Transport and environment report 2022
Digitalisation in the mobility system: challenges and opportunities

European Environment Agency

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Executive summary

Digitalisation plays an ever-increasing role in our mobility system. Progressively more complex, capable and affordable digital technologies are increasingly common, relentlessly shaping the evolution of the sector and how we address mobility in our society. The drivers behind this transformation are not necessarily linked to sustainability but rather are often associated with technological innovation, development of new markets, societal benefits and cultural changes. However, digitalisation has the potential to support a sustainable transition of the mobility system, promoting positive behavioural shifts, fair business models and system(s)-wide optimisation possibilities.

How we currently satisfy our mobility needs through transport often causes substantial environmental problems and is expected to continue doing so in the future — unless further action, such as demand management, is taken.

For these reasons, this report explores how and to what extent digitalisation can be instrumental in reducing the environmental impacts of both passenger and freight transport in urban and non-urban settings. Despite the advances in the control of air pollutant emissions, especially from road vehicles, the transport sector is still a significant emitter of greenhouse gases, with additional concern arising from currently unregulated compounds such as ultrafine particles or methane and nitrous oxide, both gases with strong global warming potential. The main driver underpinning this trend is the continuously increasing demand for transport, both for passengers and for freight. This is coupled with a shift away from collective transport modes, such as buses and trains, in passenger mobility and an increasing share of goods being transported by trucks rather than less greenhouse gas-intensive modes such as trains or ships. Realising a modal shift to more sustainable transport modes is one of the domains in which digitalisation can be an enabler, improving the integration of the freight transport system or increasing the attractiveness of multimodality for passengers.

Managing demand remains one of the most critical challenges for the successful transition towards sustainability in the mobility system. Digitalisation can also contribute here, providing practical tools to internalise the external costs of transport and raise awareness of the pressures exerted by our mobility needs and preferences. Acceptance, political willingness and social aspects remain crucial barriers to fully considering such costs.

Digitalisation can not only contribute to increasing the attractiveness and accessibility of public transport or enabling the realisation of a seamless multimodal freight transport sector by promoting modal shifts and dynamically managing demand by internalising the external costs. It can also support better policymaking. Advanced monitoring tools and increased availability and generation of data, enabled by digital technologies, can fill knowledge gaps and facilitate the enforcement of existing or future regulations.

The message is clear: digitalisation has the power 'not only to do more but also to do things differently' (EEA 2019a). It can foster creative approaches to tackling the climate and other environmental problems we currently face, providing that this transition is guided and closely monitored by policymakers and institutions. Indeed, digitalisation also has the power to considerably worsen the pressures exerted on the environment, increasing demand for transport because of improved efficiency and reduced costs and increasing the attractiveness of less sustainable personal mobility modes such as private cars. To realise the potential that digital technologies can bring, it will be fundamental to keep our natural environment at the centre; only in this way can we achieve a sustainable and just transition.

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1
Introduction

Since the first ARPANET link was made in 1969, which contributed to the realisation of the internet a few years later, the evolution of digital electronics, computing and communication technologies has been relentless. This third industrial revolution has, in just 50 years, reshaped the world and the societies we live in through countless inventions — from personal computers and smartphones to modern artificial intelligences able to create art or solve complex problems. The effects of digitalisation on mobility systems have the potential to be equally transformational. Exploring this potential is the purpose of this report.

It is curious to note the parallels with another disruptive technological innovation: the development of the first internal combustion engine by Eugenio Barsanti and Felice Matteucci in 1854. This led, through a long series of pioneering innovations, to the mass production of cars just a few decades later, with Henry Ford's Model T completely changing our way of imagining mobility.

Both transport and digitalisation are today at the edge of a new phase of their evolution, facing the challenges coming from the dramatic changes we are experiencing in the climate and the massive damage to the environment induced by ever-increasing anthropisation. In addition, the recent crises induced by first the COVID-19 pandemic and then the Russian invasion of Ukraine have put the EU's economy, society and ecosystems under further pressure. This report has the ambition of providing an overview of some of the numerous points of contact and complex interdependencies between these two sectors, exploring the criticalities and opportunities they can offer to tackle the immense challenge that lies ahead of us: 'living well, within the limits of our planet'.

To mitigate environmental problems, categorising actions according to the 'Avoid-Shift-Improve' framework (EEA, 2010) can contribute. 'Avoid' actions address the demand for transport and the impact of transport on the environment by reducing the number and/or length of trips. 'Shift' approaches contribute to environmental sustainability by realising the modal shift from less to more environmentally-friendly and energy-efficient modes. 'Improve' actions reduce the energy consumption and environmental impact of travel modes by, for example, increasing the uptake of more sustainable energy sources. In all three categories, digitalisation can offer opportunities but can also create new challenges. These are important to identify upfront to shape the developments in digitalisation such that its full potential in the sustainable transition of mobility is realised.

The structure of this report is as follows (Figure 1.1):

- **Chapter 2** presents the evolution of transport volumes in the EU-27 (see Box 1.1), for both passenger and freight transport, and an overview of the main environmental impacts associated with transport and their evolution over time;

- **Chapter 3** introduces the concept of digital transformation, its relevance for transport and its environmental effects. It presents a taxonomy of the way in which digitalisation can affect the environmental performance of the sector, which will be applied in later chapters to frame the impacts of a selection of digital technologies relevant for transport;

- **Chapter 4** gives an overview of the EU digitalisation policy context more generally and in the transport domain;

- **Chapter 5** presents brief factsheets summarising challenges and opportunities that nine selected digital technologies can bring to the sector and how they can reduce its environmental impacts;

- **Chapter 6** identifies and discusses a number of general challenges related to digitalisation in transport. These include the environmental impacts of the solutions themselves, data privacy and protection, liability issues, digital inclusion, market power and dependency on raw materials;

- **Chapter 7** summarises the key messages from the report and some points that chart the way for future work;

- Lastly, **nine technical annexes** present a more detailed assessment of the nine digital technologies introduced in **Chapter 5**. The annexes are complemented with case studies illustrating practical examples of implementation at pilot scale, simulation studies or ongoing research in the field and with a preliminary quantification of the environmental impacts.

Figure 1.1 Structure of the TERM 2022 report

Chapter 1
Introduction

Chapter 2
The environmental impacts of transport

Chapter 3
Digitalisation and transport

Chapter 4
EU policy context

Chapter 5:
Challenges and opportunities of selected digital technologies in the transport sector

- Factsheet 1 — Teleworking and virtual mobility
- Factsheet 2 — Shared autonomous urban vehicles
- Factsheet 3 — Autonomous freight transport
- Factsheet 4 — Multimodal digital mobility services
- Factsheet 5 — Smart logistics
- Factsheet 6 — Vehicle-grid integration
- Factsheet 7 — Digitalisation in road transport pricing
- Factsheet 8 — Air traffic management
- Factsheet 9 — Digitally enabled monitoring solutions

Chapter 6
General challenges

Annexes 1-9
Technical discussion and detailed analysis

Box 1.1 Country groupings

Throughout the report, abbreviations are used to refer to specific country groupings. The following definitions are used:

- EU-27: the 27 EU Member States as of 1 February 2020.
- EEA-32: EU-27 + Iceland, Liechtenstein, Norway, Switzerland and Türkiye.
- EEA-38: EEA-32 + Albania, Bosnia and Herzegovina, Kosovo, Montenegro, North Macedonia and Serbia.
- European Free Trade Association (EFTA) member states: Iceland, Liechtenstein, Norway and Switzerland.

2
The environmental impacts of transport

Key messages

- **Motorised passenger transport performance (measured in passenger-km) increased by almost 21% between 2000 and 2019. The passenger car remains the dominant transport mode and has increased its share since 2000, while the strongest growth in terms of passenger-km is recorded for high-speed rail and aviation. In 2020, the first year of the COVID-19 pandemic, passenger transport volumes fell by 26%, with the largest reduction in aviation.**
- **Freight transport performance (measured in tonne-km) grew by 23% in the same period. In 2019, more than half was due to road transport, an increased share compared to 2000. Sea shipping was the second dominant mode in 2019. The COVID-19 pandemic affected freight transport volumes less than passenger transport, with total tonne-km transported 3.6% lower in 2020 than in 2019.**
- **By fulfilling human mobility needs, transport brings large benefits to society. Transport is also a key economic sector, given its share of employment and added value. It is, after housing, the most substantial household expenditure.**
- **Transport also has negative effects in the form of accidents, congestion, noise and environmental impacts. Users usually do not fully take these into account in their transport choices.**
- **The exhaust emissions of greenhouse gases from the transport sector increased by 33% between 1990 and 2019, while the EU's overall emissions fell by 24%. Due to the exceptional circumstances created by the COVID-19 pandemic, greenhouse gas emissions from transport were 18.6% lower in 2020 than in 2019.**
- **It is estimated that 18.4 million people experience chronically high levels of annoyance due to noise pollution from transport. At the same time, 5.5 million people are estimated to experience chronically high levels of sleep disturbance.**
- **In between 1990 and 2019, nitrogen oxides emissions decreased by 34%, sulphur oxide emissions by 53%, carbon monoxide emissions by 74% and non-methane volatile organic compound emissions by 77%. In 2019, fine particulate matter emissions (2.5 μm or smaller) decreased by more than 47% compared to 2000 levels. However, the situation varies across modes, with NOx and PM emissions increasing in aviation and international shipping.**
- **In 2015, the number of fragmented landscape elements was about 1.5 per km^2, a 3.7% increase compared to 2009 (EU excluding Romania). Approximately 28% of the area of the EU (excluding Romania) was strongly fragmented; a 0.7% increase compared to 2009.**

2.1 Introduction

Transport fulfils mobility needs that result from activities such as living and working and from the consumption, trade and production of goods and services. Transport is needed because, generally, such activities do not all take place in the same location. In this sense, the term 'mobility' identifies the need and the possibility of moving from one place to another, while transport is the tool used to realise this necessity in practice (Eltis, 2019).

Satisfying mobility needs brings important benefits to society. However, it also has negative effects in the form of accidents, congestion and environmental impacts (EC, 2019a). The costs associated with those are often not internalised, and this contributes to an incomplete perception of the real impact of the sector on society and the environment.

This chapter presents the evolution of transport volumes in the EU-27, for both passenger and freight transport, and an overview of the main environmental impacts associated with transport.

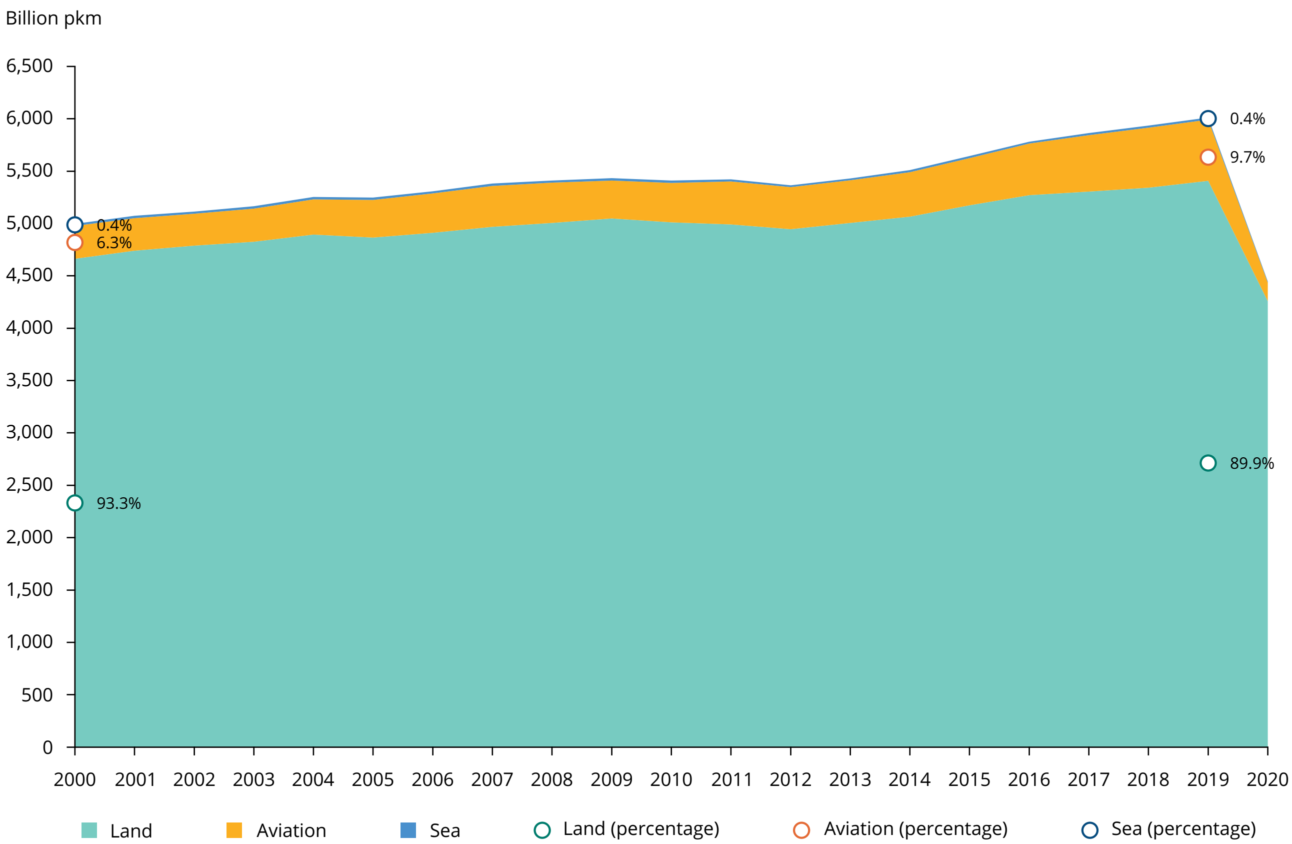
2.2 Passenger transport volumes

In 2019, a total of 6,038 billion passenger-km ([1]) were travelled in the EU-27 using motorised transport modes. This is an increase of 20.8% compared to 2000 (Figure 2.1), which corresponds to a compound annual growth rate ([2]) of 1% (EC, 2022a). By comparison, in the same period gross domestic product (GDP) per capita in the EU-27 increased by 25% (after removing the effect of price changes), or at a compound annual growth rate of 1.2% (Eurostat, 2022a).

As shown in Figure 2.1, land-based transport accounted for the largest share (90%) of passenger-km travelled in 2019. The share of aviation was 9.7% and that of sea transport 0.4%. Compared to 2000, the total passenger-km travelled by air have grown substantially (by 86%) compared to an increase of 16.6% for land-based transport and a reduction of 1% for sea transport. In 2020, the first year of the COVID-19 pandemic, passenger transport volumes dropped by 26% compared to 2019, with the largest reduction for aviation (-70%) and sea transport (-51%). Land-based transport fell by 21%.

In different units, the average number of kilometres travelled per person increased from 11,663km/year to 13,525km/year between 2000 and 2019, which corresponds to an increase of 16%. The average annual number of kilometres travelled per person by air in the EU-27 increased by almost 80%, land-based kilometres travelled per person increased by 12%, while the increase in sea-based kilometres travelled was marginal. Digitalisation can provide tools to manage such increasing demand for transport, and some of them will be discussed in Factsheet 7 and in Annex 7.

Figure 2.1 Passenger transport in the EU-27, 2000-2020 (billion pkm) and modal share in 2000 and 2019



Note: The percentage values represent the shares of the three modes in passenger transport volumes in 2000 and 2019.

Source: EEA compilation based on EC (2022a).

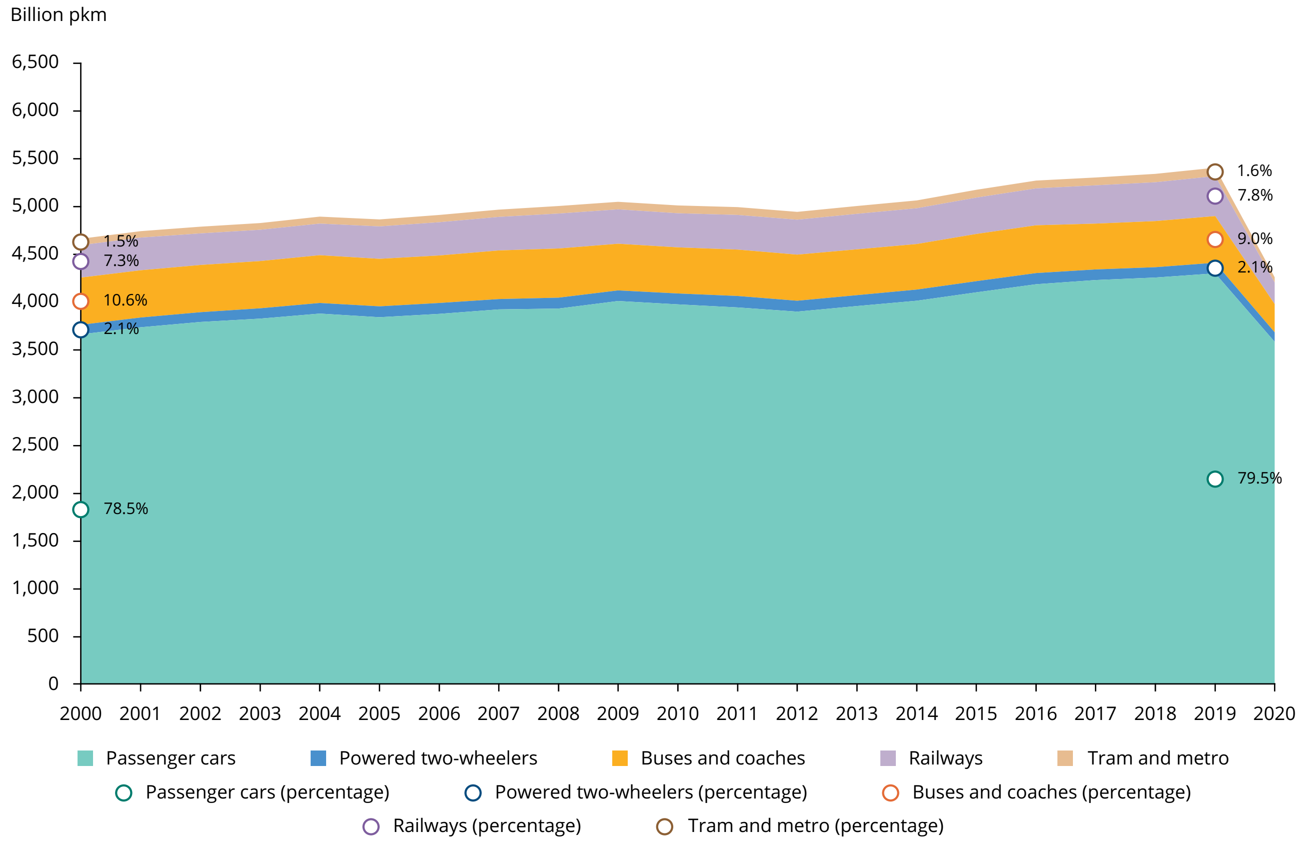
([1]) Eurostat defines a passenger-kilometre as 'the unit of measurement representing the transport of one passenger by a defined mode of transport (road, rail, air, sea, inland waterways etc.) over one kilometre'. 100 passenger-km can refer to one person travelling 100km or, for example, five people each travelling 20km.

([2]) Compound annual growth rate (CAGR): $CAGR(t_0,t_n) = \left(\frac{V(t_n)}{V(t_0)}\right)^{\frac{1}{t_n-t_0}} - 1$, where V and t indicate a value and a moment in time, respectively.

Within the land-based modes, the passenger car is still the dominant means of transport with a share of 79.5% of the overall passenger-km travelled in 2019 (Figure 2.2). The shares of the other motorised modes are as follows: 9.0% for buses and coaches, 7.8% for rail, 2.1% for powered two-wheelers and 1.6% for tram and metro. Compared to 2000 the shares of car transport and rail have risen, while that of buses and coaches has fallen. The share of the remaining modes has remained approximately constant. The car motorisation rate increased from 412 to 553 cars per 1,000 inhabitants between 2000 and 2019 (an increase of 34.2%). How digitalisation can contribute to promoting the attractiveness of public transport, promoting a modal shift away from privately owned vehicles, is extensively discussed throughout the report; for example, in Factsheet 4 on multimodal digital mobility systems and in Factsheet 2 on shared autonomous vehicles.

In 2020 the COVID-19 pandemic led to a significant decrease (-21%) in land-based transport compared to 2019. This reduction was most pronounced for the public transport modes: -38% for passenger-km travelled by tram and metro, -40% for bus and coach transport and -46% for rail transport. The volume of transport by car fell by 17% and that by powered two-wheelers by 10%.

Figure 2.2 Land-based passenger transport in the EU-27, 2000-2020 (billion pkm) and modal share in 2000 and 2019



Note: The percentage values represent the shares of the land-based passenger transport modes in 2000 and 2019.

Source: EEA compilation based on EC (2022a).

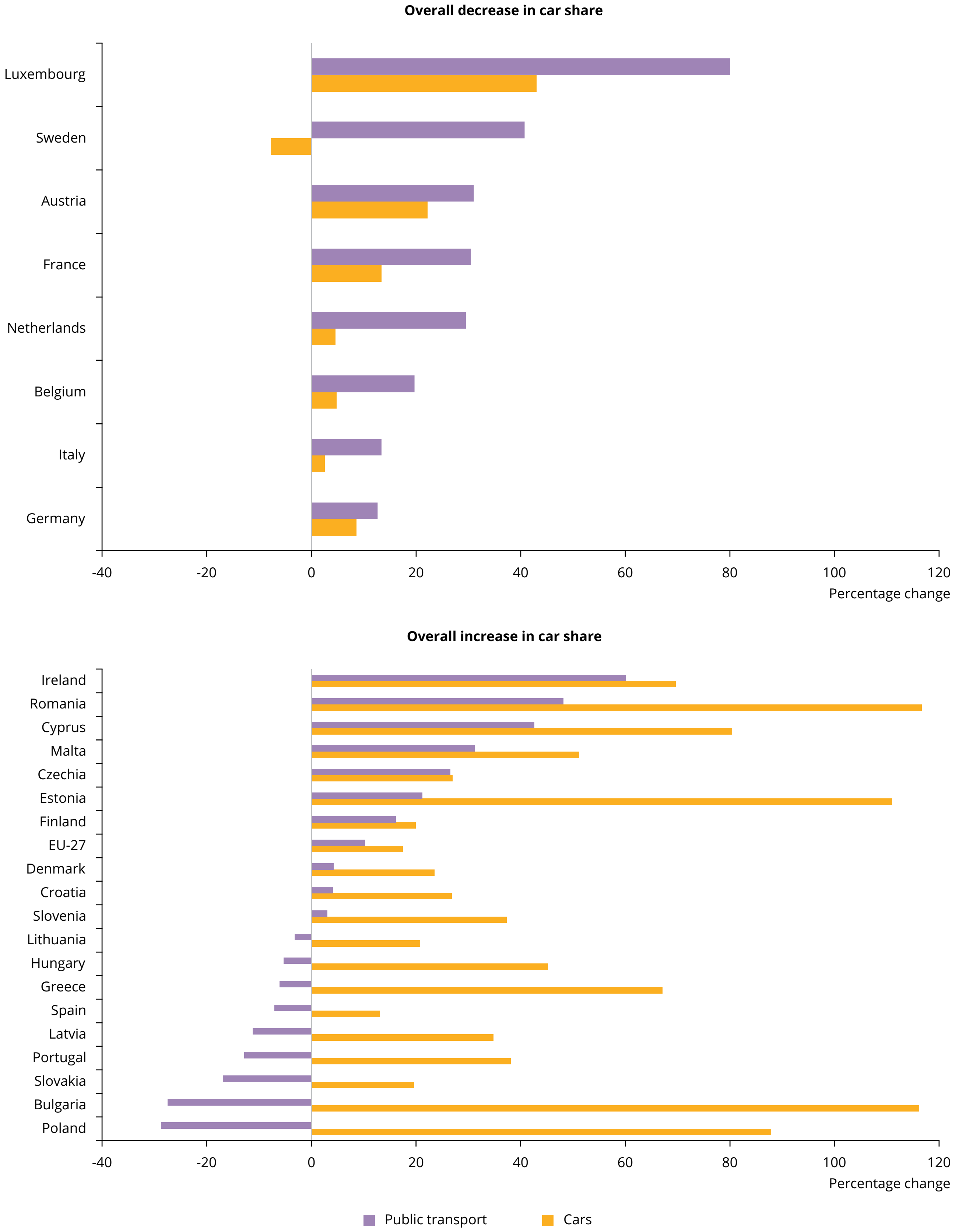
Figure 2.3 presents the change in the EU-27 since 2000 in car and public transport volumes (in passenger-km). In eight Member States car transport grew at a lower rate than public transport (upper panel). Consequently, the share of car transport fell in these countries, while in the other countries and the EU-27 as a whole (lower panel), the share of car transport increased. In Bulgaria, Romania and Estonia, passenger-km travelled by car more than doubled. In nine Member States, public transport volumes decreased between 2000 and 2019, with the percentage decrease ranging between -3% (Lithuania) and -29% (Poland).

Figure 2.4 gives more detail on the developments in the public transport modes in the EU-27. For rail transport, the growth has been greatest for high-speed rail, for which passenger-km travelled more than doubled between 2000 and 2019 (growth of 125%, from 59 to 132 billion passenger-km). Travel by conventional rail (in passenger-km) increased by 3.4% in the EU-27.

EU-wide data on the relative importance and characteristics of transport within cities, between cities and outside cities are unfortunately not always directly available. Nor are EU-wide data on passenger-km travelled on foot or by bicycle or on multimodal transport. The EMTA barometer offers some evidence for 31 main cities and 28 surrounding metropolitan areas situated across Europe that are served by the members of EMTA, the association of European Metropolitan Transport Authorities. In 2019, i.e. before the onset of the COVID-19 pandemic, on average, 32% of trips in the selected metropolitan areas were made on foot or by bicycle, 20% by public transport and 48% by private motorised transport. In the main cities the average shares of journeys made on foot or by bicycle and on public transport were higher, at 37% and 29%, respectively. Moreover, in large urban areas with good public transport people relied much less on cars (EMTA, 2021).

For the period after 2020, the EU Reference Scenario 2020, which takes into account policies in place in December 2019, projects an increase in passenger transport volumes by 2025, following the COVID-19 pandemic, and a further increase after that (Figure 2.5). The consequences of the pandemic and the Russian invasion of Ukraine (see Box 2.1) on the economic system are not included in the scenario. Compared to 2015, the number of passenger-km travelled by road and rail is forecast to be about 13% higher by 2030 and 27.4% higher by 2050. Passenger car transport is also forecast to increase, but its share in road or rail transport is projected to fall to 78.1% in 2050, mainly to the benefit of rail, whose share is forecast to increase to 11.3% in the same year (compared to 6.5% in 2015). Rail is projected to transport 741 billion passenger-km by 2050 (compared to 470 billion in 2015). This is the consequence of the higher costs of road transport (both monetary costs and congestion costs), in combination with improved rail services in the Reference Scenario (EC, 2021a). The scenario also projects a considerable increase in intra-EU aviation between 2015 and 2050: 91%. These trends could be strongly affected by deploying automation in the passenger transport sector, as described in Factsheet 2 and Annex 2.

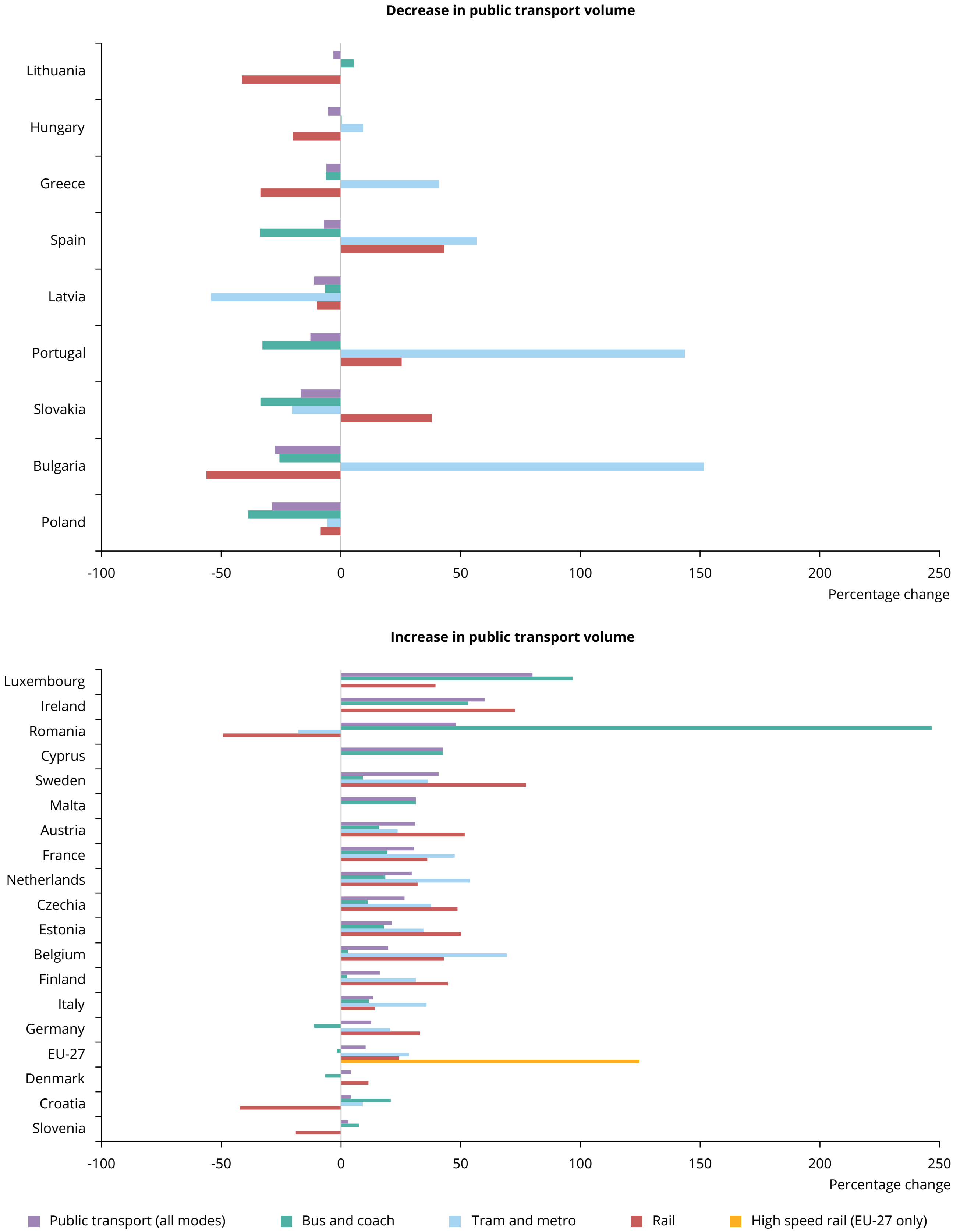
Figure 2.3 Change in passenger-km travelled between 2000 and 2019 in the EU-27



Note: Public transport refers to travel by bus, coach, tram, metro and rail.

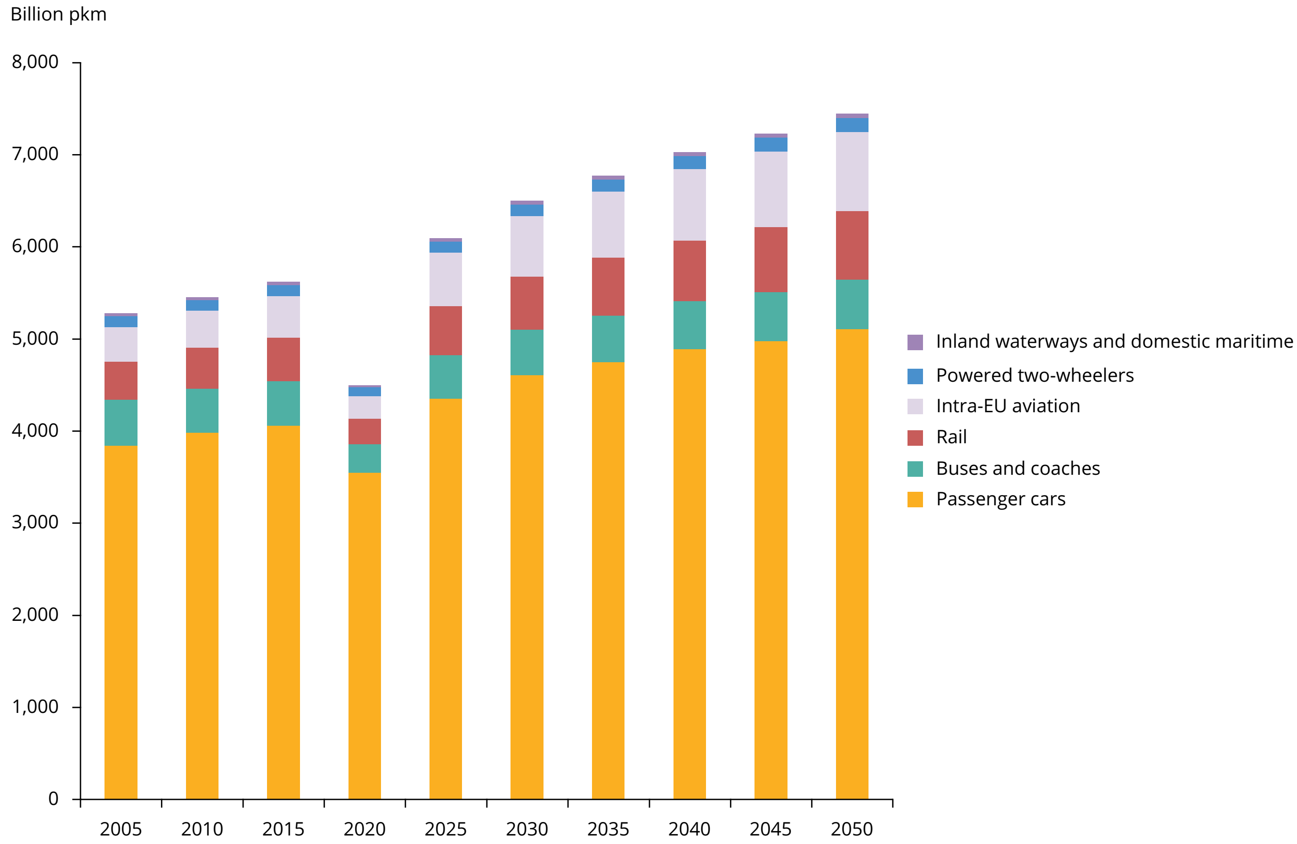
Source: EEA compilation based on EC (2022a).

Figure 2.4 Change in passenger-km travelled by public transport modes between 2000 and 2019 in the EU-27



Source: EEA compilation based on EC (2022a).

Figure 2.5 Passenger transport volumes in the EU Reference Scenario 2020



Note: Projections as from 2020.

Source: EEA compilation based on EC (2021a).

Box 2.1 Economic consequences of the Russian invasion of Ukraine and the COVID-19 pandemic

The Russian invasion of Ukraine is causing high humanitarian costs. Together with the measures to address the COVID pandemic, it has also led to a cost-of-living crisis across the globe. The Organisation for Economic Co-operation and Development reported that global growth slowed to 3.2% in 2022. There were large increases in energy and food prices combined with disruptions in the supply chain. The outlook for 2023 is that global gross domestic product (GDP) growth will still be low at around 2.6%, with a continued low growth in 2024 (2.9%). In the euro area, real GDP is projected to grow by a meagre 0.8% in 2023 and 1.4% in 2024 (OECD, 2023).

