), kevlar-epoxy, graphite-epoxy.
Leaf spring	Part of the suspension system. Supporting vehicle weight, providing stability whilst driving, ensuring contact between road and tyres, and absorbing shocks.	High strength, low elasticity, high fatigue resistance	Carbon fibre-epoxy, glass fibre-epoxy. Note: Currently under development and not in widespread use.
Fuel tank	Stores the fuel required in internal combustion engine vehicles.	High corrosion resistance, good toughness, fire resistant, thermal stability,	High density polyethylene (HDPE).
Intake manifold	Carry air to engine cylinders for combustion in internal combustion engine vehicles.	High strength, high stiffness, high chemical stability, low thermal conductivity.	Glass fibre reinforced polyamide (PA6 and PA66), glass fibre reinforced polypropylene

Table 3: Summary of typical plastic uses in light-duty vehicles (Pradeep et al., 2017)

Lyu & Choi (2015) identify the plastics used in different car components; the results are similar to Pradeep et al. (2017) for plastic uses, in terms of components and plastic types, with additional information provided about the mass of plastic found in different components (Figure 8).

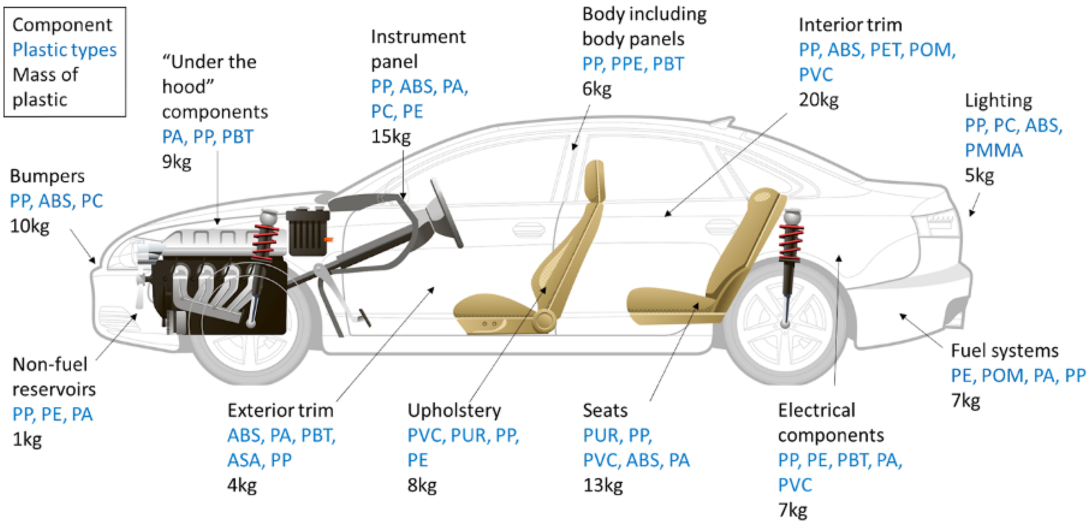

Figure 8: Schematic showing the components and types and quantities of plastic in an average car (Lyu & Choi, 2015). *ABS - Acrylonitrile-butadiene-styrene, ASA - Acrylonitrile styrene acrylate, PA - Polyamide (Nylon), PBT - Polybutylene Terephthalate, PC Polycarbonate, PE - Polyethylene, PET - Polyethylene Terephthalate, PMMA - Polymethylmethacrylate, POM - Polyoxymethylene, PP - Polypropylene, PPE - Polyphenylene oxide, PUR - Polyurethane, PVC - Polyvinyl Chloride*

Current strategies to reduce plastic use in automotive supply chains

Strategies to reduce plastic use in automotive supply chains include the reduction of packaging, increasing recycled content, and recycling or remanufacturing at the end of life. One strategy for OEMs to reduce plastic use is through collaborating with upstream suppliers to reduce the amount of unnecessary plastic packaging used to deliver components, equipment, and tools. Aston Martin aims to eliminate plastic waste from packaging by 2025 (Aston Martin Lagonda, 2021) and Toyota is increasing the recycling rates for plastic not directly required for car manufacture (Toyota Motor Corporation, 2022).

Another strategy to reduce the demand for virgin plastics is to increase the amount of recycled material used in vehicles. The recycled material content varies between vehicles manufactured in the UK. In 2019, Nissan utilised 11% recycled plastic for its best-selling European model (Nissan Motor Corporation, 2020). As of 2021, BMW was investigating the potential of using recycled plastics for interior and exterior components; BMW indicates the need for additional component testing before committing to mass production (BMW Brilliance automotive, 2021).

Supply chain circularity can be improved by designing products that can easily be repurposed, recycled, or remanufactured (see also Section 3.2). For example, Volkswagen is labelling plastic components with ISO plastic standard classification to improve component sorting for recycling (Volkswagen Group, 2022). Fuel tanks are particularly suitable for manufacture with recycled plastic. For example, Fiat-Chrysler produced gasoline tanks made from 45% recycled plastic by weight for certain European applications (Stellantis, 2020). In their Wolfsburg factory, Volkswagen uses plastic waste from the co-extrusion of gasoline fuel tanks to make diesel fuel tanks through mono-extrusion; this process saves 1,600 tonnes of material and reduces annual emissions by 2.5 kt CO_2 (Volkswagen Group, 2022). Nissan Motor Corporation (2020) and Toyota Motor Corporation (2022) recycle bumpers and parts that have been replaced and collected from dealerships to create engine under covers. Remanufacturing components is a strategy that has been used to reduce the demand for virgin plastics. In 2021, BMW group recycled 389 tonnes of metal (80% steel and iron, 20% aluminium), 140 tonnes of plastic, and 43 tonnes of paper from their remanufacturing processes (BMW Brilliance automotive, 2021).

2.2.2 Battery electric vehicles

The adoption of battery electric vehicles (EV) is anticipated to increase, driven by the forthcoming UK ban on the sale of new petrol and diesel cars (Davis & Boundy, 2021). Consequently, the material requirements of new vehicles will change as internal combustion engine powertrains are replaced with electric counterparts. While there is a growing body of literature on the supply of critical materials required for battery packs, less research is available on the changes in plastic types and quantities that will be required to enable the transition to EVs (Fishman et al., 2018; Watari et al., 2019). Plastics are used as the separator between the anode and cathode in the battery cells and for the cell packaging (Dai et al., 2019). Overall, car batteries contain approximately 5% plastic by mass, with Volkswagen reporting that a 400 kg battery contains about 21 kg of plastic (Volkswagen Group, 2022).

