Report

Phasing out plastics

The automotive sector

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Cover photo: Car dashboard. © Viktor Theo/Unsplash

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Acronyms and abbreviations

ABS	acrylonitrile butadiene styrene
BAU	business as usual
CO_2	carbon dioxide
CO_2e	carbon dioxide equivalent
EU	European Union
EV	electric vehicle
GHG	greenhouse gas
HDPE	high-density polyethylene
IT	information technology
LDPE	low-density polyethylene
LED	low energy demand
MaaS	mobility as a service
Mt	million tonnes
OECD	Organisation for Economic Cooperation and Development
PE	polyethylene
PET	polyethylene terephthalate
PP	polypropylene
PPA	polyphthalamide
PS	polystyrene
PUR	polyurethane
PVC	polyvinyl chloride
SUV	sports utility vehicle

Executive summary

Background

Today, plastics are almost always made from fossil fuels and use fossil-fuel energy in their manufacture. Globally, in 2015, about 4% of greenhouse gas (GHG) emissions could be attributed to the manufacture and use of plastics (Zheng and Suh, 2019). In the same year, 7% of all plastics produced were for the 70 million cars and 25 million commercial vehicles manufactured by the automotive industry (Geyer et al., 2017). Because GHG emissions need to be reduced to net zero by 2050 to avert catastrophic climate change (IPCC, 2018), fossil-fuel plastics in cars and other vehicles need to be phased out.

This report, therefore, explores the technical feasibility of phasing out fossil-fuel plastics in the automotive industry by 2050. It is part of a broader research project investigating the technical potential for phasing out virgin (new) plastics made from fossil fuels. The study compares a business-as-usual (BAU) scenario for automotive plastics in 2050 with a low-plastic-consumption scenario that is compatible with pathways towards a 1.5°C maximum rise in average global temperature.

The analysis identifies the different uses of plastics in the automotive sector, focusing on their use in passenger vehicles. It compares the sector's consumption of six bulk plastics in 2050 under BAU assumptions with consumption under the hypothetical low-plastic scenario. Polypropylene, for example, accounted for about a quarter of all plastics used in cars globally in 2018 (Khemka, 2019). The potential to reduce plastics consumption in the automotive sector considers technically feasible opportunities for dematerialisation and reuse (for example, avoiding materials consumption) and substitution (shifting plastic consumption to other materials). We also explore the key factors that could influence the reduction of plastic consumption in the automotive sector.

Plastics account for about 15% of the weight of the average passenger car today (IEA, 2019a). They are increasingly being used to replace steel in car bodies and chassis, as well as for hundreds of other components, including lights, bumpers, engine components, dashboards and internal furnishings. For vehicle design, the advantages of plastics are their light weight, limited corrosion and flexibility. Using plastics to reduce the weight of vehicles leads to greater fuel efficiency. Despite this, however, the average weight of a passenger car has increased in recent years and now includes around 200 kg of plastic (Plastics Industry Association, 2019).

Automotive plastics in 2050

Under our BAU assumptions, the automotive sector would consume 76 million tonnes (Mt) of plastics in 2050, almost three times the level of 2015 (27 Mt). Global sales of passenger cars would increase from 66 million in 2015 to 97 million in 2050, with a higher plastic content in each car.

Although we assume the overall demand for passenger and freight transport services will grow to 2050, especially in emerging economies, the number of passenger vehicles in use and sold annually would increase at a much lower rate in our low-plastic-consumption scenario. The widespread uptake of ride-sharing, car-sharing and mobility-as-a-service business models would drive a reduction in the number of passenger cars sold in 2050, compared with the BAU scenario, as a result of increased vehicle utilisation, occupancy and lifespan.

Radical changes in vehicle design, shape and form, a lower average total weight and enhanced recycling of vehicles at the end of their life would be enabled by a significant shift from private vehicle ownership to professionally managed fleets. These shifts would also be facilitated by improvements in the availability, accessibility and quality of public transport services, combined with changes in urban physical environments and digital technologies to ease transfers between modes of transport.

Currently, there is little incentive to recycle plastic waste from the automotive sector because of challenges in recovering it, the frequent use of speciality plastics with low to no recycling potential and the use of additives, which can impede the quality and purity of recycled feedstock. As a result, high-value recycling is not feasible or economic, so there is little motivation for vehicle manufacturers to consider recycling needs. By 2050, a shared mobility system with managed fleets and associated changes in vehicle design could create the incentives for enhanced recycling rates and help reduce the need for virgin plastics.

Under our low-plastic-consumption vision for the automotive sector, the level of mobility services required in 2050 could be provided by half the passenger cars in the BAU scenario. Annual sales of passenger cars would total about 53 million globally, compared with 97 million under BAU conditions (and 66 million in 2015). These cars would be lighter, on average, than they are today (weighing about 900 kg rather than 1,200 kg for private vehicles and about 600 kg for shared cars), but the quantity of plastic would increase by about 50% to around 300 kg per vehicle. In aggregate, the total quantity of plastics consumed by the sector in 2050 would be 63 Mt, equivalent to a 17% reduction on business as usual.

The lower level of plastics consumption in the 2050 low-plastic-consumption scenario is due to dematerialisation (fewer vehicles), thanks to reduced private car ownership and the extensive availability of mobility-as-a-service operations with managed fleets of shared vehicles. Substitution as a strategy to reduce plastics consumption in the sector is constrained by factors such as the continued need for light-weighting and innovative vehicle design, which plastics could provide at relatively low cost.

1 Introduction

1.1 Background

Almost all modern plastics are made from fossil-fuel raw materials (oil, gas and coal) and use fossil-fuel energy in their manufacture. They account for 9% of global demand for oil and 3% of global demand for gas and, by 2050 could account for 20% of oil demand (World Economic Forum et al., 2016). Plastics were the source of about 4% of global GHGs in 2015 (Zheng and Suh, 2019). We calculate that by 2050, when the global economy needs to achieve net zero emissions, emissions from plastics will be three times greater on current trends.

Over the past two decades, plastics have assumed an increasingly important role in the automotive industry. The sector is now responsible for about 7% of global annual plastics consumption. By weight, the average modern passenger car is still made mostly of metal, but plastics now account for about 15%. By volume, plastics often make up about half of a car's total material (IEA, 2019a), comprising as many as 2,000 or more plastic parts of all shapes and sizes (Plastics Europe, 2018).

Recently, plastic waste and pollution have dominated the narrative on the negative side of plastics. As well as the effects of plastic pollution in sea life, concerns about toxicity and health arise from plastic microfibres found in the air, water and food. These are challenges that cannot be addressed solely by better materials handling or waste management. Nor would they be resolved by substituting plastics derived from fossil fuels with those derived from biomass – these would also lead to waste and pollution. From a climate and broader environmental perspective, it is necessary to curtail the consumption of new (virgin) plastic materials.

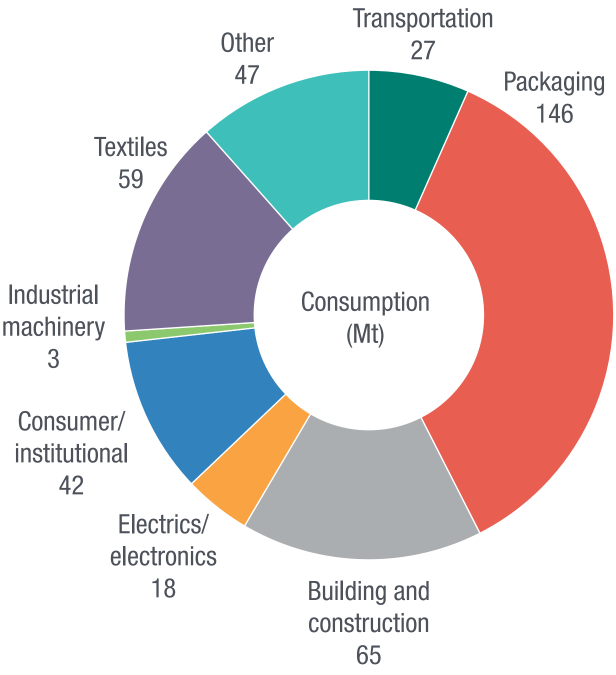
To date, the focus on the climate-change impact of vehicles has mainly been on their use. Vehicle fuel emissions account for about 70% of the total lifecycle emissions of a typical car today. Current trends suggest a continued increase in the use of plastics in vehicles to achieve weight reductions for both fossil-fuelled and electric vehicles (EVs), to improve energy efficiency and reduce fuel emissions. As batteries improve and the electricity powering EVs becomes cleaner, the carbon savings from light-weighting (reducing the weight of cars) are likely to decline (IEA, 2019a) and the embodied emissions of vehicle production and materials use may become a vehicle's main source of carbon emissions (Material Economics, 2018).

This report explores the potential to reduce the amount of fossil plastics used in the automotive sector. It is part of a broader research project investigating the technical potential for the phase-out by 2050 of virgin plastic materials produced from fossil fuels. The study complements existing forecasting and circular economy analysis, but our method is different. We take a bottom-up approach to assessing the use of plastics in four sectors (automotive, packaging, construction, and electrical and electronic appliances), which together account for around 60% of total plastics consumption (see Figure 1). The broader study considers the upstream and downstream aspects of the plastic value chain in aggregate across sectors and discusses opportunities to reduce the environmental impacts of plastics consumption through changes in the production, recycling and disposal of plastics. The technical sector reports focus on minimising the demand for plastic materials, as reductions in aggregate demand facilitate easier management of the associated upstream and end-of-life processes.

1.2 Methodology

The purpose of our analysis is to illustrate the technical and high-level political feasibility of phasing out the use of fossil plastics in the

Figure 1 Plastics consumption by sector in 2015



Source: Geyer et al. (2017)

automotive sector. It begins by identifying the amount of plastic used in the sector for a baseline year (2015) and uses recent trends to project BAU demand for plastics in the automotive sector in 2050. We then investigate the different uses of each bulk plastic type in the sector today to provide a basis for reducing future plastics consumption.

The technical potential to reduce the use of new plastic materials in 2050 compared with a BAU scenario is assessed by considering the following opportunities in cascading fashion:

1. dematerialisation and reuse (avoiding the need for new materials demand)
2. substitution with non-plastics (shifting the demand for new plastics to demand for other materials)
3. plastics recycling (optimising the waste-management schemes associated with plastics)
4. non-fossil feedstocks (meeting residual demand that cannot be reduced by the above approaches).