The war in Ukraine and the sanctions imposed on Russia affect also Europe's transport sector. The European Commission has taken initiatives to address these (European Parliamentary Research Service 2022). In addition to the direct consequences, transport in Europe will also be affected by lower economic growth and high inflation. The impact on passenger and freight transport in future years could be large and still needs to be assessed.

2.3 Freight transport volumes

In 2019, a total of 3,392 billion tonne-km ([3]) of freight were transported. This is 23.0% higher than in 2000, which corresponds to a compound annual growth rate of 1.1%. In the same period, the overall GDP in the EU-27 increased by 31% in real terms (after removing the effect of price changes; this corresponds to a compound annual growth rate of 1.4%).

In 2019, 52.0% of freight (in tonne-km) was transported by road, compared to 48.7% in 2000 (Figure 2.6) (EC, 2022a). The volume of freight (tonne-km) transported by road increased at approximately the same rate as the economy.

As for passenger transport, no EU-wide data are available on the relative importance of freight transport within cities, between cities and outside cities. However, Eurostat publishes statistics on the share of the different distance classes transported by road, also reported for 2019 in Figure 2.7. While it fluctuated somewhat between 2011 and 2019, it did not change significantly (Eurostat, 2022b).

The second most important freight transport mode in terms of volume (tonne-km) was sea transport, which accounted for 28.9% in 2019 compared to 28.1% in 2000. The volume transported by sea increased by 26.2% in this period. The share of rail transport fell from 14.1% to 12.0% in the same period. The volume transported by rail grew less than the total freight volume, namely by only 4.8%. The share of the other transport modes taken together was 7.1% in 2019.

Because of the COVID-19 pandemic, freight transport was 3.6% lower in 2020 than in 2019. Freight transport was less affected than passenger transport, which fell by 26%. Road freight transport decreased less than average, by 1.1%. The largest percentage reduction was recorded for air transport (11.2%).

In 2020, combined transport ([4]) accounted for 89.6 billion tonne-km, of which approximately half was transported between 300km and 900km and half over 900km. While combined transport increased by almost 130% in 2020 compared to 2012, its share of total freight transport is small.

Similarly to what is observed for passenger transport, the situation in the EU for freight transport is heterogeneous. Its evolution between 2000 and 2019 differs in the EU-27, as shown in Figure 2.8 for road transport and the other land-based modes. For road transport the figure shows the changes both according to the nationality of the vehicle and according to the country where the transport takes place (territoriality principle).

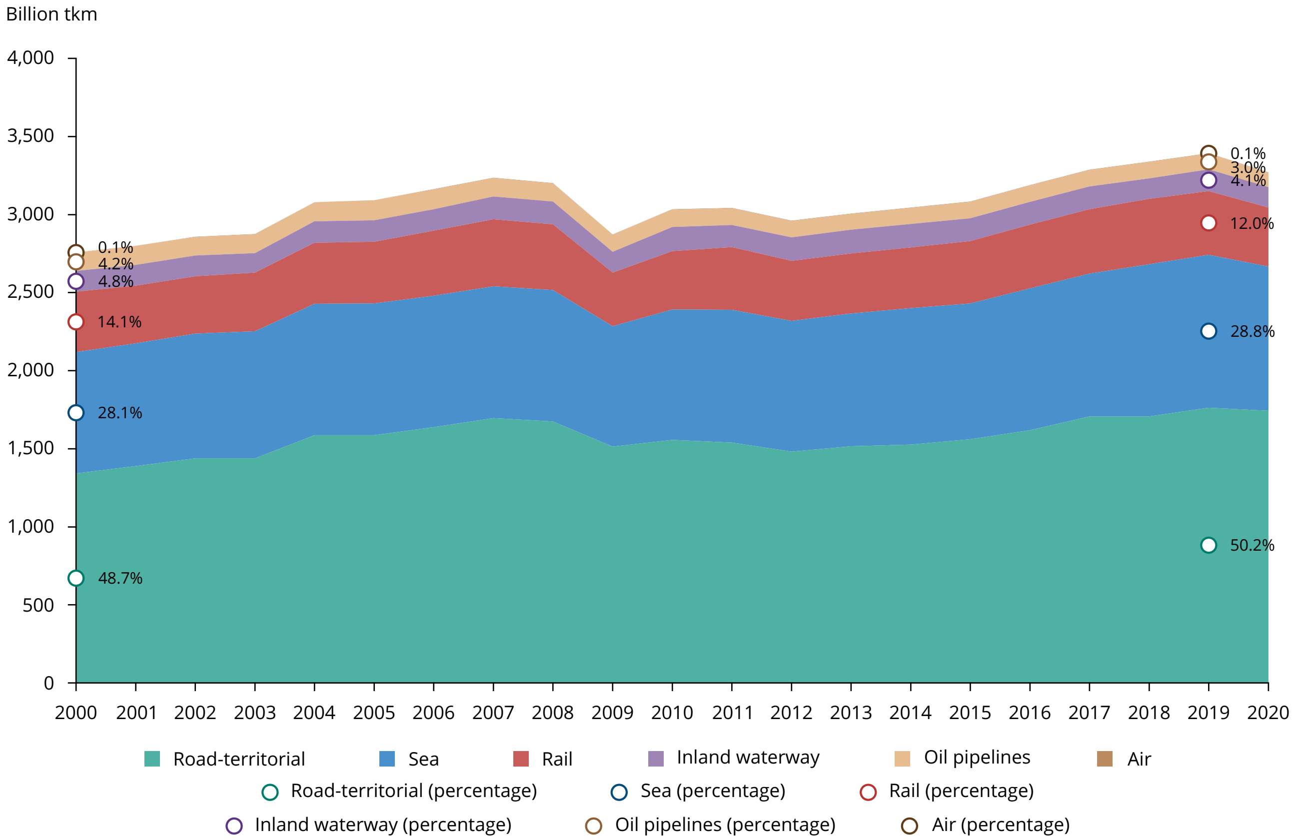
In a number of countries there was a substantial increase between 2000 and 2019 in the volume of goods transported by road, when transport is classified according to the nationality of the vehicles. It more than tripled in Bulgaria, Hungary, Lithuania, Poland, Romania and Slovenia and more than doubled in Slovakia. The vehicles registered in these countries transported more freight in the territories of other EU Member States and elsewhere in 2019 than in 2000. Indeed, in some countries since 2005 the change in road transport in the territory is larger than or of the opposite sign to the change in transport by vehicles registered in the country, indicating the growing share of freight transport by foreign vehicles.

Figure 2.8 also shows the relative changes in transport by the non-road land-based modes (rail, inland waterways and pipelines).

([3]) Eurostat defines a tonne-km as 'a unit of measure of freight transport which represents the transport of one tonne of goods (including packaging and tare weights of intermodal transport units) by a given transport mode (road, rail, air, sea, inland waterways, pipeline, etc.) over a distance of one kilometre'. 100 tonne-km can refer to 1 tonne that is transported over a distance of 100km or, for example, to 100 tonnes transported over a distance of 1km.

([4]) Combined transport is defined as 'intermodal transport where the major part of the journey, in Europe, is by rail, inland waterways or sea, and any initial and/or final legs carried out by road are as short as possible' (OECD 2003).

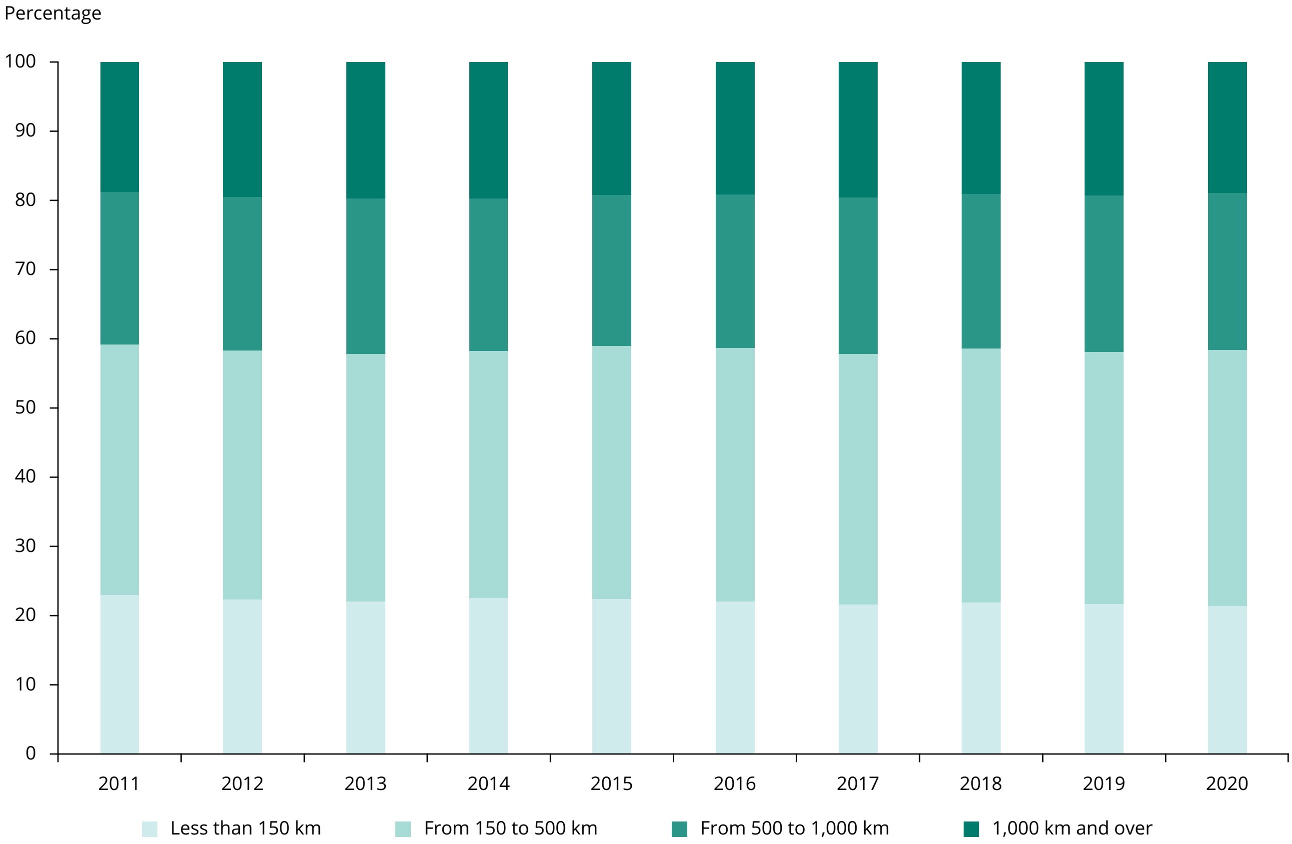
Figure 2.6 Freight transport in the EU-27, 2000-2020 (billion tkm) and modal share in 2000 and 2019



Note: The percentage values represent the shares of the transport modes in freight transport volumes in 2000 and 2019.

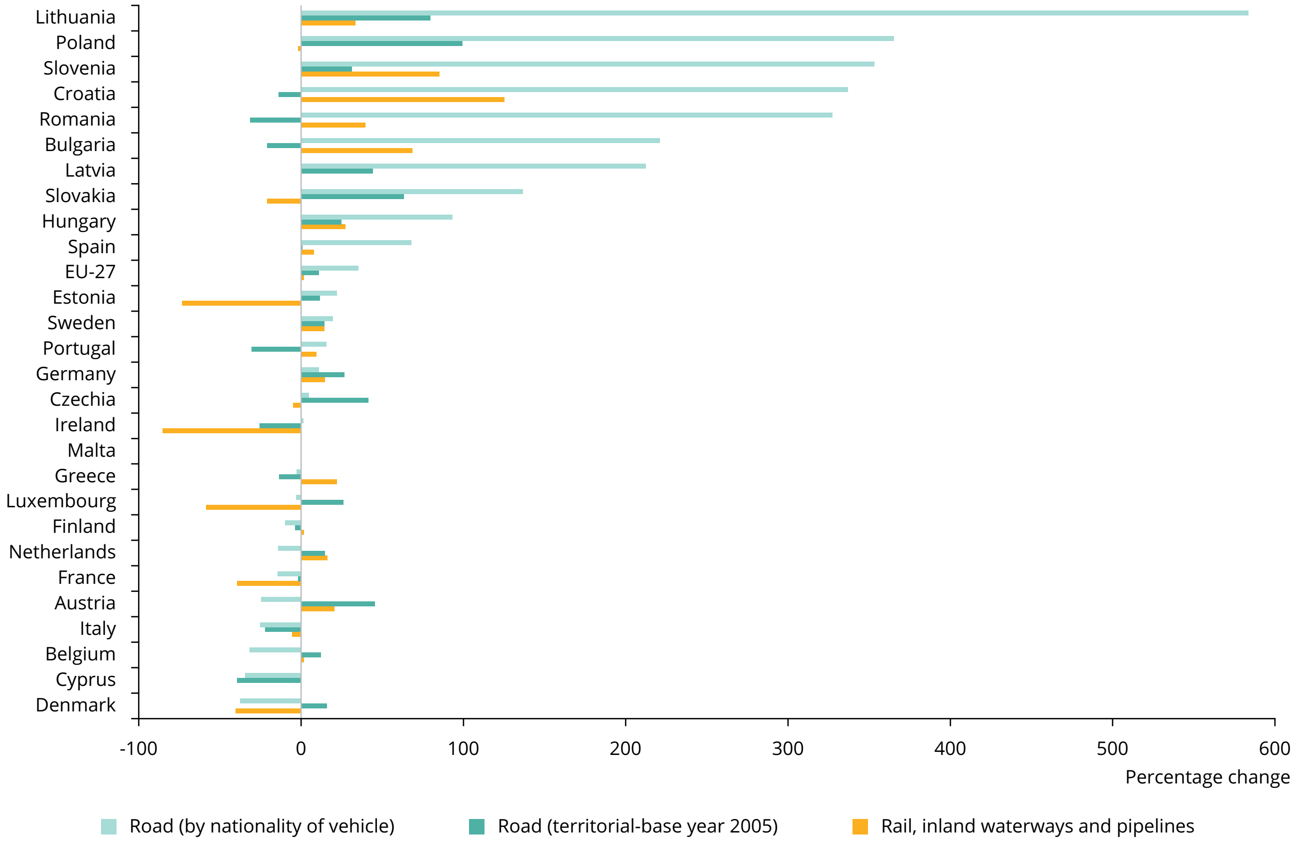
Source: EEA compilation based on EC (2022a).

Figure 2.7 **Share of distance classes in freight volumes (tonne-km) transported by road in the EU-27 in 2011-2020**



Source: EEA compilation based on Eurostat (2022b).

Figure 2.8 **Change in volume (tonne-km) transported by road and other land-based modes between 2000 and 2019 in the EU-27 and its Member States**

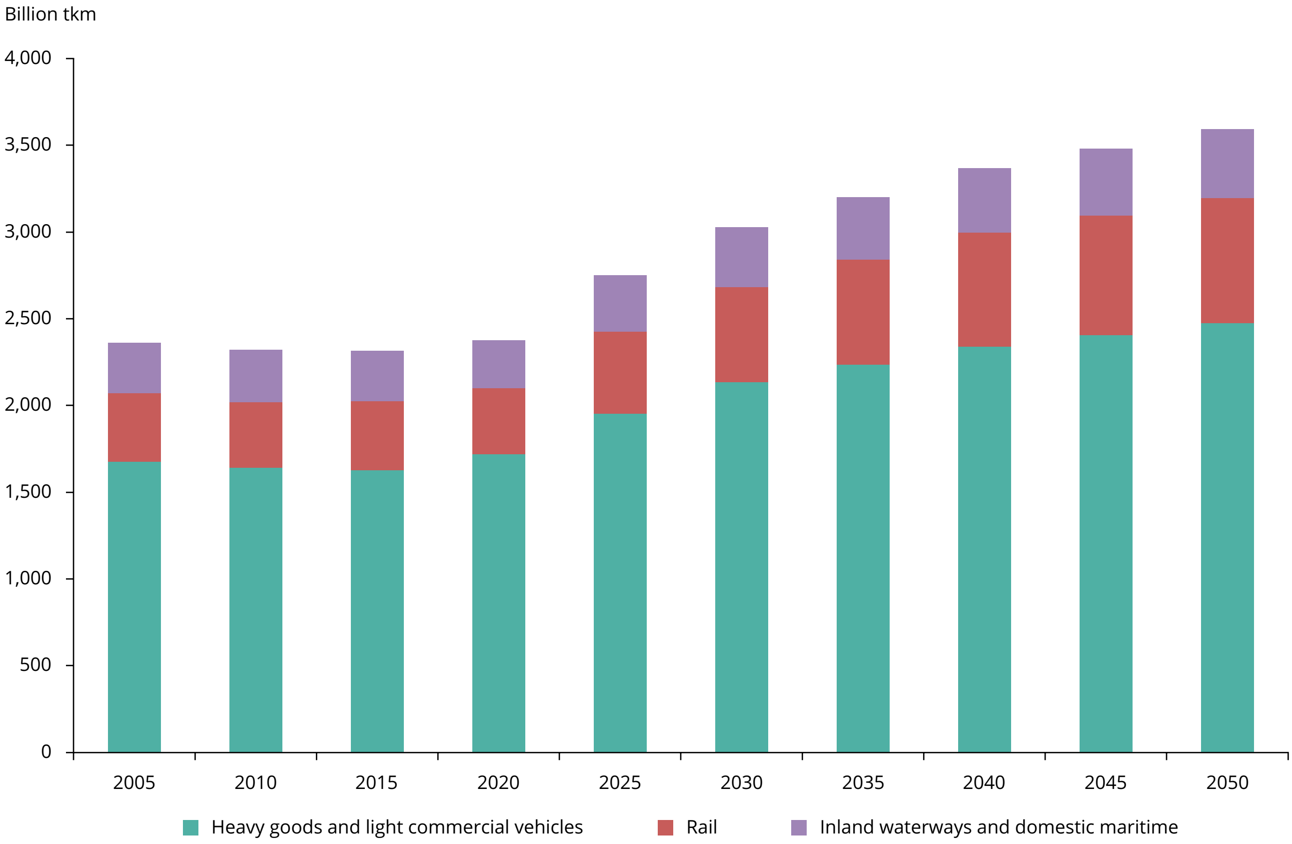


Notes: For road transport in accordance with the territorial principle the base year is 2005.
Road transport includes only transport by heavy-duty trucks.

Source: EEA compilation based on EC (2022a).

For the volume of inland freight transport, the EU Reference Scenario forecasts an increase of 31% by 2030 compared to 2015, and an increase of 55% by 2050. However, the impact of the Russian invasion of Ukraine and the more recent developments in the COVID-19 pandemic on these projections could be important (see Box 2.1). In the Reference Scenario the rail share would grow (20% by 2050 compared to 17% in 2015, corresponding to 726 billion tonne-km in 2050) and that of the other inland modes would fall (Figure 2.9). While rail, inland navigation and national maritime transport are all targeted by the completion of the Trans-European Transport Network (TEN-T) core and comprehensive network that is assumed in the Reference Scenario, rail is projected to benefit from it the most (EC, 2021a). These trends are likely to be strongly affected by deploying automation in the freight transport sector, as described in Factsheet 3 and Annex 3.

Figure 2.9 Freight transport volumes in the EU Reference Scenario 2020



Note: Projections as from 2020.

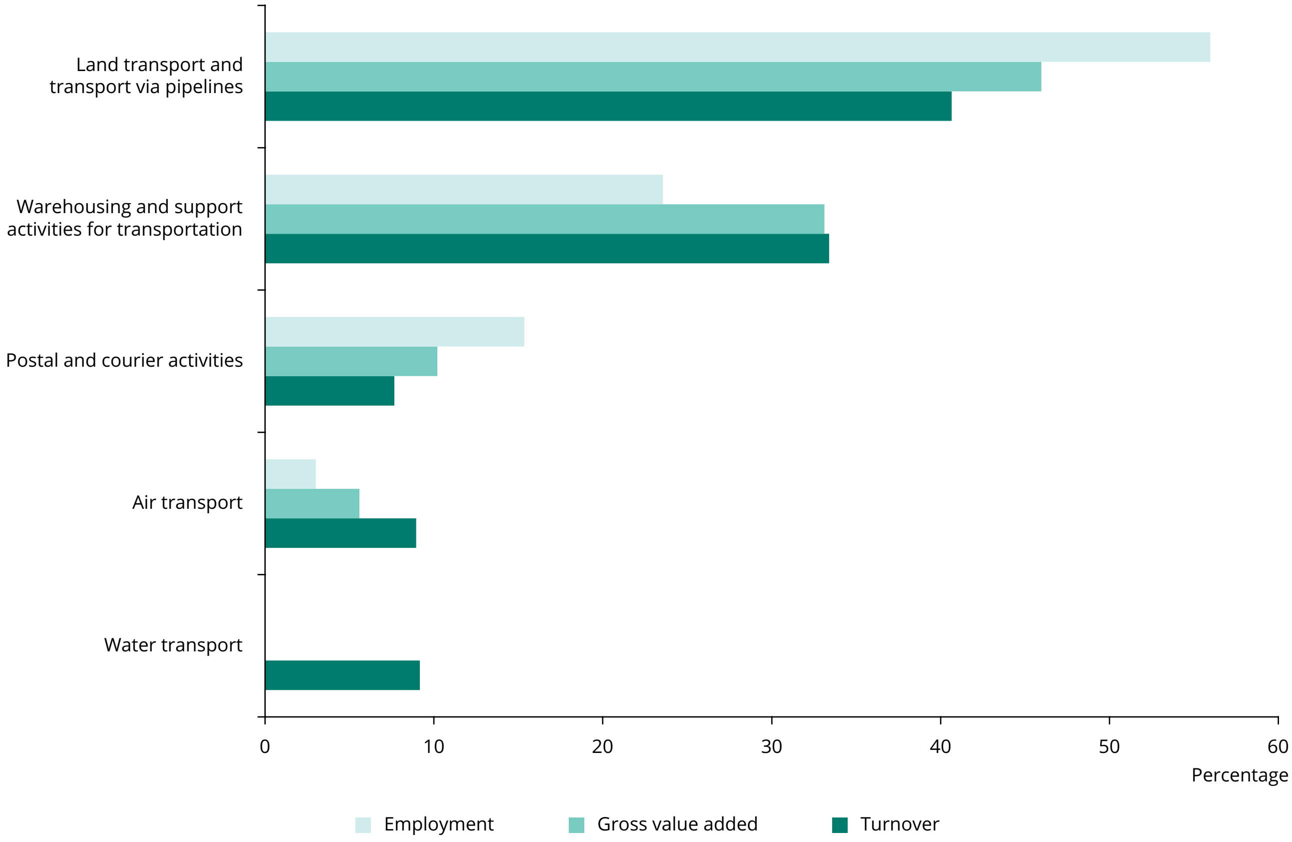
Source: EEA compilation based on EC (2021a).

2.4 Economic indicators of transport

The transport and storage sector is an important part of the economy. In 2019, it employed 10.4 million people and recorded an added value of EUR 510.3 billion, without accounting for upstream or downstream activities. This represents 7.9% of those working in non-financial businesses and 7.4% of the wealth generated in that part of the economy (Eurostat, 2022c). The sectors included in these activities are industry, construction and services, excluding financial and insurance activities (Eurostat, 2022d). Within the transport and storage sector, land transport and the warehousing and support services sectors are the two largest in terms of employment and value added (Figure 2.10). Apart from buying such services, firms and households also operate their own means of transport. These are not included in the statistics above, leading to an underestimation of the actual figures. Regarding research and development (R&D) activities, Grassano et al. (2020) classify the sectors of auto parts, automobiles, commercial vehicles and trucks as those with medium to high R&D intensity, whereas transport services are among those with low R&D intensity.

In 2019, households in the EU-27 spent 13.1% of their total consumption expenditure on transport, and 11.6% in 2020, the first year of the COVID 19-pandemic (Table 2.1). In 2019, this represented a total expenditure of over EUR 0.96 trillion (at current prices), equivalent to 6.9% of the EU GDP or EUR 2,150 per EU inhabitant. In 2020, this was EUR 1,750 per inhabitant. Transport is the EU's second largest household expenditure item after housing (including the costs of water, electricity, gas and other fuels) which was responsible for 23.5% of total consumption expenditure in 2019 and 25.7% in 2020 (Eurostat, 2022e). The largest part of the transport budget is spent on the operation of vehicles, which includes fuel, spare parts and accessories, maintenance and miscellaneous services.

Figure 2.10 Sectoral analysis of the transport and storage sector: share of subsectors in employment, gross value added and turnover in the EU-27 in 2019



Note: Data for employment and gross value added in water transport were not available.

Source: EEA compilation based on Eurostat (2022d, 2022c).

Table 2.1 Share of transport in consumption expenditure of households in the EU-27, 2019-2020

	Share of total consumption expenditure (%)		Spending per capita (EUR at current prices)	
	2019	2020	2019	2020
Total			16,400	15,100
Transport (total)	13.1	11.6	2,150	1,750
Purchase of vehicles	3.8	3.6	620	550
Operation of transport equipment	7.1	6.5	1,160	980
Transport services	2.3	6.4	370	220

Source: Eurostat (2022e).

2.5 Environmental impacts of transport

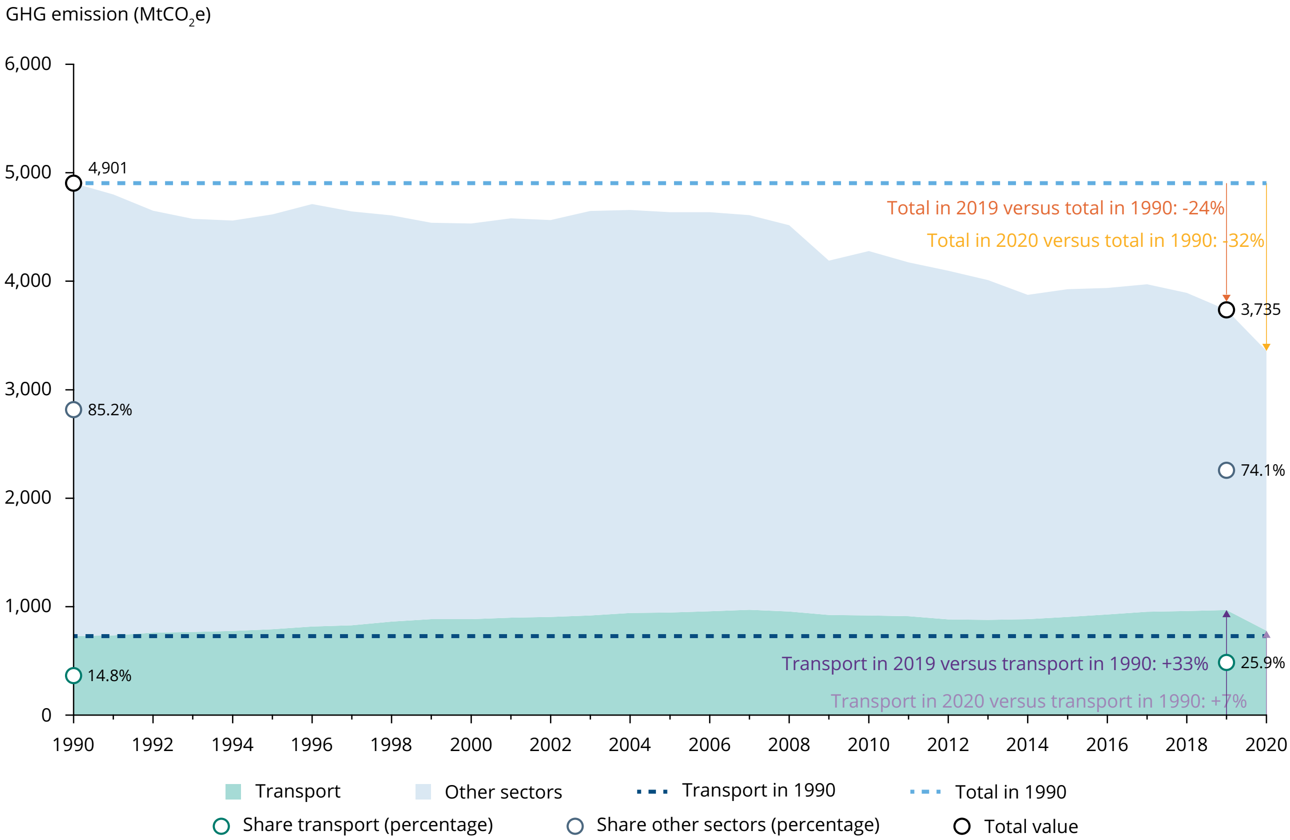
2.5.1 Greenhouse gas emissions

The transport sector is a major contributor to greenhouse gas (GHG) emissions in the EU-27 because of its strong dependence on fossil fuels. The exhaust emissions of transport (including aviation bunkers) were responsible for 25.9% of total GHG emissions in the EU-27 in 2019. While over time, overall GHG emissions have fallen by 24%, those of transport have risen by 33%. Consequently, transport's share of GHG emissions has grown (Figure 2.11).

Due to the exceptional circumstances created by the COVID-19 pandemic, the EU's GHG emissions were substantially lower in 2020 than in 2019. This was also the case for transport's GHG emissions. In 2020 they were 18.6% lower than in 2019, but compared to 1990 GHG emissions were 7% higher in 2020.

In 2019, CO_2 emissions accounted for 98.8% of the exhaust GHG emissions from transport. However, in addition to these, there are also those related to the production and distribution of fuels and electricity for transport. These are included in the emissions of the 'other sectors' as far as they take place within the EU-27. GHG reporting also does not yet account for the non-CO_2 impacts of aviation (Lee, et al., 2021).

Figure 2.11 Greenhouse gas emissions from transport and other sectors in the EU-27 (million tonnes CO_2e), shares in emissions and change between 1990 and 2020 (%)



Notes: Transport emissions including air bunkers but not maritime bunkers.
CO_2e, CO_2 equivalent.

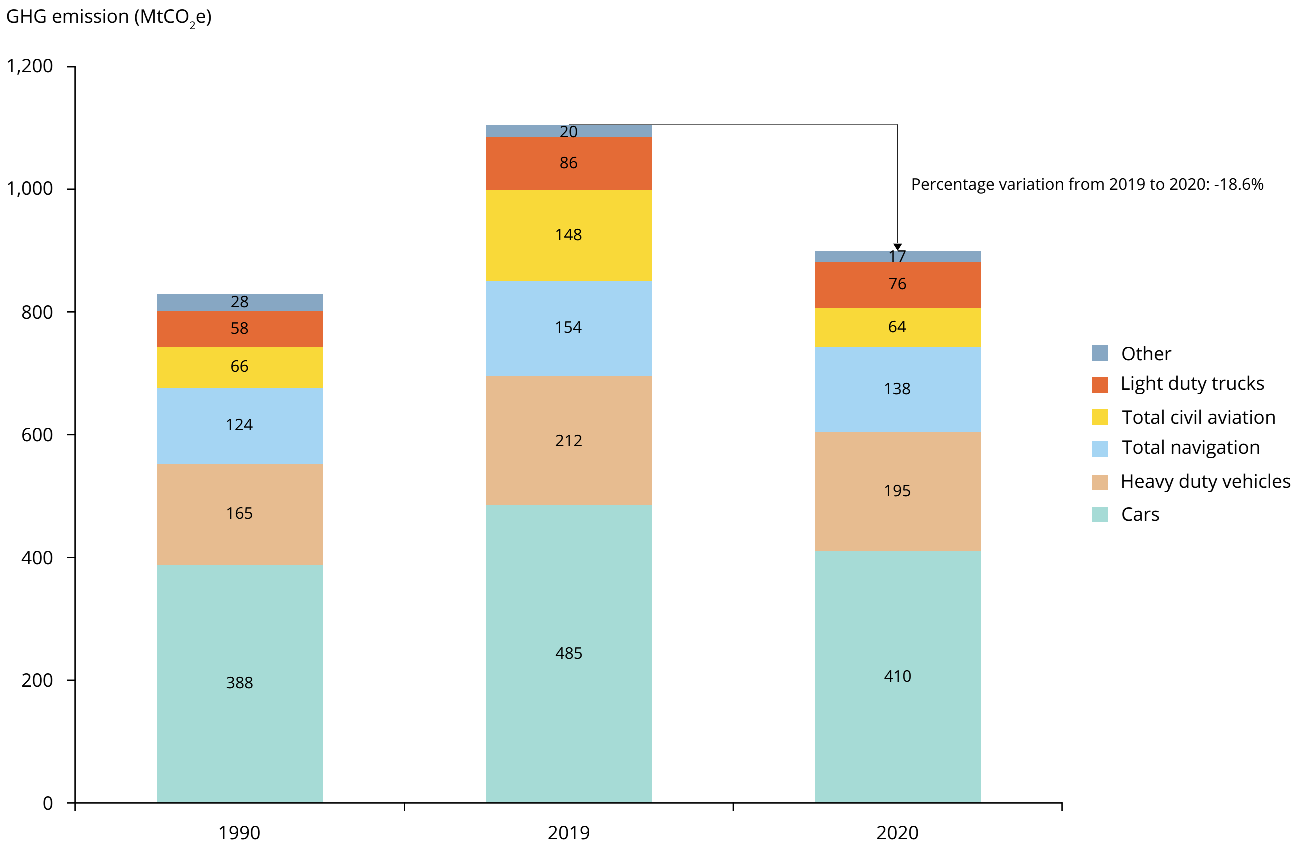
Source: EEA (2021a).

Within the whole sector (including airplanes and vessels), car transport accounted for 43.9% of GHG emissions in 2019. Other important modes are heavy-duty vehicles, navigation, civil aviation and light-duty trucks, with shares reported in Figure 2.12. Over time, the share of cars, heavy-duty vehicles and navigation has decreased, while that of light-duty trucks and civil aviation has increased (Figure 2.12).

The TERM 2021 report included a decomposition analysis of the GHG emissions of passenger cars and heavy-duty trucks, which showed that the main driver of the increase in emissions between 2000 and 2019 of these two vehicle types was the increase in transport activity, strengthened by an increase in their dominance in passenger and freight transport, respectively (EEA, 2022a).

In 2020, the CO_2e (CO_2 equivalent) emissions from transport were 18.6% lower than in 2019. The largest reduction was observed for aviation (56.8%). The GHG emissions from car transport fell by 15.4%. For the other modes the reductions were as follows: 12% for light-duty trucks, 10.8% for navigation, 7.7% for heavy-duty trucks and 15.2% for the other modes.