The GREET model provides a breakdown of the material quantities used in different battery chemistries. The model estimates that lead acid and nickel metal hydride batteries contain 6.1% and 22.5% plastic by weight, respectively (Burnham et al., 2006). Elgowainy et al. (2016) confirms this assumption for lead acid batteries. Lithium-ion batteries are also reported to contain 2% polypropylene (PP) and 1% to 2% polyethylene terephthalate (PET) (Elgowainy 2016). Dai et al. (2019) provide a breakdown, to be integrated into the GREET model, of plastic types included in batteries. A 165 kg 23.5 kWh nickel, manganese, cobalt -111 battery contains 1.8 kg polypropylene (PP), 0.6 kg polyethylene (PE), and 0.34 kg polyethylene terephthalate (PET); the cell separator (2.1 kg total) is composed entirely of plastic (80% PP and 20% PE by weight), and the cell container (2.7 kg total) contains 13% PET and 6% PP plastic content.

2.2.3 Heavy-duty vehicles

In 2021, over 37,000 new lorries and 3,500 new buses were registered in the UK (Society of Motor Manufacturers and Traders, 2022). However, there is limited publicly available information on the material composition and plastic use of heavy-duty vehicles. Wolff et al. (2020) scale and adapt data on material composition from light-duty vehicles to estimate the environmental impact of a heavy goods vehicle (vehicle class N3) in a life cycle assessment. The authors estimate that the sleep cab component contains 212 kg of thermosets and 257 kg of thermoplastics, with the rest of the glider (vehicle components other than the powertrain) containing 323 kg of plastics. However, no other components are identified as containing plastic and the plastic types are not specified (Wolff et al., 2020).

There is a trend towards increased use of plastics in non-structural components in the heavy-duty vehicle sector. Wolff et al. (2020) indicate that plastics make up approximately 20% of the mass of a typical European heavy-duty lorry. Plastic is used in oil sumps, roof fairings, mirror casings, side deflectors, bumper corners, mudguards, steps, front under-run protection, instrument panel elements, storage boxes and bed structures (Hill, 2015). Glass fibre reinforced polymers (GFRPs) are commonly used for refrigerated and box model panel components such as roofs, floors, and side walls in both buses and lorries. Hill (2015) suggests that the use of GFRPs is expected to increase, with leaf springs and axles made from GFRPs expected to contribute to component weight reductions of 25% to 35%.

2.3 End of life

Around 2 million cars reach the end of their service life every year in the UK (Raugei et al., 2021). The waste generated from end-of-life vehicle processes can either be placed in landfills, incinerated for energy recovery, or recycled via chemical or mechanical recycling (Stallkamp et al., 2023). Of all European automotive plastics (1,443 kt), 19% is recycled, 42% is incinerated for energy recovery, and 39% is landfilled (Plastics Europe, 2022b). In this section we cover the current state of end-of-life processing used in the UK automotive industry.

Vehicles undergo a 3-stage process at end-of-life: depollution, dismantling, and shredding (Figure 9). Depollution is a pre-treatment where components that may be valuable for resale and reuse (e.g., batteries, fuel, tyres and motor oil) or components that hinder subsequent processes (e.g., airbags and seats) are removed. Typically, 3% of a car's mass is removed in the depollution phase (Berzi et al., 2013). Next, spare parts and components to be recycled (such as glass and bumpers) are dismantled. Finally, the remaining vehicle components are then shredded. The shredded mixture contains around 70% to 75% ferrous metals, 5% non-ferrous (Cossu & Lai, 2015) metals and 20% to 25% automotive shredder residue (ASR), which contains leftover plastics (Cossu & Lai, 2015). ASR is typically disposed of in landfill or diverted to thermal treatments, such as pyrolysis or gasification, for energy recovery due to its complex heterogeneous material composition (Martinez Sanz et al., 2022).

The end of life vehicle directive (ELV directive) provides clear targets for managing end of life vehicle processes, aiming to prevent and limit waste from end of life vehicles and their components. Circular economy principles are a key part of the directive and cover aspects of design, sale and end of life treatment and contain aspects aimed at reducing the impact of automotive plastic use.

- ➔ OEMs should improve circular design of vehicles to enable material and component removal for re-use and recycling.
- ➔ 25% of plastic used to manufacture new vehicles should be from recycled sources with 25% of this from recycled end of life vehicles.
- ➔ Regulations should gradually expand to cover all road vehicles including motorcycles, buses and lorries (European Commission 2023).

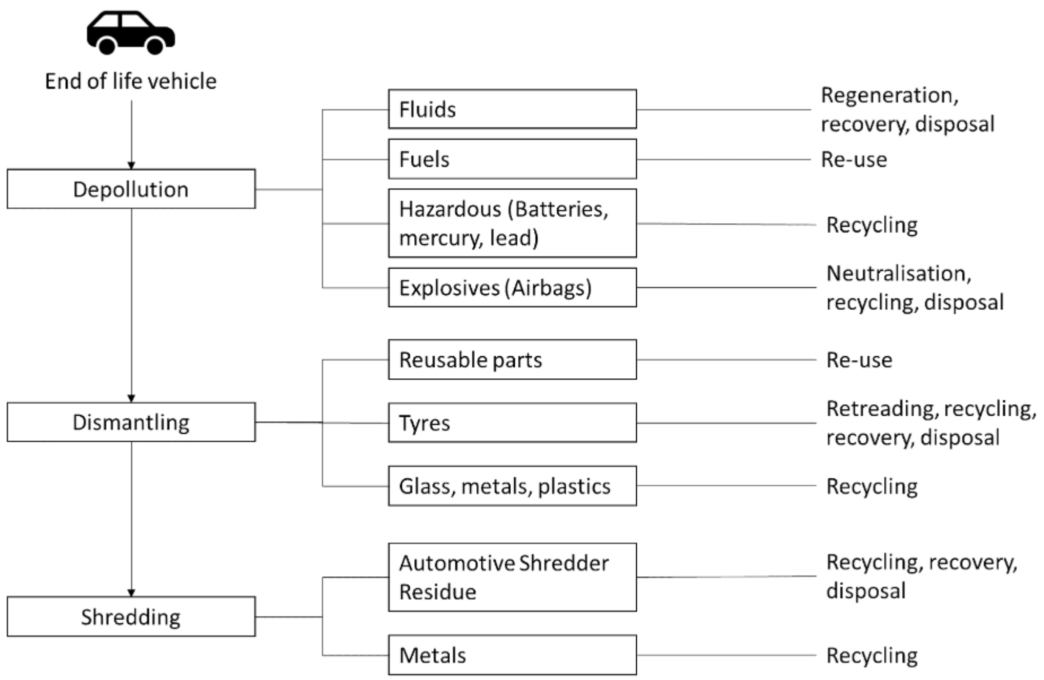

Figure 9: Typical end of life process for end-of-life vehicles (adapted from Cossu & Lai (2015)and Berzi et al., (2013).