This report focuses on the first two steps of this analysis in the automotive sector. The accompanying synthesis report addresses the question of how to accommodate residual demand (steps 3 and 4) in aggregate across all sectors.

We complement our assessment of the technological feasibility of changing plastics use in the sector by 2050 with some high-level insights into the factors that could influence such change. However, we do not assess the likelihood of these changes, nor do we explore in detail their economic, political and behavioural dimensions. We aim to provide a possible future scenario and illustrate how it may come about, rather than attempt to predict the future.

We also set out a detailed 2050 mobility vision for the possible future scenario, building on published and well-researched scenarios and drawing a distinction between Organisation for Economic Co-operation and Development (OECD) and non-OECD countries.[1] The vision and subsequent global analysis focus on light-weight passenger vehicles, the most numerous type of vehicle, with around a billion cars already plying the roads worldwide. We do not include the use of rubber for tyres, which are made of natural or, more commonly, synthetic rubber and a range of additives, including plastics, and can be a major source of microplastics in local waterways.

We consider the implications for the production of fossil plastics in 2050 for six main plastic types: polyethylene (PE), polypropylene (PP), polystyrene (PS), polyvinyl chloride (PVC), polyethylene terephthalate (PET) and polyurethane (PUR), which account for 75% of global plastics production (Geyer et al., 2017).

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[1] For the purposes of this report, we approximate OECD as the sum of the OECD countries minus Mexico, plus Russia, based on Grubler et al. (2018).

1.3 Structure of the report

The remainder of this report is structured as follows:

- Chapter 2 provides an overview of current plastics consumption by the automotive sector.
- Chapter 3 describes our vision of the sector in 2050, highlighting potential changes in the organisation of and market for mobility services that could affect vehicle numbers.
- Chapter 4 assesses how these changes could be realised and potential key determining factors.
- Chapter 5 outlines the implications of achieving the 2050 vision for plastics consumption in the automotive sector, compared with BAU.
- Chapter 6 provides some conclusions of our analysis.

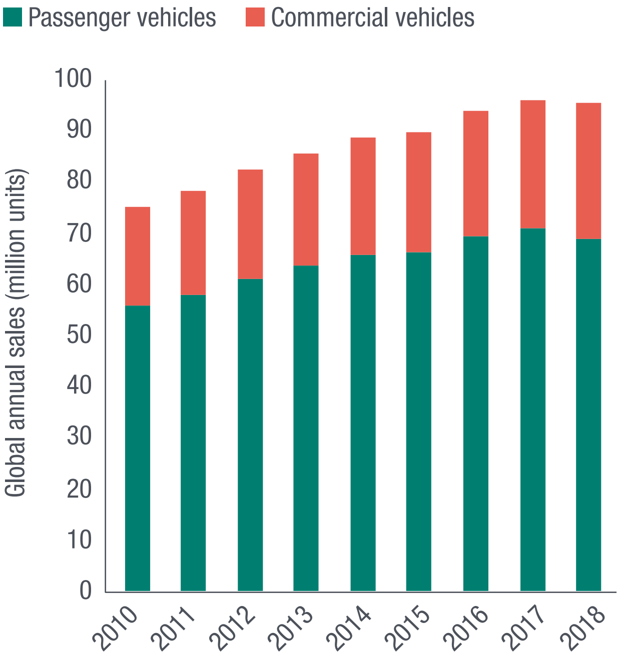
2 Plastics in the automotive sector

2.1 Context

Worldwide, about a billion passenger cars plied the roads in 2015, supplemented by another 300 million commercial vehicles (light commercial vehicles, buses and trucks). More than 70 million cars and 25 million commercial vehicles are now produced each year (OICA, 2018). Figure 2 shows global annual vehicle sales.

The production of passenger vehicles is mainly concentrated in China, Japan and Germany, which have produced around 24 million, 8 million, and 5–6 million vehicles annually, respectively, in recent years. They are followed by India, South Korea, the United States, Brazil, Spain, France and Mexico, which each produce between 1.5 million and 4 million units a year (OICA, 2018). China is the leading country in the demand for new vehicles, as measured by car sales, followed at some distance by the United States, Japan, Germany and India (OICA, 2019).

Figure 2 Global annual vehicle sales, 2010–2018



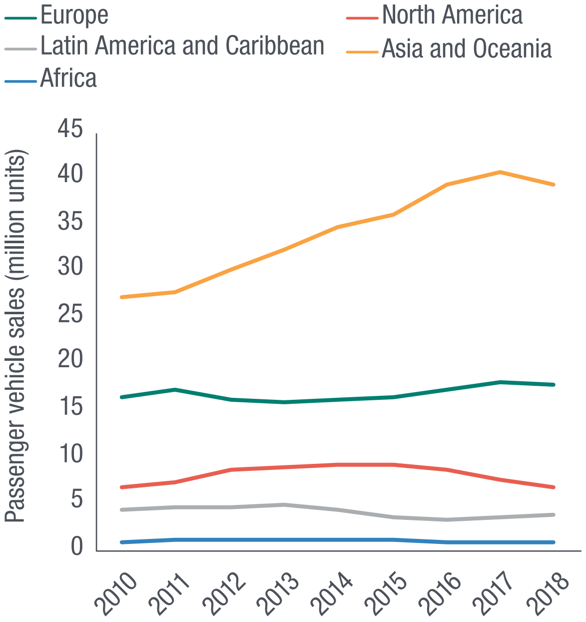
Source: International Organization of Motor Vehicle Manufacturers (OICA, 2019)

With the majority of absolute demand now coming from Asia, vehicle production is also increasingly shifting to economies in the region (Grand Review Research, 2019). Plastic use in cars varies by region, however. European manufacturers, for example, are known to use more plastics on the whole than their counterparts in Japan or North America (Rouilloux, 2012). Even so, in the United States alone, the market for finished automotive plastic and polymer composite products is valued at $20.6 billion, with automotive plastic products produced at 1,622 plants in 45 states (American Chemistry Council, 2018).

While the United States has almost 800 cars per 1,000 people, in India, the number stands at 22 cars per 1,000 (Petit, 2017). The strongest growth in vehicle sales and ownership is in Asia (Figure 3), where in (large) cities, in particular, there has been a rapid rise in personal car ownership – often adding to already considerable congestion and air pollution.

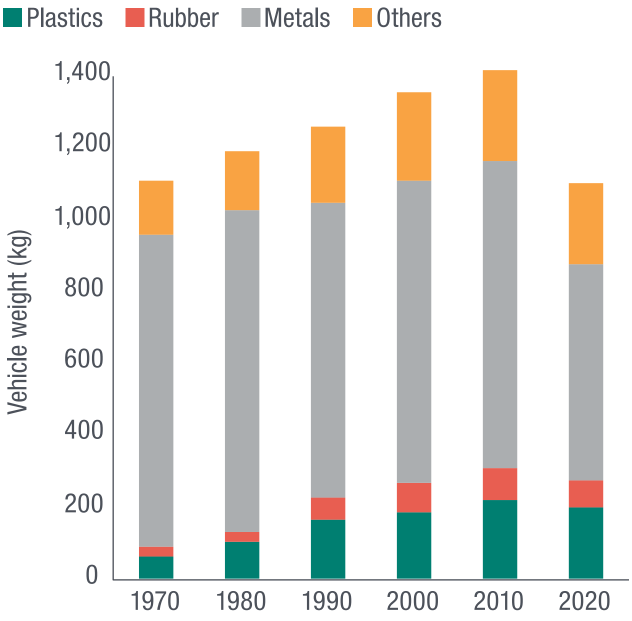
Material use in car manufacture is dominated by steel, aluminium and plastics, totalling an average 1,200 kg per car. Plastics account for 10–15% of this weight (Figure 4), but a much higher share by volume. The amount of material lost as scrap during manufacturing can also be considerable. Consequently, in the European Union (EU), the automotive sector consumes about 25% of all aluminium, 12% of all steel and 9% of all plastics (Material

Figure 3 Passenger vehicle sales by region, 2010–2018



Source: International Organization of Motor Vehicle Manufacturers (OICA, 2019)

Figure 4 Vehicle weight by key materials



Source: Rouilloux (2012); Grand Review Research (2019)

Economics, 2018). Steel in car bodies and chassis is increasingly being replaced with plastics and composite materials, while plastics in interior furnishings, car safety-system elements and electronics have also seen a considerable increase in recent decades (IEA, 2019a). It has been estimated that the automotive sector consumed around 27Mt of plastics globally in 2015 (Geyer et al., 2017).

Light-weighting has enabled vehicle designers to achieve weight reductions of 5–15% within one to five model years (Isenstadt et al., 2016). Despite this, the global average weight of newly registered cars, according to the Global Fuel Economy Initiative (2017), actually increased by more than 5% between 2010 and 2015. The trend appears to have continued, with 2017 data for North America pointing to a 0.7% increase in average light vehicle weight compared with 2016 (American Chemistry Council, 2018). Reasons include a shift to larger cars, such as sports utility vehicles (SUVs), as a result of a significant increase in consumer demand for larger vehicles and relatively stable fuel prices; added car features and functionality, which can add weight and require more supporting material, such as steel; and a shift to hybrid electric cars, which can require heavier powertrains and, in turn, more supporting materials (IEA, 2019b).

2.2 Uses of plastic in the automotive sector

The key advantages of using plastics in the automotive sector include their ability to achieve greater fuel efficiency as a result of light-weighting; their minimal level of corrosion compared with metals, prolonging vehicle life; the greater freedom they afford in terms of vehicle design, which can spur innovation; enhanced flexibility in integrating components; and their ability to provide improved safety and comfort (Craftech Industries, 2018).