Figure 2.12 Greenhouse gas emissions from transport (million tonnes CO_2e and shares of modes in transport emissions) in 1990, 2019 and 2020



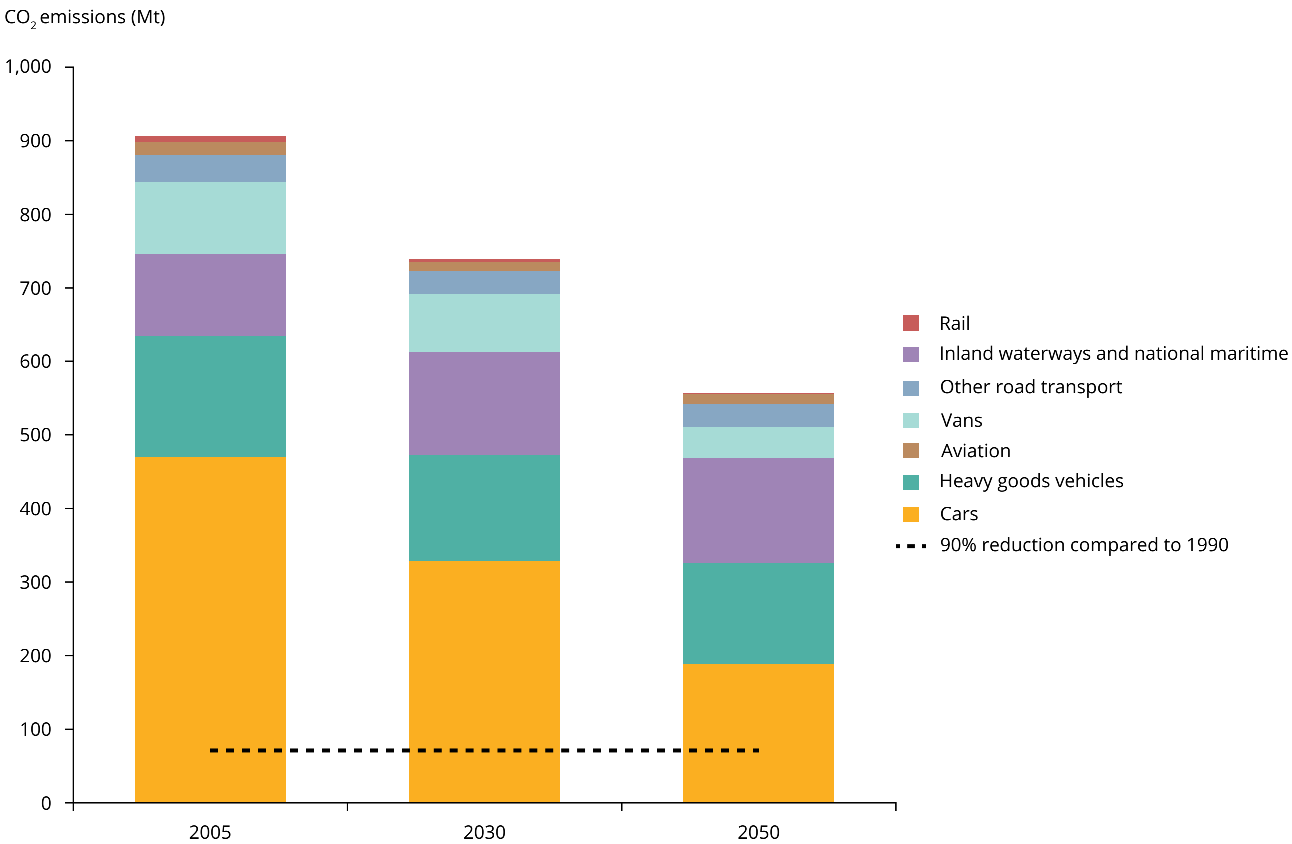
Note: Transport emissions including international aviation and maritime bunkers.

Source: EEA (2021a).

According to the *Special Eurobarometer* 501 survey, conducted in December 2019, about three quarters of Europeans (76%) indicated that climate change is a very serious problem in the EU as a whole as well as in in their country (Kantar, 2020). The European Green Deal states that a 90% reduction in GHG emissions from transport with respect to 1990 will be needed by 2050 to achieve climate neutrality in the EU.

With existing policies and for an economic outlook before the Russian invasion of Ukraine and the more recent developments of the COVID-19 pandemic, the EU Reference Scenario 2020 projects that, compared to 1990, CO_2 emissions from transport will be 3.5% higher in 2030 and will decrease by 22% by 2050 compared to 1990 (Figure 2.13). The distance from these projections to the 2050 transport target, -90% compared to 1990, is large. While emissions from road transport are projected to fall over time, it will remain the most important sector in terms of its contribution. The emissions from aviation are also projected to grow (EC, 2021a). A potential approach to reducing these emissions by using digital technologies and data sharing in the sector is discussed in Factsheet 8 and Annex 8. The European Commission has proposed updated measures in the Fit for 55 package (EC, 2021b) and the REPowerEU plan (EC, 2022b) to further reduce GHG emissions, which are now going through the legislative process.

Figure 2.13 **CO_2 emissions from the transport sector (including international aviation but excluding international maritime) in the EU Reference Scenario 2020**



Note: Transport emissions including international aviation but excluding international maritime.

Source: EEA compilation based on EC (2021a).

2.5.2 Air pollution

The health of European residents suffers from air pollution, among other things. Exposure to air pollution can cause cardiovascular and respiratory diseases (including lung cancer). It may also lead to diabetes and neurological development problems in children. Some population groups are more vulnerable than others; for example, people of lower socio-economic status, elderly people, children and those with underlying conditions (EC, 2021c). In addition to the negative impacts of illness on the well-being of European residents, air pollution also leads to economic impacts, as, for example, the associated healthcare costs are high and working days are lost.

According to the 2019 Eurobarometer 501 survey, somewhat less than half of the respondents (46%) think that air pollution is the most serious environmental problem (Kantar 2020).

Table 2.2 shows that, in 2019, a large majority of the urban population in Europe was exposed to air pollution levels that exceeded the air quality guidelines put forward by the World Health Organization (WHO) in 2021. As the current EU limit values are less stringent than the WHO guidelines, a smaller part of the urban population is exposed to pollution above those limit values.

In 2019, the EEA (2022b) attributed 307,000 premature deaths to exposure to particulate matter with a diameter of less than 2.5µm ($PM_{2.5}$), 40,400 premature deaths to chronic exposure to nitrogen dioxide (NO_2) and 16,800 premature deaths to acute exposure to ozone (O_3). This corresponds to a total of 4.0 million years of life lost or on average 11.0 years per person who died prematurely.

For $PM_{2.5}$ the EEA estimates that, if the 2021 WHO guideline had been respected, the number of premature deaths could have been reduced by 58% (177,300 premature deaths).

According to the zero pollution action plan (EC, 2021d) the number of premature deaths due to exposure to fine particulate matter, estimated to be 456,000 in 2005, should be reduced by 55% by 2030, compared to 2005. In 2019, premature deaths linked to exposure to fine particulate matter fell by 33% in the EU-27 compared to 2005. If this trend is maintained in future years, it is expected that the EU will reach the zero pollution action plan's target (EEA, 2021b).

The EEA (2019b) indicates that the impacts of air pollution (and noise, which is discussed in the next section) are unevenly distributed across groups with different levels of vulnerability.

In the EU-27, transport (including both urban and non-urban transport) was the largest emitter of nitrogen oxides (NOx) in 2019, with a share of 46.6% (Figure 2.14). Transport also emits particulate matter with a diameter of less than 10µm (PM_{10}) and 2.5µm ($PM_{2.5}$), having both contributed 12% each to these pollutants in 2019. For these two, fuel combustion in the residential, commercial and institutional sector is the largest source of emissions. The impact of road transport emissions of NO_2 and PM on air quality, especially in urban areas, is high, because they take place close to the ground and the dilution effect is lower. Transport is also a large emitter of ultrafine particles, hardly accounted for in PM measurements because of their small mass. For this reason, particle number is also a relevant indicator, as discussed in Box 2.2. In urban areas the resulting air pollution levels also have greater impacts on health than in non-urban areas as the population density is higher (EEA, 2018). Figure 2.14 presents the emissions of air pollutants from transport. Apart from the emissions in national territories, which are defined below the figure, it also presents the emissions from aviation during the cruising phases and from international maritime navigation.

Table 2.2 Share of EU citizens in urban areas exposed to high levels of air pollution in 2019

	EU limit value ([a])	WHO guideline value ([a])	Share (%) of urban population exposed to levels above:	
			EU limit	WHO guideline
$PM_{2.5}$	25µg/m³	5µg/m³	4	97
PM_{10}	40µg/m³	15µg/m³	15	81
O_3	Long-term objective: 120µg/m³	100µg/m³	34	99
NO_2	40µg/m³	10µg/m³	4	94

Note: ([a]) Annual limit value, unless stated otherwise.

Source: EEA (2022b).

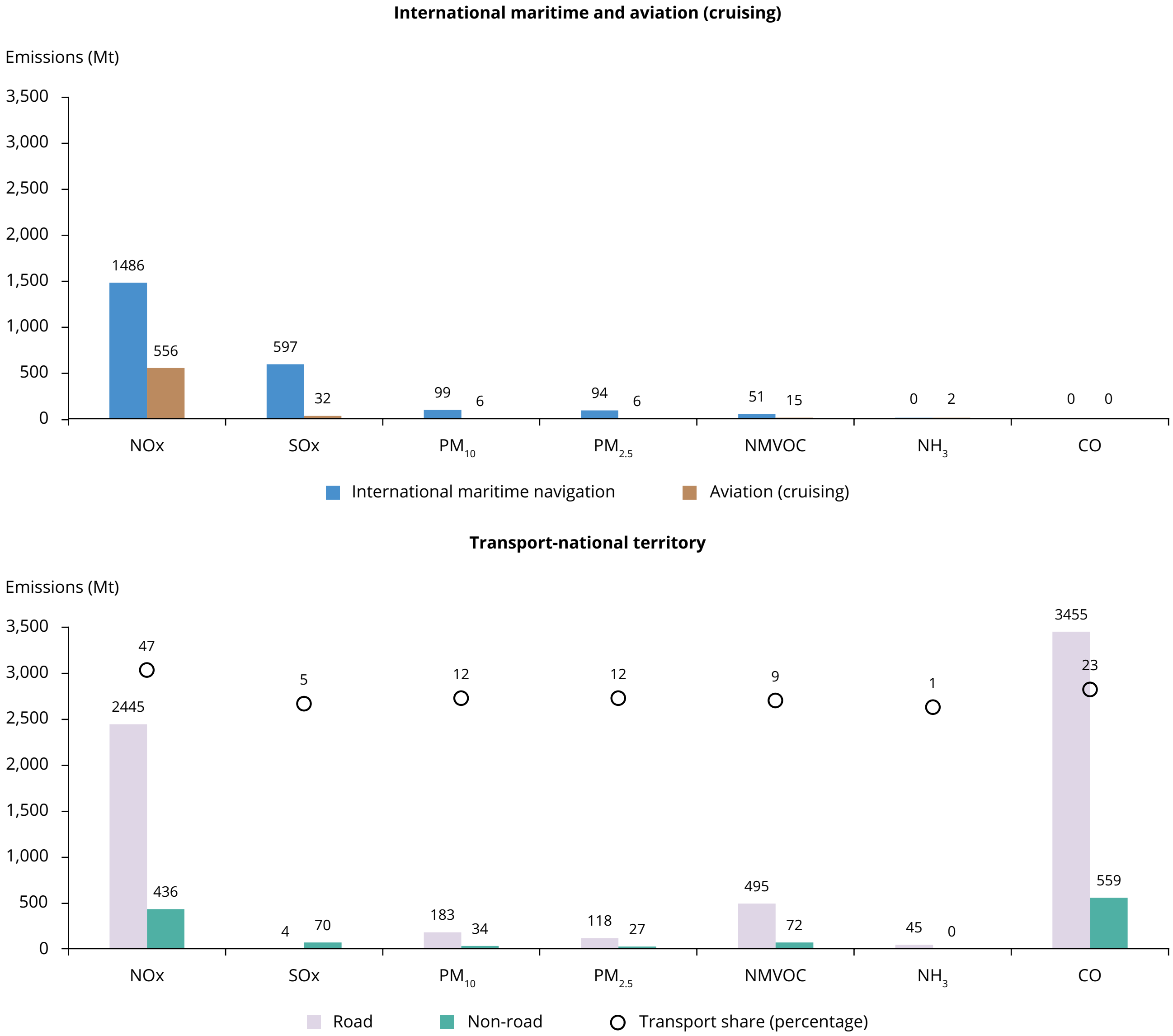
Box 2.2 Particulate matter and particle number

The transport sector is a significant source of airborne particulate matter (PM), a pollutant with significant impacts on air quality in cities and on human health. Both short- and long-term exposure to it correlate with an increased mortality rate. The share of the EU population exposed to levels that are above those indicated by World Health Organization guidelines is relevant, as shown in Table 2.2. Traditionally, PM emissions from vehicles were measured using a gravimetric method, consisting in weighting a filter that traps the particles contained in the exhaust gas passed through it. In recent years in Europe, PM emissions have decreased significantly, despite an increase in both passenger and freight transport volumes, as discussed above. This has been possible thanks to, among other things, the implementation of stricter emission standards (also known as Euro standards) and the concurrent development of after-treatment systems that include particulate filters. This dramatically reduced PM emissions from transport. In addition, a new method, much more sensitive than the gravimetric PM mass method, was introduced under EU regulation, making particulate filters de facto essential. The methodology was developed by the Particle Measurement Programme group (PMP) of the Working Party on Pollution and Energy (GRPE) of UNECE (United Nations Economic Commission for Europe) during the first decade of the 21st century. It was introduced into EU transport regulations for light-duty (2011), heavy-duty vehicles (2013) and non-road mobile machinery (2019). Currently vehicles circulating on roads must comply with a particle number limit for particles larger than 23 nanometres (nm) diameter. The lowering of this threshold to include smaller particles is under discussion (Giechaskiel, et al., 2021; Giechaskiel,, Melas, et al., 2022). Additional information on particulate filters and methods to ensure their proper functioning throughout their lifetime can be found in Annex 9.

Since 1990, significant progress has been made in the transport sector to reduce the emissions in national territories of many air pollutants. This has been possible thanks to various EU legal mechanisms that have been put in place to improve air quality (including that influenced by transport sources): limit or target values for ambient concentrations of pollutants, limits on total emissions (e.g. national totals) and the regulation of emissions from transport, either by setting emissions standards (such as Euro emissions standards for vehicles) or by setting requirements for fuel quality. Figure 2.15 shows the trends in emissions of several pollutants currently regulated and unregulated across the different transport modes. In the EU-27, emissions from all transport types have fallen since 2000, despite higher demand for transport (see Figures 2.1 and 2.6). By 2019, emissions of $PM_{2.5}$ had decreased by 47% compared to 2000 levels. Between 2000 and 2019, transport emissions of NOx decreased by 34%, those of sulphur oxides (SOx) by 53%, carbon monoxide (CO) by 74% and non-methane volatile organic compounds (NMVOCs) by 77%. Similarly, methane (CH_4) transport related emissions were reduced by 58% and ammonia (NH_3) ones by 53%. Interestingly, nitrous oxide (N_2O) emissions in 2020 were only 18% lower than those in 2000 and only 3% lower if the variation with respect to 2019 is considered instead.

The impact of the COVID-19 pandemic in 2020 can clearly be seen in Figure 2.15.

Figure 2.14 Emissions of air pollutants by transport in the EU-27 in 2019 (million tonnes)



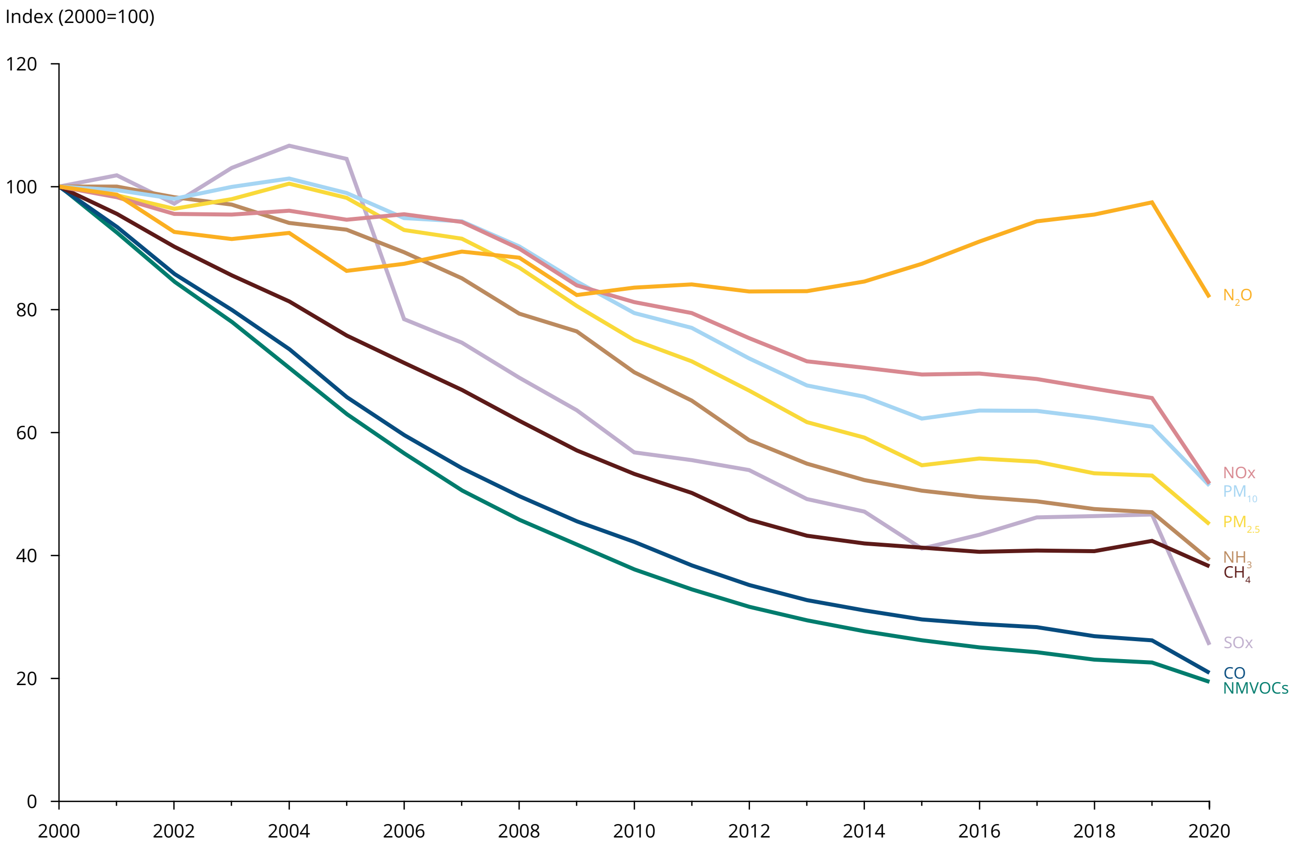
Notes: Transport share is the share of national territory emissions from transport in total national territory emissions.

Transport-national territory is the emissions from transport by road, rail, pipelines, international inland waterways and national navigation, the landing and take-off emissions of domestic and international aviation, and other transport in the national territory.

CO, carbon monoxide; NH_3, ammonia; NMVOC, non-methane volatile organic compounds; NOx, nitrogen oxides; SOx, sulphur oxides.

Source: EEA compilation based on EEA (2021c) and EEA data reported by Eurostat (2021a).

Figure 2.15 Trends in emissions of air pollutants from transport



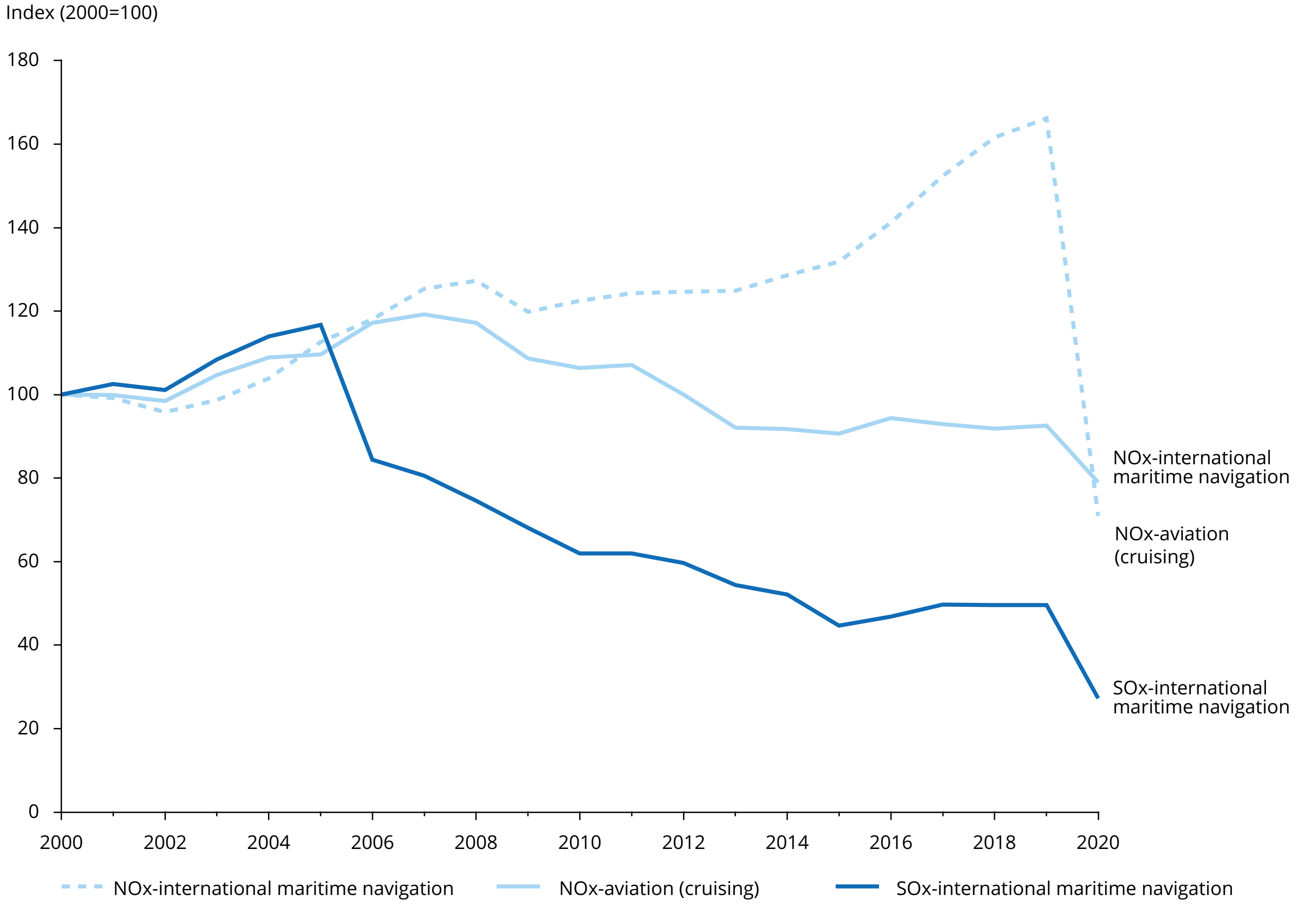
Note: National territory transport emissions. They include emissions from transport on road, rail, pipelines, international shipping and inland waterways, the landing and take-off emissions of domestic and international aviation, and other transport.

Source: EEA (2021c).

Despite this overall decreasing trend, for some transport modes and pollutants the trend is different. For example, the cruising emissions of NOx from aviation show a strong increasing trend between 1990 and 2019. (Figure 2.16). EASA et al. (2019) indicate that since 2005 NOx emissions have grown more slowly than air passenger-km but faster than the number of flights. These emissions have an impact on the local composition of the atmosphere, modifying the amounts of greenhouse gases, ozone and methane. This can result in either warming or cooling effects. For maritime navigation, the NOx and SOx emissions increased initially after 1990 and then fell, with a more pronounced reduction in the SOx emissions before they stabilised in the most recent years up to 2019. The emissions of air pollutants from the maritime sector will be an important aspect to consider in the effort to shift some freight transport away from road. This will also be discussed in Factsheets 3 and 5 on autonomous ships and smart logistics.

In Figure 2.16 it can be seen that in 2020, the impact of the COVID-19 pandemic on emissions was much larger for aviation than for international maritime navigation.

Figure 2.16 **Trends in emissions of the main air pollutants from international maritime navigation and aviation (cruising)**



Source: EEA compilation based on EEA data reported by Eurostat (2021a).

2.5.3 Noise pollution

Living in an area affected by transport noise is associated with poorer health, well-being and quality of life. Long-term exposure to noise from transport sources can lead to annoyance, stress reactions and sleep disturbance and cognitive impairment in children, and can have negative effects on the cardiovascular and metabolic systems (WHO Europe, 2018; EEA, 2019c).

Reducing environmental noise was a key objective under the Seventh Environment Action Programme (EAP) (EU, 2013) and the Environmental Noise Directive (END) (EU, 2002). More recently, the European Commission's zero pollution action plan (EC, 2021d) aims to reduce, by 2030, the number of people chronically disturbed by noise from transport in the EU by 30%, compared to 2017. This ambition will continue to be pursued in the 8th EAP. Box 2.3 below summarises the most common noise indicators and definitions used in the following.

Box 2.3 Noise indicators and definitions used

- dB: decibel
- L_{den} (day-evening-night noise level): the long-term average indicator designed to assess annoyance and defined in the Environmental Noise Directive (END). It refers to an A-weighted average sound pressure level over all days, evenings and nights in a year, with an evening weighting of 5dB and a night weighting of 10dB.
- L_{night} (night noise level): the long-term average indicator defined in the END and designed to assess sleep disturbance. It refers to an A-weighted annual average night period of exposure.
- A-weighted decibel (dBA): decibels with the sound pressure scale adjusted to conform with the frequency at which the human ear responds.

Road traffic is the most significant source of noise pollution both inside and outside urban areas. Railways and aircraft also lead to noise problems at specific locations. The most recent figures are for 2017 (EEA, 2021d) (Figure 2.17):

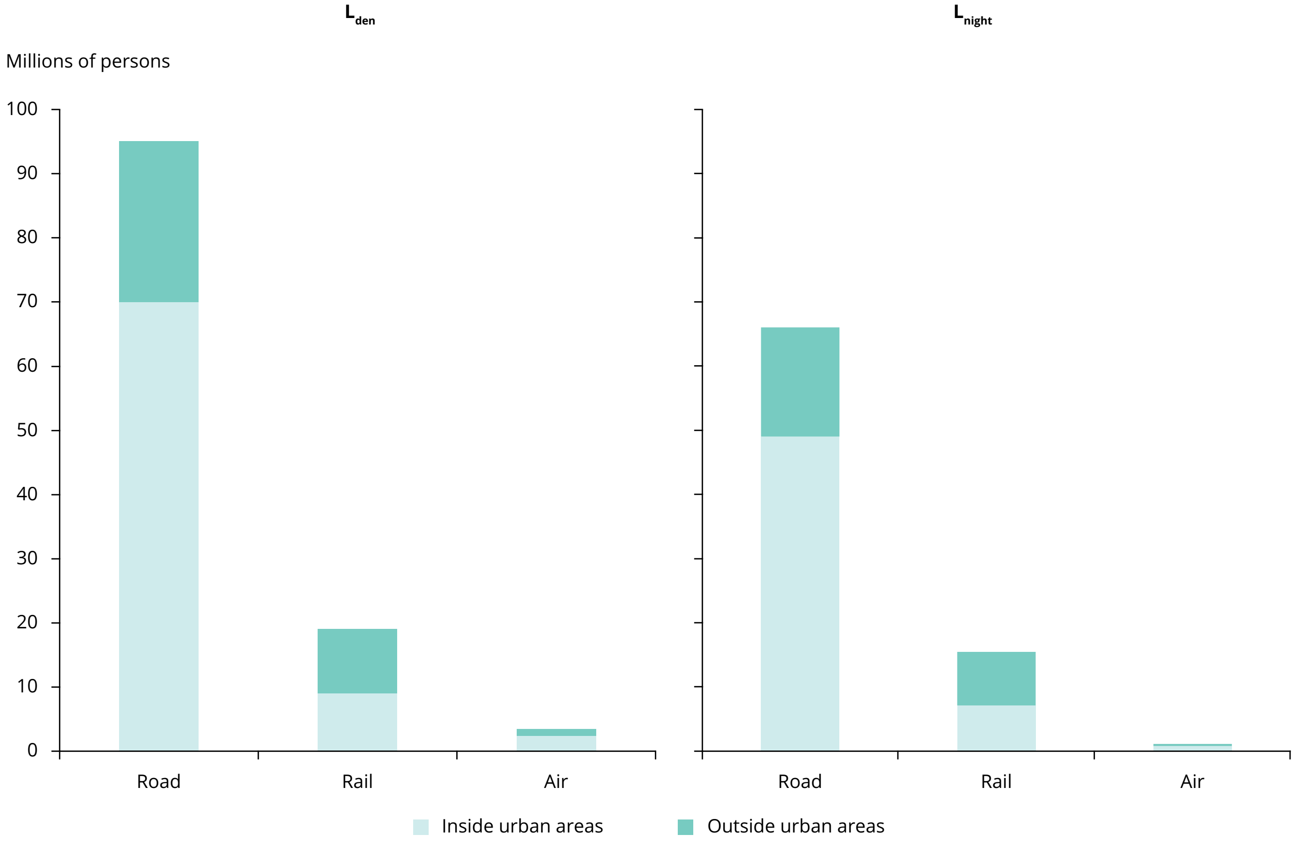
- More than 95 million people in the EU-27 or 21.3% of the population were exposed to day-evening-night level (L_{den}) noise levels of at least 55dB from road traffic. About 70 million of these people lived in urban areas.
- In the case of railway and aircraft noise, 19 million and 3.4 million people, respectively, were exposed to L_{den} ≥55dB. While the majority of people affected lived in urban areas, the impacts were spread more equally inside and outside urban areas than those of road noise.
- Road traffic was the most important source of noise during the night. More than 65 million people (about 15% of the population) in the EU-27 were exposed to night-time noise levels of at least 50dB from road transport, 15.5 million (3.5%) from railways and about 1.1 million (0.2%) from aircraft.

It is estimated that there are 10,600 premature deaths and 39,800 new cases of ischaemic heart disease per year due to long-term exposure to environmental noise from transport in the EU-27. High levels of annoyance are estimated to affect 18.4 million people, while 5.5 million people are estimated to experience high levels of sleep disturbance (EEA, 2022c).

The EEA (2020a) points out that these negative impacts are likely to be underestimated, as the END's reporting thresholds of 55dB L_{den} and 50dB L_{night} are higher than the levels at which noise causes adverse effects. For example, WHO recommends a threshold of 53dB during the day-evening-night period for road traffic noise pollution levels and 45dB during the night. Moreover, the spatial coverage of the reporting of strategic noise maps under the END is not complete.

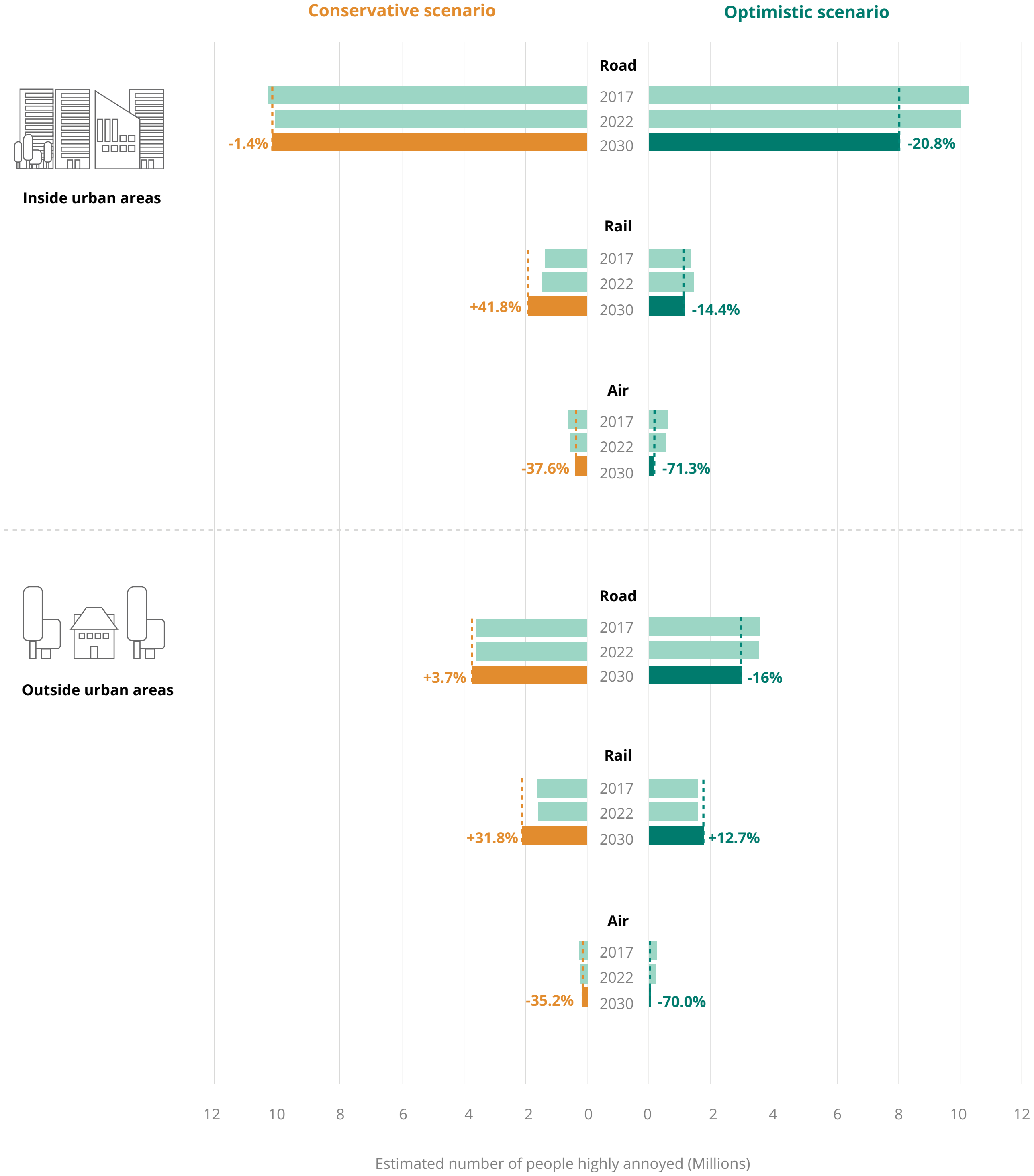
The EEA (2021d) concludes that the number of people exposed to high levels of noise has not decreased over the past decade, and millions of people remain exposed to noise levels harmful to health. Therefore, the 7th EAP objective of significantly reducing noise pollution in the EU and moving closer to the WHO recommended levels by 2020 was not achieved. For 2030, the 8th EAP adopts the objectives of the zero pollution action plan (EC, 2021d). For noise pollution, this means that by 2030 the share of people chronically disturbed by transport noise should be reduced by 30% compared to 2017. The EEA (2022d) projects that these targets are unlikely to be met (Figure 2.18). Under an optimistic scenario in which several ambitious measures are taken, the number of people chronically disturbed by transport noise is reduced by only 19%. Under a conservative scenario with less ambitious measures, there would even be an increase of 3%. In the latter scenario, the benefits of the measures taken would be overcome by the projected growth in population and transport.

Figure 2.17 Estimated number of people exposed to unhealthy noise levels from transport (L_{den} ≥55dB and L_{night} ≥50dB) in the EU-27 in 2017



Source: EEA (2021d).