There are four main approaches to recycling solid plastic waste:

1. **primary recycling or closed loop process**: the re-extrusion of uncontaminated single type polymers with properties near to that of the virgin material;
2. **mechanical recycling**: transforms the plastic via mechanical processes to produce products or components for less demanding applications. It involves cutting/shredding, contaminant separation, washing, drying and extrusion to make the new product;
3. **chemical recycling**: recovers monomers through de-polymerisation processes such as pyrolysis, cracking, gasification and chemolysis;
4. **quaternary recycling**: recovers energy through polymer incineration, reducing the mass of waste which is then sent to landfill (Singh et al., 2017).

At present, the UK has a limited recycling capacity (0.4 Mt per year), with low yields for products containing mixed materials, which is characteristic of automotive plastics (Drewniok et al., 2023). About one-third (1.0 Mt) of end-of-life plastic in the UK is landfilled, one-third (1.3 Mt) is incinerated, and one-third (1.1 Mt) is recycled in the UK and abroad (Drewniok et al., 2023). However, Drewniok et al. (2023) argues that increasing the UK recycling capacity would not necessarily result in a reduction in virgin plastic production; plastic recycling suffers from high yield losses due to polymer mixing in waste streams and mechanical recycling limitations. Miller et al. (2014) also indicate that a lack of infrastructure and a market for recyclates, as well as a knowledge gap about the reality of plastic recycling, limits automotive plastic recycling rates. Stallkamp et al. (2023) indicates that economically, energy recovery of automotive plastic performs better than chemical recycling, however, chemical recycling has lower net environmental impacts; there is a conflict between the economic and environmental impacts of automotive plastic end of life options.

Automotive plastic recycling technologies

Total plastic recycling is known as a complex method because it involves multiple stages, including processing, disposal, sorting, distribution, and utilisation (Singh et al., 2017; Hahladakis and Iacovidou, 2019). When automotive plastic reaches the end of its life cycle, it typically undergoes one of three processes: it can be recycled to create reprocessed plastic pellets, recover monomers, or be converted into bio-oil. Various technologies can be used to recycle end-of-life plastic, including mechanical, thermal, chemical (such as pyrolysis, gasification, and hydrolysis), hydrothermal, and electrochemical methods.

The physical breakdown of plastic waste occurs through different processes, primarily shredding and grinding, which are the key stages of mechanical recycling (Serranti et al., 2019). Mechanical recycling is usually the most straightforward and initial recycling method, often considered inefficient owing to the complexity of plastic waste mixtures (Ragaert et al., 2017). While it is a well-established process for clean, source-segregated thermoplastics, it tends to yield lower-quality materials. The final products generated through mechanical recycling vary depending on the type of plastic being treated and the specific recycling techniques applied. Common products include reprocessed plastic pellets, plastic sheets, films, fibre, and textile products, among others (Maris et al., 2018).

Thermal recycling of waste plastic materials includes melting the plastic wastes by elevating their temperatures and then casting or injecting the molten into a mould to form products. For the chemical recycling of plastic wastes, the polymer chains can be broken down and converted to their initial monomers that can be used instead of virgin raw materials in developing raw plastic materials (Kalali et al., 2023).

Chemical recycling has the capacity to process a broader variety of polymers and mixed plastics, resulting in the production of materials that are of a quality similar to virgin-grade plastics. However, it has restrictions when it comes to certain polymer groups and is susceptible to contaminants like PVC (which generates HCl), oxygenated plastics, or brominated flame retardants (Manzuch et al., 2021). Additionally, chemical recycling demands a significant amount of energy, which results in a portion of the feedstock being consumed and consequently lowers the product yields (approximately 30% to 40% for pyrolysis and gasification) (Goldberg et al., 2019), further contributing to carbon losses within the system.

Hydrothermal plastic recycling is an innovative and promising approach to address the challenges associated with plastic waste management and environmental sustainability. It involves the treatment of plastic waste with high-temperature and high-pressure water to break down the polymers into valuable products (Aslam et al, 2020). It is a promising complementary approach to recover plastics from non-segregated residual wastes and offset system carbon losses by valorising non-fossil organic waste components or sustainable sourced biomass. However, hydrothermal recycling may not be applicable to every plastic type. For instance, Polyolefins such as LDPE, HDPE, and polypropylene exhibit strong resistance to subcritical hydrothermal conditions, with less than 10% conversion observed at

350°C (Souza dos Passos et al., 2020). A recent study of residual municipal solid waste reveals the accumulation of LDPE within the solid component, whereas bio-based waste and PET were predominantly broken down when employing hydrothermal recycling methods (Okoligwe et al., 2022)

Electrochemical hydrogenation represents an advanced method for plastic recycling, typically applied as a subsequent step in conjunction with other plastic recycling processes, such as pyrolysis, to enhance the quality of bio-oil. Notably, electrochemical hydrogenation eliminates the need for external hydrogen sources, as it generates hydrogen through the process of water electrolysis. This approach reduces costs and mitigates the challenges associated with hydrogen storage (Li et al., 2012; Guedes et al., 2018; Chen et al., 2021). Moreover, electrochemical hydrogenation can be carried out under mild conditions, with temperatures below 80°C and at 1 atmosphere of pressure. Operating at lower temperatures helps prevent catalyst deactivation due to coke formation and membrane fouling, potentially decreasing expenses related to catalyst procurement and recycling (Garedew et al., 2019).

Electrochemical hydrogenation is particularly well-suited for upgrading water-soluble bio-oil, which is one of the products of plastic pyrolysis in certain conditions. This treatment results in an increase in the H:C ratio (hydrogen to carbon) and a decrease in the O:C ratio (oxygen to carbon) of the bio-oil. Additionally, it reduces the content of various organic groups, including acids, esters, carbonyls, phenols, sugars, and furans. The process significantly elevates the alcohol content and enhances the selectivity of polyhydric alcohols. These findings suggest that this technique has the capability to saturate unsaturated components in water-soluble bio-oil (Zhang et al., 2018). However, there are research gaps that need to be addressed, such as identifying the optimal catalysts, membranes, cell configurations, and methods to enhance the low conductivity of the oil. Electrochemical hydrogenation is a relatively new technology and requires further study to be fully optimised. Understanding the reaction mechanism and the behaviour of the compounds involved is a crucial aspect of this process.