The use of plastics to reduce the weight of cars leads to greater fuel efficiency. In general, a 6–7% reduction in fuel consumption can be achieved for each 10% reduction in the weight of an average car if the engine is downsized to maintain constant performance[2] (Luk et al., 2017) and 4–5% if the engine is not downsized (ICCT, 2017). Plastics are, therefore, often

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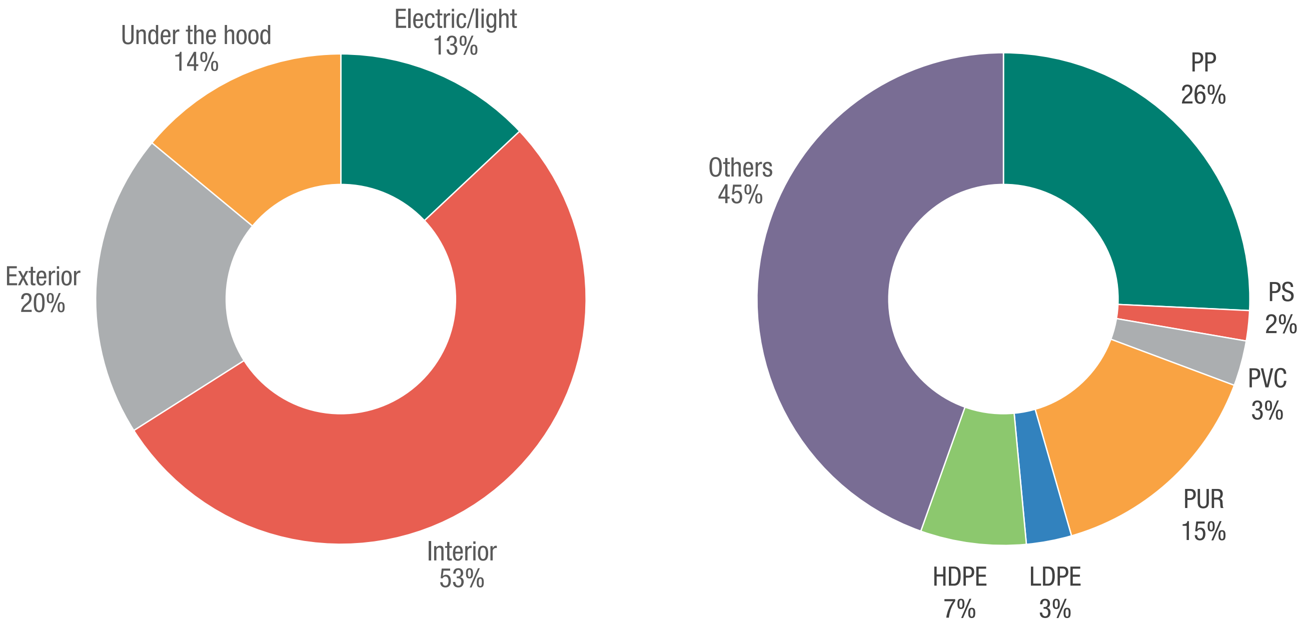
[2] Engine downsizing is the use of a smaller engine in a vehicle that provides the same power as a larger engine through the use of advanced technologies.

Figure 5 Plastics use in the European automotive sector, 2016



Note: HDPE, high-density polyethylene; LDPE, low-density polyethylene; PE, polyethylene; PET, polyethylene terephthalate; PP, polypropylene; PPA, polyphthalamide; PS, polystyrene; PUR, polyurethane; PVC, polyvinyl chloride.
Source: Plastics Europe (2018)

used in important strategies to ensure vehicle compliance with increasingly strict emissions standards (IEA, 2019a).

Despite a push for light-weighting,[3] the average weight of a modern car has increased in recent years, typically to between 1,100 kg and 1,500 kg (Rouilloux, 2012; Plastics Europe, 2018). At the same time, the average car incorporates ever more plastic – around 150 kg to 200 kg (Plastics Industry Association, 2019). Dozens of different plastics are used to make 2,000 or more parts of varying shapes and sizes, from lights and bumpers, to engine components, dashboards, headrests, switches, clips, panoramic roofs, seats, airbags and seat belts (Plastics Europe, 2018; Figure 5). Indeed, plastics can form around half of a car's material in volume terms (IEA, 2019a).

Plastics are also increasingly being used in vehicles because of their ability to improve vehicle construction, performance, functionality and safety. In many ways, plastics have helped revolutionise vehicle design and operation. Plastic and composite materials,[4] for instance, are frequently used to replace steel in car bodies and chassis, providing excellent strength and rigidity while better resisting corrosion (IEA, 2019a). Single-mould components allow car manufacturers to cut vehicle assembly time and swiftly introduce design innovations (Plastics Europe, 2018).

Overall, interior furnishings accounted for more than 50% of the total plastics volume used in cars in 2018, including light displays and panels, seat covers, steering wheels and fascia systems.[5] Digitalisation has also led to greater demand for plastics in car dashboards to support electronics (Plastics Europe, 2018).

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[3] Light-weighting involves reducing vehicle weight (for instance, by replacing heavy materials, such as steel, with lighter materials, such as plastics), in particular, to achieve better fuel efficiency.

[4] Composites are any combination of a polymer and fibrous reinforcement, such as glass, carbon, aramid, or other fibres that provide strength and stiffness.

[5] Fascia refers to the decorative panels of a car's dashboard or the dashboard assembly.

2.3 Plastic types

Eighty per cent of the plastics used in cars are of five main types – polypropylene (PP), polyurethane (PUR), polyvinyl chloride (PVC), acrylonitrile butadiene styrene (ABS) and fibreglass. The remaining 20% are polyethylene, polyamides, polyacrylates and polycarbonates. For the purposes of this report, we focus on six main plastic types: polyethylene, PP, polystyrene (PS), PVC, PET and PUR, which together account for more than half of the plastics used in vehicles (Khemka, 2019).

PP is the main type of plastic used in the design and manufacture of cars, accounting for about a quarter of plastics used in cars globally in 2018. It offers excellent resistance to very high temperatures, is semi-rigid and translucent. It is widely used as a thermal insulator and to damp noise and vibration. Other common uses include bumpers, fuel tanks, cable insulation, petrol cans and carpet fibres.

PUR is the second most commonly used plastic in cars. It is strong but flexible, and able to withstand weather extremes and chemicals. It is, therefore, commonly used for insulation, interior trims and seat cushioning (Grand Review Research, 2019).

2.4 Waste and recycling

About 40 million cars reach end of life annually, corresponding to about 4% of total global car ownership. However, in the EU, in 2015, 94% of cars had a second life, while the majority also had a third before being scrapped (CSE, 2018).

Once a vehicle reaches the end of its life, it is usually sent to a scrappage facility. Although many countries have such facilities, many end-of-life vehicles are still traded to low- and middle-income countries in Africa and South Asia. In Africa, 80–90% of imported vehicles are, in fact, relatively old, either destined for further use or for dismantling. End-of-life vehicles shipped to Africa mainly come from the United States, Europe and Japan, while those in South Asia are mainly shipped from within the region, particularly from India, Japan and China. Scrappage in receiving countries is often largely informal, with limited or no regulatory oversight.

As environmental regulations on fuel efficiency and emissions for vehicles become tighter in regions such as Europe, cars are retired or pushed out of the market more rapidly, often before they have reached the end of their economic life, swelling the availability of end-of-life vehicles. At the same time, with more stringent regulations on scrapping in these regions, legally or illegally exporting used vehicles is sometimes used to evade such requirements and reduce scrappage costs (CSE, 2018). One recent study found that, in Germany, only one in four end-of-life vehicles remained in the country for proper disposal (Gonzalez, 2019).

End-of-life vehicle recycling currently focuses primarily on recovering spare parts and avoiding the release of hazardous substances, with limited value placed on recovering a car's materials while retaining their quality. For a large share of the plastics used in vehicles, high-value recycling is currently not feasible or economically attractive, resulting in low recovery rates (IEA, 2019a). The reasons include the use of reinforced plastics, which can include glass or carbon fibre, plastic blends of two or more types, or two- or multi-component injection-moulded parts. This often leaves car plastics in a category of mixed waste that is subsequently incinerated to recover the energy value, or more often just landfilled. A move to (carbon or glass) fibre-reinforced plastics for light-weighting purposes also leads to plastics that are difficult to recycle and which can contaminate other plastics flows (Material Economics, 2018).

More stringent EU regulations, introduced in 2015 as part of the existing End of Life Vehicles Directive (originally introduced in 2000), now require 95% of end-of-life vehicles to be valorised and 85% of the resulting value to be recycled (Eurostat, 2019). Thus, to comply with the Directive, some of a vehicle's plastic components will have to be recycled, even though their design may not have been optimised for this purpose.

Tighter regulations are likely to encourage vehicle producers to make the recycling of vehicle components easier. Another disincentive to designing cars that allow the high-quality recycling of plastic components, however, is the fact that end-of-life recycling is based on weight, not volume, and that the value of a car's material recovery only accrues 10–15 years in the future – but not to the manufacturer (Material Economics, 2018).

A current challenge with reusing recycled plastics from end-of-life vehicles in the design of new vehicles (rather than for other purposes) is that they are generally less pure because of the many additives used to enhance plastic properties, so may not perform as well as virgin resins (Rouilloux, 2012).

2.5 Materials efficiency

Cars are significantly underused assets, contributing to a costly and wasteful global transportation system. They are the largest source of transport costs, accounting for the majority of passenger kilometres on land, but generally used for less than 10% of the day. Considering the average weight of a car and its low occupancy rate (just 1.5 of the typical 4–5 seats, on average, when in use), no more than 2% of a passenger car's energy is used to move people, while as much as half of inner-city land is devoted to roads and parking (Material Economics, 2018). This means that cars account for considerable material value and embodied emissions while delivering a relatively low level of benefit in return (Material Economics, 2018).

This points to considerable waste in the system and its use of resources to deliver an economic benefit. With average car occupancy remaining virtually unchanged and the number of cars worldwide growing fast, particularly in emerging economies, there are no signs of improvement (Winton, 2017). At the same time, average vehicle weight is increasing. This all comes at a high social cost in the form of air pollution, traffic congestion, noise and accidents, large claims on land and the need for considerable public expenditure on infrastructure (Material Economics, 2018).

When considering where the adverse environmental impacts of plastics occur in the automotive sector, upstream impacts (83%) dominate because of the use of fossil fuels for plastics production and the associated embodied carbon emissions. Trucost values the environmental cost of plastics production for the automotive sector at $5.5 billion a year, including $3 billion from GHG emissions, while the downstream impacts (17%) of plastics use cause damage and adverse impacts worth $1 billion (UNEP, 2014). The latter are mainly the result of un- or ill-managed waste from chemical additives, land disamenity[6] and marine litter.

This suggests there is a strong case for reducing the volume of virgin plastics used in the automotive sector, both by reducing the overall volume of plastics used and by increasing their reusability, recyclability and recovery from end-of-life vehicles for repurposing.

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[6] The local impacts of landfill or littering activity that generate negative reactions from those in the immediate vicinity of a site.