Figure 2.18 **Estimated number of people in the EU-27 highly annoyed by noise from road, rail and aircraft for the period 2017-2030 under conservative and optimistic scenarios**



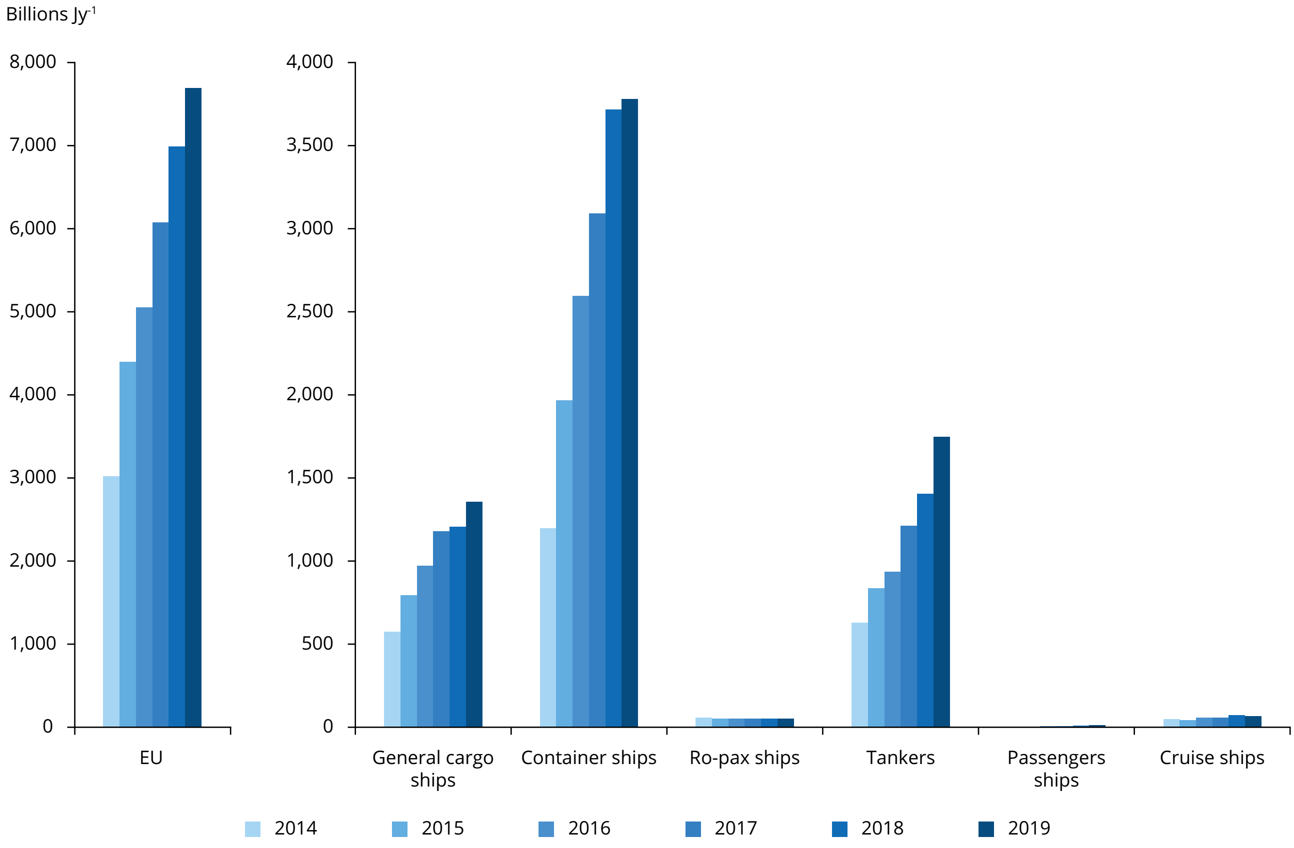
Source: EEA (2022d).

2.5.4 Impacts on ecosystems and biodiversity

Transport can have significant negative impacts on ecosystems and biodiversity in different ways, including altering the quality and connectivity of habitats and creating physical barriers to the movement of animals between habitat areas or the growth of plants.

Terrestrial noise has an impact on wildlife, as animals are stressed by noisy environments. A literature survey by Shannon et al. (2016) found that terrestrial wildlife responses start at noise levels of about 40dBA. 20% of the papers in their survey found impacts below 50dBA. In marine environments, scientific evidence links underwater noise from shipping to harmful effects on marine mammals, sea turtles, fish and invertebrates. A modelling study for the EU indicates that the level of underwater noise from shipping increased between 2014 and 2019, with the largest contributions from container ships, followed by tankers and general cargo ships (Figure 2.19). However, further research is needed to correctly assess the magnitude of the problem and its impacts on the marine fauna (EMSA and EEA, 2021).

Figure 2.19 Underwater noise energy (J) at 125Hz one-third octave band centre frequency in the EU (left) and by type of ship (right), 2014-2019



Source: STEAM (2021), as reported in EMSA and EEA (2021).

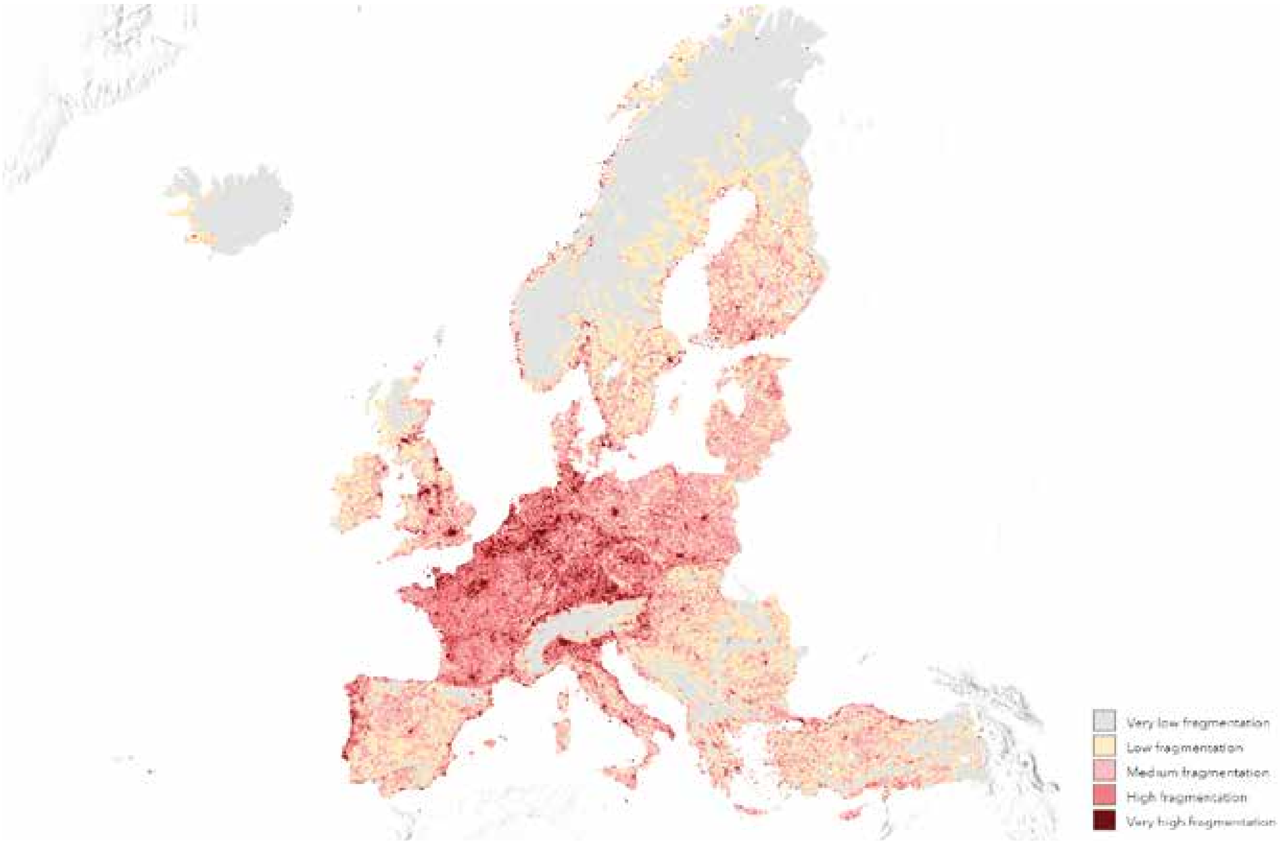
Air pollution, including that caused by transport, affects ecosystems via eutrophication, acidification and excess ozone flux. While NOx emissions from transport have fallen in recent years, as shown in the previous section, the levels of nitrogen deposits are still above critical loads and a threat to biodiversity, particularly in Natura 2000 areas. Further improvement is projected in the future, but the share of Nature 2000 areas affected by eutrophication will remain significant (EC, 2021c).

Water pollution is caused by different sources and types of ship operations, including the use of antifouling biocides on hulls, ship-generated waste, and accidents of varying magnitudes (e.g. lost containers, oil spills). Moreover, air pollution can also cause damage to the marine environment via atmospheric deposition of pollutants, which leads to the contamination and eutrophication of the marine environment (EMSA et al., 2021).

Species can become isolated by habitat fragmentation. This can be defined as the transformation of large habitat patches into smaller, more isolated pieces. This process is most evident in urbanised or otherwise intensively used regions, where fragmentation is the product of linking built-up areas via linear infrastructures, such as roads and railroads (e.g. Saunders et al., 1991; Forman, 1995). Fragmentation of landscapes reduces the connectivity of the remaining ecological network. The latest data on habitat fragmentation in the EU are for 2015. In that year, the number of fragmented landscape elements was about 1.5 per km^2, a 3.7% increase compared to 2009 (EU excluding Romania). Approximately 28% of the area of the EU (excluding Romania), was strongly fragmented, a 0.7% increase compared to 2009. Luxembourg (91%), Belgium (83%) and Malta (70%) were the countries with the highest shares of strongly fragmented landscapes in 2015. In the EU, the lowest shares were recorded in the Baltic countries, Finland and Sweden (Map 2.1) (EEA, 2021e).

The development and use of transport infrastructure can also increase pollution in surrounding habitats and can lead to the spread of non-native and invasive species.

Map 2.1 **Effective mesh density — fragmentation status — in the EEA-38 + UK in 2015**



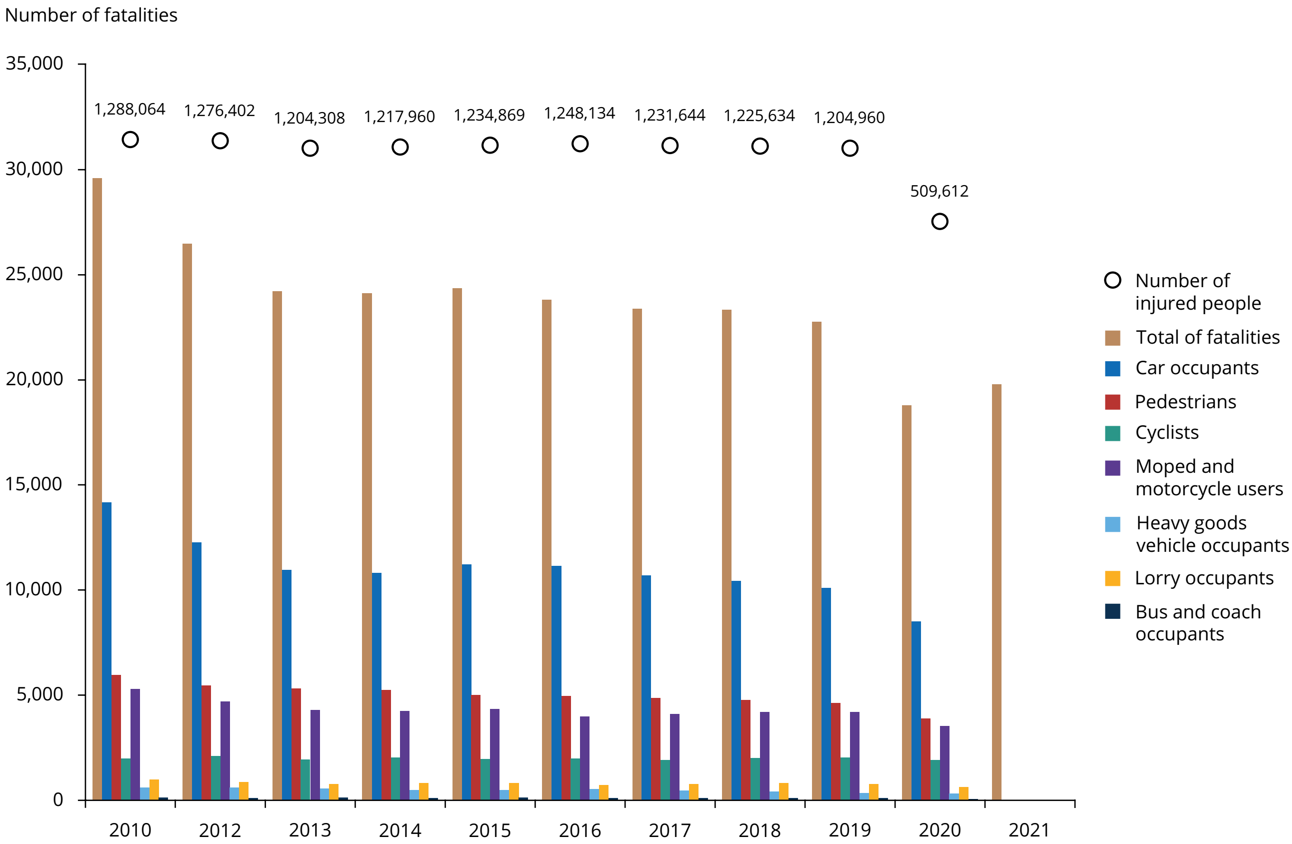
Note: Effective mesh density is a measure of the degree to which movement between different parts of the landscape is interrupted by fragmentation geometry (FG), defined as the presence of impervious surfaces and traffic infrastructure, including medium-sized roads. The more FG affects the landscape, the higher the effective mesh density and the greater the degree of fragmentation.

Source: EEA (2021f).

2.6 Other external costs of transport

Apart from the environmental costs, transport also causes other external costs. The European Commission (EC, 2019a) estimates that the total external costs of transport were EUR 987 billion in 2016. Accident costs account for 28.6% of these costs and road congestion for 27.4%. Road transport accounts for most of the accident costs. Over time, the number of fatalities resulting from road transport shows a decreasing trend, which became flatter between 2013 and 2019 (Figure 2.20). In 2020, the number of fatalities was lower because of the COVID-19 measures that were in place. In 2021, these measures were gradually wound down. The number of fatalities arising from road transport was estimated to be 19,800 in 2021. The EU has set the objective of achieving a 50% reduction in road fatalities between 2010 and 2030, with the long-term goal of reducing road fatalities to zero by 2050 ('Vision Zero'). It also has the aim of halving the number of serious injuries by 2030 compared to 2020 (EC, 2020a).

Figure 2.20 Number of fatalities and people injured in road traffic accidents (total and by mode of transport) in the EU, 2010-2020



Note: Data for 2011 were not available.

Source: EEA compilation based on EC (2021e, 2022c).


100% electric

3
Digitalisation and transport

Key messages

- **A digital transformation of our economy and society is taking place. The range of digital technologies applied to transport is broad and the pace at which they evolve differs. Some of them, such as the internet and communication technologies enabling teleworking, are already widely applied. Others, such as machine learning and artificial intelligence applied to connected and autonomous vehicles, are just taking off but are expected to have considerable impact in the future.**
- **Various elements in the transport system can be affected by digitalisation: the demand and supply of transport services (including new business models), the efficiency of use of the existing transport infrastructure's capacity, the environmental performance of vehicles and the amount and sources of energy used for transport. Moreover, digitalisation can support the development of better transport policies, considerably influencing the environmental impacts of transport.**
- **The environmental effects of digitalisation in transport depend on both the direct effects and the higher order or indirect effects. The latter include different types of so-called rebound effects, which are not always easy to quantify. Nevertheless it is important to take them into account. Failure to do so may lead to inappropriate policy or misallocation of monetary incentives.**

3.1 Digital transformation: an introduction

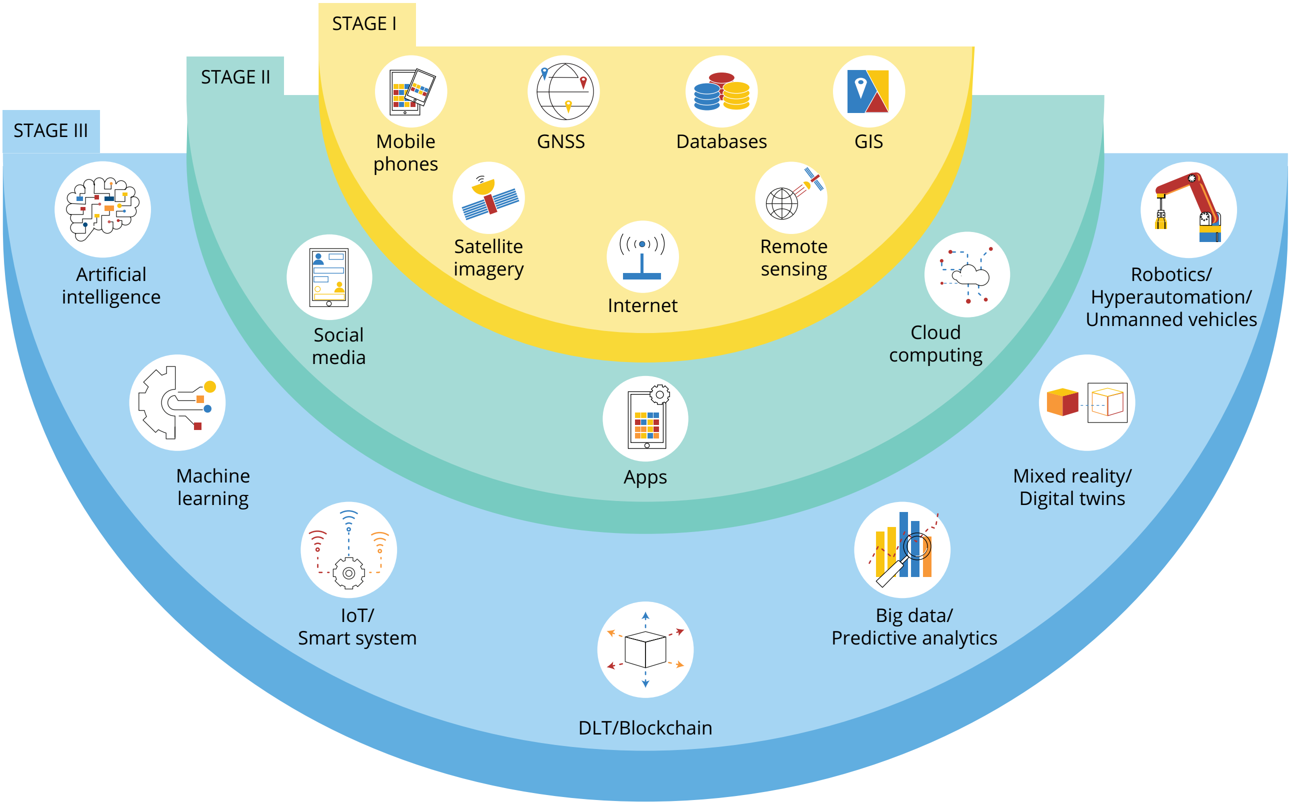
Digital transformation refers to 'the profound changes that are taking place in the economy and society as a result of the uptake and integration of digital technologies in every aspect of human life' (Desruelle et al., 2019). Digital technologies already have important benefits and could provide even more in the future. They contribute to economic growth, expand opportunities and enable improvements in services. Digitalisation is at the core of the European Commission agenda with its 'Europe fit for the digital age strategy'. This will be delivered through a series of initiatives specifically detailed in Chapter 4 and including the EU Digital Compass launched in 2021 (EC, 2021f) and more broadly the second digital agenda.

The range of digital technologies is wide and, generally speaking, includes devices, systems and resources that generate, store or process data and information. Information technology (IT) and information and communications technology (ICT) are two examples of these. The first term refers to computing technologies including hardware, software and the internet (TechTerms, 2010b). The second term refers to technologies that provide access to information through telecommunications, with a focus on communications (TechTerms, 2010a). Typically, it includes the internet, mobile phones and wireless networks.

Based on a literature review, a recent publication of the Asian Development Bank (2021) categorises digital technologies for climate change mitigation, climate change adaptation and disaster risk management into three stages of development and deployment to the market (Figure 3.1). These technologies can be seen as building blocks necessary for bringing to life all the transport technologies that will be discussed later in the report. Technologies in stage I are currently already used to a large extent and are part of everyday life. Stage II includes technologies that are available and for which widespread use is taking off. However, their potential for the above-mentioned purposes has not yet been fully tapped. For example, in the case of cloud computing, the Asian Development Bank points out that barriers, more particularly lack of trust due to cybersecurity risks, still prevent its use on a very large scale. Finally, stage III contains innovations that still must need to through commercially but are expected to have a large impact in the future.

Box 3.1 contains a glossary of a selection of stages II and III technologies. The Asian Development Bank (2021) and Vivid Economics (2021) give an introduction to the individual technologies represented in Figure 3.1. Chapter 5 and Annexes 1-9 of this TERM report will explore a selection of digital tools relevant to transport that make use of a combination of these technologies.

Figure 3.1 Digital technologies in mobility



Note: DLT, distributed ledger technology; GIS, geographical information system; GNSS, global navigation satellite system; IoT, internet of things.

Source: Asian Development Bank (2021).

The Digital Economy and Society Index (DESI) (EC, 2021g) monitors Europe's overall digital performance (Figure 3.2) and tracks the progress of EU countries in their digital competitiveness. The index is numerical, can assume values between 0 and 100 and is structured around four cardinal points of the Digital Compass (EC, 2021f). The first point, 'human capital', refers to internet users' skills and advanced digital skills. 'Connectivity', the second point, covers fixed broadband uptake, fixed broadband coverage, mobile broadband and broadband prices. The third point is 'integration of digital technology' and refers to the extent of business digitalisation and e-commerce. The fourth point is the level of e-government or 'digital public services'. In 2022, the average score for the EU was 52.3. In the same year, seven countries had a score of at least 60 out of 100: Finland, Denmark, the Netherlands, Sweden, Ireland, Malta and Spain. Romania, Bulgaria and Greece had a score below 40 (Figure 3.2). The countries whose score increased the most in absolute terms between 2017 and 2022 are Denmark followed by the Netherlands, Finland, Ireland and Italy (Figure 3.3). The countries that increased their score most in relative terms are indicated by the boxes with a red border. For the EU-27 as a whole, the DESI increased by 55%, from 33.7 to 52.3, between 2017 and 2022. Digital literacy will be a fundamental precondition to accessing the services offered by many of the technologies discussed in this report such as multimodal digital mobility services, explored in Factsheet 4, or teleworking, discussed in Factsheet 1.

Box 3.1 Glossary

Artificial intelligence (AI): 'systems that display intelligent behaviour by analysing their environment and taking actions — with some degree of autonomy — to achieve specific goals' (EC, 2018a).

Big data: 'large amounts of data produced very quickly by a high number of diverse sources. Data can either be created by people or generated by machines, such as sensors gathering climate information, satellite imagery, digital pictures and videos, purchase transaction records, GPS (global positioning system) signals, and more. It covers many sectors ...' (EC, 2022d).

Blockchain: 'a shared, immutable ledger that facilitates the process of recording transactions and tracking assets in a business network. An asset can be tangible (a house, car, cash, land) or intangible (intellectual property, patents, copyrights, branding).' (IBM, 2019). Blockchain technology is an example of distributed ledger technology. It 'allows people and organisations who may not know or trust each other to collectively agree on and permanently record information without a third-party authority' (EC, 2022e).

Cloud computing: 'enables ubiquitous access to shared pools of configurable system resources and higher-level IT services that can be dynamically provisioned with minimal management effort, usually over the Internet. Cloud computing relies on the sharing of resources to achieve coherence and economies of scale, similar to a public utility. The key characteristics of cloud computing are that IT resources are provided on-demand in an 'elastic' way (i.e. they scale up or down dynamically to meet fluctuating demand), the service is metered (you only pay for what you actually consume) and services are requested through a 'self-service' online control panel.' (Cloud Strategy of the European Commission (EC, 2019b)).

Digital twins: 'digital representations of real-world entities or processes. Digital twins use real-time and historical data to represent the past and present, and create models to simulate future scenarios' (EC, 2022f).

Distributed ledger technologies: 'a class of technologies which support the distributed recording of encrypted data' (EU, 2022e).

Geographical information system (GIS): 'an information system designed to capture, store, manipulate, analyse, manage, and present all types of geo-referenced data. Geo-referenced means that data are associated to their geographical location.' (Eurostat 2018).

Global navigation satellite system (GNSS): 'a constellation of satellites providing signals from space that transmit positioning and timing data to GNSS receivers. The receivers then use this data to determine location.' (EU Space Agency, 2016) .

Hyperautomation, also known as 'robotic process automation': 'a computer software or a 'robot' that can emulate and integrate humans' actions to capture data and execute a digital system process ... these software robots can mimic many repetitive activities performed by human users' (Futurium, 2020).

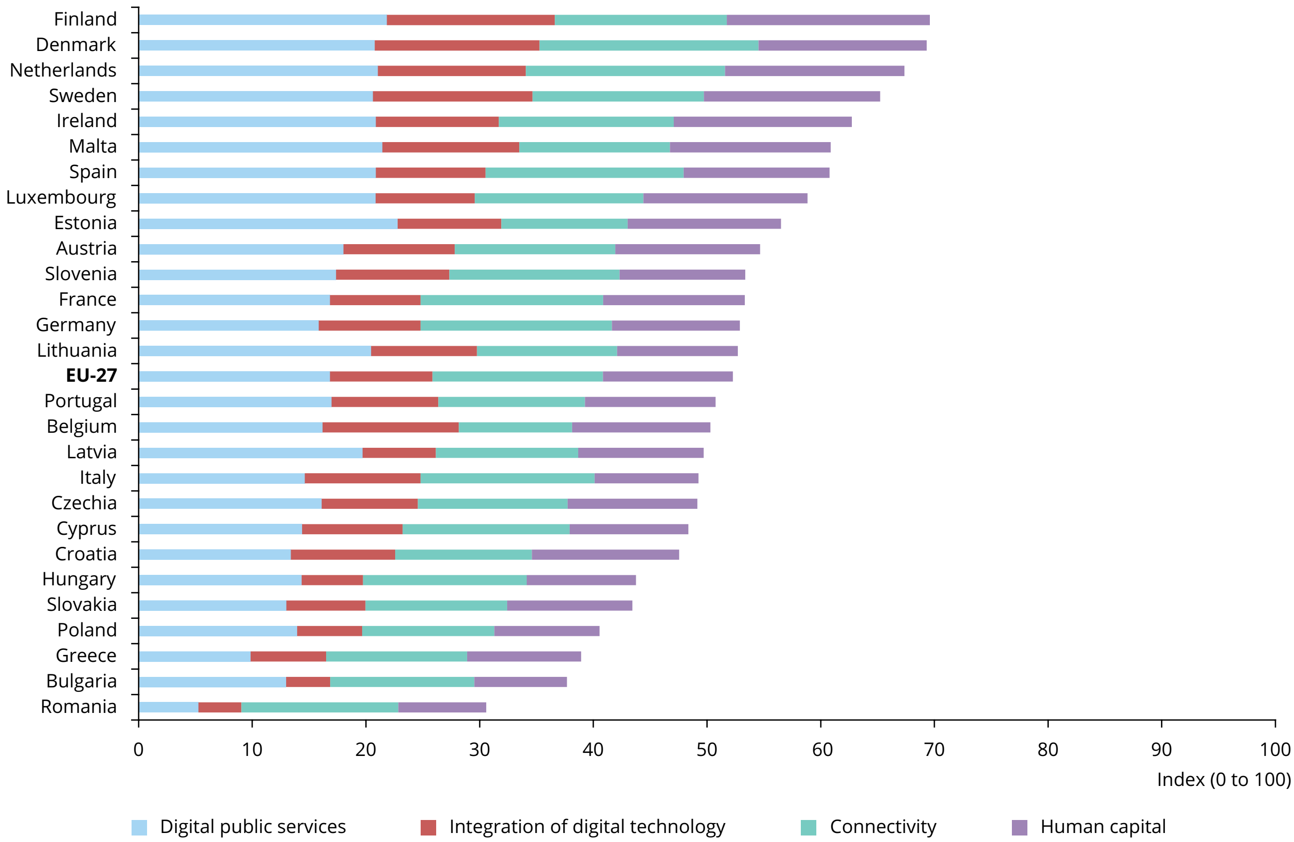
Internet of things (IoT)/smart system: 'a network of dedicated physical objects (things) that contain embedded technology to sense or interact with their internal state or external environment'. It 'comprises an ecosystem that includes things, communications, applications and data analysis' (JoinUp, undated).

Machine learning: 'a type of AI, works by identifying patterns in available data and then applying the knowledge to new data' (EC, 2018a).

Mixed reality (MR): 'produces new environments and visualisations where physical and digital objects co-exist and interact in real time' (Datta, 2019).

Predictive analytics: 'the use of data, statistical algorithms and machine learning techniques to identify the likelihood of future outcomes based on historical data' (SAS, 2022).

Figure 3.2 **Digital Economy and Society Index in the EU-27 in 2022**

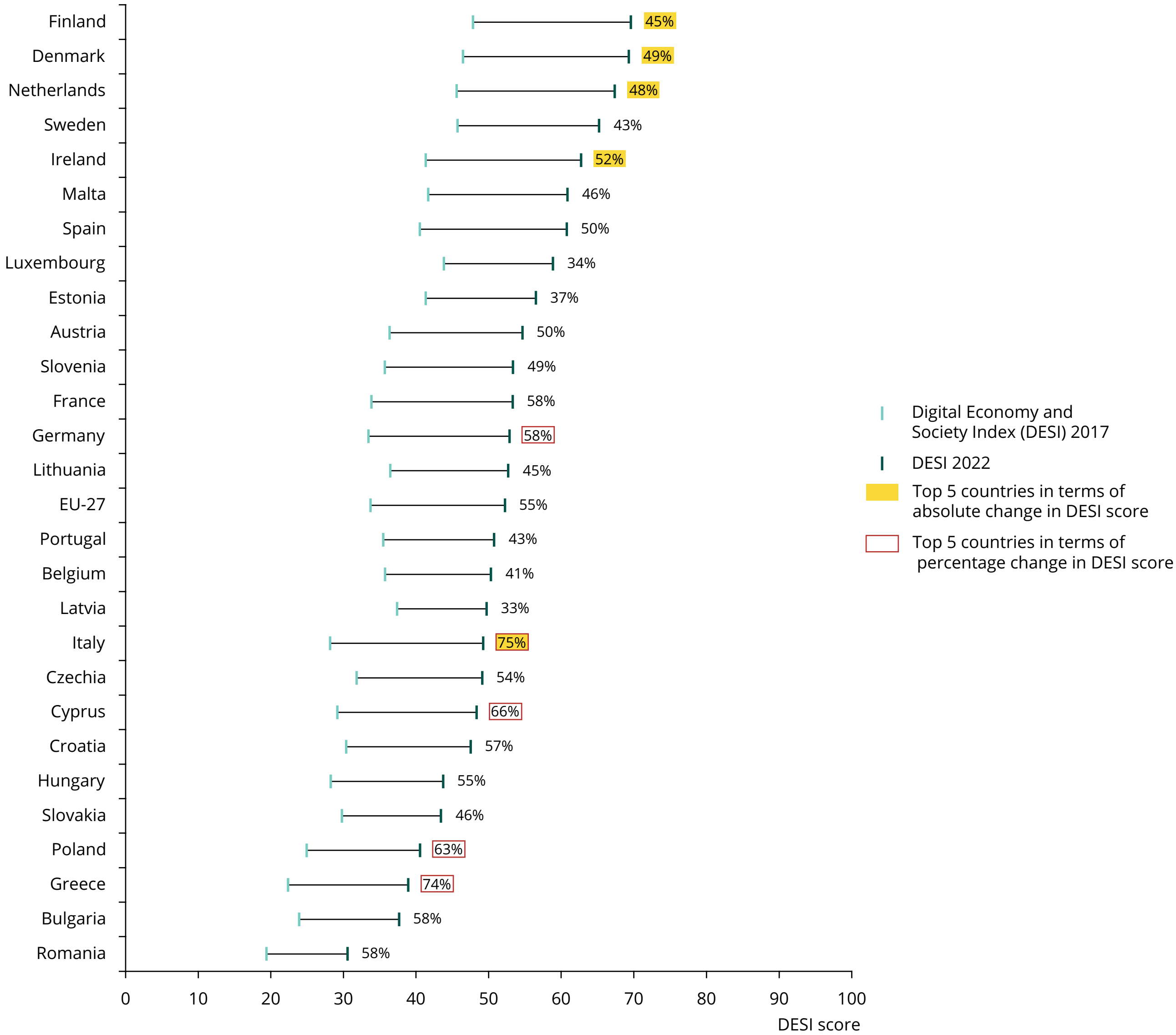


Source: EC (2022g).

The adoption of digital technologies is reported to be generally higher in larger enterprises than in small and medium-sized enterprises (SMEs). In 2021, 14.2% of all enterprises ([5]) said that they used big data, and 34% reported using cloud computing. E-commerce was reported to account for almost 12% of SME turnover (excluding financial sector). Only 7.9% of enterprises reported adopting artificial intelligence (AI) technologies (e.g. for text mining, data analysis or image recognition), with the largest uptake in large enterprises. The transport sector reported lower levels of AI adoption than some other sectors. A large share of enterprises (66%) said that they used ICT for environmental sustainability, with facilitation of teleworking and reduction of business travel being the two main purposes (Figure 3.4). This was based on a survey carried out in 2021, after the start of the COVID-19 pandemic.

([5]) Enterprises employing 10 or more people. All manufacturing and service sectors, excluding the financial sector.

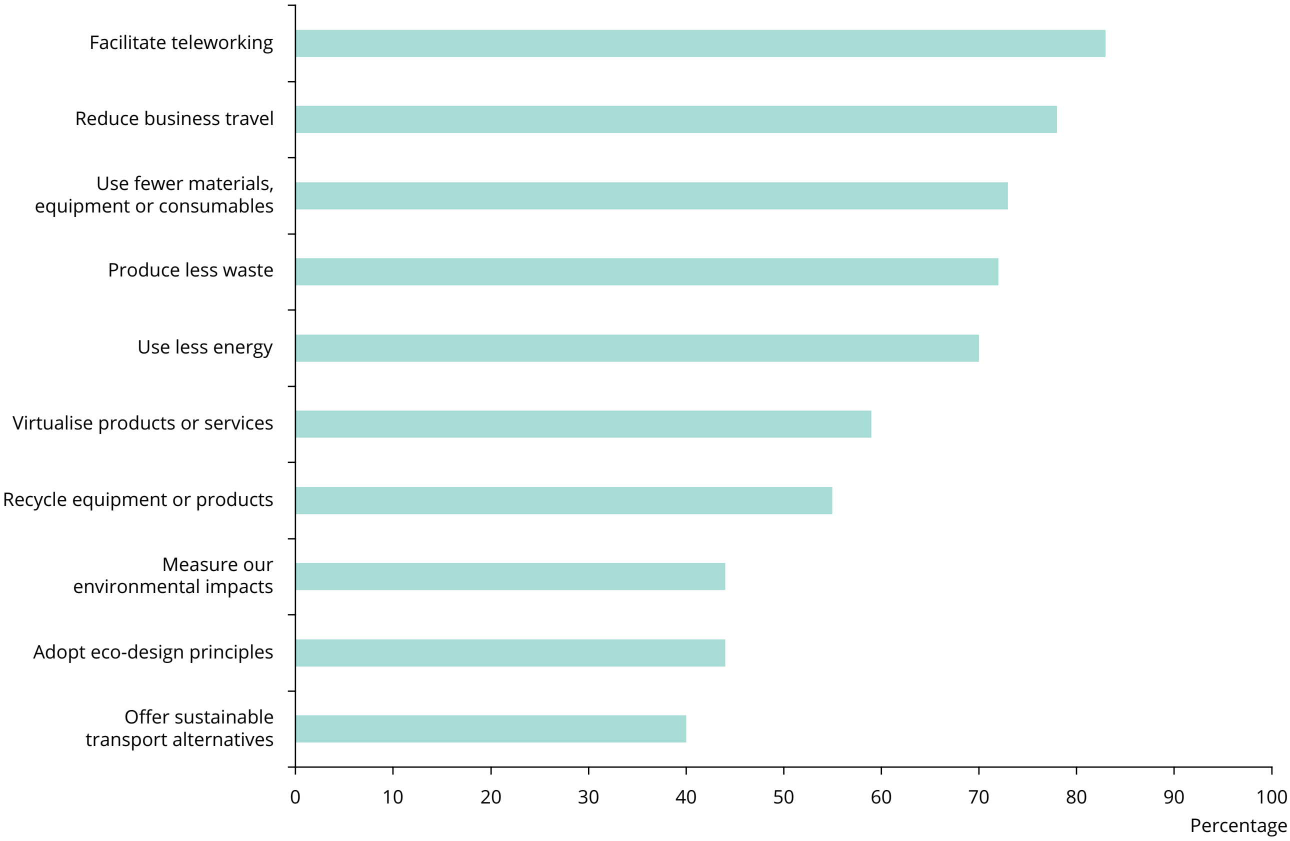
Figure 3.3 **Digital Economy and Society Index scores in 2017 and 2022 and percentage change, EU-27**



Note: Percentage change refers to the change in scores between 2017 and 2022.