Section 3: Options for change to improve the circularity of the automotive plastics supply chain

Section 2 reviewed the current state of automotive plastics including plastic use in light-duty, battery electric, and heavy-duty vehicles. Current end of life options are limited; the majority of automotive plastics are incinerated for energy recovery or landfilled. To address this gap, this section presents opportunities for change to improve the circularity of the UK automotive plastics supply chain across three areas: supply side changes, component design, and end of life. The section concludes by identifying key drivers and barriers that impact the implementation of a circular automotive plastics supply chain.

3.1 Supply side changes to improve automotive plastics circularity

What can be done to improve automotive supply chain circularity?

As section 1.2 demonstrated, plastic use in vehicles is increasing due to the emissions and fuel saving benefits of light weighting. At present, reducing plastic use in vehicles is unlikely, therefore improving the circularity of automotive plastics requires the use of alternative, non-crude oil-based materials and feedstocks, in addition to reducing supply chain emissions.

3.1.1 Alternative materials and feedstocks

How can biosourced plastics be used to reduce emissions in the automotive supply chain?

Increasing the diversity of feedstocks used to manufacture plastic components by incorporating alternative materials, such as biobased feedstocks, is one method to increase the circularity of the automotive supply chain. Biosourced plastics (or biopolymers) can be defined as materials made from corn, potatoes, wheat, and vegetable oil, which may be biodegradable or compostable (Vieyra et al., 2022). Highly biodegradable polymers refer to biopolymers or biosourced plastics that are starch and protein based and completely biodegradable. High biodegradable polymers have low mechanical properties and are not applicable for long-term-service-life applications such as vehicles. Additionally, at present they are not scalable due to low production capacity and high cost (Vieyra et al., 2022). For this reason, Vieyra et al. (2022) suggests that biosourced plastics, natural-fibre composites, and fibre-reinforced polymer composites are viable alternatives to fossil fuel derived automotive plastics.

Biosourced plastics currently used in the automotive industry include soy, hemp, juste, sisal, bio-polyamides (bio-PA), DuPont Zytel, polylactic acid (PLA), and bio-based polypropylene (bio-PP) (Vieyra et al., 2022). Natural-fibre composites, such as cellulosic plant fibres are made from jute, kenaf, hemp, flax, sisal, banana, bamboo or coconut fibre (Vieyra et al., 2022). These natural-fibre composites can be used to replace fibre-reinforced composites which have good mechanical properties but are not biodegradable. Chauhan et al. (2022) suggest that natural fibre-reinforced engineering plastic (NFRP) composite materials are inexpensive to make and have a small environmental impact with properties similar to metals and other composites. Thermoplastic polymers in NFRP composites can be easily recycled and are an appropriate substitute for virgin polymers. However, NFRP composites pose some challenges for use in transportation; they have “high water absorption, variation in fibre properties, lack of adhesion between the fibre and matrix, low fire resistance, and limited processing temperature" (Chauhan et al., 2022). The low fire resistance of NFRP composite materials poses a problem for use in vehicles, however treatment with fire retardants, and coating are suitable solutions. Chauhan et al. (2022) indicate that NFRP composite materials are used to make floor and door panels, dashboards, door linings, and luggage compartments among other components. Recycled engineering plastics reinforced with natural fibres can be advantageous for car manufacturers to reduce their environmental impact. However, Aguilar Esteva et al. (2021) indicates that while bio-based plastics are potential replacements for petroleum-based plastics they may not be completely circular, and they have the potential to divert agricultural crops away from food production.

How can recycled materials be used to reduce emissions in the automotive supply chain?

Meng, McKechnie, et al. (2018) demonstrate that recycled carbon fibre (CF) from industrial waste has a lower environmental impact compared to virgin CF and can be produced at approximately 15% of the cost. Additionally, Meng et al. (2017) suggest that carbon fibre reinforced plastic (CFRP) recycling (i.e. pyrolysis, fluidised bed, and chemical recycling) can be achieved in a more efficient process that requires significantly less energy and produces less emissions than virgin CF production. Recycled CFRP can be used to replace non-structural light weighting vehicle components; currently recycled CFRP may not be appropriate for applications that require high integrity materials (Meng, Olivetti, et al., 2018).

In addition to biosourced plastics, automotive plastic components can be manufactured from recycled (oil-based) materials. Using recycled automotive plastics may not always be feasible due to the lack of material integrity and downcycling processes, however implementing design choices that allow for materials with less mechanically demanding uses, such as fuel tanks, to be made from recycled plastics may be advantageous. Using recycled plastics in vehicles is increasing; Ford, Toyota, and Audi have pledged to increase the use of recycled plastics in their vehicles (Vieyra et al., 2021). Vieyra et al., (2021) further suggest that using biosourced plastics or recycled plastics in automotive manufacturing poses two problems: (1) the production cost of biosourced plastics; (2) the growth of automotive solid waste and plastic litter. For these reasons, plastic automotive components also need to be designed for circularity (Section 3.2).

3.1.2 Reduce supply chain emissions

How can supply chain emissions be reduced?

In addition to replacing virgin oil-based polymers with biosourced plastics and recycled CFRP, the automotive sector can improve its environmental impact by reducing supply chain emissions through Carbon Capture Utilisation and Storage (CCUS) and supply chain electrification of plastic production processes.

CCUS refers to a mitigation technology that captures carbon dioxide (CO2) emissions from stationary CO_2 sources. CO_2 is captured via chemical absorption, membrane separation, and adsorption, before being transported and stored in CO2 utilisation, saline formation storage, or unmineable coal-bed storage (Zhang et al., 2020). CCUS can be used in the automotive sector to mitigate the CO_2 emissions from OEM production sites, however, CCUS infrastructure is expensive, which hinders the application of CCUS technology at scale (Zhang et al., 2020).

Zero-carbon electricity for direct electrification of plastic production processes is another strategy to reduce emissions. Electrifying processes in the automotive plastic supply chain benefits from the planned reductions in emissions intensity for the electrical grid. At present, significant investment in electric infrastructure, and energy storage is required to make electrification beneficial (Rightor et al., 2020). The potential for electrification to reduce emissions is dependent on the manufacturing process; plastic manufacturing uses a large amount of process heat. Electrification strategies for plastic production include improving the energy efficiency of electrical equipment already in use, implementing intermittent fuel switching, electrifying process heating by installing heat pumps and electric boilers, and recovering waste heat (Rightor et al., 2020).

In addition to CCUS and supply chain electrification, supply chain emissions can be reduced by improving material and energy efficiency without changing technologies, localising manufacturing to shorten supply chains, optimising logistics, and changing business models.

3.2 Designing automotive plastics for circularity

How can the component design of automotive plastics incorporate the principles of circular economy?