3 The automotive sector in 2050

3.1 Personal mobility vision 2050

3.1.1 2050 vision: OECD countries

By 2050, 90% of all vehicles could be fuelled by clean energy (Department of Transport, 2018; Vorrath, 2018),[7] mainly electricity, with hydrogen in a supporting role, alongside major improvements in powertrain efficiency.[8] With the global population increasingly living in urban areas, a strong emphasis on reducing air pollution, curbing greenhouse gases and tackling traffic congestion could prompt cities to switch away from fossil-fuelled vehicles and private cars towards clean, shared and public modes of transport. By embracing a wide and closely integrated array of alternative forms of transport, cities would be driving a substantial decline in private car ownership.[9]

We estimate this would mean 50% fewer passenger vehicles on the road in urban areas, offering the same or better intra-urban mobility. A closely integrated web of shared and flexible transport options under a mobility-as-a-service (MaaS) model would emerge. This would include extensive use of ride-sharing through a mix of autonomous and chauffeured vehicles, plus access to car-sharing through, for example, car clubs for trips to rural areas and the like. The new transport system would incentivise the adoption of new and enhanced vehicle designs that are optimised for materials and energy efficiency, as well as for the purpose of the trip. While today's automobiles are being designed for a wide variety of uses, ride-sharing allows a narrower range of vehicle capabilities, with vehicle types matched to the needs of individual trips.

Ride-sharing would be complemented by high-quality public transport operating at high frequency on main routes and an increase in walking and cycling and related infrastructure. Many of the new or improved forms of mobility would be characterised by a greater focus on flexibility and choice and often follow pay-per-use and/or subscription models. Sharing services could come in various forms, providing more convenient and affordable mobility compared with maintaining and operating a private vehicle, with significant reductions in overall trip time, because shared autonomous vehicles would allow for much more efficient road use and traffic flow. The resulting reduction in the overall number of vehicles on the road could free up part of the existing road infrastructure for repurposing.

This range of new and improved public and private transport options, brought together in a seamlessly integrated booking and payment platform (MaaS), would expand opportunities for taking various transport modes. It would help reduce the number of new private vehicle

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[7] Recent studies from the EU, UK and Australia show that under a high EV adoption scenario, 90% EVs on the road could be achieved by 2050.

[8] A vehicle's powertrain consists of the engine, transmission and drivetrain – the components that get the engine's power to the wheels and down to the ground.

[9] Grubler et al. (2018), 2050 Low Energy Demand (LED) scenario: modal share of 60% of passenger kilometres by light passenger vehicles (both private and shared), 26% by bus, 10% by train and 4% by two- and three-wheel vehicles.

registrations and the total number of vehicles on the road, and increase vehicle occupancy. These could collectively result in a dramatic increase in asset utilisation and a reduction in trip times. This would be further enhanced by sensors embedded in vehicles and by the emergence of vehicle-control centres to enable route and speed optimisation almost instantaneously, depending on traffic conditions, peak times, events, accidents and weather.

Journey times in autonomous vehicles could also free up time for productive uses. Dramatic improvements in connectivity would greatly enhance passengers' experience and access during their trip. Adaptable and reconfigurable vehicle interiors and in-vehicle pods would make rides more comfortable, accessible, private and safe. They could also provide commuters with a productive environment not unlike that of the office.

Many of the new passenger vehicles on the road would bear only remote resemblance to contemporary passenger vehicles and would be far more efficient, with some even generating their own electricity. The average weight of a car used for shared transport would drop to about 600kg from the 1,200kg of the average car today (Material Economics, 2018).

Public transport would be seamlessly integrated with these flexible transport modes and last-mile transport options. This would include two- and three-wheeled vehicles, such as scooters, electric bicycles, motorbikes and rickshaws. Fuelled by the digital revolution, the increase in 'usership' of transport modes could start to weaken cultural norms of 'must-have' ownership, with service, flexibility and value taking precedence over the desire to own and take responsibility for a vehicle.

Cities in 2050 could see increased adoption of a model of compact urban expansion. New brownfield urban development would lead to greater urban density, promoting the uptake of MaaS and reducing average proximity to transport hubs and other services. This, in turn, could lead to cities converting un(der)used car parks and roads into housing, parks or other facilities. Urban citizens would be provided with a high level of convenience in terms of transport options close to where they live, work and socialise. This is in contrast to the costly and time-consuming urban-sprawl model dominating some regions today, which forces municipalities to maintain large swathes of infrastructure, serving a relatively small number of people and making many transport options other than privately owned vehicles economically unattractive.

The need for transport would decline as neighbourhoods included buildings that aggregated offices, products and services, while deploying a range of low-impact courier services for distribution, pick-up and drop-off. For instance, companies could increasingly have flexible offices spread across neighbourhood office-aggregation buildings, allowing staff to work closer to home. Many neighbourhoods could have product- or service-aggregation buildings that collected and redistributed resources from the local area, providing a wide range of services and acting as central goods-distribution centres, including product-as-a-service offerings. Together, these developments could change urban dynamics, reducing the amount of vehicle kilometres citizens have to make to fulfil their needs.

Inter-city freight deliveries would occur mainly between centralised centres and could increasingly be delivered by rail, barge, and dedicated road lanes for autonomous clean (EV, hydrogen) vehicles. Smaller purpose-built vehicles could distribute goods to their destination within cities. In addition, the uptake of the sharing economy in other sectors and the increasing trend towards dematerialisation as a result of digital advances, as well as the move towards distributed, additive manufacturing (such as on-demand, at-location 3D printing) would reduce the overall volume of physical consumer goods distributed throughout the economy, thus reducing associated vehicle movement.

For out-of-town trips, a web of high-speed railway lines with integrated last-mile solutions could halve road-vehicle use. Major tourist destinations could have a network of shuttle services, having banned car use from core tourist areas. EV-sharing and communal services could provide attractive alternatives to private car ownership for those looking to spend the weekend away, seeking a personal form of transport.

3.1.2 Main differences in non-OECD countries

Annual mobility levels in non-OECD countries are, on average, around 5,000 passenger kilometres per capita,[10] far below levels in OECD countries of roughly 10,000 (in Japan) to 25,000 (in the United States) (Grubler et al., 2018). Overall mobility levels are expected to double in non-OECD countries as rising incomes open up greater opportunities for work, leisure and social activities requiring transport. Also, personal car ownership is expected to see a sharp increase in non-OECD countries, as governments rapidly improve vehicle efficiency standards and other policy measures to ensure vehicles become cleaner.

In non-OECD nations, the shift to alternative-fuel vehicles, such as fully electric vehicles (rather than hybrids), is expected to progress at a slower pace than in OECD countries, mainly as a result of the ongoing rise in the number of personal vehicles, many of which may not be the latest models, as well as the need to introduce a comprehensive charging infrastructure network for EVs. For shared fleets in non-OECD countries, however, the shift to EV is expected to be rapid, with EVs penetrating expanding vehicle stocks (Grubler et al., 2018).

On a per capita basis, however, non-OECD countries are set to remain at far lower mobility levels than OECD countries, with the number of anticipated annual passenger kilometres about 75% lower by 2050. Further growth in passenger kilometres would be constrained mainly by the density of urban areas, and the greater presence of shared and public transport modes, as rapidly developing cities take action to curb air pollution and reduce congestion (Grubler et al, 2018).

3.1.3 Determining factors

There are several key determinants of the vision for 2050, which together achieve much greater material efficiency and, thus, a decline in the overall quantity of plastics demanded by the automotive sector. These are:

- **Increased utilisation and occupancy**. The 2050 vision implies a fundamental shift in the ownership and operation of cars, switching to asset- and ride-sharing, increasing the frequency of utilisation and occupancy of each vehicle. This creates a virtuous circle that could lead to the faster adoption of electric and automated vehicles, as shared systems are better suited to these types of vehicle. Higher utilisation allows upfront investments to be paid back more quickly and over a much larger number of kilometres driven (Material Economics, 2018).
- **Weight reduction**. A reduction in average car weight would occur because an integrated mobility system allows better matching of vehicle type to the needs of individual trips. Currently, most passenger vehicles are dimensioned for maximum capacity (typically, five passengers), while a shared system could provide for greater variety of vehicle size. This includes right-sizing vehicles for distinct usage profiles and optimising vehicle designs across a variety of passenger loads and trip purposes (IEA, 2019b). The higher utilisation of shared fleets, as well as the use of automated vehicles for shared services, would further act as a strong incentive to alter and accelerate the innovation cycle for enhanced vehicle design. It would incentivise changes in material composition, as manufacturers design more for durability, modularity and other characteristics to optimise a vehicle's usability in a shared fleet (IEA, 2019a).
- **Increased lifespan (on a passenger–kilometre basis)**. Longer vehicle lifespans in professionally managed fleets of shared vehicles would create strong incentives for designs that provide a greater number of passenger kilometres during a car's operational life. They would also facilitate predictive maintenance and the close monitoring of cars for issues that may require repair. This does not necessarily mean that cars would be in service longer, but they would spend more time on the road and not sit idle.

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[10] Passenger kilometres include both motorised and non-motorised vehicles.

- **Enhanced end-of-life management.** By retaining ownership over the vehicles, service providers could overcome the high transaction costs and inventory problems that currently limit reuse and remanufacturing. The new mobility system would create more predictable end-of-life flows of materials, while manufacturers could look to increase vehicle lifespan by switching to a more modular design that allowed components with shorter lifespans to be easily replaced and long-lived components to be easily disassembled and reused (Material Economics, 2018).

3.1.4 Rebound effect

The convenience of a MaaS mobility system and the ability to travel longer distances with greater ease and speed might result in a degree of rebound, incentivising users to travel more (often) or encouraging them to live further away from work or recreation hubs, such as city centres, thus increasing the distance travelled.

This could have an impact on the size of the shared fleet and alternative modes of transport, and/or on their replacement rate, due to the rise in demand for mileage. This, in turn, could influence the volume of plastics in use, as well as the service life of in-use plastics. Although rebound could not be entirely prevented, targeted policy interventions could be used to reduce and mitigate its effects.

4 Pathways to 2050

Achieving this vision for personal mobility would require action between now and 2050. Some changes in the automotive sector could be made immediately, without changes to existing technologies. Further action in some areas may be feasible in the near term, while action may only be possible over a longer period in others. This chapter describes what needs be done to realise the 2050 vision for the automotive sector, using currently available or rapidly emerging technology and building on trends affecting the sector that are consistent with a pathway to a future low-plastic-consumption scenario. The chapter ends with a high-level analysis of political-economy factors to be considered when action is taken to reduce plastics consumption in the automotive sector.