Source: EC (2021g).

Figure 3.4 Reported use of ICT for environmental sustainability, 2021



Source: EC (2021g), based on IPSOS and iCite (2021).

3.2 The relevance of digitalisation for transport

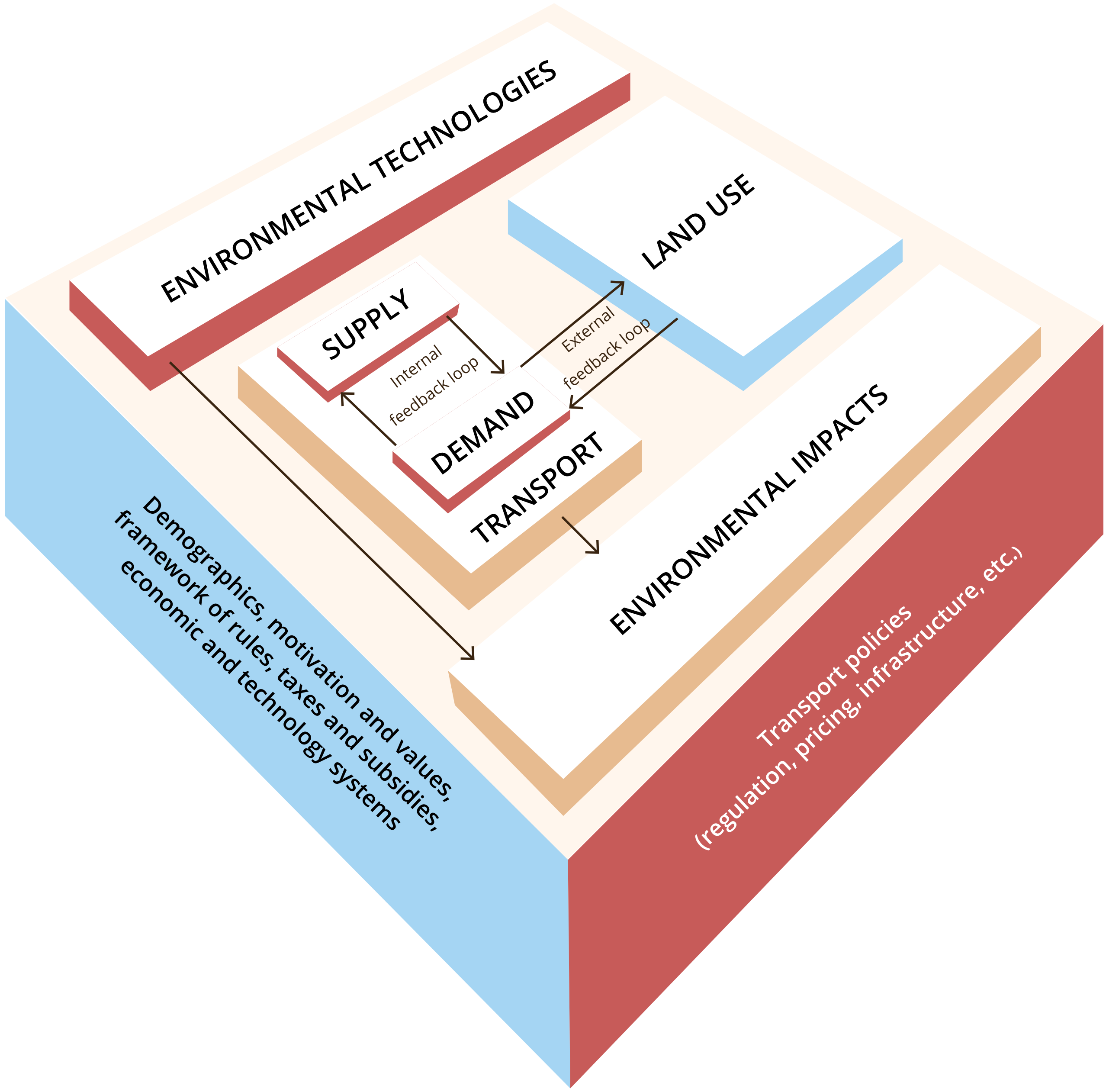
The traditional concepts of mobility are being transformed by digital technologies, combined with connectivity and digital platforms.

To understand what digital technologies could mean for transport, it is first important to consider in general terms the functioning of the transport system that satisfies citizens' mobility needs. Figure 3.5 starts from the schematic overview of the transport system and its interactions with land use included in Alonso Raposo et al. (2019). It extends the scheme with general factors (e.g. taxation) that have an impact on both the transport system and land use, the role of technology and the environmental impacts and by highlighting the role of digitalisation. In the transport system itself the volumes of travel by the different modes and the generalised costs of transport per unit of travel by those modes (i.e. time and monetary costs) are determined by the interaction between the supply and demand. The generalised costs of transport are affected by the level of service, which depends on how the demand compares to the available capacity for each mode. If the latter is increased (e.g. by improving the frequency or capacity of the vehicles or infrastructure), the level of service is improved, the generalised travel costs fall, and more demand is created (internal feedback loop), until a new equilibrium is reached. Capacity can be increased either physically or, for example, by digital technologies that allow more efficient use of the existing physical infrastructure.

The transport system also interacts with land use: its general performance affects the accessibility of locations, which will determine, together with other factors, where households and firms will be established. In the past, the availability of public transport and the relatively low costs of private transport modes have enabled people to live farther away from the city centres, in locations with more attractive and more affordable living conditions, leading to urban sprawl. This creates additional demand for transport and can decrease the level of service (external feedback loop).

Many other elements also play a role: economic and cultural factors, socio-demographic ones, the technological system, etc., and transport and spatial policies. The former include the taxes and subsidies on transport services, vehicles and energy, as well as infrastructure policy, emission and safety regulations, etc.

Figure 3.5 Schematic visual representation of the transport system and related systems



Digitalisation and digital technologies can have a direct impact on the transport system, affecting also its environmental performances.

Digitalisation can play a role in other sectors inducing indirect effect on the transport system.

Source: Extension of figure 11 in Alonso Raposo et al. (2019).

Digitalisation can have an impact on various elements of the transport system and thereby on its environmental performance. These elements are indicated with a red background in Figure 3.5.

- Travel demand can be affected, for example, by virtual mobility solutions such as teleworking, explored in Factsheet 1, videoconferencing, e-learning, e-health, e-publications, etc. In addition, digital mobility services, such as those explored in Factsheet 4, or demand management strategies, such as those presented in Factsheet 7, can influence demand.

- The supply of certain transport services or their combinations can be made more attractive by digital solutions; for example, by providing real-time information, by making it easier to book tickets, by enabling smart logistics, and by providing multimodal services for both passenger and freight transport. This will have an impact on their uptake and the overall demand. It can also provide new types of transport services, such as shared mobility, to replace privately owned means of transport, creating new business cases and paradigms. Examples of such technologies are discussed in Factsheet 4 for passenger transport and in Factsheet 5 for freight.

- Digital solutions can lead to a more efficient use of the existing physical capacity of the transport infrastructure for certain modes (e.g. with autonomous and connected vehicles, discussed in Factsheets 2 and 3), making them more attractive or reducing their environmental impacts.

- Digital solutions can help improve the environmental performance of vehicles (greater energy efficiency, sensors, etc.) and energy used in transport (e.g. vehicle-grid integration, discussed in Factsheet 6).

- In addition, more generally, digitalisation can affect the environmental impact of transport because it can provide more complete information (including real-time data) to policymakers. For example, having access to real-time emissions of vehicles could make enforcing future emission standards easier, or a better understanding of traffic flows could facilitate implementing dynamic road pricing. Details of the possibilities offered by digital technologies in these fields are discussed in Factsheets 7 and 9.

Of course, the transport system is also influenced by the broader impacts of digitalisation on the economic and technological systems, on land use, and on behavioural and organisational shifts induced in people and firms (such as the potential impacts of the metaverse (Accenture, 2022; World Economic Forum, 2022). These are indicated with a blue background in Figure 3.5. Finally, the figure highlights the internal feedback loop arising from the interaction of transport supply and demand and the external feedback loop with land use. Both will be important when assessing the full environmental effects of digitalisation in transport, as discussed in Section 3.3.

The above-mentioned effects can be also categorised in terms of the 'avoid-shift-improve' framework or 'A-S-I' (EEA, 2010). For example, 'avoid' approaches address the demand for transport and impact on the environment by reducing the number and/or length of trips. 'Improve' strategies, represent ways of reducing the energy consumption and environmental impact of all travel modes by increasing the uptake of environmentally friendly vehicles and more sustainable energy sources. 'Shift' approaches contribute to environmental sustainability by realising the modal shift from less to more environmentally friendly and energy efficient modes.

Table 3.1 lists some examples of digital developments that have implications for transport and its environmental performance. It indicates whether they are relevant for passenger and/or freight transport, and whether they intervene on the supply side or the demand side of the market, or through the environmental characteristics of the infrastructure, vehicles or fuels. It also indicates through which mechanism the main direct environmental impact can be expected to take place. Some of these digital solutions are analysed in more detail in Chapter 5 and in Annexes 1-9.

In addition to what has been discussed so far, digital solutions in transport may have a positive effect on the efficient use of materials and the circularity of the transport sector. An example is digital passports for products. Their aim is to make materials traceable along supply chains and facilitate information exchange among supply chain actors. The many existing initiatives to develop and implement digital product passports for vehicles or for batteries in electric vehicles mainly aim to provide information on the material composition of vehicle or battery parts. This creates the opportunity for the targeted recovery of valuable resources (including critical raw materials) from end-of-life vehicles. Moreover, more advanced digital product passports can provide real-time information about the health and functionality of vehicle or battery parts, thus enabling preventive maintenance and/or easier repair, which prolongs the useful life of vehicles and batteries. This has the potential to reduce demand for new vehicles and batteries and, therefore, the demand for extraction of new material resources needed to produce them. The European Commission proposal for a regulation on eco-design for sustainable products sets out general requirements for digital product passports in the EU ([6]).

([6]) Sustainable products initiative (europa.eu)

Table 3.1 Examples of digital developments with implications for the environmental performance of transport

	Transport market		Intervention via			Potential main direct environmental impact via		
	Passenger transport	Freight transport	Demand	Supply	Environmental characteristics of infrastructure, vehicles, fuels	Number and length of trips	Modal choice	Energy efficiency and environmental performance of modes
Teleworking	■		■			■		■
Videoconferencing, e-learning, e-health	■		■			■		
Virtual tourism	■		■			■		
e-commerce	■	■	■			■		
3D printing		■	■			■		
Smart logistics		■	■	■		■	■	
Unimodal or multimodal ticketing, information and booking services	■	■		■		■	■	
Shared and collaborative or on-demand mobility services (vehicle sharing, ride sharing, ride hailing, mobility as a service, improvements in public transport, etc.)	■	■		■		■	■	■
Connected, cooperative and automated mobility	■	■		■	■	■	■	■
New modes: delivery drones, personal air vehicles	■	■		■			■	
Digital solutions for vehicles	■	■			■			■
Vehicle-grid integration	■	■			■			■
Enhanced digitalisation in public transport	■	■		■			■	■
Digital solutions for capacity allocation and traffic management	■	■		■				■

Source: EEA compilation.

3.3 Taxonomy of the environmental effects

To structure the discussion in Chapter 5 and Annexes 1-9 on the environmental impacts of digital solutions relevant for transport, this report uses a taxonomy of the effects whenever it is relevant. The extensive literature on such taxonomies traditionally focuses on energy and improvements in energy efficiency. However, the concepts developed are also relevant for analysing the impact on other resources (water, materials, etc.). Many studies, including reviews, and taxonomies exist on the energy and environmental effects of ICT and digitalisation ([7]).

As will be discussed in Chapter 6, the digital technologies themselves incur direct environmental costs if additional equipment is needed, which must be produced and later disposed of, and because of the additional operation of the equipment (e.g. additional energy consumption) and the systems that it interacts with (e.g. the internet). The concept of additionality is important: the environmental effects of the equipment that is already available should be considered only to the extent that the digital solution implies a shorter lifetime and/or more use of that equipment and related services.

If there are direct environmental costs, a digital solution is beneficial for the environment only if these costs are more than completely offset by the environmental benefits arising from its uptake. This depends on the magnitude and sign of the so-called higher order effects, which are also sometimes referred to as 'indirect effects' in the literature (e.g. Horner et al., 2016; Pohl et al., 2019).

Environmental benefits arise if a digital solution improves efficiency or it allows processes to be optimised (e.g. a potential increase in energy efficiency in shared autonomous vehicles, discussed in Factsheet 2), or because it substitutes a less environmentally friendly product or service (e.g. by making public transport more attractive and efficient, thus avoiding the use of private cars; see, for example, multimodal digital mobility services in Factsheet 4). These effects are often most prominent when people think about the environmental potential of digital solutions.

To understand the ultimate effect of digital solutions, the scope of the analysis needs to be enlarged, however. If the digital solution leads to lower costs and/or greater ease of use, then people will use it more, leading to higher environmental impacts. This is called the direct rebound effect. If it frees up time and/or budget, it will also affect the use of other goods and services (indirect rebound effect), which have their own effects. A possible way of tackling this issue, through the internalisation of the external costs of transport, is discussed in Factsheet 7. In addition to these, from the user's perspective, there may also be broader system impacts. Economy-wide rebound effects arise when the uptake of the digital solution leads to readjustments in the entire economy due to changes in prices and quantities. Furthermore, digital solutions can also lead to transformational changes in people's preferences and in economic and social institutions.

Coroamã and Mattern (2019) refer to the different rebound effects of digitalisation as the 'digital rebound' and stress the importance of taking them into account. Failure to do so may lead to 'inappropriate policy or misallocation of monetary incentives'. Note that, while rebound effects are often cast in a negative light, for consumers and producers they may mean an increase in the quality or attractiveness of the goods and services available and hence are a benefit.

None of these effects are easy to assess, although for some digital solutions and some environmental effects the difficulties and uncertainties of the assessment are lower than for others. First, for digital solutions that are already used or close to the market, the uncertainty is generally lower than for others that have a lower so-called technology readiness level. For example, the degree of uncertainty is lower for teleworking (Factsheet 1) than for autonomous vehicles (Factsheets 2 and 3). However, for technologies that are already in use, their future environmental impacts can be uncertain, as they are likely to evolve further. Second, as the scope of the analysis is broadened from the technology to the system perspective it becomes progressively more difficult to quantify the environmental effects. This is especially true for transformational changes but also for economy-wide impacts. It is difficult to assess them not only *ex ante* but also *ex post*, as it is not easy to identify which changes were made possible by a digital solution and which ones would have taken place anyway. In this respect, filling knowledge gaps through monitoring and research is seen as a fundamental step towards a more comprehensive understanding of the interconnection in and within the systems and the way they react to the introduction of more or less disruptive technologies. The difficulties of and uncertainties in assessing the environmental impacts have implications for policy, as will be discussed in Chapter 5 and in Annexes 1-9.

([7]) Some examples are Berkhout and Hertin (2004), Gossart (2015), Bieser and Hilty (2018), Creutzig et al. (2019), Coroamã and Mattern (2019), WBGU (2019), Court and Sorrell (2020) and Bieser and Höjer (2022).

4
EU policy context

Key messages

- **Environmental policy has been at the core of EU action for more than 30 years. It is now in the spotlight with the European Green Deal and all the various initiatives connected to it.**
- **In the transport domain, positive results have been achieved for air pollution, albeit with differences across modes. Additional efforts are needed to curb greenhouse gas emissions from the sector, and multiple initiatives are under development.**
- **Digitalisation is a more recent policy area but one undergoing active development, especially because of the fast pace at which technology evolves. This is another priority of the current European Commission, identified under the Europe fit for the digital age strategy.**
- **Digitalisation is expected to bring several developments in the transport sector. Their impact on the environment is largely unknown, with policy having a key role in shaping this forthcoming transformation.**

4.1 Environmental policies for transport

The Single European Act (1987) provided the first legal basis for addressing environmental matters in the EU. Following the Maastricht Treaty (1993), these become an official EU policy area. Although the EU has been legislating on environmental topics for more than 30 years, this has recently gained a new momentum because of the ambitious objectives highlighted in the European Green Deal and the overarching climate challenge that needs to be addressed.

Important progress has been made in the domain of air pollution thanks to a substantial set of initiatives, including the EU emission standards (also known as Euro standards), Directive 2001/81/EC on national emission ceilings (EU, 2001) and the Air Quality Directive, Directive 2008/50/EC (EU, 2008). Especially in road transport, as pointed out in Chapter 2, exhaust emissions of the main air pollutants have been reduced substantially since the early 1990s starting with the introduction of the first Euro standard in 1992 with Council Directive 70/220/EEC and subsequent amendments to it. Progressively more stringent limits have followed and, currently, the new Euro 7 standard has been proposed and is under discussion (EC, 2022h).

Climate and energy policies in the EU have resulted in significant reductions in greenhouse gas (GHG) emissions in all sectors, except transport. Indeed, in road transport the increase in activity has more than offset any positive effects from stricter CO_2 emission standards and the alternative energy sources used. Transport sector emissions increased by 33.5% between 1990 and 2019 (EEA, 2022a), as explained in Chapter 2. It should be noticed that regulation of the global aviation and maritime sectors is further complicated by the wider geographical scope and the different interests at stake.

The European Commission, under President Ursula von der Leyen, reoriented its strategic priorities, with decarbonisation as one of the major priorities. The decarbonisation strategy is set out in the European Green Deal communication (EC, 2019c). This aims to make Europe the first climate-neutral continent by 2050.

In July 2021, the European Commission published a set of detailed legislative proposals, called the 'Fit for 55' or 'Delivering the European Green Deal' package, to achieve the targets agreed in the European Climate Law. It binds Europe to achieving climate neutrality by 2050 and sets an intermediate target of a 55% reduction in GHG emissions by 2030.

The three headline policies to achieve this goal are the Emissions Trading System (ETS), the Effort Sharing legislation and the Land Use, Land Use Change and Forestry (LULUCF) Regulation ((EU) 208/841). The EU ETS covers GHG emissions from power plants, large industrial plants and aviation, the last being for flights within the European Economic Area. The Effort Sharing legislation sets 2030 targets at EU and Member State levels and covers the remaining domestic GHG emissions not covered by the EU ETS such as part of the transport sector, buildings, agriculture, small industrial installations and waste. The LULUCF Regulation sets a climate target for the carbon stock contained in soils and biomass, stating that there should be no net loss. This is known as the no-debit rule, which each Member State must respect. The Fit for 55 package supplemented these three headline policies with even more ambitious objectives.

Further proposed revisions of the Fit for 55 package are:

- The revision of the revised Renewable Energy Directive (Directive 2018/2001/EU), which aims to reach a 40% share of renewables in the EU energy mix by 2030;
- The increased level of ambition in the EU fleet-wide CO_2 emission performance standards for new passenger cars and new light commercial vehicles (vans) (EU, 2019a). The regulation sets stricter limits and requires all new cars and vans to have zero CO_2 exhaust emissions from 2035 (EC, 2021i). In addition, EU fleet-wide CO_2 emission targets for heavy goods vehicles have been introduced in the past: a reduction of 15% by 2025 and of 30% by 2030 compared to the reference period (1 July 2019 to 30 June 2020) (EU, 2019b). In October 2022 the Council and the European Parliament reached a provisional agreement on the stricter CO_2 emission performance standards for new cars and vans (Council of the EU 2022). After further negotiations, the Council gave the final approval in March 2023. In a statement accompanying the vote, the European Commission has committed to submit proposals to enable the registration of cars and vans exclusively running on carbon-neutral fuels (often called e-fuels) after 2035, as stipulated in the adopted Regulation. In February 2023 the European Commission has submitted a proposal for the revision of the CO_2 emission performance standards of heavy goods vehicles (EC, 2023a) .
- A proposal for a new regulation on the new deployment of alternative fuels infrastructure that will repeal the previous directive. On 28 March 2023 the European Parliament and EU ministers reached a provisional agreement on the new Regulation (EC, 2021h).
- The FuelEU Maritime proposal on sustainable maritime fuels aims to drastically reduce carbon emissions from maritime shipping. Similarly, on 23 March 2023 EU ministers and institutions reached a provisional agreement on the new Regulation.

After the Russian invasion of Ukraine, the European Commission proposed the REPowerEU plan, which includes a set of integrated actions to save energy, diversify and secure energy supplies, boost renewable energy deployment and smartly combine investments and reforms. REPowerEU increased the ambition of Fit for 55 package legislative proposals for energy efficiency and renewables (EC, 2022b). For the latter it took the 2030 target share in the energy mix from 40% to 45%. The European Commission has also taken a range of other actions in view of the increases in energy prices since the second half of 2021, an overview of which is given in its report *State of the Energy Union 2022* (EC, 2022i).

On 30 March 2023 the European Parliament, the European Commission and the EU member reached the provisional agreement on a legally binding target to raise the share of renewable energy in the EU's overall energy consumption to 42.5% by 2030. EU countries that choose to do so can complement this target with an additional 2.5% indicative top-up that would allow reaching 45%.

4.2 Digitalisation in general

European legislation in the field of digitalisation is more recent than that in the environmental field. However, the first regulation on data protection, an initial building block of digitalisation, was adopted in 1995. It was called the Data Protection Directive (Directive 95/46/EC). It regulated the processing of personal data within the European Union and its free movement. The General Data Protection Regulation superseded it in 2016 and entered into force in 2018. Data protection is extremely relevant also for the transport context as it will be discussed in more details for autonomous vehicles in Factsheets 2-3 and related annexes, where the use of big data analytics is seen as crucial for the development of higher automation levels.

The European Commission deepened the digitisation framework with the first (2010-2020) and the second (2020-2030) EU Digital Agendas, discussed below.

4.2.1 First digital agenda

In 2010, the European Commission introduced its **first digital agenda 2010-2020** for Europe. It focused on giving consumers and business better access to digital goods and services. It achieved lower prices for electronic communications and the end of roaming charges, more harmonised regulation of communications in the single market, better internet connectivity, better protection of consumers in telecommunications, secure and seamless payments, regulation of electronic identification, and trust services for electronic transactions.

Further data regulation and acts on cybersecurity were also decided upon at the end of the 2010-2020 decade. These were Regulation (EU) 2018/1807 on the free flow of non-personal data and Directive (EU) 2019/1024 on open data and the reuse of public sector information (EU, 2019c). The EU's Directive on Security of Network and Information Systems

(NIS Directive; EU 2016/1148) was the first piece of EU-wide cybersecurity legislation. It aims to achieve a high level of common network and information system security across the EU's critical infrastructure. The EU Cybersecurity Act (EU, 2018) strengthens the European Union Agency for Cybersecurity (ENISA) and establishes a certification framework for products and services. The revised Directive on measures for a high common level of cybersecurity across the EU (NIS 2), which recently entered into force (EU, 2022a), and the proposal for a directive on the resilience of critical entities address the cyber-resilience and physical resilience of critical entities and networks, including transport infrastructure. Ensuring the safety of electronic information is fundamental for deploying many of the digital technologies explored in this report such as autonomous vehicles (Factsheets 2 and 3) or smart logistics (Factsheet 5).

Digitalisation also provides an opportunity for the European Commission to support EU industry. In 2015, the Commission launched the **digital single market strategy** and, as part of it, it launched the Digitising European Industry initiative. The initiative does not regulate but supports Member States' actions concerning industry, allowing the Commission to engage in a dialogue with stakeholders. A total budget of EUR 50 billion was expected to be mobilised.

In 2016, the ***Digitising European industry*** communication followed (EC, 2016). It supported and complemented the various national initiatives for digitalising industry. The aim was to trigger further public and private investment in all industrial sectors and create the framework conditions for the digital industrial revolution via different policy instruments, financial support, coordination and legislative powers (European Parliament, 2022a).

4.2.2 Second digital agenda

The second agenda has the ambition of getting actors, households, companies and public authorities ready for the digital era. It is about **funding, artificial intelligence and data sharing**. The Digital Compass launched in 2021 (EC, 2021f) aims to have 80% of adults digitally skilled, 75% of companies using cloud computing services and big data, all households having gigabit connectivity and all public services available online.

Enabling secure electronic payments and digital education will help to reach these objectives. The digital education plan (2021-2027) will help citizens to prepare for the digital age (EC, 2021j). As discussed in detail in Chapter 5, for many digital technologies explored in this report, digital literacy is a fundamental precondition for accessing the services offered. This is the case, for example, for multimodal digital mobility services, explored in Factsheet 4, or teleworking, discussed in Factsheet 1.

Different **funding programmes** are put in place by the digital agenda. A specific digital Europe programme funds digital technology with a budget of EUR 7.5 billion over the period 2021-2027. Other funding sources such as Horizon Europe, the Connecting Europe Facility (CEF Digital) infrastructure, and others complement this specific fund.

To ease the development of **artificial intelligence**, three pieces of legislation were adopted on ethics, civil liability and intellectual property themes (EP (2020)). In 2023, the Artificial Intelligence Act (EC, 2021k) including a technology-neutral definition of artificial intelligence is expected to be adopted.

Data sharing is the second main axis of the second digital agenda. It launched the EU strategy on data in February 2020. The main consideration is to maximise data access and guarantee their free flow while preserving privacy, security, safety and ethical standards. The objective is to create a European data space built on Gaia-X, an open, transparent, secure digital data system.

The proposal for a **Data Act** (EC, 2022j) aims to ensure that access to certain data is guaranteed (e.g. by users for data generated by them) and to rebalance negotiation power for small and medium-sized enterprises by preventing contractual abuses and providing a means for **public sector bodies to access and use data** held by the private sector that is necessary in exceptional circumstances. Data sharing in a secured and harmonised way is at the core of the digital technologies discussed in Factsheet 4, for multimodal digital mobility services for passenger transport, and Factsheet 5, for smart logistics in the freight transport sector.

The **Digital Services Act package** is another building block to ensure a good working digital economy. It is composed of the Digital Services Act and the Digital Markets Act. Both want to contribute to a safer digital space with protection for users' rights and to establish a level playing field to foster growth in innovation and competitiveness. The **Digital Services Act** (EU, 2022b) should guarantee better protection of users' rights, more choice and lower prices. For digital service providers, it makes it easier to start up a business and upscale in Europe. The Digital Services Act should reduce or prevent the trade in and exchange of illegal goods, services and content online. It also aims to prevent the misuse of manipulative algorithmic systems that amplify the spread of disinformation.

The **Digital Markets Act** (EU, 2022c) sets out rules for gatekeepers of digital markets. Today, the accelerating digitalisation of society and the economy has created a situation in which a few large platforms control important ecosystems in the digital economy. There is the risk that these actors, in predominant positions, can impose unfair take-it-or-leave-it conditions. This is further discussed in Chapter 6.

The Digital Markets Act, among other things, will guarantee business users the same access to information on advertisements and ranking of sites as gatekeepers. In other words, it aims to avoid market distortion by monopolist market powers. The latter can be important when developing mobility as a service or multimodal mobility services, as discussed in Chapter 5 and Annex 4.

The industry also takes initiatives in the field. In 2021, the European Green Digital Coalition was formed. Twenty-six chief executive officers of information and communications technology (ICT) companies signed a declaration to support the green and digital transformation of the EU (EC, 2021l).

4.3 Policy framework for digitalisation in the context of transport

Transport, as discussed in Chapter 2, is an important economic sector with a direct impact on the environment. Reducing absolute GHG emissions remains one of the biggest, if not the biggest, environmental challenge for the transport sector, as already mentioned. Taking into account the European Green Deal ambition to achieve climate neutrality by 2050, drastic reductions in GHG emissions will be necessary.

The European Commission believes that technological innovation and digital transformation is one of the approaches that will address this challenge in the transport sector. Digitalisation has the potential to create new business models, innovative mobility, such as connected and automated transport, and further advances in the field of artificial intelligence, ultimately producing environmental benefits. (Tsakalidis et al., 2020).

In 2010, the Intelligent Transport Systems Directive (EU, 2010) was adopted. At that time, the aim was to agree within the next 7 years upon specifications (i.e. functional, technical, organisational or services provisions) to address the compatibility, interoperability and continuity of intelligent transport solutions across the EU. The first priorities were traffic and travel information.

4.3.1 Commission mobility package — Europe on the move

The 2017-2018 European Commission mobility package, **Europe on the move**, includes aspects of digitalisation. The mobility package is composed of three parts, containing communications and legislative initiatives. Below we point out the main elements in each part of the package that are linked to digitalisation.

The **first part** of the mobility package consists of a communication and several legislative initiatives. The communication *Europe on the move* (EC, 2017a) stresses some advantages of digitalisation, to wit, better compliance with and enforcement of social legislation, easier implementation of differentiated road charging systems, facilitating the development of new mobility systems and more efficient transport and logistics operations by improving traffic flows, optimising the use of infrastructure and reducing administrative burdens, a better combination of public and private transport and facilitating the shift to cleaner transport modes.

It furthermore supports smart digital technologies. Some of these were targeted in legislative initiatives to facilitate and structure their development. For example:

- **Multimodal travel information systems.** It is expected that multimodal digital mobility services will contribute to the promotion of public transport and active and sustainable modes, including bicycle- and car-sharing schemes (EU, 2017a) (see Chapter 5 and Annex 4).

- **Smart road charging.** This is a means of contributing to the financing of infrastructure and reducing the external costs of transport. At the same time, smart road charging systems stimulate innovation. Early in 2022 Directive (EU) 2022/362 (EU, 2022d) was adopted, which sets new rules for road charging, revising the Eurovignette Directive (EU 1999) (see Chapter 5 and Annex 7).

The Commission provides important financial means to realise the objectives via the structural funds and the research funds.

The **second part of the package** (2018), focused on clean mobility and the alternative fuel infrastructure. Successful development of the alternative fuel infrastructure also needs digitalisation in order to optimise the use of alternative fuels, renewable energy and batteries.

The **third part of the package** (2018) supports a safe, clean and **connected** mobility system. The European strategy for autonomous vehicles, *On the road to automated mobility: an EU strategy for mobility of the future* (EC, 2018b), is part of it. It stresses the potential for decarbonisation, emission reductions, safety gains and new ways of curbing the ever-increasing demand for mobility. It also points also to threats and risks such as the rebound effect caused by autonomous vehicles, the safety of pedestrians and cyclists as long as autonomous vehicles communicate only with each other, the risk of cyberattacks and liability issues in the event of accidents.

It spotlights the importance of a technology-neutral approach to vehicle-to-vehicle communications and a level playing field for data use, in line with the EU strategy on cooperative intelligent transport systems and mentions the framework for **vehicle approval** that was overhauled in 2018 and now allows innovative vehicle automation technologies.

Further initiatives, regulations, directives, revisions and communications have also been taken more recently and are discussed below.

4.3.2 Sustainable and smart mobility strategy

In December 2020, the European Commission launched the sustainable and smart mobility strategy (EC, 2020b), in line with the European Green Deal and the EU digital strategy. It contains 10 complementary key areas for action ('flagships') and an action plan listing **82 initiatives** to be implemented over the following 4 years. Many of the initiatives are included in the Fit for 55 package. Two of the flagships have a direct link with mobility.

- **Flagship 6: Making connected and automated multimodal mobility a reality.** It mentions the following actions, most of which are explored in the factsheets in Chapter 5: adopting and adapting legislation, taking full advantage of smart digital solutions and intelligent transport systems, seizing the opportunities of connected, cooperative and autonomous vehicles (see Factsheets 2 and 3 on partnerships and coordination of relevant traffic rules), planning and purchasing of multimodal tickets (Factsheet 4), providing of paperless options in transport (Factsheet 5), exploring further options to support connected vehicles, allocating capacity more efficiently, and updating technical specificities for interoperability;

- **Flagship 7: Innovation, data and artificial intelligence for smart mobility.** It contains a long list of initiatives including the validation of new technologies and services, the drive for further research and employment of innovative technologies, the building of a European mobility data space, and further efforts on data availability, access and exchange. Among the new and innovative technologies, the strategy mentions autonomous vehicles (see Factsheets 2 and 3), electric personal air vehicles, hyperloops, electric waterborne transport, drones and unmanned aircraft. It is unclear today to what extent some of these technologies can contribute to sector decarbonisation, nature restoration and increased social inclusion, ultimately realising the sustainable transition.

4.3.3 Proposal for revision of the TEN-T Regulation

Concerning digitalisation, the proposal (EC, 2021m) mentions the use of innovative technologies such as 5G to further advance the digitalisation of the transport infrastructure, increasing its efficiency, and improving the safety, security and resilience of the network. The Trans-European Transport Network (TEN-T) is also important, as it determines the scope of the deployment of intelligent transport systems (and alternative fuel infrastructure) (EC, 2021n).

4.3.4 Proposal for revision of the ITS Directive

The proposal (EC, 2021o) aims to update the Intelligent Transport Systems Directive (EU, 2010) in line with new priorities on better multimodal and digital services. It plans to stimulate the faster deployment of new, intelligent services by proposing that certain crucial road, travel and traffic data are made available in digital format, such as speed limits, traffic circulation plans or roadworks and essential safety-related services. It also points to better encompassing emerging services, such as multimodal information, booking and ticketing services (such as apps to find and book journeys that combine public transport and shared car or bike services), communication between vehicles and infrastructure (to increase safety) and automated mobility. In addition ,it mandates the collection of crucial data and the provision of, for example, real-time information services informing the driver about accidents or obstacles on the road (EC, 2021p). Factsheet 4 and Annex 4 explain the potential of intelligent transport services in more detail for passenger transport. Factsheet 5 and Annex 5 do so for smart logistics.

4.3.5 New European urban mobility framework

The framework aims for a transition to a safe, accessible, inclusive, smart, resilient and zero emission urban mobility (EC, 2021q). It therefore focuses on active, collective and shared mobility, underpinned by low and zero emission solutions. The Commission communication therefore pays attention to **attractive public transport services**, supported by a multimodal approach and digitalisation, leading to increased frequency and reduced costs.