Reducing the emissions of the plastics supply chain and using alternative materials can improve the circularity of automotive plastics. However, the unique challenges of automotive plastics (i.e. high number of polymers and difficult disassembly), which make recycling and remanufacturing at end of life difficult require component re-design. Vehicles are a 'product of service' and can thus be designed for a technological cycle, where the materials, particularly plastics, can be "continuously and safely recycled into new material or products" (Bocken et al., 2016, p. 311). For automotive plastics to be designed for a circular economy, they must be able to be upcycled (i.e. the material can be reprocessed to a high value product) rather than downcycled through energy recovery (thermal recycling). This section proposes three options for designing automotive plastics for circularity: design for light weighting, design for longevity, and design for recyclability and reuse.

3.2.1 Design for Light weighting

How can the vehicle weight be reduced through design choices?

Reducing vehicle mass can improve energy efficiency in the vehicle use phase and reduce material quantities required in production (Elgowainy et al., 2016). Design for light weighting refers to designing automotive plastic components that require fewer materials for the same functionality (i.e. dematerialisation) and reducing the material intensity (i.e. using down-gauged parts to achieve the same vehicle durability) (Aguilar Esteva et al., 2021). Another principle of design for light weighting includes material efficiency (i.e. more feedstock converted into product), which can be achieved with the use of computers in vehicle design (computer-assisted engineering). Computer-assisted engineering allows for the optimisation of vehicle weight with the introduction of advanced materials, without compromising safety (Isenstadt et al., 2016).

Material selection has also been used to achieve light weighting, specifically, plastics and composites are widely used in vehicles for their weight reduction potential and mechanical properties. Thermoplastics and composites can be used for some part applications in chassis components which currently comprise 60% to 65% of vehicle mass (Isenstadt et al., 2016). Thermoplastics are used to replace metal in front and rear bumpers which can save about 2 kg per bumper. For example, the 2014 Ford Fusion has a single-piece front bumper made from a PC and PBT blend which is 40% lighter than steel (Isenstadt et al., 2016). Thermoplastics and thermosets are not widely used to replace steel in fenders, closures, and body panels, but uptake is increasing; a thermoplastic fender is 2.9 kg lighter than the steel alternative (Isenstadt et al., 2016). Thermoplastics allow for design flexibility and can thus also be used to improve the aerodynamics of exterior body panels such as air guides, spoilers, air intake, and air fins (Isenstadt et al., 2016). Alternative materials can also be used for light weighting; substituting cellulose and kenaf for glass fibres in automotive components can reduce the vehicle life cycle energy demand and emissions (Boland et al., 2016). Using CFRP in car body components can result in lower primary energy demand than using traditional steel. However, the reduction in global warming potential is found to be greater than equivalent lightweighting strategies using aluminium and advanced high strength steel. To maximise the energy and emissions savings from material substitution, vehicle lifetimes should be extended and the amount of material used should be minimised (Sun et al. 2019).

Light weighting can also be achieved via functional integration where components and materials are integrated such as metal/plastic components. However, integration can result in difficult disassembly which goes against the aim of design for circularity. There are trade-offs between the benefits of light weighting (i.e. decarbonisation) and the goal of circularity; for example, lightweight integrated components can improve fuel efficiency and reduce emissions, while being difficult to disassemble and easily recyclable. In the design of automotive plastics, it is important to consider the competing goals of vehicle performance, passenger safety, production cost, and circularity.

3.2.2 Design for Longevity

How can vehicle design increase the useful life of vehicles?

The mean plastic product lifetime in the automotive sector is approximately 13 years. Increasing plastic component life spans means that stocks remain in use for longer. Therefore, waste is produced at a slower rate and the rate at which in use stocks must be replaced is also reduced (Geyer et al. 2017). Design for longevity refers to extending the utilisation period of the product by creating long-life products and extending the product's life (Bocken et al., 2016). Vehicles are already being designed as long-life products and designed for ease of maintenance and repair. However, plastic use in vehicles is not standardised or designed for ease of disassembly, which hinders the efficiency of recycling automotive plastics. Designing automotive plastics for longevity includes designing plastic components to be simple (modular) so that they can be easily serviced, disassembled, remanufactured, and reused (Aguilar Esteva et al., 2021).

Carlsson et al. (2021) suggest that design for longevity is not always optimal; products should be designed for the specific (i.e. optimal) longevity of the product. The optimal lifetime of a product should be determined by needs of the user, the business, and the material (Carlsson et al., 2021). Further, design for longevity includes designing the product to be easily reused, repaired, refurbished, remanufactured, recycled, and repurposed (Carlsson et al., 2021). In the case of automotive plastics, design for longevity includes designing the plastic component so that the polymer type can be easily identified to aid the circular process.

3.2.3 Design for Recyclability and Reuse

How can design choices increase the recyclability of vehicles and reusability of components?

Design for recyclability and reuse refers to designing automotive plastics to be dismantled from vehicles for reuse or to be recycled, rather than designing components to be made from recycled materials (see Section 3.1.1). He et al., (2021) suggests that design for recyclability should incorporate reusability, recoverability (i.e. ease of disassembly), and recyclability into product design. Hallack et al. (2022) identify three principles of design for recyclability of exterior automotive plastics: (1) check the component against the identified end of life practices to identify any problems and generate solutions for design improvements; (2) compare the environmental impacts of the design improvements; (3) evaluate the economic recycling benefits of the design improvements. When designing for recyclability, cost related factors (i.e. material identification, ease of disassembly), and design related factors (i.e. material choice, recycling inhibitors, joining techniques) must be considered (Hallack et al., 2022).

One of the main challenges for recycling automotive plastics is the difficulty of separating the numerous polymer types. Thus, designing components with fewer polymer types, and implementing a national or international classification standard for polymer identification would enable recyclability. He et al. (2021) suggests design for recyclability and reuse can be enabled by using thermoplastic materials, which are easy to recycle, using materials that have mature recycling technologies, using materials with good compatibility (i.e. they can be recycled together), and avoiding toxic materials. Further, design for disassembly, which ensures that products can be easily separated, would enable plastics to be easily removed from end-of-life vehicles saving time and money allowing the plastics to be recycled (Bocken et al., 2016). Design for disassembly can be achieved through modular design and designing components to be easily separated (He et al., 2021). Current joining techniques for plastic components (i.e. bonding, adhesives, welded joints) are a barrier to recycling (Zhao & Chen, 2015). Zhao et al. (2015) suggests designing for disassembly include replacing adhesives and bonding with snap-fit or nut/bolt designs, which can be disassembled more easily..