4.1 Technical possibilities

Table 1 lists key actions required to achieve the low-plastic-consumption scenario in 2050 and outlines when each of these actions will be technically feasible. This is distinct from when they are likely to be implemented, which involves political, economic and behavioural considerations. We divide the actions into three degrees of technological readiness:

- **possible now** – changes that can be made today with existing technology
- **possible soon** – the technological requirements to carry out these changes are already being developed; they typically require incremental advances or repurposing of existing technologies
- **possible later** – changes that require fundamental technological advances; they

Table 1 Technical possibilities to reduce plastics in the automotive sector

Key actions	Possible now	Possible soon (by 2035)	Possible later (by 2050)
Promote the uptake of electric vehicles	✓		
Provide high-quality mass public transport	✓		
Enhance low-impact and active transport modes including for the ‘last mile’	✓		
Support ride- and car-sharing	✓		
Favour compact urban expansion	✓		
Discourage larger vehicles	✓		
Enhance recyclability of automotive plastics		✓	
Introduce autonomous vehicles		✓	
Facilitate MaaS platforms		✓	
Optimise vehicle design for more efficient materials management		✓	
Apply alternative light-weighting materials			✓
Use of alternative plastics with a lower carbon footprint			✓

may currently be at the concept stage of technological development or require a plausible but unrealised technological breakthrough.

These various actions are specific to plastics used in the automotive sector and complement those set out in the synthesis report for plastics in general (for example, to develop widescale chemical recycling). These actions also complement the broader societal changes that would lead to the outcomes envisaged in the LED scenario (clean, compact cities, for instance) and the policy and sectoral trends described in the following sub-section.

4.1.1 Promote the uptake of electric vehicles

Many national, state and city governments ambitiously promote the electrification of contemporary vehicles as a means to meet commitments or regulations on air quality and carbon emissions. An increasing number of governments are setting very high future uptake targets for EVs (Klein, 2019). The city of Los Angeles, for example, announced in 2019 its intention to move to 25% EVs by 2025 and 100% by 2050 (Gordon, 2019). Several recent analyses complement this with an estimate of 90% EVs on the road in regions such as the UK, Australia and the EU under a high-uptake scenario (FuelsEurope, 2018).

Amid this active promotion of a switch to EVs, ever more hybrid and fully electric vehicles are becoming available in OECD and, to a lesser extent, non-OECD markets. Upfront cost, range anxiety[11] and limited (public) charging infrastructure aside, EVs are a reality today and increasingly available in a variety of price categories.

A switch from fossil-fuelled to electric, privately-owned vehicles does not, on its own, support a reduction in plastic consumption in the automotive sector, as it does not reduce the total number of vehicles in use. The relatively high weight of EV batteries is also causing many manufacturers to pursue further light-weighting strategies, including the use of plastic composites.

Nonetheless, the switch to EVs will act as an enabler for the 2050 vision described in chapter 3, together with the ongoing and rapid advance of IT capabilities allowing connected vehicles and integrated transport platforms, as well as the (anticipated) widespread uptake of autonomous vehicles. The advancement in electrification technologies, charging or battery swap-out infrastructure, and the associated optimisation of demand–response management of the vehicle fleet's energy demand can support the emergence of a dense and seamlessly integrated network of shared and other alternative forms of transport.

4.1.2 Provide high-quality mass public transport

Improving the availability, accessibility, comfort, speed and frequency of public transport on high-capacity routes, and ensuring swift connections between different public-transport routes and modes, could play an important role in making alternative forms of transport more desirable than privately owned vehicles. The latter are costly to run and, in cities, subject to ever greater delays and parking difficulties as a result of congestion and local-government measures to deter cars from certain city areas.

Reflecting that metro, light rail and trains require high upfront capital investments and can take many years of planning to implement, many cities – particularly non-OECD countries – are opting for Bus Rapid Transit (BRT) as a relatively quick and low-cost means of providing high-frequency public transport that is faster than conventional bus transport (UITP, 2019).

Alternative options are also emerging. SkyTran, for instance, is an experimental, elevated personal rapid-transit system of computer-controlled, small 'jet-like' vehicles. Cities in various parts of the world are showing interest in using it. SkyTran promises high-speed mobility at a cost that is 10–20 times lower than comparable light rail, and transporting almost 12,000 people an hour

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[11] Concern on the part of a person driving an EV that the battery will run out of power before they reach their destination or a suitable charging point.

per track – comparable to a three-lane highway (Rabinovitch, 2014).

High-quality public transport will play an important role in a MaaS system, providing an integrated mix of shared, public and other transport modes. Research shows that a mixed fleet of mainly shared autonomous vehicles and some part-private vehicles without high-capacity public transport would increase the number of vehicles on the road during peak times, which would not alleviate congestion or free up road space compared with a system incorporating mass public transport (ITF, 2018).

Furthermore, taking Uber as an example, at the current cost of ride-sharing, this transport option is still mostly geared towards wealthier groups. In the United States, using Uber exceeds the cost of owning and operating a vehicle if someone travels more than 5,600 km (3,500 miles) a year, which most US drivers do (Hensley et al., 2017). A MaaS system predominantly based on ride-sharing, therefore, may fail to provide mobility at an affordable cost to all with a much smaller fleet.

4.1.3 Enhance low-impact and active transport modes, including 'last mile'

One of the key reasons citizens use private vehicles for short trips is the absence of suitable alternatives. In North America, for instance, many cities are characterised by an urban sprawl, creating relatively large distances between homes and often-frequented facilities and services, such as supermarkets and schools. Pavements and cycle paths for safe walking and cycling, as well as good-quality public transport, may be lacking, leaving people with few options.

High-quality walking and cycling infrastructure and small (electric) vehicles, from covered pods to electric kick-scooters, could play an important role in providing 'last-mile' transport – the first and last stretches of a journey connecting the place of departure and the final destination with nearby public transport. Having good public transport without convenient options for covering these short connecting stretches may still prompt many people to opt for a private vehicle for part or all of the trip.

A good example of using cycling for last-mile transport is *OV fiets*, a public bicycle service in the Netherlands. At most Dutch train stations, commuters can use their public transport swipe card to instantly rent a bicycle, costing a few euros for a 24-hour period, with no deposit or cash required (Bicycle Dutch, 2019).

4.1.4 Support ride- and car-sharing

A rapid surge is evident in the number of public and private initiatives encouraging mode-shifting or ride-sharing, with a view to reducing reliance on privately owned cars for mobility. An estimated $50 billion was invested in ride-sharing in 2014–2017 and the market continues to grow rapidly (Tsang et al., 2018). In China, Didi Chuxing, the leading ride-sharing platform, had about 30 million drivers and 260,000 EVs registered on its platform in early 2018 (Huang, 2019).

Ride-sharing is rapidly gaining popularity in many cities with the emergence of platforms such as Uber, Lyft, BlablaCar (Europe) and Didi Chuxing (China). At the same time, as it is more expensive than taking public transport or using a car for more than 5,600 km a year,[12] ride-sharing is still geared mostly towards wealthier groups. Furthermore, ride-sharing in its current form suffers from issues of fairness and safety. Since driver costs make up a considerable part of the total cost, there is an incentive to keep labour costs as low as possible, sometimes leading to underpayment of drivers. Incidents of harassment by drivers, particularly of female passengers, have also affected the image of ride-sharing in some regions.

Moreover, the rapid rise in popularity of ride-sharing in cities with underdeveloped public or alternative transport systems has led to an increase of up to 80% in passenger kilometres travelled in large metropolitan areas in the United States. More than half of users in these cities indicated they would have taken public transport, walked or cycled if an equally convenient option had been open to them (Wolfe, 2018).

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[12] The current average cost of ride sharing in North America exceeds the cost of owning and operating a vehicle if someone travels more than 5,600 km (3,500 miles) a year, which most US drivers currently do (McKinsey).

A facilitating environment for ride-sharing, therefore, needs to be developed in conjunction with enhanced forms of public and alternative transport, as part of an integrated mobility system to realise the 2050 vision of greatly improved mobility with only half as many vehicles in operation.

In addition to ride-sharing, in many cities, citizens now have access to car-sharing services, allowing them to use a car when needed, without owning one. The cars can often be reserved via an app and are available from dedicated parking places in close proximity to medium- to high-density residential areas.

4.1.5 Favour compact urban expansion

For public transport and low-impact modes, such as walking, cycling and (electric) kick-scooters, to be truly effective, at least a medium-dense urban landscape is required. Urban sprawl and low-density neighbourhoods increase distances and, therefore, the cost of infrastructure, discourage active forms of transport and result in fewer potential riders living in the catchment area of a public transport stop or station. They may also require more last-mile solutions due to the dispersed nature of development.

The same is true for car-sharing, which requires sufficient potential users to live within close proximity of the service. For ride-sharing, a low-density urban landscape increases distance and, thus, the cost of a shared ride for the user, making it a solution mainly for wealthier parts of society.

An important means of realising the 2050 vision is, therefore, to favour transit-oriented new housing developments with sufficient density to support a vibrant offering of transit and other services, such as shops and schools, at short distance, and to aim for compact city design by encouraging infill on brownfield and underused locations (Zortis, 2015).

4.1.6 Discourage larger vehicles

Despite the push for light-weighting and the frequent use of plastics and composites for this purpose, average vehicle weight has increased. Consequently, light-weighting mainly serves to compensate for the larger size of the car. One important reason for the increase in vehicle weight is growing consumer demand for sport utility vehicles (SUVs) and similar large cars. SUVs take up more road and parking space, while most models have lower fuel efficiency than a conventional car (Sivak, 2019). Another impact of more SUVs on the road is a major increase in pedestrian fatalities, as in the United States, for instance. A collision with an SUV carries a much greater chance of serious injury or death for pedestrians (Wamsley, 2018).

Thus, current growth in demand for SUVs does not align with a vision for a drastic reduction in either vehicle numbers or weight. Some governments are responding by making it less attractive to own an SUV than a conventional car, using fiscal policy to penalise SUV owners.

4.1.7 Enhance automotive plastic reusability and recyclability

Currently, the majority of plastics used in vehicles have low recycling value and do not contain recycled content. Recycled automotive plastics are generally less pure because of the many additives used to enhance their properties, so may not perform as well as virgin resins (Rouilloux, 2012). A lack of information on the possible presence of chemicals of concern (such as flame retardants) also creates a significant obstacle to higher recycling rates. Easier traceability of such additives in recycled streams can make it simpler to process or remove these substances during recycling (European Commission, 2018).