4.3.6 The action plan on the digitalisation of the energy sector

Digital technologies are an important tool to harvest the full potential of flexible energy generation and consumption. It will enable the uptake and utilisation of more renewable energy in general and for the transport sector in particular, reducing GHG and air pollutant emissions. The action plan (EC, 2022k) aims to develop a competitive market for digital energy services and digital energy infrastructure. Vehicle-grid integration will be part of these, as described in Factsheet 6 and in more detail in Annex 6.

5 Challenges and opportunities of selected digital technologies in the transport sector

This chapter provides nine factsheets on digitally-enabled technologies relevant to the mobility system (Figure 5.1). These highlight the most relevant elements from an environmental perspective, identifying the challenges and opportunities associated with each innovation. The list of technologies includes examples for both passenger and freight transport sectors, across multiple modes and for different dimensions, ranging from the need for individual mobility up to system-wide monitoring for improved policy.

Each of these factsheets is complemented by a more detailed technical annex (Annexes 1-9) including a detailed discussion on the messages summarised in the factsheets. The annexes also give examples in the form of case studies to further illustrate the potential environmental benefits and pitfalls associated with the various digital technologies explored.

Figure 5.1 Overview of the factsheets

Virtual mobility

Factsheet 1 — Teleworking and virtual mobility

Connected, cooperative and automated mobility

Factsheet 2 — Shared autonomous urban vehicles

Factsheet 3 — Autonomous freight transport

System integration

Factsheet 4 — Multimodal digital mobility services

Factsheet 5 — Smart logistics

Factsheet 6 — Vehicle-grid integration

System management and digitalisation for policy

Factsheet 7 — Digitalisation in road transport pricing

Factsheet 8 — Air traffic management

Digitalisation for policy

Factsheet 9 — Digitally enabled monitoring solutions

5.1 Factsheet 1 — Teleworking and virtual mobility

The definition of teleworking has evolved over time, following technological developments. Presently, the term is often used to identify work arrangements outside employers' premises, performed on a regular basis or occasionally and enabled by information and communications technology. Teleworking has recently become increasingly popular as a response to the restrictions imposed to contain the COVID-19 pandemic, demonstrating that it can be applicable on a large scale.

5.1.1 Motivation

From a mobility perspective, teleworking is of interest mainly because it allows a worker to avoid one or more commuting trips during the week, shorten their distance (e.g. if work is carried out in a co-working space closer to the employee's place of residence) or shift them to times at which their societal and environmental impact is lower (e.g. due to reduced congestion; for a detailed discussion of this aspect, see also Factsheet 7 and related Annex 7). Teleworking can potentially not only reduce the demand for transport and environmental impacts associated with commuting but also influence the energy consumption of buildings or even the configuration of urban space (less demand for offices in the city centre or changes in individual choices about where to live).

5.1.2 Key conclusions

- Teleworking was applied on a large scale during the COVID-19 pandemic as a response to the restrictions imposed. Its viability has been demonstrated in many work situations.
- There are indications that these flexible work arrangements will remain important in the future, progressively becoming part of the new normal.
- The availability of teleworking is uneven across Member States, income and education levels (higher share of teleworking among wealthier and better educated people), geographical location (urban vs rural areas) and type of work (primary vs tertiary sector, self-employed vs employees).
- Teleworking can effectively reduce the environmental and societal impacts associated with commuting, but evaluating its net effect is significantly complicated by the rebound effects involved.
- Saving money and time by avoiding commuting trips can generate additional demand for transport due to the additional resources available. Working from home (or in a different location) will increase its use of electricity and heating/cooling. Depending on what happens at the usual working location (i.e. the office), this can have the net effect of increasing the demand for energy.

5.1.3 Bottom line

Quantifying the net environmental impacts of teleworking is generally difficult. Many studies indicate that the net effect on energy use (and the related environmental impacts) may be small or even negative, because of the potentially significant rebound effects involved. Teleworking can act in synergy with policies aimed at managing traffic volumes, such as those described in Factsheet 7. Additional information can be found in Annex 1 and in the case studies discussed there.

5.2 Factsheet 2 — Shared autonomous urban vehicles

Automated driving or piloting systems for transport use a combination of different technologies to partially or entirely replace human intervention in operating a vehicle, a vessel or a plane. Automation can be classified into different levels, depending on the complexity of the tasks that can be carried out independently of human input. The associated technological challenges, potential impacts and opportunities for the passenger transport sector all increase significantly with the automation level. In this factsheet we focus on shared road vehicles for urban transport.

5.2.1 Motivation

As discussed in Chapter 2, the demand for transport is increasing, with projections to 2050 showing that this trend will continue. The sector's impact on the environment and society remains significant. Among these, road accidents are of concern, with costs estimated at around EUR 237 billion in 2016. Although the number of road fatalities is decreasing, with a 61% reduction in the period 2001-2021, this improvement has been slowing down recently. It is estimated that human error plays a part in approximately 95% of road accidents. The public passenger transport sector is also struggling to attract users, with a slow but constant decrease in demand in the past 20 years. In addition, the EU population is ageing and is likely to have increasing difficulty in accessing transport and other public services.

5.2.2 Key conclusions

- Automation in shared road urban mobility (and beyond) has the potential to reduce several categories of accidents and the associated fatalities, increasing safety in urban areas.
- Shared autonomous vehicles (SAVs) can be a useful tool to address the first/last mile problem in public transport, increasing the accessibility and attractiveness of existing public services.
- SAVs can be instrumental in improving the connection between urban and rural areas, offering transport services in these areas.
- SAVs' environmental impact is largely uncertain. Despite having the potential to reduce the number of private cars circulating, the net effect on total passenger-km driven, due to higher occupancy rates, and the space needed for parking in urban areas will strongly depend on whether mechanisms to manage the demand for transport are also in place (for details, see Factsheet 7).
- Indeed, the lower costs that can be achieved through automation may have significant rebound effects by drastically increasing the demand for transport.
- The technology has been demonstrated mostly on a pilot scale, and commercial applications with high automation levels are not yet available. This is due to a combination of technical and regulatory barriers that are discussed in Annex 2.

5.2.3 Bottom line

Using SAVs for passenger transport may have a significant impact by increasing safety, enhancing the accessibility of public transport, and promoting a modal shift with associated environmental benefits. However, the uncertainties are still very high. Additional information can be found in Annex 2 and in the case studies discussed there.

5.3 Factsheet 3 — Autonomous freight transport

Automated driving or piloting systems for transport use a combination of different technologies to partially or entirely replace human intervention in operating a vehicle, a vessel or a plane. Automation can be classified into different levels, depending on the complexity of the tasks that can be carried out independently of human input. The associated technological challenges, potential impacts and opportunities for the freight sector all increase significantly with the automation level. In this factsheet we focus on road and maritime modes, as they are the most relevant in transporting goods.

5.3.1 Motivation

As discussed in Chapter 2, the demand for transport is increasing, with projections to 2050 showing that this trend will continue. The freight sector's impact on the environment and society remains significant. Among these, road accidents are of concern, with costs estimated at around EUR 43 billion (EUR 23 billion for heavy-duty trucks only) in 2016. The freight transport sector is also facing increasing difficulty in finding operators such as drivers or seafarers, and labour costs remain the dominant part of the total costs of the operators. Lastly, the sector is also called on to optimise its energy efficiency and reduce its emissions of greenhouse gases and air pollutants. Despite the significant technological challenges and associated uncertainties, automated driving or piloting systems have the potential to bring benefits to the system, lowering transport costs while increasing both safety and efficiency.

5.3.2 Key conclusions

- Automation in both the road and maritime (or inland waterway) sectors has the potential to reduce several categories of accidents and the associated fatalities and environmental impacts (e.g. in the case of oil spills).

- Labour costs are a relevant cost item for the freight transport sector. For example, in road freight transport, labour is estimated to account for 42% of the total transport costs. Automation has the potential to lower such costs by partially or completely replacing vehicle or ship operators. The impact on workers can be significant and should be carefully considered.

- By reducing the impact of labour on total costs, automation can enable modes of operation, such as reducing speeds, that have been economically challenging. This could have a positive environmental impact by reducing fuel consumption and thus emissions of greenhouses gases and air pollutants.

- The lower costs that can be achieved through automation may have significant rebound effects by drastically increasing the demand for transport or by promoting a shift to the transport mode that can deploy autonomous systems quickly (very likely to be the road sector), which may not necessarily be the most sustainable choice. Internalising external costs can be an effective measure to support this transition.

- The technology has been demonstrated mostly on a pilot scale, and commercial applications with high automation levels are not yet available. This is due to a combination of technical and regulatory barriers that are discussed in Annex 3.

5.3.3 Bottom line

Autonomous systems for freight transport may have a significant impact by increasing safety, lowering costs and enhancing environmental performance. However, the uncertainties are still very high. Additional information can be found in Annex 3 and in the cases studies discussed there.

5.4 Factsheet 4 — Multimodal digital mobility services

Multimodal digital mobility services (MDMS) can be defined as 'systems providing information about, inter alia, the location of transport facilities, schedules, availability and fares, of more than one transport provider, with or without facilities to make reservations, payments or issue tickets'. This definition is similar to that of mobility-as-a-service (MaaS), and most of the considerations for MaaS also hold in the case of MDMS. Currently, an unambiguous definition of MaaS is lacking in the scientific literature.

5.4.1 Motivation

In Chapter 2, we showed how privately-owned vehicles remain a dominant mode in the passenger transport system. This is true not only outside cities but also in urban areas. Here, the externalities associated with individual motorised transport modes, as discussed in more detail in Factsheet 7, are particularly relevant. It is necessary to promote a shift to a more sustainable type of mobility such as one of the collective transport modes such as buses or trains. Recent data show that this is currently not happening, with a progressively decreasing share of users choosing these modes, as shown in Chapter 2. MDMS is one of the tools that can be used to promote the accessibility and attractiveness of public transport, at the same time realising environmental benefits. However, trials are still relatively limited and the uncertainties are significant.

5.4.2 Key conclusions

- MDMS trials are not widespread and, as a consequence, experimental evidence in the scientific literature is scarce. This contributes to significant uncertainty over the potential societal or environmental benefits that such services can actually deliver.
- MDMS facilitate access to the transport system without creating per se additional services if those are not available. For example, if there are no mobility solutions apart from the private car, MDMS will not be able to provide a transport service.
- Significant policy developments are expected in this field with the revision of the Intelligent Transport System Directive and the proposal of a new regulation specifically aimed at enabling the development of MDMS.
- MDMS have the potential to reduce energy consumption from transport, especially in urban areas or for trips to them. This is achieved mainly by promoting a modal shift away from privately owned cars to public transport and other collective and active modes.
- MDMS have the potential to promote awareness of environmental impacts by users through, for example, dynamic pricing or simply providing easy access to environmental information.
- Automation can operate in synergy with MDMS, especially in the case of shared vehicles such as those described in Factsheet 3. Internalising the external costs of transport, as also extensively discussed in Factsheet 7, is likely to support and complement the environmental benefits that can be achieved through MDMS.

5.4.3 Bottom line

Assessing the net potential environmental impacts of MDMS is difficult. This is also due to the current lack of fully integrated MDMS systems. In particular integrating ticketing is often difficult. According to experts, MDMS have the potential to bring environmental benefits if well managed, especially in combination with other alternatives. Indeed, such services can be considered complementary to policies that aim to internalise transport externalities and to strengthen public transport. In isolation MDMS may not be sufficient themselves to bring significant environmental benefits. Additional information can be found in Annex 4 and in the case studies discussed there.

5.5 Factsheet 5 — Smart logistics

A simple definition of smart logistics is 'the effective use of data to improve the efficiency of traffic and logistics'. Logistics includes the organisation, planning, control and execution of the flow of goods. Following this, smart logistics cannot be limited to a specific digital service but can include different technologies. It has points in common with autonomous vehicles for freight transport, which can bring about disruptive changes in the organisation of a logistics system, and can reduce the administrative burden.

5.5.1 Motivation

As discussed in Chapter 2, demand for freight transport is increasing, with projections to 2050 showing that this trend will continue. The sector's impact on the environment and society remains significant. The sector is called on to optimise its energy efficiency and reduce its emissions of both greenhouse gases and air pollutants. Because of its specific characteristics (such as technical complexity, business organisation), the sector is also more difficult to decarbonise compared to passenger transport. In this context, limiting the inefficiencies in the management and operation of logistic distribution seems an attractive complement to other measures such as using low-carbon fuels and technical advances (e.g. automation) in the design of trucks, ships and planes.

5.5.2 Key conclusions

- Today, the vast majority of goods shipments will require an exchange of paper-based information or documentation, either for business or to demonstrate compliance with existing provisions.
- The administrative burden of paper documentation is significant, limits sector efficiency and hampers multimodality.
- The European Commission estimates that the transition to a fully electronic data exchange platform will reduce administrative costs in the transport and logistics sector by EUR 27 billion over a period of over 20 years (2018-2040). This could induce a 0.2-0.3% modal shift to less greenhouse gas-intensive transport modes, corresponding to a reduction of 1.3 billion tonnes of CO_2. However, a shift to sea shipping should take into account its currently higher emissions of some air pollutants such as nitrogen oxides and particulate matter, including black carbon.
- Digital technologies are already significantly impacting the sector, but further benefits can be realised by promoting system integration and data sharing and enabling synchromodality.
- It is important to control the rebound effects generated by an increase in system efficiency. In the context of realising a sustainable transition and decarbonising the system, the demand for transport should also be managed.

5.5.3 Bottom line

Digitalisation has the potential to make logistics more efficient and have a positive environmental effect. However, optimising the freight transport system should not trigger a further increase in demand with the risk of nullifying any environmental gain. In this context, policies aimed at managing the demand, such as those described in Factsheet 7, could be seen as an important complement to deploying advanced smart logistics systems in the sector. Smart logistics could also benefit from the monitoring solutions described in Factsheet 9 to better account for the overall impacts of modal choice. Additional information can be found in Annex 5 and in the cases studies discussed there.

5.6 Factsheet 6 — Vehicle-grid integration

Vehicle-grid integration (VGI) is a system that enables interaction between electric vehicles (i.e. vehicles with an electric motor) and the power generation and distribution systems. This is considered a key element in the context of integrating the energy and transport sectors. This interaction can be either unidirectional or bidirectional. Through it, connected vehicles can render specific services useful for the proper functioning of the electricity grid. VGI is enabled by digitalisation, which makes it possible to manage the simultaneous connection of several distributed electric vehicles, matching in real time their availability to provide energy to the grid with the needs of the power generators and the transmission or distribution systems, at different scales.

5.6.1 Motivation

As discussed in Chapter 2, the demand for transport is increasing, with projections to 2050 showing that this trend will continue. In parallel, electrification in the road transport sector is ongoing, and it is perceived as a fundamental technological development necessary to meet the ambitious policy objectives specified for the sector. At the same time, in the energy sector there is a strong drive towards deploying variable renewable energy sources such as wind and photovoltaic solar power, as confirmed by the most recent policy initiatives — notably the RePowerEU plan. In this context, a strong increase in the demand for electricity for transport is expected, and a significant fraction of this will have to be provided by variable sources, posing unprecedented challenges for both the transport and the energy systems. VGI is seen as a technology, enabled by digitalisation, with the potential to mitigate these challenges, by promoting the simultaneous uptake of electric vehicles and renewable energy sources.

5.6.2 Key conclusions

- VGI allows the total ownership cost of an electric vehicle to be reduced through the provision of ancillary services useful for the proper functioning of the power grid. This could promote faster uptake of such vehicles.

- Through VGI, it is possible to actively manage the charging of electric vehicles. In this way, it is possible to avoid further consumption during periods of high energy demand (peak demand). This could result in better use of variable energy sources, thus lowering their emissions of greenhouse gases and air pollutants.

- In some conditions, significant use of VGI can lead to faster depletion of the vehicle's battery, as discussed in more detail in Annex 6. Pilot studies and simulation results have shown that this degradation can be managed in specific conditions. However, it is important to take this into account when evaluating the environmental benefits the technology brings.

- VGI will benefit from policies addressing existing regulatory barriers and the lack of a market framework, as discussed in more detail in Annex 6.

- The technology has been demonstrated on a pilot scale. However, currently, the lack of VGI-enabled infrastructure and the general public's unfamiliarity with the concept will have to be addressed to facilitate faster uptake of the technology.

5.6.3 Bottom line

VGI is a technology with the potential to simultaneously promote faster uptake of electric vehicles and greater and more efficient deployment of variable renewable energy sources. Additional information can be found in Annex 6 and in the cases studies discussed there.

5.7 Factsheet 7 — Digitalisation in road transport pricing

Road pricing is an instrument that can be used to account for, in a fair way and with a system-wide perspective, the externalities caused by the transport sector that are mostly ignored by users. Road pricing can assume various forms and target different transport modes.

5.7.1 Motivation

Road transport has substantial impacts on society, as detailed in Chapter 2. These are often overlooked by the final users because they do not or only partially contribute to the full price of the specific transport solution. Examples of these impacts include accidents, congestion due to traffic, climate change, noise and air pollution and habitat damage. The concept of internalising the costs incurred by these impacts through specific taxation was put forward for the first time in 1920. However, only recently and through the development of the digital technologies discussed in Chapter 3, has it become possible to implement road pricing schemes that can fully account for such costs. Pricing schemes and their implementation can vary widely, but the general concept is to establish a transport price that accounts for transport mode, vehicle type and its environmental characteristics, location, time of day, road type, distance driven and so on.

5.7.2 Key conclusions

- The digital technologies required for a full-scale introduction of comprehensive road pricing schemes are already available.
- Examples of road pricing schemes in major European cities already exist and have demonstrated the potential to promote a modal shift to public transport and to reduce volumes of car traffic, with resulting positive social and environmental impacts.
- Road pricing is a useful tool to limit the digital rebound effects that can be induced by deploying other technologies. These can reduce some operational costs of road transport or can make it more attractive, thus increasing the demand for it.
- Road pricing offers an alternative source for revenue for government that fuel taxation may not provide at a time when electrification is taking off. Road transport will continue to have impacts even once full-scale electrification is realised.
- User acceptance and lack of political willingness are currently the main barriers to a greater uptake of such schemes.

5.7.3 Bottom line

The internalisation of road transport costs enabled by digitalisation is an effective tool to raise awareness among end users of the real impact of their transport choices and to account for the significant costs the transport sector incurs for society. It is seen as an effective tool to promote a shift to more sustainable and considerate modes of transport. Additional information can be found in Annex 7 and in the cases studies discussed there.

5.8 Factsheet 8 — Air traffic management

Air traffic management (ATM) is a term that encompasses all those services necessary for the sound operation of the infrastructure that supports safe air travel. ATM is one of the many operations that enables air mobility and has its own specific tasks and responsibilities. It comprises three main services: air traffic services including air traffic control, air traffic flow management and airspace management.

5.8.1 Motivation

In recent years, the aviation sector has seen significantly increasing volumes of traffic (excluding contingent contractions due to exogenous shocks such as the COVID-19 pandemic) with consequent increases in emissions of both greenhouse gases and different classes of air pollutants. Due to its specific characteristics (such as technical complexity, safety requirements, business organisation), the sector is also particularly difficult to decarbonise. In this context, limiting inefficiencies in the management and operation of the airspace seems an attractive tool to complement other measures such as managing transport demand, deploying low-carbon fuels and technical advances in the design of aeroplanes.

5.8.2 Key conclusions

- The continuously increasing demand for air transport has caused a significant increase in both greenhouse gas emissions and air pollution from the sector. It is unlikely that technological advances alone will be able to curb this increasing trend.
- Digitalisation can play an active role in optimising ATM, increasing fuel efficiency and limiting non-CO_2 effects such as the formation of stable contrails in ice-supersaturated regions.
- The aviation sector is very complex, with many stakeholders involved (e.g. airlines, network managers) that often have conflicting needs and requirements. This will mean that the various trade-offs should be optimised (e.g. noise vs emissions, capacity vs emissions) and that the need to identify priorities is particularly important.
- The indicators used to assess the operational performance of ATM are not always comprehensive in assessing the environmental impacts of inefficiencies in flight planning and selected trajectories and there is room to further improve them.
- Policy will play a key role in reaping the benefits that optimising ATM through advances in digital technology could bring.

5.8.3 Bottom line

Digitalisation has the potential to improve the overall operational efficiency of air traffic by reducing taxi time at airports and optimising flight routes and landing and take-off trajectories. This could reduce emissions by reducing the fuel burned and potentially avoiding contrail formation. Due to the complexity of air travel, there are, however, numerous trade-offs and reducing one externality can exacerbate another. For this reason, these advances should be seen as complementary to additional measures such as using sustainable fuels in aviation. Additional information can be found in Annex 8 and in the cases studies discussed there.

5.9 Factsheet 9 — Digitally enabled monitoring tools

Digital solutions, combining the use of sensors, data transmission and data processing algorithms, can significantly improve the potential of environmental monitoring solutions. These can now be more targeted, operate in real time and in real-use conditions and ultimately support policy development, implementation and enforcement. In addition, they can also be instrumental in transport planning, particularly when considering urban mobility and allocation of the transport infrastructure.

5.9.1 Motivation

The transport sector is constantly growing and, despite the significant progress made in some domains, such as air pollution, remains a source of concern from the environmental perspective, as summarised in Chapter 2. Policies aiming to reduce air pollution or greenhouse gas emissions have become progressively ambitious, setting more stringent targets and at the same time widening their scope of application to, for example, real-world conditions. Innovative monitoring solutions are needed to ensure the proper implementation and enforcement of such policies. These are made possible by some of the digital technologies discussed in Chapter 3. Environmental problems are also becoming increasingly complex, requiring a wider perspective, often spanning different interconnected sectors, as shown, for example, in Factsheet 6. More advanced, improved and a wider scope of monitoring will be a fundamental tool to address these future challenges.

5.9.2 Key conclusions

- Various advanced monitoring techniques exist, with unique features that make them suitable for distinct applications.
- There are still some areas in which there is currently a lack of monitoring (e.g. road vehicles malfunctioning and deliberate tampering). The magnitude of the impacts of these unmonitored issues is not well understood but is expected to be large. Real-time monitoring can fill this knowledge gap, allowing better enforcement of current policies and supporting the development of new ones.
- Remote sensing installations can provide real-time information on air pollution in specific areas, supporting the development and implementation of local policies.
- Plume chasing techniques can easily identify vehicles that are malfunctioning or have been tampered with or vessels that are violating the emission limits in force.
- Continuous onboard real-time monitoring of air pollution emissions and vehicles' energy consumption are solutions that are easily implemented and can enable malfunctioning or non-compliant vehicles to be identified. In addition, they can provide important information on the environmental performance of the circulating fleet. This can be used to support the development of new policies.
- Simple and easy-to-use, digitally-enabled, monitoring tools can be used in citizen science projects, engaging the public in developing and implementing local policies.
- Remote monitoring of oil spills in maritime transport through a combination of satellite imagery and targeted inspection has already demonstrated significant potential to reduce illegal spills with real benefits for the environment.

5.9.3 Bottom line

Digitalisation enables the development of sophisticated monitoring solutions. These allow large amounts of data with an unprecedented level of detail to be collected, filling existing knowledge gaps and ultimately improving the policymaking process. Additional information can be found in Annex 9 and in the cases studies discussed there.

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6
General challenges

Key messages

- **Digitalisation will bring general challenges that are common to the different technologies presented and sectors other than transport.**
- **Digitalisation and the associated infrastructure consume a significant amount of electricity. The International Energy Agency estimates the electricity demand of data centres worldwide in 2020 at approximately 1% of the global final electricity demand. The figure for data transmission networks was 1.1-1.4% in the same year.**
- **The life cycle impact of electrical and electronic appliances is significant. The waste (e-waste) they generate increased from 3 to 4.5 million tonnes between 2011 and 2019. Information technology and telecommunications contributed 14.1% of this waste. Less than 40% of e-waste is recycled.**
- **It is estimated that only 54% of European citizens have at least basic digital skills, and the figure varies across Member States. Digital literacy will become a necessary condition for accessing the innovation digitalisation brings to the mobility system.**
- **With an increasingly digital transport system, data privacy and cybersecurity will be fundamental.**

6.1 Direct environmental impacts

The digital technologies that are discussed in this report also incur direct environmental costs if **additional** equipment is needed, which must be produced and later disposed of, and because of the **additional** operation of the equipment (e.g. additional energy consumption) and the systems that they interact with (e.g. the internet, data centres).

6.1.1 Additional energy consumption

The use of digital technologies and the manufacturing and disposal of the additional equipment needed for their use require additional energy. According to the International Energy Agency (IEA, 2021), global data centres electricity use in 2020 was 200-250TWh, which corresponds to approximately 1% of global final electricity demand (excluding energy used for cryptocurrency mining). In the same year data transmission networks consumed 260-340TWh (1.1-1.4% of global electricity use). Internet traffic was 17 times higher in 2020 than in 2010, and the data centre workload was 9.4 times higher. In the same period, the energy consumption of data centres increased by only 10%. This increase in energy efficiency is expected to improve further in the future (IEA, 2021). The report by the IEA stresses the need for further action by regulators and data centre and network operators to improve efficiency and the uptake of renewable energy in the sector. Furthermore, collecting better data can help to achieve this. The digital strategy of the European Commission (described in Chapter 4) includes as one of its key actions 'initiatives to achieve climate-neutral, highly energy-efficient and sustainable data centres by no later than 2030'. In the voluntary Climate Neutral Data Centre Pact of 2021 European data centre operators and trade associations pledged to make data centres climate neutral by 2030 (Climate Neutral Data Centre Pact, 2021). In 2021, the EU adopted a revised regulation on the ecodesign of servers (EU, 2021a), and the ongoing revision of the Energy Efficiency Directive will also affect future energy consumption in data centres (European Parliament, 2022b).

Apart from the environmental impacts related to data centres and transmission networks, the different digital technologies, such as the automation systems in autonomous vehicles or the sensors that are used for monitoring emissions or traffic, also consume energy.

6.1.2 Life cycle impacts of electrical and electronic equipment

A second environmental externality is related to the production and disposal of the equipment and components used, for example in data centres, networks, sensors and connected devices. Regarding data centres and networks, as the share of renewable energy used in the sector increases, these impacts will become relatively more important (IEA, 2021).

Regarding the end-of-life impacts, it is estimated that 53.6 million tonnes of electronic waste were generated worldwide in 2019 (Statista, 2021). In the EU-27, the amount of electrical and electronic equipment brought to the market increased by almost 50% from 7.6 million tonnes to 11.2 million tonnes between 2011 and 2019. The waste electrical and electronic equipment (e-waste) collected increased from 3 to 4.5 million tonnes (Eurostat, 2022f). Information technology (IT) and telecommunications equipment contributed to 14.1% of this. Less than 40% of e-waste is recycled, with the recycling rate varying widely between EU Member States: from 20.8% in Malta to 81.3% in Croatia (European Parliament, 2020). Similar figures were reported in a recent EEA publication (EEA, 2021g), stressing the fact that such waste streams not only have negative impacts on the environment but also represent a consistent loss of critical resources from EU industry and economy. However, electrical and electronic equipment causes environmental damage not only during its end-of-life stage but also in its manufacturing stage, especially in the raw material sourcing stage.

Several EU policies contribute to reducing the environmental impacts of e-waste. The recast of Directive (2012/19/EU) (EU, 2012) on waste electrical and electronic equipment (WEEE) requires EU companies to follow detailed guidelines on the sourcing, sorting and disposal of electronic waste**.** The EU's proposal for a regulation on eco-design for sustainable products, presented in 2022 (EC, 2022l), includes measures to change the design of equipment such that their lifespan increases, circularity is promoted and the repairability and recyclability of the equipment increases.

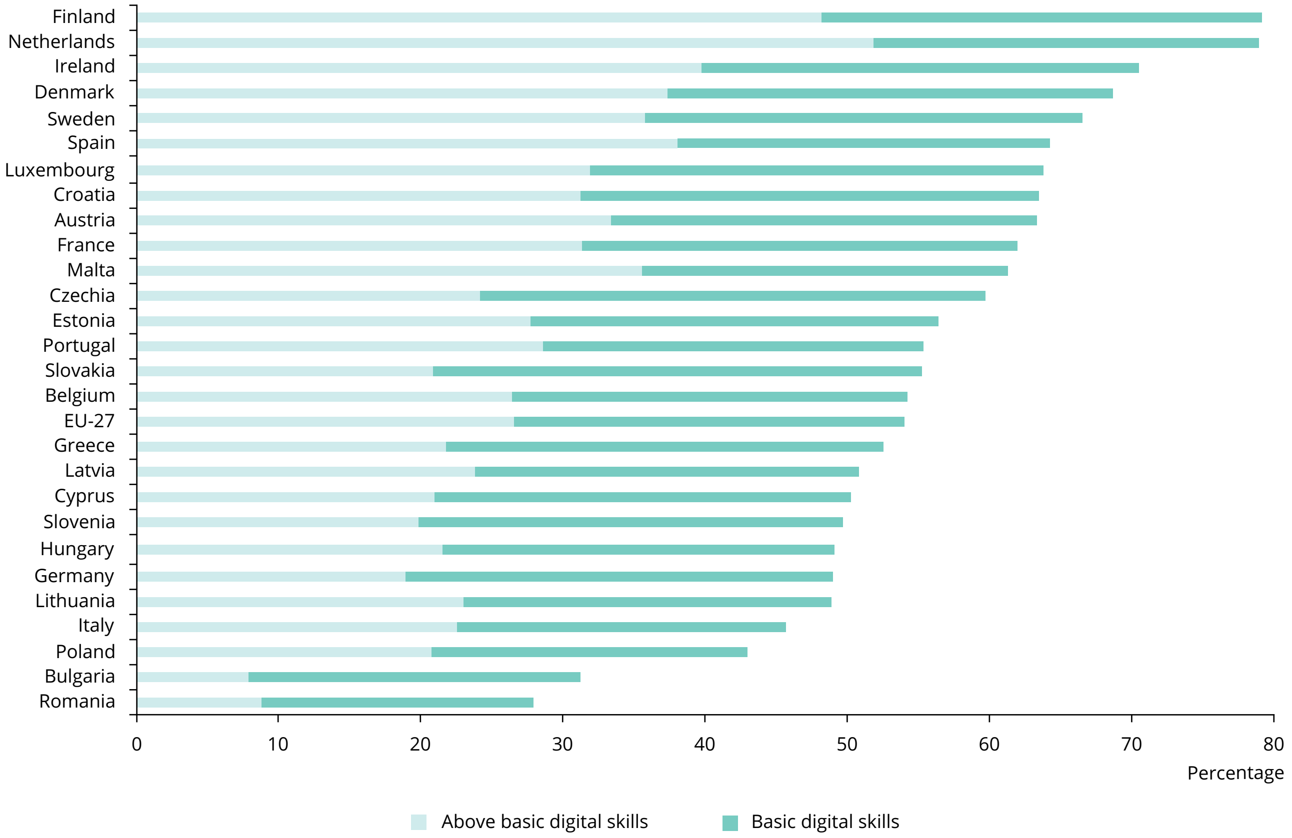
6.2 Digital inclusion

The Digital Economy and Society Index shows that digital skills are still unevenly distributed. Currently, only 54% of European citizens have at least basic digital skills. In 2021 there were 8.9 million information and communications technology (ICT) specialists in employment. The EU target is for at least 80% of people have at least basic digital skills and to increase the number of ICT specialists to 20 million (approximately 10% of total employment). The aim is also to have achieve gender balance by 2030. Currently, only 19% of ICT specialists are women (EC, 2022g). As shown in Figure 6.1 some EU Member States are further from the targets than others. In terms of socio-demographic characteristics, young people are more likely than older people to have at least basic skills (71% in age category 16-24, compared to 25% of people 65 years and older). The share of people with at least basic skills increases with their education level and is larger in urban areas (61%) than in rural areas (46%).

The increasing digitalisation in transport, and in society in general, relies heavily on modern communications technology. Digital literacy will become even more important than it is today. This may pose a problem for people who are digitally less savvy, both in their working life, where digital skills will be required for a wider range of jobs, and in their everyday life (for instance, if they want to access mobility services). Digitalisation is also likely to be used more and more in managing the transport system (e.g. pricing) and its monitoring. Digital skills will therefore be needed to comply with upcoming policies and to have control over the way in which they are monitored.

There are also several co-benefits associated with the digital transformation. For example, providing good traveller information through different channels will lower the threshold for using transport services, as it will for more vulnerable groups, many of which, at least the young members, are also digitally literate. Citizen science projects such as the WeCount project, discussed in Annex 9, give information to a potentially wide range of citizens and can empower them to take part in the mobility debate. Another example is that, in the case of high-performance mobility services and shared autonomous vehicles, the threshold for occasional mobility is lower than when using a private car. Such services could give people with lower incomes and people with mobility problems (e.g. people with a disability, elderly people) access to attractive mobility services, promoting their inclusion.

Figure 6.1 **Basic and above basic digital skills (% of all individuals) in EU Member States, 2021**



Source: EC (2022g).

6.3 Data privacy and protection

The basis of further developments in the transport sector, such as mobility-as-a-service, ride sharing, vehicle sharing, e-working and autonomous vehicles, lies in the evolution of IT. Policies such as road pricing and the monitoring of policies also rely on detailed transport data. All of this means that privacy issues should be considered explicitly.

Centralising data creates large economies of scale in its collection and processing. By performing meta-analyses on these data, personality profiles and other characteristics of individuals can be determined with fairly high accuracy (Sartor, and Lagioia, 2020).

The combination of the abundance of new mobility data and existing data and the availability of new digital approaches to analysing them makes determining individual profiles and characteristics even easier. Through mobility data it is possible, for example, to learn about dining and nightlife preferences, the frequency of visits to someone's favourite café, the location of someone's network of friends and their favourite leisure activities, but also, for example, doctor and hospital visits. If not carefully protected, all of this data collection could cause significant privacy issues (WBGU 2019).

In addition, it is also true that norms and values evolve. Just because a certain behaviour or opinion is acceptable today does not mean that it will be tomorrow. The concept of 'deviating opinion' evolves, and governments also modify their approach to such opinions. It is therefore possible that today certain information may appear non-sensitive and its use generally accepted, but that this will no longer be the case in the future.

Such issues are recognised by the EU and are reflected in the General Data Protection Regulation and the first and second digital agenda, as discussed in Chapter 4.

6.4 Cybersecurity

The growing importance of digital infrastructure and mobility services creates cybersecurity risks (WBGU, 2019). Cyberattacks (sabotage or espionage) on important digital systems could be used militarily (cyber-war). This can create substantial problems if critical infrastructure and services are targeted. Chapter 4 describes a number of legislative actions on this matter that the EU has undertaken.

6.5 Market power of providers of mobility services

In the logistics sector there is a tendency to evolve towards increasing economies of scale: the bigger the company, the more efficiently supply and demand can be matched, which increases competitiveness. This could potentially result in situations in which a few dominant firms develop the capability to distort the market to their advantage. In the longer run, this can even increase the risk of inefficiencies and lack of innovation.

This problem can also occur if, for example, a private player is able to acquire a dominant position as a mobility integrator for passenger transport (see, for example, the discussion in Annex 4). It can put pressure on service providers to promote certain services in a more or less effective way, depending on the margins that the integrator can make. It will be important to have an appropriate framework in place to prevent or mitigate the negative impacts of such distortions.

Similar considerations may hold for any digital platform, including social media, that plays an active role in providing mobility services.