Innovation in recycling automotive plastics is occurring; for example, Audi recycles plastic parts (fuel tanks, wheel trims, radiator grills) into pyrolysis oil to create new plastic goods (Vieyra et al., 2021). Wyss et al. (2022) propose reusing waste plastic in vehicles by turning it into flash graphene, which can be used to enhance vehicle PUF (polyurethane foam) composites. Flash graphene can be used as an additive with other materials such as plastics, concrete, and asphalt, which reduces the amount of host material required to achieve the same material properties. Vieyra et al. (2021) indicate that not all automotive plastics, such as ABS (Acrylonitrile Butadiene Styrene), are easy to recycle; some plastics are unsuitable for recycling as they release large amounts of CO_2.

Data on the reuse of automotive plastics is limited, however, Khalid et al. (2022) suggests that oligomers from polymeric resin can be reused as chemical crude materials in the recycling process for carbon fibre. The authors also indicate that recycled polymers can be used in wood plastic composite applications, and phenolics from car parts have been used to make level crossing panels for railway crossings (Khalid et al., 2020). Further, recycled polymers can be used in asphalt for road pavement, and in the automotive sector recycled carbon fibre has been used to make C-pillars using the sheet moulding compound technique (Khalid et al., 2020). Sawyer-Beaulieu & Tam (2015) suggests that the greatest potential for reusing automotive components is in remanufacturing parts. While not all automotive plastic components are suitable for re-use or remanufacturing, Sawyer-Beaulieu & Tam (2015) indicate that maximising reuse requires supply and demand, end markets, infrastructure, as well as positive customer attitudes and economics.

Numerous barriers to recycling automotive plastic exist, including a lack of policy, regulation, plastics-labelling, recycling facilities, and the low market value of recycled plastics (Vieyra et al., 2021). The process of mechanical recycling can also reduce the quality of the recycled plastics (down-cycling). Automotive plastics that cannot be recycled are landfilled or undergo thermal treatments (i.e. pyrolysis) at the end of life.

3.3 Drivers and barriers for change

What are the drivers and barriers that are affecting change in the automotive sector?

Achieving circularity for plastics in the automotive sector requires advancing technical knowledge but also acknowledging the non-technical driver and barriers that impact change, with van Bruggen et al. (2022) suggest that barriers and solutions are interconnected. Thus, achieving a circular economy for plastics in the automotive sector will require both policy and technical solutions to achieve systemic change. The authors identified the lack of regulation, a lack of economic incentives, hazardous substances contained in plastics, and negative attitudes about recycled products as key barriers (van Bruggen et al., 2022). Similarly, Baldassarre et al. (2022) identified four barriers to increasing the amount of recycled plastic in the EU automotive sector including OEMs trying to gain a competitive advantage (culture), lack of traceability and verification of recycled plastics (regulatory), cost fluctuations of virgin and recycled plastics (economic), and the quality of recycled plastics (technical).

Van Bruggen et al. (2022) identify potential solutions for increased circularity in the automotive sector, which include establishing a norm that stimulates upcycling and using recyclate, designing for recycling, collaboration of stakeholders, using water-based adhesives, and using modular and reconfigurable parts. Baldassarre et al. (2022) identified drivers, which include increasing consumer awareness (cultural), implementing policies for plastic recycling (regulatory), high volumes of post-consumer plastic water (economic), and improved chemical recycling technology (technical). Further, Amir et al. (2023) indicate that remanufacturing automotive spare parts requires improved organisational processes, specifically efficient reverse logistics to integrate forward and reverse flows to reduce inefficiencies and cost.

Drewniok et al. (2023) estimates that avoiding exported waste and the production of virgin plastics in the UK could be achieved by increasing the recycling capacity from the current rate of 0.4 Mt per year. However, a reduction in demand is still required to further reduce the negative impacts of plastics, including emissions and waste pollution. A reduction in virgin plastics demand can be achieved through alternative material use, increasing the recycled content in vehicle components, light-weighting strategies to reduce the amount of material required, and ensuring recyclability by reducing the diversity of plastic types used. Further, circularity can be encouraged by changing the purchasing models of vehicles from individual ownership to a servitization model (car-as-a-service). In the servitization model customers rent the vehicle from a company which assumes the repair and maintenance costs; the company makes profit throughout the lifetime of the vehicle encouraging longevity.

Policy is a key driver of automotive circularity. The Global Plastics Treaty aims to end plastic pollution by forging an international legally binding agreement by 2024 that once implemented will change our management of plastic and its associated waste (United Nations Environment Assembly of the United Nations Environment Program, 2022). Also, the World Economic Forum and SYSTEMIQ (2021, p. 7) indicate three policy actions required to enable automotive circularity in the EU: (1) “create new, cross-cutting market enablers for the transformation to a circular automotive industry”; (2) “reshape the economic incentives… to enable profitability and investability of circular products and services; (3) “harmonise and strengthen existing policy measures…across life stages and components” (p. 7).

Recent policy proposals include:

- ➔ EU ‘Proposal for a Regulation on circularity requirement for vehicle design and management of end-of-life vehicle’ (European Directorate-General for Environment, 2023)
- ➔ JRC Science for Poly report on recycled plastic content targets in new vehicles (Maury et al., 2023).
- ➔ UK Guidance, Regulations: End-of-life vehicles (Regulations: End-of-Life Vehicles (ELVs) , 2021).

Conclusion

In this critical review, we explored the academic and grey literature to provide the knowledge base for the research project and workshop: Decarbonised and circular automotive plastics supply chain. This project aims to answer the question: *How can transitioning to a circular supply chain reduce the impact of plastic use in the UK automotive industry?*

This review covered the lifecycle and supply and demand factors of the automotive plastics supply chain (Section 1), assessed the types, quantities, and uses of plastics in the automotive sector (Section 2), and identified opportunities for change to improve the circularity of the UK automotive plastics supply chain (Section 3).

Key takeaways identified in this critical review include:

- ➔ Currently there is a lack of dynamic Material Flow Analysis (MFA) models which specifically track automotive plastic flows in the UK. Therefore, results are inferred from data about material quantities and wider scope MFA studies. Better data collection including detailed breakdowns of plastic types would enable sector specific MFA studies in the future.
- ➔ There is a lack of granularity of plastic types in Life Cycle Assessment studies and reports of material breakdowns. Plastics are often grouped as one material in Life Cycle Assessment studies and studies that report vehicle material breakdowns. Identification and reporting of specific polymer types in material breakdowns is required.
- ➔ Current studies are lacking in downstream product use coverage. Information provided in case studies of plastic use from vehicle manufacturers is typically not detailed. Specifically, the quantity of plastics that use circular techniques (e.g., biosourced plastics, recycled plastics in new components) is not specified.
- ➔ The circularity of automotive plastics can be improved by reducing the number of polymer types, implementing design principles that enable easy disassembly, and using non-petroleum-based materials.