Increasingly, however, car manufacturers are actively seeking solutions that make automotive plastics economically recyclable. Lexus, for instance, aims to make 95% of its cars recoverable and is exploring a range of new materials, including those produced from renewable plant sources, such as sweet potato, maize and sugarcane (Omega Plastics, 2017). However, such bioplastics may not necessarily support light-weighting goals, as some have higher material densities than conventional petroleum-based plastics, as demonstrated by seat foams and upholstery made from the soy-based materials used in some European vehicles (Cantos, 2019).

Jaguar Land Rover, meanwhile, is exploring opportunities to upcycle domestic waste plastic otherwise destined for landfill or incinerators, through chemical recycling.[13] This process basically transforms end-of-life plastics back into oil that can be used instead of virgin material to create a plastic product of comparable quality (Moore, 2019). An emerging technology, its high cost currently makes this feasible only for cars at the higher end of the price range. In addition, the high energy requirements and potential for adverse environmental impacts of chemical recycling plants may currently limit its scalability.

Car manufacturer Renault is taking a third approach, through the 'short-loop' recycling of raw materials, such as steel, copper, textiles and plastics from end-of-life vehicles into high-quality products for new vehicles, creating as much of a closed-loop system as possible. Currently, 36% of the total mass of a newly produced Renault vehicle in Europe is made from recycled materials, while 85% of its mass is recyclable. This is in part the result of tighter European legislation on the recovery of materials from end-of-life vehicles. An important challenge is the supply chain for recycled plastic, which is poorly developed. This includes the lack of a predictable and secure stream of materials for recycling from end-of-life vehicles (Ellen MacArthur Foundation, 2017).

Some plastic uses in the automotive sector could be phased out or converted in the medium term. These suggest potentially realisable actions, but due to certain technological barriers and limitations or 'material' trade-offs, it may be some time before they can be implemented. For instance, they may rely on technologies under development that may only become widely available in 5–10 years.

4.1.8 Optimise vehicle design for more efficient materials management

While extending vehicle lifetimes will reduce material demand for vehicles, modular designs with replaceable components would enable better material management. Better control over inventories and material flows of managed fleets, including the repurposing of materials through reuse or recycling, would allow much more predictable end-of-life flows. The greatest incentives for such a shift in design are expected to come from the switch to shared fleets, which will transform ownership, business and revenue models. This will make it in fleet managers' interests to have durable, long-lasting, highly efficient, lighter vehicles on the road, which can be easily maintained and repaired. In turn, this would be expected to have positive implications for the treatment of end-of-life plastics from vehicles (Ellen MacArthur Foundation, 2015).

4.1.9 Use alternative light-weighting materials

The most common focus for light-weighting in vehicles is the body structure and chassis, which account for 60–65% of vehicle mass and are essential to meeting multiple safety, strength, stiffness and noise-transmission targets.

Further light-weighting of vehicles is expected to continue in the near future due to ever more stringent regulation on fuel efficiency and emissions, greater demand for larger cars, such as SUVs, and the switch to EVs with heavy batteries. A shared fleet would further reduce the weight of vehicles, which could be designed for more specific usage profiles than the broad range of uses a car is designed to accommodate today.

In addition to plastics and composites – including carbon-fibre composites, which provide high performance, but are currently expensive for widespread use in cars and have poor recyclability – a number of other materials are commonly used for light-weighting purposes.

These include advanced high-strength steel, which is used in a variety of applications and can reduce component weight by up to 25%; aluminium, which can reduce component weight by 60%, but faces barriers in both cost and manufacturing, although selected uses are expected to increase; and magnesium alloys, which have the potential to reduce component weight by up to 70%. Magnesium's use is limited, however, by high cost and a number of technical challenges, as well as its limited supply, which is insufficient to meet automotive needs (Tech Briefs, 2018).

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[13] A term used to describe technologies which convert plastic waste back into chemical monomers, which can be used again as feedstock.

Nonetheless, current developments point to a strong interest in the greater use of plastics in designing the cars of the future. The Japanese Iron to Polymer (ItoP) vehicle project, for instance, has developed a futuristic-looking car made mostly of plastic, with a weight of about 850kg versus the usual 1,300kg. The vehicle is made of an enhanced polymer that is 10 times tougher and 1.6 times more flexible than usual. The team is currently trying to apply the same techniques to biodegradable plastics to increase strength while retaining biodegradability (Harding, 2018).

Car manufacturers, such as Ford, are also starting to integrate captured CO_2 into foams and plastics. The CO_2-based polyols can drastically reduce the fossil-fuel input required for the manufacturing of plastics and are reportedly easily recyclable. Foamed plastics using pressurised CO_2 can also considerably reduce the weight of injection-moulded plastic parts (Markham, 2016).

4.2 Drivers and trends

The 2050 vision for a low-plastic-consumption automotive sector is based on existing trends and innovations for mobility. The elements of this vision can already be found in many cities today. By scaling them up, the 2050 vision could become a reality by – or, in certain parts of the world, even before – then.

4.2.1 MaaS

Public transport, ride-sharing and alternative transport methods need to be more than just available in order to provide a compelling alternative to car ownership. Consumers of these public and privately financed means of transport are usually left to their own devices to identify the optimum (combination of) ways to cover a journey and understand differences in terms of pricing, time and convenience.

MaaS considers all the transport modes provided by different operators as one co-operative, interconnected ecosystem and meets consumers' day-to-day mobility needs through a single, unified interface. The starting point for a journey is, therefore, not a map or a timetable, but the point-to-point trip the customer seeks to make, whenever and wherever that may be (Atkins, 2015).

This would lead to a much more dynamic, flexible and customer-centred means of providing on-demand mobility. Software and big data are now key enabling factors in creating the MaaS interface, bringing demand and supply together. The service matches customers' individual preferences for cost, speed, and comfort with live network performance and capacity, calculating and plotting optimum use and routing (Xerox, 2015). In recent years, the MaaS concept has caught the interest of many stakeholders in North America, Europe and Asia and an increasing number of cities are now trialling its implementation.

MaaS could, therefore, be the integrating factor that personalises mass and collaborative, public and private modes of transport, and helps to incentivise the use of active, alternative and/or underused methods. This could bring about considerable social change, prompting many people to give up individual car ownership and encouraging car manufacturers to switch from a model focused on selling cars to individuals to establishing or selling to 'pooling' entities, which sell mobility services rather than vehicles to individual customers (Tackaberry, 2015).

New collaborations are also emerging between automotive manufacturers and a broad range of actors, such as the information technology (IT) and telecommunication sectors, which allow new business models and consumer propositions to flourish. MaaS platforms are being trialled or gradually introduced in various cities (SmartCitiesWorld, 2019), while in some countries, such as the Netherlands, unified payment platforms for public and shared transport solutions have been in use for several years.

MaaS platforms are expected to typically offer one or more payment options to customers (Hietanen, 2015):

- Monthly (targeted or customised) subscription packages, somewhat similar to mobile phone plans. Users pay a monthly fee for access to, for example, unlimited travel on urban public transport plus a capped use of other transport services. The MaaS operator purchases

transport services in bulk and guarantees availability and reliability to customers.
- Pay-as-you-go, similar to intermodal swipe-card systems, such as Oyster in London or the OV-chipkaart in the Netherlands, with each leg of a journey having its own price, set by the operator. The MaaS interface would act more like a flight-search engine in this instance, drawing providers into one system to readily provide the customer with all options available and allowing instant single payment. Pay-as-you-go can also supplement a package for non-subscribed modes or where usage caps are exceeded.
- Bolt-on extras may be available to supplement the customer with services such as peak-time or discounted travel.

MaaS is likely to advance in urban areas through an evolutionary process rather than a 'big bang', because many consumers will continue to choose to own a car. Gradually, households will reduce the number of cars they own as they begin to appreciate the benefits of an integrated, flexible transport system, and may eventually give up their cars altogether (Xerox, 2015).

4.2.2 Decline in private car ownership

In major, long-established automotive markets in the OECD, such as the US and the EU, the annual number of new private vehicle registrations is slowing (Edwards, 2019) and the percentage of young people obtaining a driving licence is declining (Delbosc and Currie, 2013). Younger citizens also appear to place a lower value on car ownership and travelling for face-to-face meetings than on interacting online (Dhawan et al., 2019).

However, in non-OECD markets, car ownership remains a major aspiration of many households. Particularly in Asia, vehicle registrations are rising and will probably continue to do so for the foreseeable future, as increasing wealth brings first-time car ownership within reach (Roughneen, 2017). While automotive manufacturers are feeling the pressure to change their models in saturated markets such as Europe, many are rapidly trying to claim as large a share as possible of high-growth non-OECD markets, by selling conventional vehicles while the market is still there (Dhawan et al., 2019).

Even so, the majority of Asians are unlikely to ever own a car. In addition to the high cost of ownership, the high-density urban areas in which they live simply do not allow large numbers of cars on the road without traffic slowing to a crawl, which is likely to make other transport options more attractive. Chinese citizens, for instance, are starting to place less value on car ownership as a result of cost and congestion, and the uptake of alternative mobility options is growing rapidly (Tsang et al., 2018).

For many people, new mobility systems will require a shift in mindset: we will need to think of mobility less as 'owning a car' and more 'a means of getting from A to B'. For existing car owners, the transition will probably play out in a gradual manner, from scaling down the number of cars in a household to forgoing car ownership altogether (Dhamwan et al., 2019).

As detailed in sub-section 4.1.1, many national, state and city governments promote the electrification of contemporary vehicles as a means of meeting commitments or regulations for air quality and carbon emissions.

4.2.3 Automated vehicles

Automated vehicles are already in operation for some freight and passenger transport applications in a number of locations around the world and the technology for its safe use in passenger cars is developing rapidly. In both the US and China, companies are testing autonomous technologies on EVs, while Tokyo was planning to use electric, autonomous shuttles for the 2020 Olympics (ICCT, 2018).

Autonomous vehicles can drastically change how passenger vehicles are designed and built. When used by ride-sharing fleets, they can be right-sized for distinct usage profiles, optimising the vehicle's design across more limited types of passenger load and trip purpose. Higher utilisation allows the use of more durable materials to enable longer lifespans and an increasingly modular design that facilitates easier and cheaper part replacement and greater recyclability of end-of-life components.

As autonomous vehicles are not yet a mature technology, their widespread deployment in passenger fleets is likely to be at least 5–10 years in the future.