6.6 Economic transitions

The uptake of new digital technologies in transport may have significant consequences for the economy. However, these are difficult to estimate and highly uncertain. For example, if autonomous trucks become a reality, this will have an impact on employment in the sectors affected. In 2019, the land transport and transport pipelines sector employed 5.8 million people in the EU-27 (Eurostat, 2022c). But, on the other hand, the system can also create new jobs by making transport more efficient. Jobs can also be created in the production and development of the vehicles and system elements such as sensors, in the development and refinement of the software, in remote control centres, in companies offering optimised travel services, etc. The switch to such new activities may be accompanied by difficulties for certain individuals because their qualifications no longer match those in demand. For others, it may create additional opportunities. Such considerations will also come into play with other technologies that are still in the process of being developed such as battery electric vehicles, fuel cell electric vehicles or advanced biofuels.

New players will enter the mobility market. In the case of autonomous vehicles, one possible development is that vehicle brands will matter less, while they may be more associated with the service offered. In addition, we can expect improvements in logistics processes to affect companies' choice of location, as it affects relative transport costs.

Improvements in teleworking applications can have a positive impact on the labour market, because teleworking can improve the matching of supply and demand in the labour market. If distance matters less because people can work remotely for several days, they can search for more attractive jobs in more distant locations and it is easier for employers to recruit people (see discussion in Factsheet 1 and Annex 1).

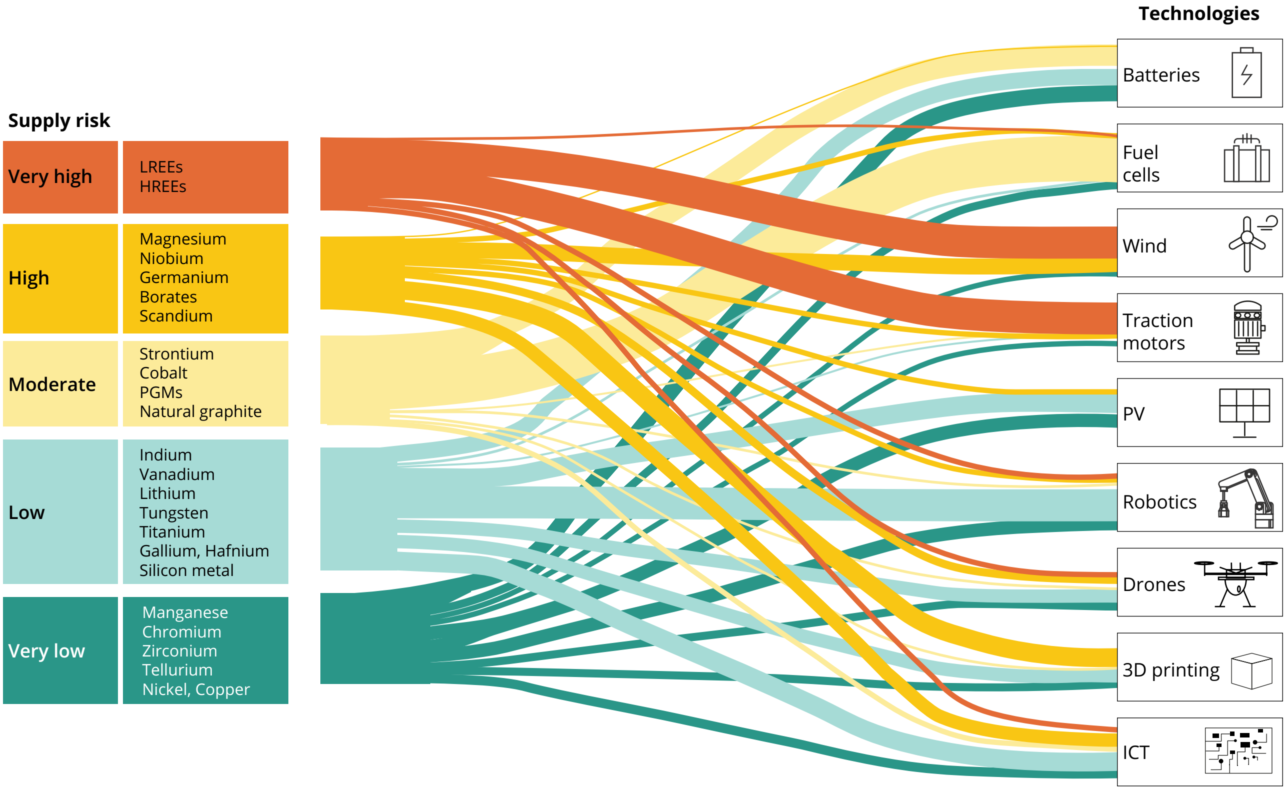
6.7 Impacts of the extraction of the raw materials

Digital technologies require the use of relatively uncommon materials, often known as critical raw materials (CRMs). These are of significant economic importance for the EU and have a high supply risk (Blengnini et al., 2020). The supply risk increases with increasing concentration of the global supply, increasing concentration of EU sourcing, decreasing indicators of the quality of governance in the supply countries, the increasing dependence of the EU on imports, etc. It also increases if there are no good substitutes for the materials or if the substitutes' supply risk is greater. The supply risk falls as the recycling rate increases. Bobba et al. (2020) conducted a foresight analysis of the supply risk for the EU of a selection of CRMs that are used in key technologies (Figure 6.2), in the light of the increasing demand that is expected in the future. The risk is assessed as very high in the case of light and heavy rare earth elements, which are used for a number of the digital technologies considered in this report (batteries, ICT). These also use raw materials with high and moderate supply risks. The EU regularly updates the list of CRMs, most recently in 2020. In its 2020 action plan on CRMs, the EU set out various actions to support the development of a resilient raw materials supply chain (EC, 2020c). In 2021, the Commission also updated its 2020 industrial strategy in the light of the lessons learnt during the COVID-19 pandemic, taking into account strategic dependencies, including those for CRMs (EC, 2021r).

As Vivid Economics (2021) have also pointed out, for materials sourced from outside the EU, problems occur in the case of minerals that are sourced in politically unstable areas and sold to finance armed groups, to fuel forced labour and other human rights abuses, or to support corruption and money laundering. These so-called conflict minerals include tin, tungsten, tantalum and gold. These are used in a variety of electronic products such as smartphones. Efforts to mitigate the use of conflict minerals in supply chains include the development of a voluntary reporting standard known as the conflict minerals reporting template (Responsible Minerals Initiative, 2022), the Organisation for Economic Co-operation and Development due diligence guidance (OECD, 2013), Section 1502 of the US Dodd-Frank Act requiring publicly listed companies in the United States to check for certain conflict minerals and ensure appropriate due diligence in the sourcing of such minerals through the supply chain, or the voluntary Chinese due diligence guidelines for responsible mineral supply chains that were launched in 2015 (OECD, 2015). The EU's Conflict Minerals Regulation, which came into force in 2021, requires EU companies in the supply chain to ensure that they import tin, tungsten, tantalum and their ores, as well as gold, only from responsible and conflict-free sources (EU, 2017b).

Apart from problems with the supply risk and conflict minerals, the mining of these raw materials can have undesirable social or environmental impacts. The International Resource Panel of the United Nations Environment Programme estimated in the recent *Global resource outlook 2019* (UNEP, 2019) that resource extraction and processing of materials, fuels and food account for about half of the total global greenhouse gas emissions (not considering climate impacts related to land use) and more than 90% of biodiversity loss and water stress. For the EU, Mononen et al. (2022) show that mining activities can have a wide variety of potential environmental impacts, depending on the location and size of the mine and the mined ore. They may be related to changes to the land and its topography and landscape (e.g. habitat fragmentation or loss of biodiversity). They may also include impacts on water (e.g. leaks of waste water from mining operations that contaminate nearby groundwater), as well as climate impacts, air pollution, noise, etc. The social impacts (economic, employment, changes in the socio-economic environment) may be both positive and negative. In some cases, human rights issues arise because of poor stakeholder inclusion and decision-making processes, or issues about the rights and consent of indigenous people. However, no systematic assessment of the social and environmental impacts at EU level is yet available (Mononen et al., 2022).

Figure 6.2 Supply risk for 25 selected raw materials for key technologies



Note: LREE, light rare earth elements; HREE, heavy rare earth elements; PGM, platinum group metals; PV, photovoltaics.

Source: Extract from figure 2 in Bobba et al. (2020).

7
Concluding remarks

The TERM 2022 report has explored some of the many ways in which **digitalisation can bring more or less disruptive innovations in the mobility system**. Ranging from teleworking to autonomous ships and trucks or the integrated management of air traffic, the range of opportunities is certainly broad.

The **mobility system is set to undergo a profound transformation**, made necessary by the gravity of the climate crisis and the seriousness of the environmental damage induced by ever-increasing anthropisation, further exacerbated by recent exogenous shocks. Indeed, **despite improvements limited to specific areas**, such as reduced emissions of some air pollutants, the **transport sector continues to exert significant pressure on our biosphere**. According to many indicators (for example, greenhouse gas emissions or the growing demand for transport), the sustainable transition sought looks not only remote but even more distant.

In this context, **digitalisation is often presented as a fit-for-all solution** and, indeed, can herald innovations capable of dramatically changing the way we now think of mobility, as we have discussed in various examples throughout this report. **However, the uncertainties and pitfalls associated with the digital transition should not be underestimated**. As discussed throughout the report and within the technical annexes, many knowledge gaps exist, and quantifying the impacts is often made extremely difficult by the significant rebound effects involved.

This is a measure of the interconnections and the links that the mobility system has with many other aspects of our economy and society: energy, land use and food systems to name a few. If this report has to convey a single message , it is that **a system-wide approach to policy**, able to embrace such complexity, **is more than ever crucial**.

We have illustrated how the efficiency increases that can be realised by introducing digital technologies in the mobility system can be easily counterbalanced by an induced rise in transport demand. Breaking this loop and **curbing this continuously increasing demand for transport services are necessary conditions to achieve the objective the sector is called on to deliver**.

The final cost of a mobility solution seldom reflects the real impact that it has on society and the environment. This gives the final users of transport services a distorted perception and results in them often choosing the option they perceive as more economically convenient. **Digital systems can be used to internalise the additional costs that transport generates and that are currently unaccounted for**. This can induce a shift to more sustainable transport modes and ultimately realise a fair mobility system.

A digital transformation of both our society and the mobility system is already occurring — and at a rapid pace. **Private actors and public authorities have** both the power and **the responsibility to** guide this transition and to **ensure that digitalisation** will live up to its promise and be the game changer that **can steer the mobility system towards a just, inclusive and sustainable transition**.

Abbreviations, symbols and units

3D	Three dimensional
5G	Fifth-generation mobile network
μm	Micrometre
A-CDM	Airport collaborative decisions-making
AI	Artificial Intelligence
ANPR	Automatic number plate recognition
ANSP	Air navigation service provider
A-S-I	Avoid, shift, improve
ASM	Air space management
ASMA	Arrival sequencing and metering area
ATC	Air traffic control
ATM	Air traffic management
ATS	Air traffic services
AV	Autonomous vehicle
CCNR	Central Commission for the Navigation of the Rhine
CCO	Continuous climb operations
CDO	Continuous descent operations
CO	Carbon monoxide
CO_2	Carbon dioxide
CO_2e	CO_2 equivalent
COVID-19	Coronavirus disease 2019

dB	Decibel
DESI	Digital Economy and Society Index
DSO	Distribution system operator
DSR	Demand-side response
DTLF	Digital Transport and Logistic Forum
EAP	Environment Action Programme
EEA	European Environment Agency
eFTI	Electronic freight transport information
EMSA	European Maritime Safety Agency
END	Environmental Noise Directive
ERTMS	European Railway Traffic Management System
ETS	Emissions Trading System
EU	European Union
EU-27	27 EU Member States
EUR	Euro
EV	Electric vehicle
FRA	Free route airspace
GDP	Gross domestic product
GHG	Greenhouse gas
GIS	Geographical information system
GNSS	Global navigation satellite system
HDV	Heavy-duty vehicle
Helcom	Helsinki Commission
ICT	Information and communications technology
IoT	Internet of things
IMO	International Maritime Organization

IT	Information technology
ITS	Intelligent transport system
km	Kilometre
kWh	Kilowatt-hour
L_{den}	Day-evening-night noise level
L_{night}	Night noise level
LEZ	Low-emission zone
LNG	Liquefied natural gas
MaaS	Mobility-as-a-service
MASS	Maritime autonomous surface ship
MDMS	Multimodal digital mobility services
nm	nanometre
NO_2	Nitrogen dioxide
N_2O	Nitrous oxide
NOx	Nitrogen oxides
OBFCM	Onboard fuel and/or energy consumption monitoring
OECD	Organisation for Economic Co-operation and Development
PEMS	Portable emissions measurement systems
PHES	Pumped hydro energy storage
PHEV	Plug-in hybrid electric vehicle
PM	Particulate matter
$PM_{2.5}$	Particulate matter with a diameter of 2.5μm or less
PM_{10}	Particulate matter with a diameter of 10μm or less

PV	Photovoltaics
R&D	Research and development
RIS	River Information Service
RPAS	Remotely piloted aircraft system
SAE	Society of Automative Engineers
SAR	Synthetic aperture radar
SAV	Shared autonomous vehicle
SECA	SOx emission control area
SES	Single European Sky
SMEs	Small and medium-sized enterprises
SOx	Sulphur oxides
SSS	Short sea shipping
TaaS	Transport-as-a-service
toe	Tonne of oil equivalent
TSO	Transmission system operator
USD	US dollar
V2G	Vehicle-to-grid
V2X	Vehicle-to-everything
VGI	Vehicle-grid integration
VIN	Vehicle identification number
VRE	Variable renewable electricity
WHO	World Health Organization

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Annex 1
Teleworking and virtual mobility

A-S-I: avoid (fewer/shorter trips)

Context: passenger road transport, urban/rural

Time frame: short term

A1.1 Definition

The meaning of teleworking has changed over time, following the evolution of technology. An early definition of the term was the use of 'telecommunications technology at home, or at a location close to home, during regular work hours, instead of commuting to a conventional workplace' (Mokhtarian, 1991). Nowadays, teleworking is often used to identify working arrangements outside employers' premises enabled by information and communications technology (EU, 2019d). In more detail, the European social partners ([8]) define telework as 'a form of organizing and/or performing work, using information technology, in the context of an employment contract/relationship, where work, which could also be performed at the employers premises, is carried out away from those premises on a regular basis' (ETUC et al., 2002). A comprehensive review of how the definition has evolved over time can be found in a recent Eurofound publication (Eurofound, 2022b).

Relevant to this factsheet is that such a working arrangement permits avoiding one or more commuting trips during the week, shortening their distance (e.g. if work is carried out in a co-working space closer to the employee's home) or shifting them to times in which their impact is lower (e.g. due to reduced congestion; for a detailed discussion of this aspect, see also Factsheet 7 and Annex 7), in which case the environmental impacts will be smaller. Teleworking can have an impact on transport demand, not only if implemented on a regular basis but also when used only occasionally, albeit to a smaller extent, as will be discussed in this annex.

Depending on how these arrangements are configured, the magnitude of their impact on the transport system and the environment could be different, as also discussed by Eurofound (2022a). One can telework at home for all or part of the day (e.g. to avoid rush hour) or at another location for all or part of a day. The other location can be a co-working space that is shared by workers of different companies or a satellite office of the worker's company. In that case workers can make use of office facilities they require for their job. It could also be a non-dedicated location (e.g. café, library). An further case is the that of people who normally work at home (e.g. self-employed people) or people with decentralised activities.

Teleworking is enabled by many of the digital technologies presented in Chapter 3, such as the internet, email, broadband connectivity, laptops, smartphones, cloud computing and videotelephony.

A1.2 Context

Teleworking mainly acts on the demand for passenger transport for commuting. As anticipated, it affects the number of commuting trips and, when it is done from a location different from the worker's home, their average distance. Depending on the remote work location, the share of urban/non-urban travel can also be affected. Considering urban mobility in 12 EU Member States ([9]), commuting is responsible on average for approximately 27-47% of the daily distance travelled, with a daily distance ranging between 5.6km and 19km (Eurostat, 2021b).

According to the Labour Force Survey reported by Eurostat, the share of employees who usually work from home ([10]) increased to 10.8% in 2020 in the EU-27, while this share ranged between 2.6% and 3.3% in the 2010-2019 period. In the case of self-employed people, the share grew less prominently, going from 16.3% to 19.4% in the previous

([8]) The social partners represent employees and employers: the European Trade Union Confederation (ETUC) and three organisations on the employers' side: BusinessEurope (private firms), SMEunited (small businesses and craft businesses; formerly UEAPME) and CEEP (public employers).

([9]) 'Urban mobility' is defined as trips made by urban residents with an origin and destination within the same functional urban area (a city and its commuting zone). The 12 Member States are: Austria, Belgium, Croatia, Denmark, Germany, Greece, Italy, Latvia, Poland, Portugal, Romania and Slovenia.

([10]) 'Usually working at home' is defined as doing at home any productive work related to the current job for at least half of the days worked in a reference period of 4 weeks.

decade to 22% in 2020. When both groups are taken together, the share grew from around 5% in the previous decade to 12.3% in 2020 (Eurostat, 2021c). In parallel, the share of people (employees and self-employed) who sometimes work at home grew from 6.2% in 2010 to 9% in 2019, falling somewhat in 2020 to 8.6%, again due to COVID-19 containment measures.

In 21 NUTS 2 regions ([11]) the share of employed people usually working from home was at least 12.0 percentage points higher in 2020 than in 2019. These included the capital regions of Belgium, Finland, Denmark, Germany, Ireland, Spain, France, Italy, Austria and Portugal, while the remaining regions mostly consisted of urban areas. One of the explanations for such geographical disparities is the economic structure of these regions, which have a large share of the professional, financial, information and communication, education and government sectors. For people working in the agriculture, manufacturing or distributive trades sectors, it is difficult or even impossible to work at home (Eurostat, 2021d).

In the past 2 years, because of the policy measures to contain the COVID-19 pandemic, a lot of people have worked from home. The Eurofound e-survey 'Living, working and COVID-19' showed that, in spring 2021, 24% of workers worked only at home and 18% in combination with working at their employer's premises or in other locations (Table A1.1) (Ahrendt, et al., 2021).

Although the COVID-19 pandemic has accelerated the uptake of teleworking and demonstrated its large-scale feasibility, not all work can be performed remotely. Sostero et al. (2020) estimate the maximum potential for teleworking in the EU-27. The study defines teleworkability as 'the technical possibility of providing labour input remotely into a given economic process'. It is determined based on occupational task descriptions and indicators from the European Working Conditions Survey and the Italian survey 'Indagine Campionaria delle Professioni'. Figure A1.1 presents the share of teleworkable employment by sector in the EU-27. It is highest in the financial services sector (93%), in information and communication (79%) and around 65% in real estate, professional, scientific and technical activities, education and public administration. The share is lower in health (30%), retail (27%) and accommodation and food services (16%). The primary sector, manufacturing and construction sector have the lowest shares (10-20%). Because of sectoral specialisation at the regional level, there are significant differences in access to telework between urban and rural areas. In cities, where the share of service employment is generally high, the share of teleworkable employment is also higher (44%) than in towns or suburbs (35%), or rural areas (29%). The differences are also significant across income quintiles. Of those employed in the highest paying quintile, 74% can telework. For the mid-paying and mid-high paying jobs (third and fourth quintiles) this lies above 40% and 50%, respectively. For the second quintile it is around 12%, and for the lowest paying quintile it is only 3%. As income quintiles are related to education level, teleworkability is also lowest for people with a low education level.

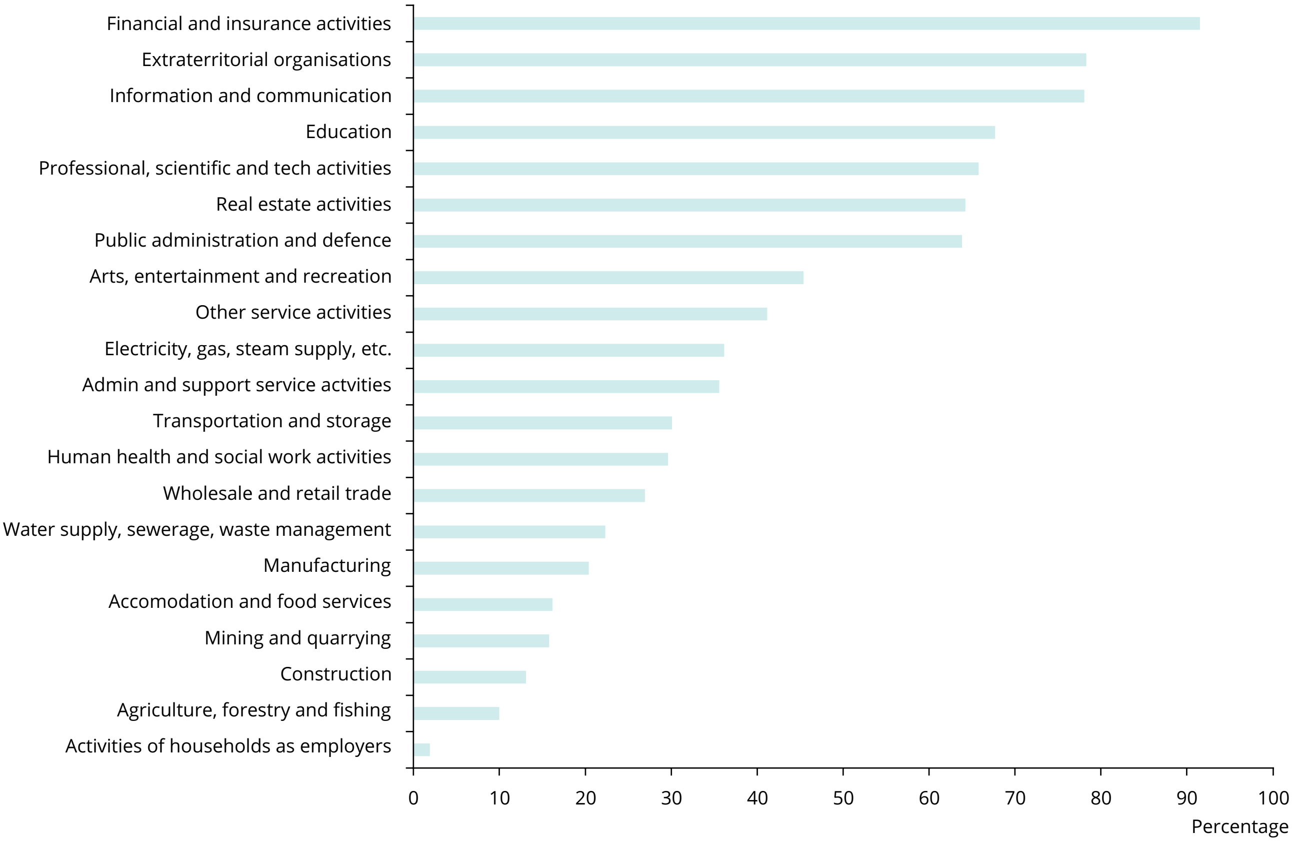
Table A1.1 Location of work and average hours worked during the pandemic in the EU-27 (%)

	Summer 2020	Spring 2021
Home only	34%	24%
Combination of home and employer's premises/other locations	14%	18%
Employer's premises/other locations only	52%	59%
Average hours worked from home (overall)	35%	36%
Average hours worked from home (for people who worked from home)	77%	73%

Source: Ahrendt et al. (2021).

([11]) The NUTS classification (Nomenclature of Territorial Units for Statistics) is a hierarchical system for dividing up the economic territory of the EU and the United Kingdom. While the NUTS 1 regions are the major socio-economic regions, the NUTS 2 regions are the basic regions for applying regional policies.

Figure A1.1 Share of teleworkable employment by sector in the EU-27

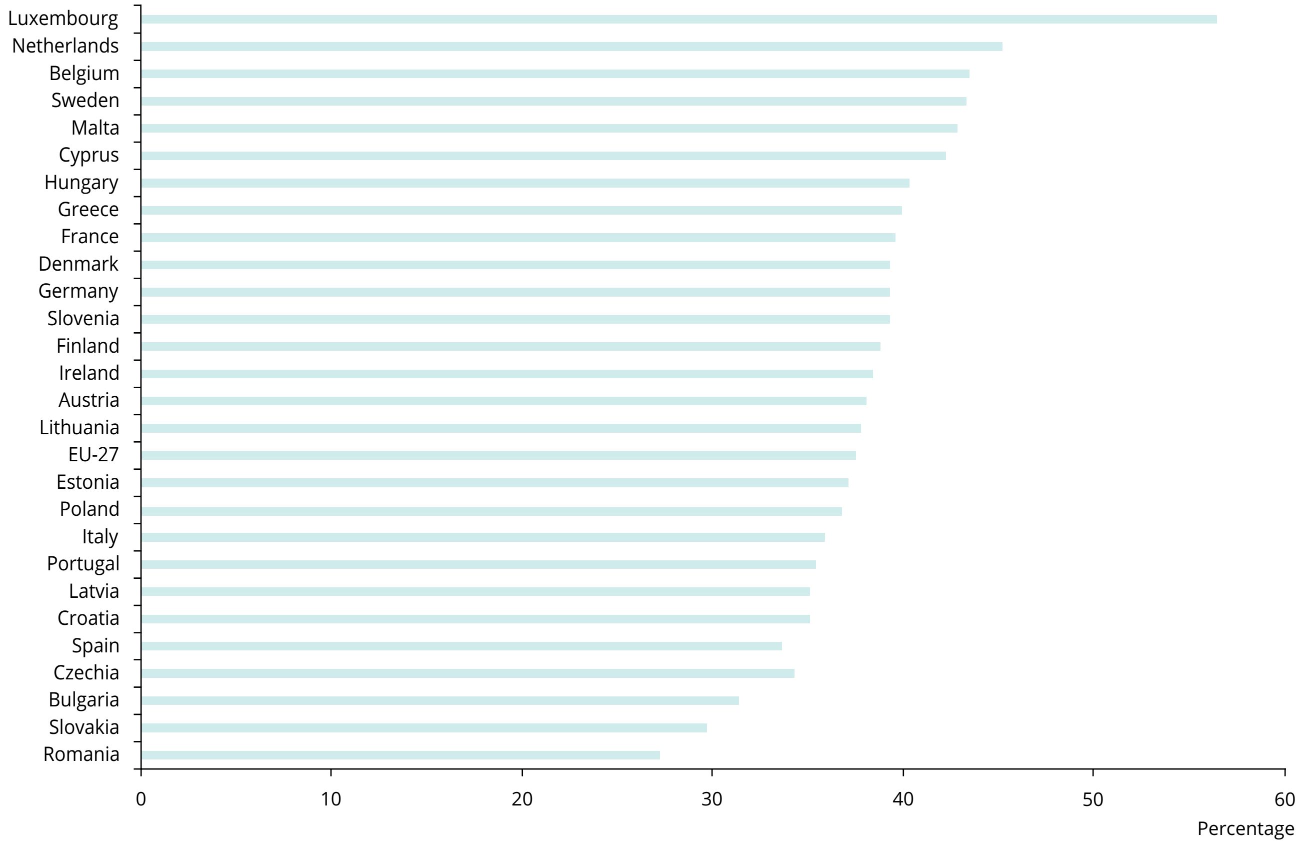


Note: Employees only.

Source: Sostero et al. (2020).

The share of teleworkable employment varies not only between urban and rural areas but also across the different EU Member States (Figure A1.2). The share ranges from 27% for Romania up to 54% for Luxembourg, with an EU-27 average of 37%. This is again linked to the relative importance of the economic sectors and their specific teleworkable profiles across the Member States. These findings on the share of teleworkable jobs are broadly in line with estimates for European countries given by Dingel and Neiman (2020).

Figure A1.2 Share of teleworkable employment in the EU-27, by Member State



Note: Employees only.
Source: Sostero et al. (2020).

A1.3 Time frame

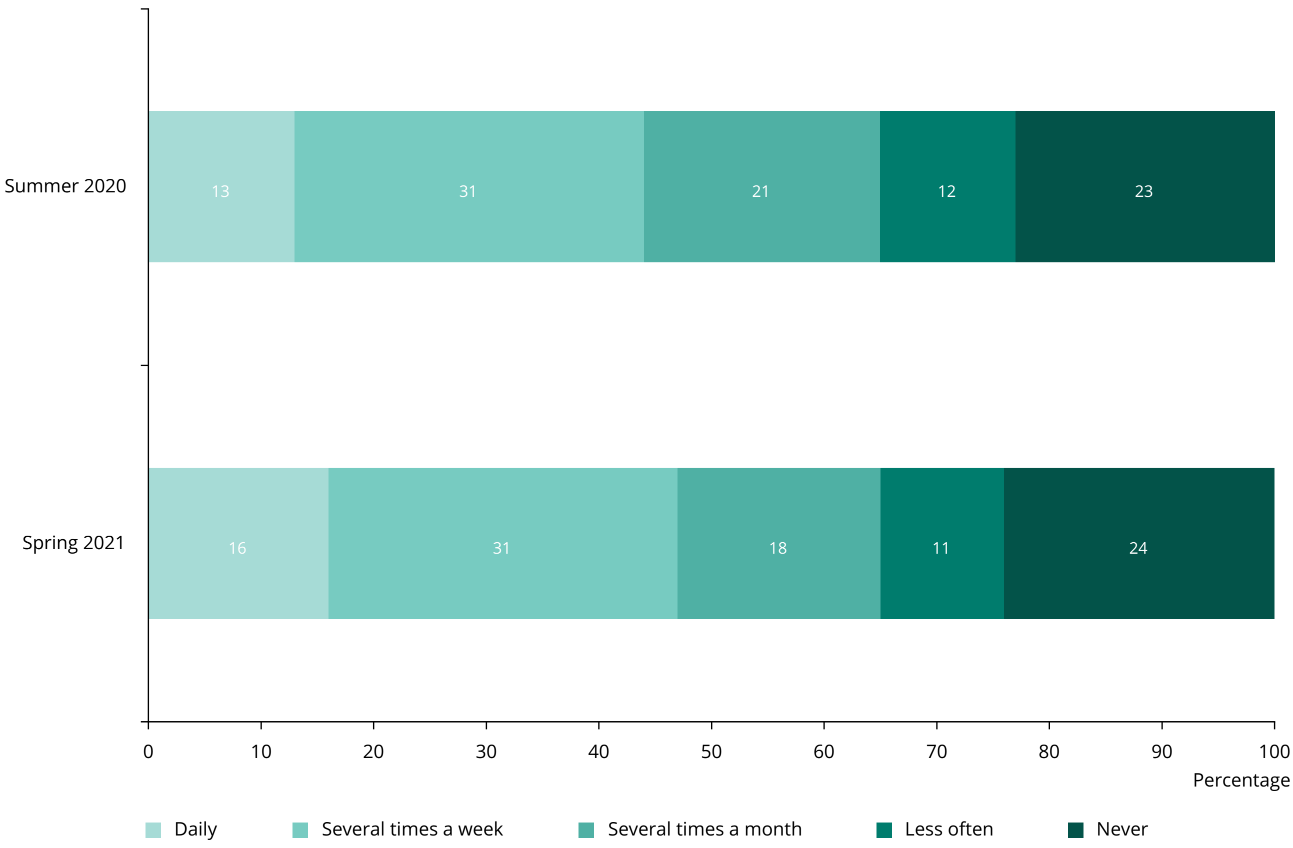
The widespread use of teleworking during the COVID-19 pandemic has made it possible to investigate on a large scale its potential advantages and disadvantages, for both workers and companies. This offers a window of opportunity for a structural increase in the uptake of teleworking in future years and to find solutions for the problems encountered. As an example of the interest in the development of this technology, in the period between January and September 2020 in the United States, the share of teleworking-related patents among new applications more than doubled (The Economist, 2022).

The positive experience of teleworking during the COVID-19 pandemic is likely to have a beneficial effect on the uptake of teleworking, especially in the short- and medium-term future. At the EU level, results from a Eurofound e-survey, 'Living, working and COVID-19', reported in Figure A1.3, indicate that in the post-pandemic period, most employees still express a preference to combine working from home with working from the employer's premises, with the most popular choice being to work from home several times a week (Ahrendt et al., 2021).

In another survey by Olde Kalter et al. (2021) among 1,515 Dutch employees, office workers state that they will telework more after COVID-19 than before. Positive experiences of teleworking, such as the potential for a better work-life balance without loss of productivity, increased familiarity with information and communications technology (ICT) facilities and other support offered by the employers, strengthened this effect. Similarly, a Eurofound e-survey indicates that 'most of the EU workers expressed a preference to work from home several times per week in the long term' (Eurofound 2021). Additional information on this specific topic can be found in a recent report from the US National Bureau of Economic Research (Bloom et al., 2022). Ton et al. (2022) studied willingness to telework after the COVID-19 pandemic among train travellers in the Netherlands (both frequent and less frequent train users). Of these people, 71% reported a high willingness to telework, which could potentially have a large impact on public transport use. In contrast, about 16% reported a low willingness to telework, mostly because they disliked it or their organisations are not yet ready. Lastly, 12% were self-employed workers whose working arrangement was almost not affected by the pandemic.

It is likely that the future uptake of teleworking will be strengthened by several ongoing developments, including those related to new regulatory frameworks, as discussed in Section A1.5. For example, with an increasingly digitally-enabled society, the potential for teleworking will also grow, expanding to include jobs in which remote intervention has been impossible until now. The growing share of the tertiary sector will also lead to greater potential for teleworking, especially for office-based knowledge-intensive work (Hurley, 2021). ICT and software tools for teleworking are also expected to be developed further, making the experience even more attractive and virtual exchanges more effective (Frey, et al., 2020).

Figure A1.3 Preference for working from home post pandemic in the EU-27 (%)



Source: Ahrendt et al. (2021).

A1.4 Expected environmental impacts

Using the taxonomy set out in Chapter 3, the following higher order environmental impacts of teleworking can be identified.

A1.4.1 Indirect effects — efficiency effects

The first group of environmental effects is related to the change from the conventional workplace to the home office or another location. For employers, teleworking offers the potential to reduce the environmental impacts of the office locations (conventional workplace, satellite offices or co-working locations). Indeed, with teleworking, firms have opportunities to optimise their offices (e.g. in terms of occupancy), which may lead to smaller offices and less need for new buildings. This is discussed in more detail in case study 1.1, in which the importance of the options chosen for office buildings is investigated.

In this context, it is important to evaluate the extent to which any reduction in energy consumption at the office is offset by a corresponding increase in energy consumption at home. This depends, first, on the energy efficiency of the home office and the share of more environmentally friendly energy sources at home. In the EU, the average energy consumption per dwelling in 2019 was 1.3 tonnes of oil equivalent (toe) ([12]). It ranged from 0.5toe/dwelling in Malta to 2.3toe/dwelling in Luxembourg. On average, space heating accounted for 65% of this average energy consumption or 0.85toe/dwelling in the EU. The consumption per dwelling fell by 1.0% per year (Enerdata, 2021). The average external cost in the residential sector in the EU in 2018 was EUR 884/toe, an estimate based on a life cycle analysis (Smith, Moerenhout et al., 2020). In 2020, the main use of energy by households was for space heating (62.8% of final energy consumption in the residential sector), while the electricity used for lighting and most electrical appliances represented 14.5% (Eurostat, 2022g). In the EU-27, since 2000, the energy consumption per m^2 for space heating fell by 2.1%/year over 2000-2014 and to 0.6%/year over 2014-2019 (Enerdata, 2021). This is a relatively slow decrease, as dwellings are typically used many decades before they are rebuilt or fully renovated. The weighted annual energy renovation rate at EU level is only around 1% ([13]). This applies to both residential and non-residential buildings (EC, 2021s). The share of renewables and biofuels in space heating was 26.8% in 2020 (Eurostat, 2022g).