Appendix A: Abbreviations

Abbreviation	Full Name
ABS	Acrylonitrile butadiene styrene
ASA	Acrylonitrile styrene acrylate
ASR	Automotive shredder residue
Bio-PA	Bio-polyamides
Bio-PP	Bio-polypropylene
CCUS	Carbon capture utilisation and storage
CENTS	Circular Economy Network + in Transportation Systems
CE	Circular economy
CF	Carbon fibre
CFRP	Carbon fibre reinforced polymer
CO2	Carbon dioxide
EPS	Expanded polystyrene
EU	European Union
EV	Electric vehicle
GFRP	Glass fibre reinforced polyester
GMT	Glass mat reinforced thermoplastic
HDPE	High density polyethylene
ISO	International Organisation for Standardisation
LDPE	Low density polyethylene
MDPE	Medium density polyethylene
MFA	Material flow analysis
NFRP	Natural fibre-reinforced plastic
OEM	Original equipment manufacturer
PA	Polyamide
PA6	Polyamide 6
PC	Polycarbonate
PE	Polyethylene
PEEK	Polyetherether ketone
PEI	Polyetherimide
PET	Polyethylene terephthalate
PLA	Polylactic acid
PMMA	Poly(methylmethacrylate)
POM	Polyoxymethylene
PP	Polypropylene
PPE	Polyphenylene oxide
PPS	Poly(p-phenylene sulfide)
PS	Polystyrene
PUF	Polyurethane foam
PUR	Polyurethane
PVC	Polyvinyl chloride
SMA	Styrene-maleic anhydride copolymers
TPO	Thermoplastic polyolefins
UK	United Kingdom

Appendix B: List of references

Category	Critical Review Section	Publication
Circular economy	Section 1	Agguilar et al. (2021) Amir et al. (2023) Baldassarre et al. (2022) Batista et al. (2018) Christoper. (2023) Corvellec et al. (2022) Cullen (2017) De Angelis et al. (2018) European Commission (2015) Kirchherr et al. (2017) Plastics Europe (2022b) van Bruggen et al. (2022)
General plastics flows	Section 1 Section 2	Cabernard et al. (2022) Cullen et al. (2022) Drewniok et al. (2023) Geyer et al. (2017) Levi & Cullen (2018) Plastics Europe (2019) Plastics Europe (2022) Wang et al. (2021) Watari et al. (2019)
Production and use of automotive plastics	Section 2.2	Economic Commission for Europe (2017) Fishman et al (2018) Rodrigues et al. (2022) SMMT (2022) Sullivan et al. (1998) Tukker et al. (2014) Wolff et al. (2020)

Data for the material breakdown of vehicles	Section 2	British Plastics Federation (n.d.) Burnham et al. (2006) Council (2023) Dai et al. (2019) Danilecki et al. (2017) Davis & Boundy (2021) Department of Transport (2023) Elgowainy et al. (2016) Isenstadt et al. (2016) Lyu & Choi (2015) Pradeep et al. (2017)
Original Equipment Manufacturers Report	Section 2	Aston Martin Lagonda (2021) BMW Brilliance automotive (2021) Nissan Motor Corporation (2020) Stellantis (2020) Toyota Motor Corporation (2022) Volkswagen Group (2022)
Options for transitioning towards a circular economy: *End-of-life*	Section 2.3 Section 3	Berzi et al. (2013) Cossu & Lai (2015) Martinez Sanz et al (2022) Miller et al. (2014) Raugei et al. (2021) Sawyer-Beaulieu (2009) Singh et al. (2017) Stallkamp et al. (2023)

Options for transitioning towards a circular economy: *Supply side changes*	Section 3.1	Chauhan et al. (2022) Rightor et al. (2020) Zhang et al. (2020) Vieyra et al. (2022)
Options for transitioning towards a circular economy: *Design*	Section 3.2	Bocken et al. (2016) Boland et al. (2016) Carlsson et al. (2021) Hallack et al. (2022) He et al. (2021) Hill (2015) Meng et al. (2017) Meng et al. (2018) Wyss et al. (2022) Zhao & Chen (2015) Isenstadt et al. (2016) Vieyra et al. (2022)
Options for transitioning towards a circular economy: *Policy and barriers to implementation*	Section 3.4	European Directorate-General for the Environment (2023) Maury et al. (2023) UK Gov (2021) World Economic Forum (2021)

Appendix C: Data

Table A1: Plastic content in cars (Sullivan et al., 1998)

Material	Mass (kg)	% weight of plastics	% weight of vehicle
ABS (Acrylonitrile Butadiene Styrene)	9.70	6.84	0.63
ABS-PC blend (Acrylonitrile Butadiene StyrenePolycarbonate blend)	2.80	1.97	0.18
Acetal	4.70	3.31	0.31
Acrylic resin	2.50	1.76	0.16
ASA (Acrylonitrile Styrene Acrylate)	0.18	0.13	0.01
Epoxy Resin	0.77	0.54	0.05
PA 6 (Polyamide 6)	1.70	1.20	0.11
PA 66 (Polyamide 66)	10.00	7.05	0.65
PA 6-PC blend (Polyamide-Polycarbonate blend)	0.45	0.32	0.03
PBT (Polybutylene terephthalate)	0.37	0.26	0.02
PC (Polycarbonate)	3.80	2.68	0.25
PE (Polyethylene)	6.20	4.37	0.41
PET (Polyethylene terephthalate)	2.20	1.55	0.14
Phenolic Resin	1.10	0.78	0.07
Polyester Resin	11.00	7.76	0.72
PP (Polypropylene)	25.00	17.63	1.63
PP foam	1.70	1.20	0.11
PP-EPDM blend (Polypropylene-ethylene	0.10	0.07	0.01

propylene diene monomer blend)			
PPO-PC blend (Polyphenylene Oxide-Polycarbonate blend)	0.03	0.02	0.00
PPO-PS blend (Polyphenylene Oxide-Polystyrene blend)	2.20	1.55	0.14
PS (Polystyrene)	0.01	0.00	0.00
PUR (Polyurethane)	35.00	24.68	2.29
PVC (Polyvinyl Chloride)	20.00	14.10	1.31
TEO (Thermoplastic Elastomeric Olefin)	0.31	0.22	0.02
Subtotal	**141.81**	**100.00**	**9.26**

Table A2: Plastic content in Volkswagen Golf Models (Danilecki et al., 2017)