4.2.4 Improvements in alternative modes of transport

A large number of cities in both OECD and non-OECD countries are rapidly improving the coverage, frequency and convenience of their public transport. BRT and light rail transit (LRT) systems, for instance, have been rapidly expanding in recent years (ITDP, 2017). The market for alternative micro-mobility options is vibrant and many new players are entering the market, in part powered by rapid advances in IT and the telecoms sector. Such options include bike-sharing schemes for both pedal and electric bicycles, and electric kick-scooters unlocked by users' mobile phones (Schneider, 2018). New, on-demand delivery services are also emerging.

Rapid improvements in IT abilities, combined with congestion at peak commuting times and parking restrictions, already make working from or closer to home, one or more days a week, an attractive option for many employees over the daily drive to work. This may encourage more people to forgo the purchase of a car, as reduced commuting needs make it more attractive to rely on other forms of transport than a privately owned vehicle.

4.3 Political economy

The key stakeholders in the automotive plastic sector are the producers of the diverse plastic components used in passenger cars and commercial vehicles and the manufacturers of motor vehicles. The use of such components is in part down to a supportive regulatory framework: emissions-standard policies incentivise light-weighting vehicles and, thus, the use of plastics. Plastics are increasingly replacing steel in car bodies and chassis as a result. The incentives for light-weighting vehicles are likely to grow further as emission standards become more stringent in response to environmental concerns and amid greater demand for more EVs. In general, the environmental policy agenda surrounding the automotive sector is mainly focused on GHG emissions from vehicle use (through fuel combustion), while embodied carbon from the production of vehicles, including their plastic components, is less visible and less regulated. The European Commission has raised its targets for end-of-life reuse and recycling but formal regulation is often lacking, especially in Asia and Africa, which import many end-of-life vehicles from OECD countries (Doherty, 2018).

4.3.1 Pathways to change

The 2050 vision for the automotive sector does not focus on disincentivising light-weighting and the use of plastic parts in cars, but rather on more substantial changes in the overall passenger transport system. The most fundamental change is a shift in incentives away from individual car ownership and usage. The policy levers for this are varied.

One pathway could focus on encouraging increased consumer demand for substitutes to private cars – either public transport or ride-sharing services. The latter may require innovations in the comfort, flexibility and convenience of existing ride-sharing services, as part of a broader shift in consumer norms away from individual car usage. From a political-economy perspective, the promotion of ride-sharing along the lines of the tiered congestion-tax structures introduced in some US cities, with lower taxes for pooled ride-sharing vehicles (Li and Fitzgerald, 2019), would have the advantage of generating influential private-sector beneficiaries. Existing ride-sharing companies, such as Uber and Didi Chuxing, could be big winners in the 2050 vision.

The vision also sees part of the consumer shift promoted by a more integrated platform for MaaS. One path to change could be through improvements in existing integrated systems in emerging economies, such as China and India, where car usage and urbanisation continue to increase. Li and Fitzgerald (2019: 8) suggest that 'China and India have the potential to leapfrog the American paradigm of car ownership, due to their rapid urbanisation and less entrenched car culture'. Such leapfrogging could be necessary to achieve the 2050 vision – and the rapid nature of change in emerging economies presents an opportunity (Schroeder and Anantharaman, 2016). More generally, advocates of MaaS systems frame them as part of broader political agendas to deregulate certain policy sectors or promote choice in public services (Enoch, 2018).

The viability of this new mobility economy and, hence, reduced automotive plastics production, may depend on increased urban density. Municipal governments, which often hold responsibility for zoning regulations and other land-use policies, are thus an important stakeholder in achieving MaaS (Ornstein, 2018). Restrictive zoning policies, inducing a shortage of housing, also push up house prices (Glaeser and Gyourko, 2002; Quigley and Raphael, 2005). Thus, building on the US experience, one pathway to limiting urban sprawl may be framing it as an issue of affordable housing, with environmental and housing advocacy groups working together. There is of course likely to be strong opposition, not least from existing homeowners. Property developers are also often in favour of urban sprawl, as they 'tend to prefer greenfield developments on the peripheries to the complexities of brownfield regeneration' (Swilling, 2016). While property developers are unlikely to be enthusiastic activists, Leo et al. (1998) describe how, in Portland, Oregon, advocates of efforts to control urban sprawl were able to gain support by persuading them of the construction business case for more intensive land use. Rural populations are likely to lose out from the vision as a whole and would probably oppose policies aimed at reducing private car ownership, but could, in the form of agricultural groups and farm lobbyists worried about urban encroachment on agricultural land, be potential allies in containing urban sprawl (Leo et al., 1998).

While clearly ambitious, a 2050 vision for reduced plastics consumption focused on changing the transport system away from private car ownership (as opposed to reducing plastic usage in any one car) has political advantages. The problems with excessive car usage (traffic, pollution) are more visible than those from embodied carbon in the production of plastic car parts. A pathway to the kind of policy changes set out here could involve substantial public advocacy to raise the political salience of the issues of personal car use, alongside the technical innovations that make alternatives more appealing.

4.3.2 Obstacles

A radically different transport system with fewer cars is disadvantageous to existing car producers, which may be a source of powerful resistance. Opposition should be expected from personal car owners who view car-pooling as an inadequate substitute, especially in more rural areas, where the envisaged new mobility economy is less viable. Consumer preferences for private car usage may be difficult to shift, especially in places such as the United States, where owning a car can represent key ideals of freedom and self-reliance (Li and Fitzgerald, 2019). Although private car ownership is not as prevalent in emerging economies, they are the areas of biggest growth and 'personal vehicles [remain] the gold standard that all new mobility services must meet or exceed' (Li and Fitzgerald, 2019: 43). With consumer norms as they are, it is unsurprising that government environmental policies tend to focus more on improving the energy efficiency of vehicles rather than reducing their number.

The incentives for continued urban growth could also pose challenges to containing urban sprawl. According to Fang and Pal (2016), continued urban land growth in China brings benefits to the state, the private sector and citizens. Increased urban development currently provides land-lease revenue for government, more profit for developers and more compensation opportunities for farmers. In contrast, the environmental costs are not felt or borne directly by any powerful stakeholders. The common sources of opposition – either from the top down on environmental concerns or from organised public groups wanting to maintain their quality of life and resist development – are lacking. The former has prioritised economic development and the latter is attracted to the appeal of urban living and the financial benefits of developing their land. As a result, urban land growth in China is much faster than (already rapid) urban population growth (Fang and Pal, 2016).

4.3.3 Building a coalition for change

The significant social costs of high private car usage could forge a coalition for the envisaged change. Campaign groups that work on air and noise pollution could collaborate with organised urban citizens concerned about traffic congestion, for example, as well as with climate and plastic campaigns. Groups with the primary aim of reducing plastics may have to accept that their goals will be best achieved in the automotive sector by not focusing on plastics and advocating for other supportive trends.

The business opportunities generated by more ride-sharing and MaaS platforms provide powerful potential allies in the private sector. Campaigns could seek the support of rising tech companies that are well placed to gain from widespread MaaS and counteract the established automotive industries. In this way, a coalition to reduce car usage, and thus embodied plastics, could align with ongoing structural changes (at least in developed economies), which are seeing traditional automotive companies struggle and technology companies becoming the most powerful private-sector actors.

A fruitful initial focus for targeting policy change, advancing technological innovation and aiming to change consumer behaviour, could well be the dense, urban areas of emerging economies. Here, there is both greater urgency to slow the growth of private car ownership and a precedent for alternatives. These areas already have some developed MaaS systems, their urban density makes them best suited to efficient car-pooling arrangements, and they may see less consumer aversion as the norm of private car ownership is less entrenched.

5 Outcomes in 2050

The 2050 vision for the automotive sector described in chapter 3 would lead to a 25% increase in passenger vehicle occupancy, while simultaneously increasing vehicle usage by 75%. This could achieve the same level of intra-urban mobility services as in the BAU scenario, but with only 50% of the vehicle fleet. The low-plastic-consumption scenario of the 2050 vision could, therefore, roughly halve the number of passenger vehicles on the road compared with BAU, to around 870 million light-duty vehicles – which is fewer than are on the road today.[14] About 530 million of these vehicles would be in OECD countries and 340 million in the rest of the world (Grubler et al., 2018).

In the low-plastic-consumption scenario, passenger vehicles would be around 25% lighter by 2050, at 900 kg on average compared with an average of 1,200 kg today (Material Economics, 2018). This is mainly the result of the use of shared vehicle services for about two-thirds of passenger kilometres, as the material requirements for a car operated as part of a shared, managed fleet would be halved, on average, from about 1,200 kg to 600 kg per vehicle (Material Economics, 2018). The average lifetime of a shared vehicle could increase to 450,000 km, compared with the current 280,000 for a private car, while average occupancy could go up from 1.5 to 1.9 passengers per car (Material Economics, 2018; Grubler et al., 2018).

Plastic consumption in the automotive sector should be considered in relation to the level of mobility services provided, as well as the number of vehicles. By 2050, the material requirements per million passenger kilometres provided through a shared car system could drop from 3,200 kg to just 400 kg, requiring just 0.6 car versus the current 2.6 cars to deliver the same number of passenger-kilometres. Moreover, the average cost per passenger kilometre could drop by as much as 77% (Material Economics, 2018).

Based on current trends in the design of advanced, dedicated-purpose vehicles that can serve tomorrow's needs of a shared, professionally managed fleet, the percentage of plastics used in a shared vehicle in 2050 is assumed to increase to about half a vehicle's total weight. In part, this would be due to a further drive for light-weighting, as well as the suitability and specific properties of certain plastics and composites for electric, autonomous shared vehicles. However, fewer vehicles on the road, the far lower total weight of shared vehicles and their considerably higher utilisation than cars today could result in a significant reduction in plastic consumption for a given level of mobility services compared with BAU.

In addition, fleets of professionally managed, shared EVs and autonomous vehicles with high utilisation rates would offer greater incentives and opportunities for innovation in material design, modular design and design for easy disassembly. High utilisation would also make better materials management more attractive, while the altered ownership model would allow fleet managers to retain a strong level of control over what happened to materials in end-of-life vehicles. This, in turn, could result in an increase in the reusability and recyclability of plastic components in these vehicles, overcoming many of today's obstacles to closing the loop on automotive plastics. As a result, vehicles could have an estimated 40% recycled plastics content (Ellen MacArthur Foundation, 2015).

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[14] The analysis for the LED scenario in Grubler et al. (2018) is based on 'light duty vehicles' which could include light commercial vehicles as well as passenger cars.

5.1 Materials forecasts

According to the International Transport Forum's (ITF) Transport Outlook 2019, global demand for both passenger and freight transport will triple between 2015 and 2050, with compound average annual growth rates in excess of 3% (ITF, 2019). The projected growth in demand for transport services does not necessarily equate to a rate of growth in the number of vehicles, as vehicle size and technology may change. Nevertheless, in our BAU scenario, plastics consumption by the automotive sector is assumed to grow by 3% a year, from 27 Mt in 2015 to about 76 Mt in 2050.

The consumption of plastics in the automotive sector is determined by the level of activity, measured in terms of annual vehicle sales,[15] and the quantity of plastic used to manufacture vehicles (intensity). Although forecasts for the sector generally tend to focus on passenger kilometres, tonne kilometres and vehicle stocks (ITF, 2017; Grubler et al., 2018), our analysis estimates vehicle sales in 2050, distinguishing between passenger cars and commercial vehicles, and the quantity (weight) of plastic in vehicle bodies.

Under the BAU scenario, annual passenger vehicle sales globally would increase to around 97 million in 2050 and commercial vehicle sales would reach about 66 million.[16] The number of passenger vehicles sold annually in the 2050 low-plastic-consumption scenario (2050 vision in Table 2) would be 53 million, as a result of a shift towards ride-sharing and other MaaS business models.[17] The number of commercial vehicles sold annually is assumed to be unchanged from BAU.[18]

By 2050, the average quantity of plastics in a passenger vehicle is assumed to increase 50% from 200 kg to 300 kg. The average quantity of plastics in commercial vehicles is assumed to increase from approximately 600 kg in 2015 to more than 700 kg by 2050 – a 17% increase. The estimated total quantity of plastics consumed by the automotive sector in 2050 is shown in Table 3 and Figure 6. In the low-plastic-consumption scenario (2050 vision), the quantity of plastics consumed by the sector is 17% lower than under BAU. This is due to dematerialisation in passenger cars through reduced car ownership and MaaS operations.

Table 2 Annual vehicles sales

	Annual sales (million units)		
	2015	2050 BAU	2050 vision
Passenger vehicles	66	97	53
Commercial vehicles	23	66	66
Total	90	163	119

Notes: 2050 data are estimates; figures are rounded.

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[15] Sales figures are used here rather than production because they are more directly related to vehicle stocks (vehicles on the road) as not all vehicles are purchased in their year of manufacture.

[16] The BAU estimates are based on the estimates for vehicle stocks in Grubler et al. (2018) for passenger vehicles and the assumed growth rate for plastics consumption.

[17] Based on the LED scenario's estimate of the stock of light duty vehicles in 2050 (Grubler et al., 2018).

[18] The lack of available of information precluded detailed analysis of the potential for reducing plastics consumption in commercial vehicles. However, the scope for reducing commercial vehicle numbers through MaaS business models is limited. Expansion of public transport services could point to increasing numbers.

Table 3 Automotive consumption of plastic by type and scenario

	Types of plastic (Mt)									
	LDPE	HDPE	PP	PS	PVC	PET	PUR	PPA	Other	Total
2015	0	3	10	0	1	0	6	0	6	27
2050 BAU	1	9	29	0	3	0	18	0	16	76
2050 vision	1	7	24	0	3	0	15	0	13	63

Note: HDPE, high-density polyethylene; LDPE, low-density polyethylene; PET, polyethylene terephthalate; PP, polypropylene; PPA, polyphthalamide; PS, polystyrene; PUR, polyurethane; PVC, polyvinyl chloride.
Source: Geyer at al., 2017 and author's calculations

5.2 Greenhouse gas emissions

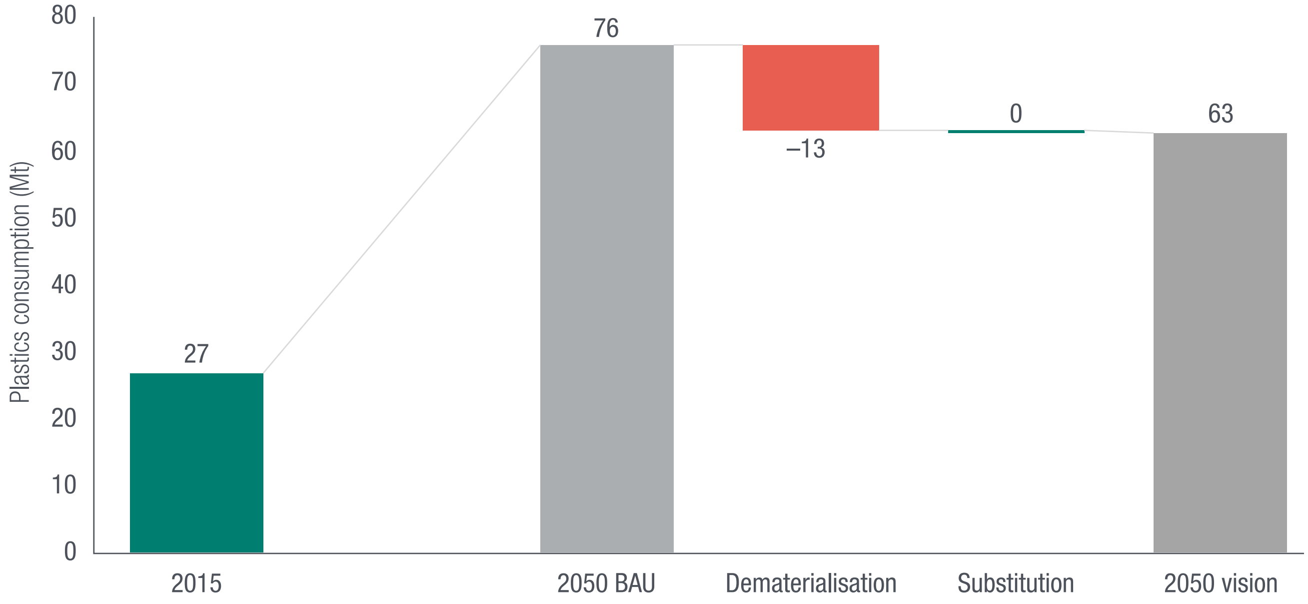
Reducing the consumption of virgin fossil plastics in the automotive sector in line with our low-plastic-consumption scenario could reduce global GHG emissions by around 65 Mt a year in 2050 compared with BAU. Achieving this reduction will depend on the end-of-life disposal of plastic waste from the sector and the extent to which recycling is constrained by continued use of engineering plastics that cannot be easily recycled mechanically.

Estimating the overall net change in GHG emissions from plastics consumption in the sector is beyond the scope of this study. To do so would require taking account of the expected increase in the plastics intensity of vehicles and whether plastics were used to substitute for more emissions-intensive materials (such as steel). Total embodied emissions per vehicle could decrease and the expected increase in vehicle utilisation could show a greater reduction in terms of emissions per passenger kilometre. The effects on GHG emissions in 2050 of changes in vehicle energy efficiency and the use of renewable electricity by EVs are also beyond the scope of this study, but would also be expected to reduce overall emissions from mobility services.

5.3 Waste

An estimated 6.4 Mt of recycled content would be incorporated into the manufacture of new vehicles coming onto the market in 2050. This would

Figure 6 Plastic consumption for the automotive sector



Source: Geyer et al. (2017) and authors

arise from an estimated 872 million passenger cars on the road in 2050, weighing an average 900 kg, including an average 300 kg of plastic. Annual passenger car sales would be 53.2 million, corresponding to consumption of 16 Mt plastic annually, of which 40% was in the form of feedstock from recycled plastics.

A considerable part of this waste is expected to be made up of more-easily recyclable plastic types, such as PE and PP, which currently make up around one-third of plastic in vehicles. Large components, such as PP car bumpers, for example, are well suited to recycling or potentially even direct remanufacture or reuse. In general, the percentage of PP and PUR in passenger vehicles is expected to increase in favour of less common engineering plastics.

Taking into account the current sources and destinations of recycled plastics in the automotive sector, in 2050, the recycled feedstock incorporated into new vehicles is also likely to be used in applications beyond the automotive sector.

6 Conclusions

The environmental costs of plastics used in the automotive sector stem from the use of fossil fuels in plastics production, embodied GHG emissions and adverse impacts from the use of plastics in vehicles due to chemical additives and unmanaged waste. The expected growth in demand for vehicles and the trend towards higher plastic content per vehicle highlight the need to reduce the use of virgin plastics in the sector by reducing the overall prevalence of plastics, as well as increasing reusability, recyclability and the rate of recycling from end-of-life vehicles.

Directly replacing plastics in cars with alternative materials is not necessarily a worthwhile solution, however. The functional replacement of plastics could result in a significant increase in vehicle weight, which would have direct implications for the fuel consumption of conventional vehicles and the energy consumption of electric vehicles. The reduction in fuel efficiency could more than offset gains in emission reduction from not using fossil plastics (American Chemistry Council and Trucost, 2016). Depending on the functionality of specific components, there may be opportunities to choose alternative materials for individual components, including non-plastic options, such as high-strength steel, aluminium or magnesium alloys. However, a more effective approach to reducing plastics use in the sector may be to focus on the mobility system as whole, rather than on individual vehicles, by reducing the large material inefficiencies in the current mobility system. This could significantly reduce the volume of cars in operation while driving major innovation in vehicle design and providing a similar level of mobility services with fewer resources.

The widespread uptake of ride-sharing, car-sharing and MaaS business models, combined with improved public transport, could spur a reduction in the number of passenger cars on the road in 2050 compared with BAU. This could be facilitated by changes in urban environments and digital technologies to ease transfers between modes of transport, including low-impact modes, such as bicycles and (electric) scooters. Reduced private vehicle ownership would be the result of changes in the organisation and operation of transport services. At the same time, professionally managed shared vehicle fleets and MaaS businesses would provide an incentive for manufacturers and service operators to optimise vehicle efficiency and durability. This could result in radical changes in vehicle design (such as an increase in modular components) and size, reducing average vehicle weight and affecting plastics consumption.

In our low-plastic-consumption scenario, the production of plastics for the automotive sector in 2050 would total 63 Mt globally. This is equivalent to more than double the consumption of plastics in 2015, but a reduction of about 17% on the 76 Mt BAU projection. The reduction would be primarily through dematerialisation.

Reducing the amount of plastics forecast under BAU projections, therefore, implies rethinking the transport system, designing out its present, extremely poor levels of asset and material efficiency. Scaling a system built mostly around professionally managed fleets of shared vehicles offers more citizens a high-quality mobility service, particularly in urban areas, with a much lower volume of vehicles. This would lead to far higher utilisation per car and create considerable incentives for innovation in vehicle design.

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