Brand	**Volkswagen**					
Model	Golf MK 1	Golf MK 2	Golf MK 3	Golf MK 4	Golf MK 5	Golf MK 6
Years of production	1976–1983	1983–1987	1991–1997	1997–2003	2006–2008	2008–2012
Type	Hatchback	Hatchback	Hatchback	Hatchback	Hatchback	Hatchback
Weight (kg)	830	875	1030	1174	1153	1215
Engine capacity (cm3)	1272	1272	1391	1390	1390	1390
Fuel consumption in NEDC (l/100 km) (combined)	7.8	6.1	6.8	6.4	6.8	6.4

Materials/ Model	**VW Golf MK1**	**VW Golf MK2**	**VW Golf MK3**	**VW Golf MK4**	**VW Golf MK5**	**VW Golf MK6**
	kg	kg	kg	kg	kg	kg
Steel, cast steel, cast iron	566.9	595	658.3	733.8	694.1	736.1
Aluminium and aluminium alloys	49.3	54.9	72.1	84.5	82.8	97.4
Acrylonitrile Butadiene Styrene (ABS)	10.9	11.4	17.6	20.4	21.3	25.2
Polypropylene (PP)	22.1	19.4	34.8	44.7	44.6	52.2
Polyamide (PA)	4.8	5	9.9	9.6	10.3	11.1
Polystyrene (PS)	3.2	4.7	5.3	7.5	7.5	7.5
Polycarbonate (PC)	0	0	0	0	0.1	0.1
Polyurethane (PUR)	6	6.2	8.1	10.2	9.9	11
Poly (vinyl chloride) (PVC)	0	0	1.4	1.7	1.6	1.8
Polyethylene (PE)	0.7	6.8	9.5	9.2	16.1	17
Polyethylene Terephthalate (PET)	0.2	0.2	1.2	1.2	0.8	0.8
Polymethyl methacrylate PMMA	0.5	0.6	0.8	1.8	0	0
Acrylonitrile styrene acrylate (ASA)	0	0	0.4	0.3	0.7	0.5

Glass	24.5	16.8	34.5	34.6	29.2	40.9
Fabrics	5.5	5.8	6.8	6.9	6.6	6.7
Gum	39.6	39.3	40.2	57.8	53.6	54
Copper, zinc, tin, nickel, magnesium	9.2	10.3	18.6	21.1	21.9	25.2
Lead	0.3	0.3	0.8	0.3	0	0.9
Gear oil	2.1	1.7	1.7	2.4	3.1	5.5
Engine oil	2.4	2.8	2.8	3.2	3.1	3
Power steering fluid	0	0.6	1	0.7	0.7	0
Brake fluid	0.5	0.5	0.5	0.4	0.6	0.7
Coolant fluid	5.4	5.4	4.4	5.5	4.3	5.7
Windshield washer fluid	1.4	2.5	2.5	1.8	5.3	2
Petrol	33.8	41.3	41.3	41.3	41.3	41.3
Multi-material components	8	8.4	12.7	12.5	12.7	10.3
Electronics and electro-technical components	32.1	33.5	40.7	48.6	45.7	48.8

Table A3: Material content as a % of total vehicle weight (American Chemistry Council 2023)

Percent %	**2012**	**2013**	**2014**	**2015**	**2016**	**2017**	**2018**	**2019**	**2020**	**2021**
Steel	52.00	51.50	51.50	51.00	50.50	50.00	49.00	48.50	47.50	47.00
Aluminium	8.80	9.00	9.20	9.40	9.90	10.20	10.30	10.40	10.60	10.60
Plastics & polymer composites	8.90	9.00	8.90	8.90	9.00	9.20	9.30	9.40	9.40	9.60
Iron	8.00	8.00	7.90	7.80	7.70	7.70	7.60	7.50	7.40	7.30
Other metals/ alloys	5.90	5.70	6.60	6.70	6.50	6.60	6.90	7.00	7.00	7.30
Synthetic rubber/ elastomers	4.90	4.80	4.80	4.80	4.70	4.80	4.90	5.00	5.00	5.10
Fluids & lubricants	4.80	4.80	4.90	4.90	4.80	4.60	4.60	4.40	4.50	4.50
Glass	2.10	2.10	2.20	2.30	2.30	2.30	2.40	2.40	2.40	2.50
Textiles	1.80	1.80	1.90	2.00	2.00	2.10	2.20	2.20	2.30	2.30
Natural rubber	2.20	2.10	2.10	2.00	2.00	2.00	2.00	1.90	1.90	1.80
Coatings	1.20	1.10	1.10	1.10	1.10	1.10	1.00	1.00	1.00	1.00

Table A4: Plastics and polymer composites in an average automobile

Mass of material (kg/vehicle)	**2012**	**2013**	**2014**	**2015**	**2016**	**2017**	**2018**	**2019**	**2020**	**2021**
Polypropylene	37	38	38	38	39	40	41	42	42	44
Polyurethane Foam	33	34	34	34	34	35	36	37	37	38
Nylon	17	17	17	17	17	18	18	18	18	19
High-Density Polyethylene (HDPE)	13	13	12	12	13	13	14	14	15	15
Polyvinyl Chloride (PVC)	11	12	12	12	12	13	13	14	14	14
Acrylonitrile Butadine Styrene (ABS)	10	10	10	10	10	11	10	10	10	10
Polycarbonate	8	8	8	8	8	8	8	8	9	9
Phenolic Resins	5	5	5	5	5	5	5	6	6	7
Polyacetal Resin	4	4	4	4	4	4	4	4	4	5
Polyvinyl Butyral	3	3	3	3	3	3	3	3	3	3
Polybutylene Terephthalate (PBT)	2	2	2	2	2	2	2	2	2	3
Polymethyl Methacrylate (PMMA)	2	2	2	2	2	2	2	2	2	2
Other plastics	15	16	16	16	16	16	17	17	17	18
Plastics & polymer composite total	**161**	**163**	**164**	**164**	**165**	**171**	**174**	**176**	**178**	**186**

Table A5: Number of polymers used in automobile parts (Lyu & Choi, 2015)

Part	**Main Plastic Type**	**Weight in Average Car (kg)**
Bumpers	PP, ABS, PC	10
Seats	PUR, PP, PVC, ABS, PA	13
Dashboard	PP, ABS, PA, PC, PE	15
Fuel Systems	PE, POM, PA, PP	7
Body (Including body panels)	PP, PPE, PBT	6
Under the Hood Components	PA, PP, PBT	9
Interior Trim	PP, ABS, PET, POM, PVC	20
Electrical Components	PP, PE, PBT, PA, PVC	7
Exterior Trim	ABS, PA, PBT, ASA, PP	4
Lighting	PP, PC, ABS, PMMA, UP	5
Upholstery	PVC, PUR, PP, PE	8
Other Reservoirs	PP, PE, PA	1
Total	**-**	**105**

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