The extent to which energy consumption at home increases with teleworking is the second factor that determines the environmental cost of teleworking at home. It can vary significantly depending on the specific situation. For example, if other household members stay at home on the days that one works in the office, and consequently the home is heated or cooled anyway, the extra energy required for teleworking will be relatively small. Moreover, the additional surface that needs to be heated or cooled will vary from person to person. Case study 1.1 illustrates the impact of teleworking on greenhouse gas (GHG) emissions at home in France.

Over time it can be expected that the environmental impact associated with the choice of a specific work location will change, as the environmental performance of the buildings will improve. Under the influence of policies such as the Renewable Energy Directive (recast) and the Directive on the energy efficiency of buildings, both of which are being revised at the moment, the building stock will become more energy efficient and energy sources will become cleaner.

A1.4.2 Indirect effects — substitution effects

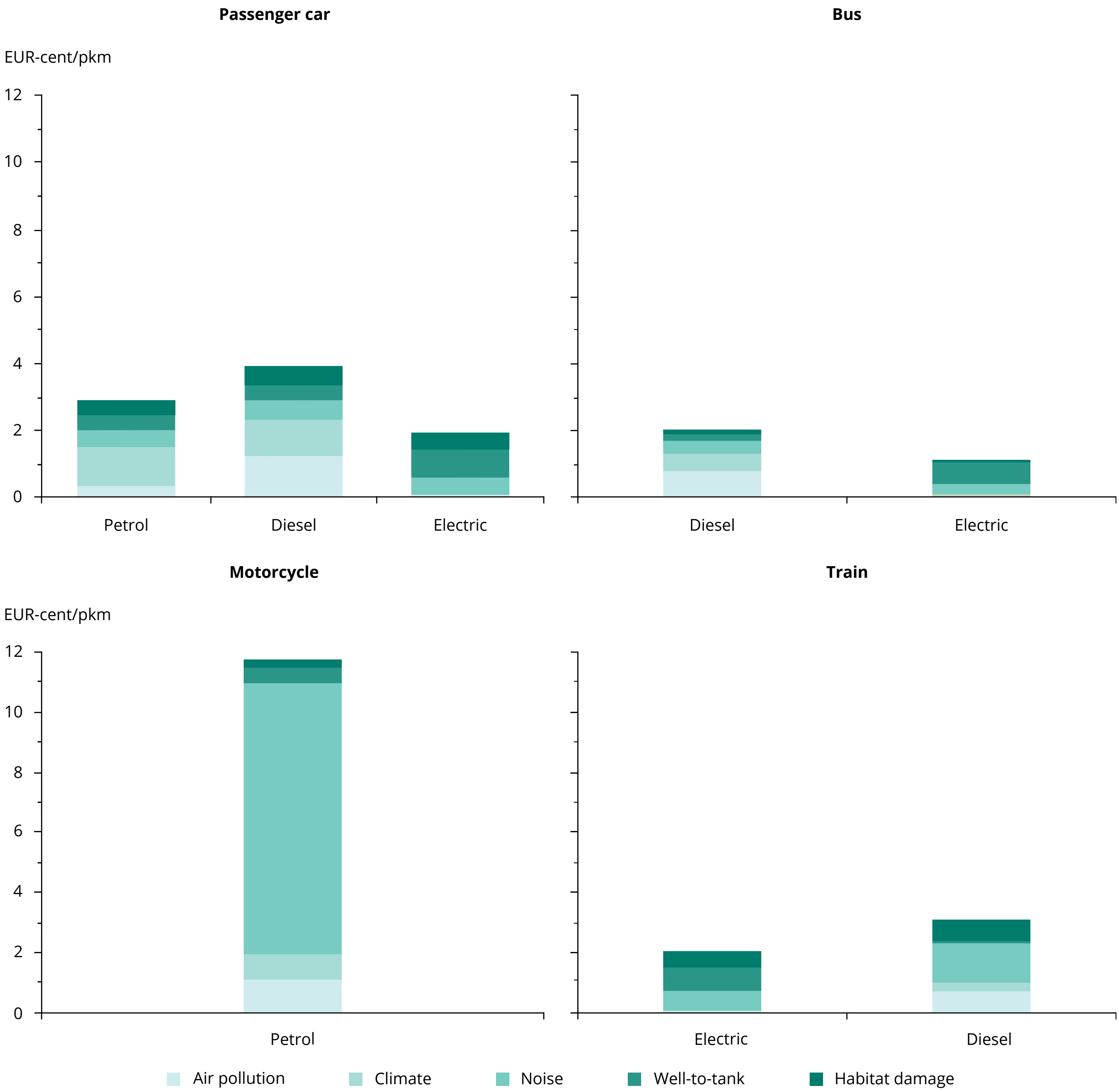
As discussed in previous sections, teleworking brings environmental benefits, as the number of commuting trips is reduced or shortened (e.g. if a co-working space closer to the employee's home is used). To a lesser extent there could also be environmental benefits when commuting trips by car are shifted to times with less road network congestion, reducing emissions per kilometre. Everything else being equal, the potential environmental benefits increase with the commuting distance to the conventional workplace. In the case of people who telework at locations other than home, they still need to make a trip. While the number of trips does not change in this case, the commuting distance does. In some cases, the distance can be much shorter, making active transport modes more attractive.

The environmental impacts also depend on the transport modes normally used when commuting to the conventional workplace. Following the approach presented in the *Handbook of the external costs of transport* (EC, 2019a), it is possible to estimate the costs per passenger-km for different transport modes. As shown in Figure A1.4, these are highest for people commuting by a petrol motorcycle, a car with an internal combustion engine or a diesel train. Hence, these people realise the highest potential benefit from teleworking. For people normally commuting by electric car, electric train, bus/tram/metro or active transport modes the positive impact is smaller or zero.

([12]) 1toe corresponds to 41.84GJ.

([13]) The term 'weighted annual energy renovation rate' refers to 'the annual reduction of primary energy consumption in the total building stock achieved through the sum of energy renovations at all depths (light, medium and deep)'.

Figure A1.4 **Average external cost per passenger-km in 2016 (EUR-cent/pkm)**

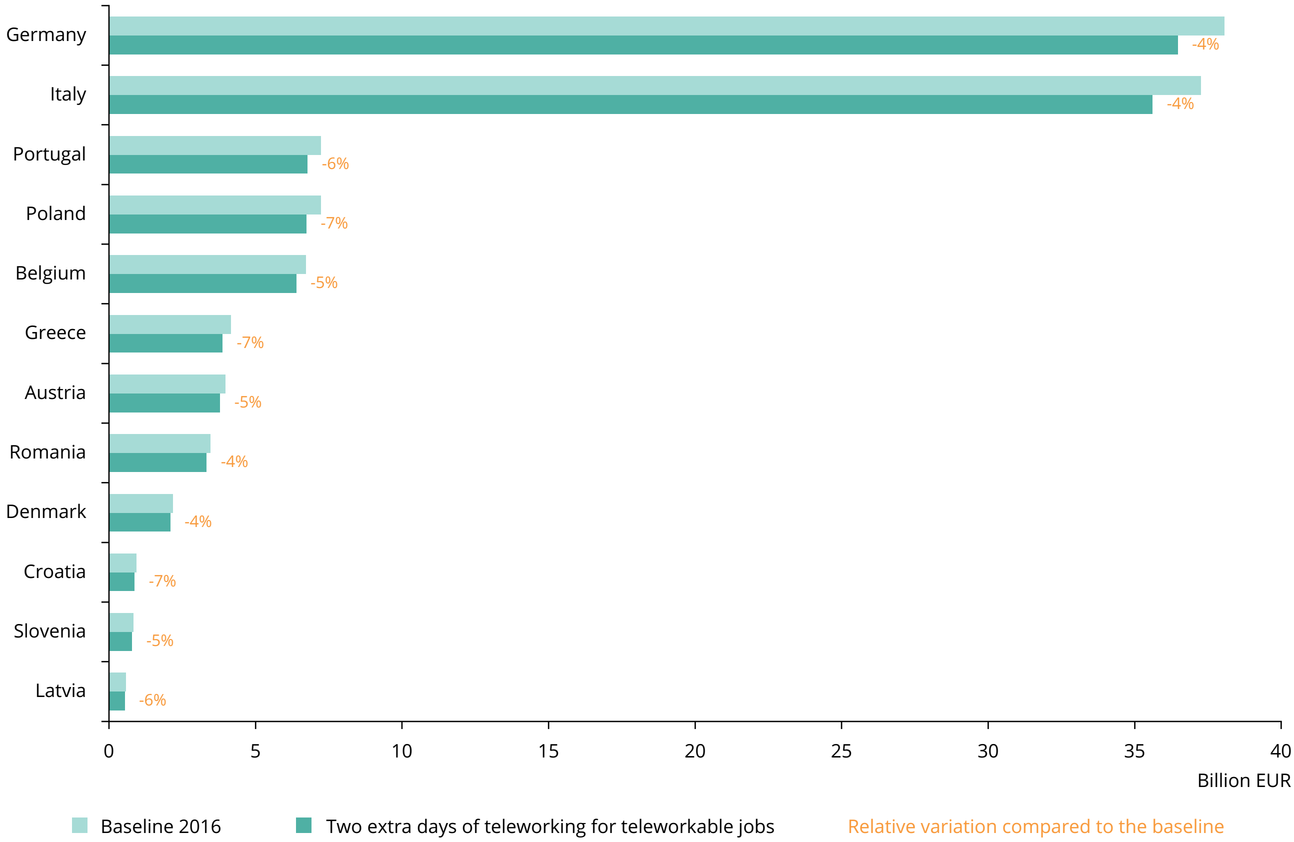


Note: Due to the unavailability of an estimate for the noise costs of electric vehicles, these are assumed to be the same as for vehicles with an internal combustion engine.

Source: EC (2019a).

On the basis of these costs, Figure A1.5 presents an approximate indication of the substitution effect that can be obtained by two extra days per week of teleworking at home (for the jobs for which this is possible) in 12 EU Member States, under a series of assumptions. First, the baseline external environmental costs are based on the Commission's estimates for 2016 (EC, 2019a). The baseline teleworking situation reflects that of the same year. Second, the share of commuting in passenger transport is based on passenger mobility statistics for the 12 countries for urban trips, as published by Eurostat (2021b). Third, the maximum share of teleworkable jobs in each country is taken from Sostero et al. (2020) and is applied to all workers, although these estimates apply to employees only, as no information is available for self-employed people (Figure A1.2). Under these assumptions, the impact of the two additional days of teleworking on environmental costs ranges between 4% and 7%. It should be stated that, given the assumptions made and not considering rebound effects, such an approximate estimate could be optimistic. It is, however, in line with other estimates, such as the two case studies discussed at the end of this factsheet and in Eurofound (2022a).

Figure A1.5 **Approximate estimate of the substitution effect of two additional days of teleworking for employees who can telework — impact on the external environmental costs of passenger transport in 12 EU Member States (EUR billion)**



Notes: Approximation assuming that the share of commuting in passenger-km is the same for all transport modes and for urban and non-urban trips, and that the share of teleworkable jobs applies to employees and self-employed people.

The percentages refer to the percentage change compared to the baseline.

Source: EEA compilation, based on EC (2019a), Eurostat (2021b) and Sostero et al. (2020),

The environmental benefits of less travel by motorised modes are likely to diminish in the future, as these modes will become more environmentally friendly. This is illustrated by the difference in environmental costs per passenger-km between vehicles with an internal combustion engine and electric vehicles in Figure A1.4. The change to cleaner transport will take place gradually, as new vehicles penetrate the fleet. The average lifespan of cars in Europe ranges between 8.0 and 35.1 years, with a mean of 18.1 years in western Europe and 28.4 years in eastern Europe (this difference reflects the importance of cross-border trade) (Held et al., 2021).

A1.4.3 Structural and behavioural effects — direct rebound effects

By teleworking people spend less money and time on commuting. This frees up resources that can be spent on other trips or other goods and services. The car used for commuting could also be used by family members. (Henderson, and Mokhtarian, 1996; Koenig et al., 1996; Zhu, 2012; Greenworking and ADEME 2020).

A1.4.4 Structural and behavioural effects — economy-wide rebound

The economy-wide rebound can include several effects. For example, if fewer people commute by car, this will reduce congestion, and this could attract new car traffic. Transport models can give an insight into the magnitude of such effects. An example is given in case study 1.2.

Similarly, a reduction in the demand for public transport may cause revenues from public transport to fall. As a consequence, the supply of public transport may be negatively affected in the short and mid-term, leading to more private transport being used by the workers that can afford it.

In general, there can be environmental impacts in multiple markets owing to economy-wide adjustments in prices and quantities (e.g. when congestion is reduced because of teleworking, this will benefit sectors that are heavily dependent on road transport).

The first two impacts will depend on transport policy, for example the extent to which transport externalities such as congestion are internalised or the extent to which public transport is subsidised. The last type of environmental impacts is more difficult to quantify. Its evaluation requires complex economic models that can capture the economic consequences of teleworking.

A1.4.5 Structural and behavioural effects — transformational changes

Teleworking can lead to transformational changes. For example, as teleworkers spend less money and time on commuting, they can decide to change their work location or place of residence. For example, they may decide to move to a more distant location with lower house prices and more environmental amenities. Such decisions have an impact on the distance of the remaining commuting trips. On the other side of the labour market, teleworking increases the recruitment area or the locational patterns of firms. Through these channels, teleworking can be expected to affect urban structures (e.g. demand for residential or office spaces) and land use in the long term. Such changes are, however, difficult to quantify.

A1.5 Policy corner

During the COVID-19 pandemic many employees and employers adopted teleworking. From this experience, lessons have been learnt about the possible advantages of teleworking, such as:

- There is a financial benefit for workers, as commuting costs are lower. In times of rising inflation and more expensive commuting, telework also offers a way to save money.
- Workers have extra flexibility in how they combine work and private life.
- Work activities become more robust in the event of exogenous shocks, of which the pandemic is an example. Other examples of shocks include the ongoing energy crisis, natural disasters, national security issues or public transport strikes.

Other advantages for employees are that they have access to more job opportunities. With the same money and time budgets for commuting, jobs at greater distances become possible. If teleworking is applied at a larger scale in combination with additional pricing measures, such as those investigated in Factsheet 7 and Annex 7, it can be expected to lead to less congestion, and therefore shorter commuting times on the days without teleworking. On public transport it may lead to less crowding during peak hours. Employers can have access to a larger pool of potential workers and increase their attractiveness compared to other employers by offering the possibility to telework.

Nevertheless, there are also challenges associated with teleworking, for example the organisation of working hours (Predotova, and Vargas Llave, 2021), which may require further legislative initiatives. A Eurofound publication presents an overview of existing regulations and the need for new regulations to improve the working conditions of teleworkers. This could involve, for example, regulations on the right to disconnect to ensure a good balance between work and private life and the employer's provision of equipment for the home office, etc. (Eurofound, 2022b). To maximise the benefits, a framework that supports the positive environmental effects of teleworking (e.g. encouraging the optimal organisation of office spaces) and mitigates the negative rebound effects (e.g. internalisation of external costs, good land use planning, taxation of housing in urban and rural areas) should also be considered.

A1.6 Bottom line

While teleworking is already in use in many cases and forms part of current possible working arrangements, also in response to the COVID-19 pandemic, its net environmental impacts are generally complex and therefore difficult to quantify. Hook et al. (2020) carried out an extensive review of 39 empirical studies on the impact of teleworking on energy use. While most of these studies indicate energy savings, the authors point out that this is because the scope of those studies is relatively narrow, as they focus on the substitution effects. The structural and behavioural effects are often not considered and are in some cases difficult to estimate properly. These are potentially large and can easily counteract the substitution effects. Therefore, it is important to include them in the analysis as far as possible.

The size of the environmental impacts may change in the future, as the environmental performance of both transport and buildings will evolve in response to the policy framework and new technological developments. The policy framework also determines the extent of the behavioural changes. Similar considerations were reported also by Eurofound (2022a).

Many studies conclude with a cautious message: the net impact on energy use may be small or even negative, due to the potentially significant rebound effects involved. This extends to the environmental impacts such as GHG and pollutant emissions. The relative size of the impacts can vary across case studies, as commuting patterns, the composition of the vehicle stock, land use, etc., can vary. For this reason, teleworking can be a measure to complement policies that aim to reduce commuting or car travel, similar to those described in Factsheet 7.

A1.7 Case study 1.1: The impacts of teleworking in France on greenhouse gas emissions

The environmental impacts of teleworking in France were recently assessed by Greenworking and ADEME (2020), on the basis of three focus groups with a total of 25 employees and interviews with 26 organisations employing 350,000 people. The aim was to estimate to what extent higher order effects can reduce the environmental benefits achieved through substitution effects. As a reference, in a previous study, ADEME found that, thanks to the substitution effect, annual GHG emissions fall by 271kg CO_2e (CO_2 equivalents) per person per weekly teleworking day. To put this in perspective, that study estimated the total GHG emissions at about 12.2 tonnes CO_2e per person per year.

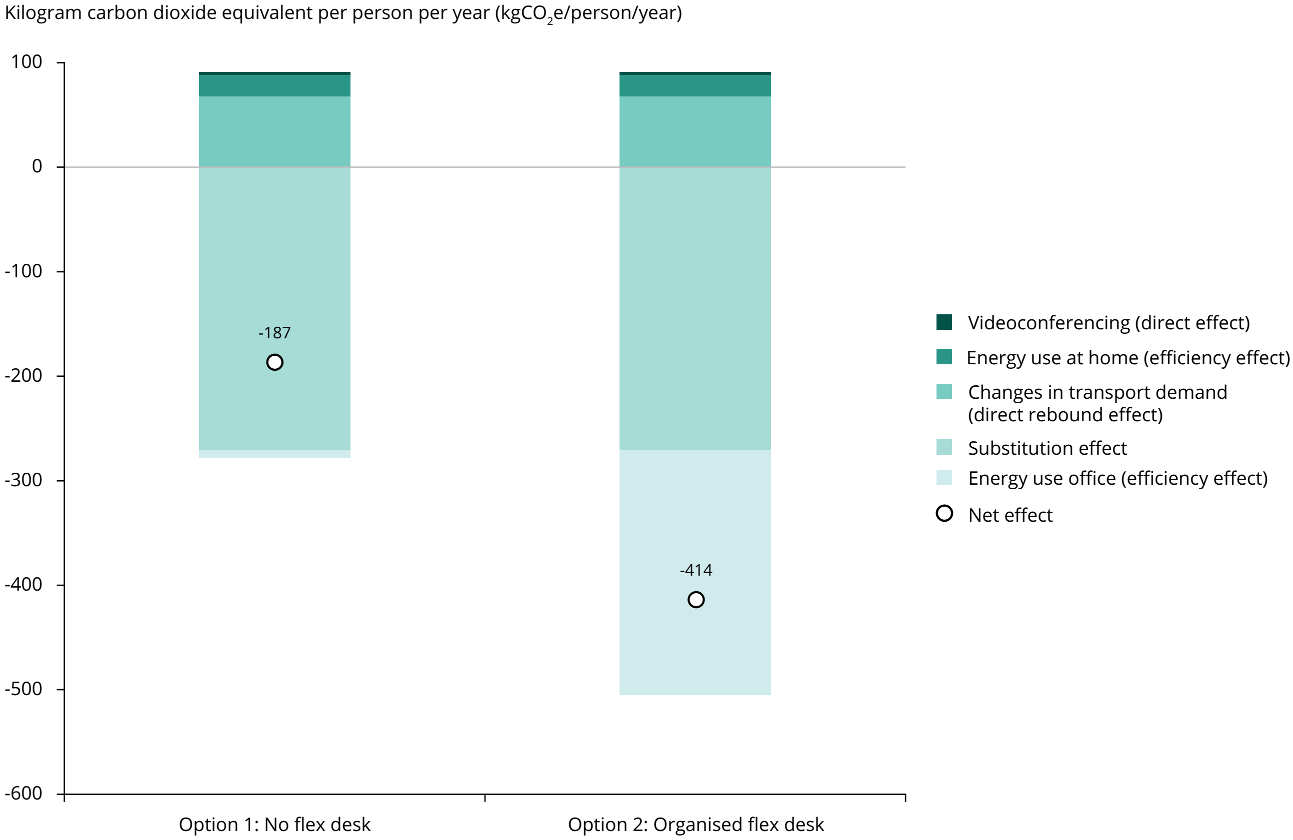
The following effects were investigated:

- changes in daily travel for non-commuting purposes by teleworkers and their household members during teleworking days, including the possibility that this travel uses other modes;
- short-term changes in living locations or recruitment areas of employers (found to be irrelevant from the responses in the surveys);
- additional energy use at home;
- the change in energy use in the office, comparing two options (depicted in Figure A1.6) and assuming an energy consumption of 78kg CO_2/year/m^2 over the life cycle of the office and an average area of 15 m^2 per employee: (1) 'no flexdesk' —energy consumption at the office is optimised without any major reorganisation of the workplace; (2) 'organised flex desk' — each additional weekly teleworking day reduces the office space by 20%;
- the environmental impact of additional videoconferencing services.

While other higher order effects are discussed in the report, such as the long-term effect on the location of households and firms, or the impact of the change in congestion on road traffic, because of the complexities related to their proper estimation, these are not quantified and hence not included in Figure A1.6.

With only optimising energy consumption at the office ('no flex desk'), the net effect on GHG emissions is 31% smaller than the substitution effect. With an organised flex desk system, the opposite is the case. In this case the net reduction in GHG emissions is 53% larger than the substitution effect. Hence, such reorganisation can significantly strengthen the effect of teleworking. All the effects quantified hold for the current emission factors of transport and buildings, but do not consider future developments.

Figure A1.6 **Impact of a weekly teleworking day on greenhouse gas emissions per person per year with two options for the organisation of the conventional office (kg CO_2e/teleworker/year)**



Source: EEA compilation based on Greenworking and ADEME (2020).

A1.8 Case study 1.2: The impact of increased uptake of teleworking on passenger transport in Belgium in 2040

The Belgian Federal Planning Bureau (FPB, 2020) considered the impact of a higher rate of teleworking in Belgium on the passenger transport outlook for 2040. It compared the baseline scenario for 2040 with a scenario in which the share of employees working at home increases from 17% to 39% and the average number of days homeworking per week increases from 1.4 to 2. A selection of results is presented in Table A1.2. While this study does not consider the environmental effects linked to energy use at home or in the office, it does shed light on another higher order aspect, namely the impact on the transport sector as a whole.

The teleworking scenario has the greatest impact on commuting to the central employment area of the Brussels conurbation, and in relative terms on commuting by rail (a reduction in passenger-km travelled of 16.2%). Both aspects are related to the typically longer distances travelled by train from home to work in Brussels and to the positive correlation observed between train use and teleworking for jobs in the administrative, financial and business services branches. These branches are largely represented in Brussels. In absolute terms, the use of cars for commuting would fall the most (a reduction of 6.9 million passenger-km per day).

Table A1.2 Impact of increased homeworking on transport demand and external environmental costs in Belgium in 2040

	Commuting			Total passenger transport		
	Baseline scenario 2040	Impact of teleworking scenario		Baseline scenario 2040	Impact of teleworking scenario	
Million passenger-km per day and % change compared to baseline 2040						
Car	96.2	-6.9	-7.2%	367.3	-2.7	-0.7%
Train	13	-2.1	-16.2%	30.5	-2.2	-7.2%
Bus/tram/metro	4.3	-0.3	-7.0%	27.7	-0.2	-0.7%
Motorcycle	1.7	-0.2	-11.8%	5.3	-0.2	-3.8%
On foot/bicycle	1.7	-0.2	-11.8%	19.5	-0.1	-0.5%
Total	116.9	-9.7	-8.3%	450.3	-5.4	-1.2%
Approximation of external environmental costs (EUR million/day and % change compared to baseline 2040)						
With ICE vehicles	3.8	-0.3	-8.1%	14.3	-0.1	-1.2%
With battery electric vehicles	2.3	-0.2	-8.6%	8.4	-0.1	-1.4%

Note: ICE, internal combustion engine.

Source: EEA compilation based on FPB (2020) and EC (2019a).

The absolute impact on total passenger-km travelled is, however, 44% smaller than the impact on solely commuting-related transport. First, the FPB takes into account that, on homeworking days, people will travel more for non-work-related purposes than in the baseline scenario (direct rebound effect). For car transport the reduction in congestion also makes the car a more attractive mode (economy-wide rebound effect). As a result, it is projected that the total impact on passenger transport is relatively small: the total number of passenger-km travelled is reduced by 1.2% compared to the baseline scenario and car passenger-km travelled are 0.7% lower than in the baseline.

The study does not calculate the environmental impacts. However, given the small effects on passenger transport and the larger share of electric cars in 2040, the environmental benefits in transport are likely to be small. This can be approximated using the estimates for the average external environmental costs of passenger transport from the European Commission handbook (EC, 2019a). Under the simplified assumption that these values, estimated for 2016, can also be used in this case, teleworking reduces the external environmental costs by about EUR 170,000 per day, which corresponds to a 1.2% reduction compared to the baseline. This is 46% lower than if only the impact on the external costs of commuting is considered. In the — optimistic — scenario that all cars, buses and motorcycles are electric in 2040, the reduction in environmental costs is only EUR 120,000 per day, or a reduction of 1.4% compared to the baseline with electric vehicles. This is 39% lower than if only the impact on the environmental costs of commuting were considered.

An older study on the Flanders region in Belgium (Delhaye, et al., 2013), which investigated the rebound effects of teleworking on energy consumption and time savings for 2010, indicated that these effects can be large. Table A1.3 presents the results for 1 teleworking day per week for 9% of employees and a car sharing rate of 51% in commuting. The net effect on energy consumption is almost zero. This could be improved if offices become smaller and/or fewer offices need to be built. Moreover, the energy consumption of residential buildings has decreased over time. For the time savings, the net effect is 29% of the substitution effect. This is because other transport users save time thanks to the reduction in congestion.

Table A1.3 Rebound effects of teleworking in Flanders, 2010

Effect	Energy consumption (million kWh/year)	Time savings (million h/year)
Substitution effect	-265	-15
Efficiency effect Energy consumption at home	+69	
Direct rebound effect and location effect	+120	+7
Impact of reduced congestion on transport system	+72	+4
Net effect	-4	-4
Net effect as percentage of substitution effect	**1%**	**29%**

Source: Delhaye et al. (2013).

Annex 2
Shared autonomous urban vehicles

A-S-I: substitute/improve

Context: passenger road transport/urban public transport

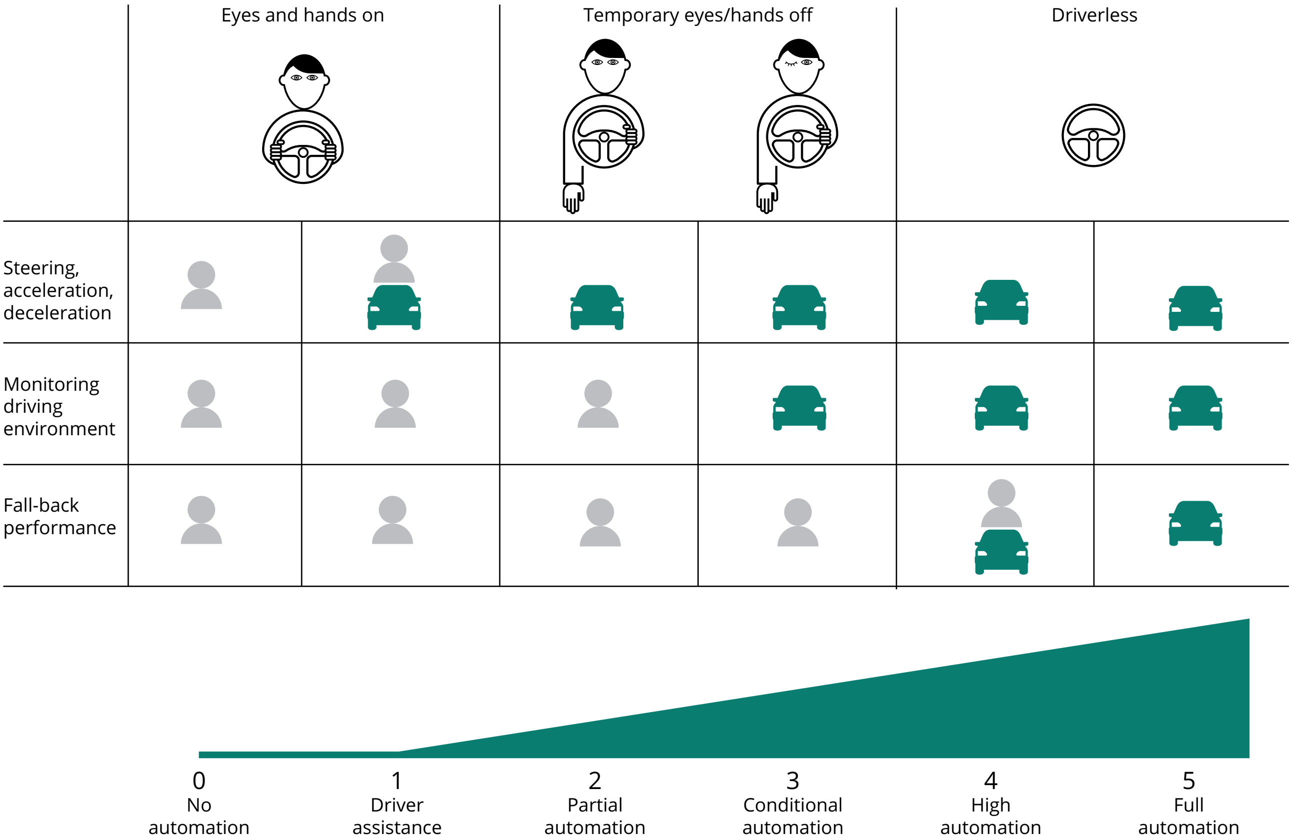
Time frame: mid- to long term

A2.1 Definition

An autonomous vehicle (AV), also known as a self-driving car, is a vehicle that can operate with only limited or no human intervention. AVs use advanced sensors, cameras, big data, machine learning and artificial intelligence to perceive their surroundings to safely travel between different locations. The Society of Automotive Engineers (SAE) has developed a widely used classification system (SAE International, 2021) with six levels based on the degree of human interaction, starting from manual driving (level 0) up to full automation on all roadways and in all environmental conditions (level 5) (Figure A2.1). This is the same framework that is discussed for autonomous trucks in Annex 3.

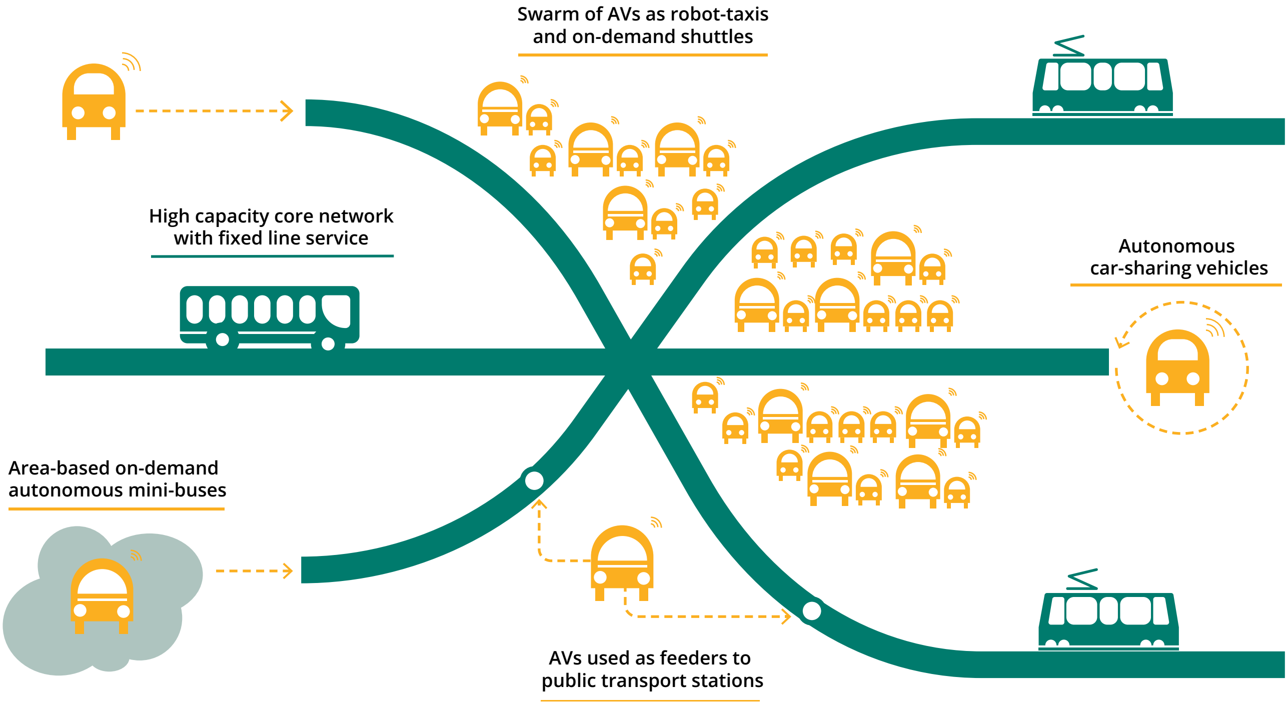
There are three main domains where automated driving can be deployed, each with its own specific features: passenger vehicles, commercial vehicles and urban transport systems (Alonso Raposo et al., 2019). This factsheet focuses on shared autonomous vehicles (SAVs), which refers to AVs that can be shared by several people (Nemoto, et al., 2021) and are used mainly in an urban context. Examples of SAVs are automated shuttles or robot buses. SAVs can be used for on-demand ride services, ride sharing or on fixed routes with fixed stops or on-demand stops (Figure A2.2). One of their main characteristics of interest is that they can be used to improve access to the existing public transport network by providing first/last mile services. They are expected to increase road safety and the efficiency and accessibility of the urban transport system as well as social inclusion.

Figure A2.1 Levels of automation in cars



Source: EEA compilation based on European Parliament (2019).

Figure A2.2 Possible applications of autonomous vehicles as part of a diversified public transport system



Source: UITP (2017).

A2.2 Context

A first important driver for AV development and uptake is the potential envisaged to increase road safety and to drastically reduce fatalities both within and outside urban areas ('Vision Zero' (EC, 2023b) and the impact assessment of the draft General Safety Regulation (EC, 2018c)). Indeed, although the number of road fatalities has decreased considerably since the beginning of the century, with a 61% reduction from 51,400 in 2001 to 19,800 in 2021 (preliminary figure) (EC, 2021e), this trend has been slowing down in recent years (EC ,2018c). It is unlikely that the EU objective of a 50% reduction in road fatalities between 2010 and 2030 will be reached. The social cost associated with these accidents (e.g. rehabilitation, healthcare, death and suffering, material damage) remains high. For 2016 it was estimated to be EUR 237 billion for road passenger transport and EUR 42.8 billion for road freight transport (EC, 2019a). On average, about half of road fatalities are among cyclists and pedestrians. It is estimated that, in approximately 95% of road accidents, human error plays a part (EC, 2018c).

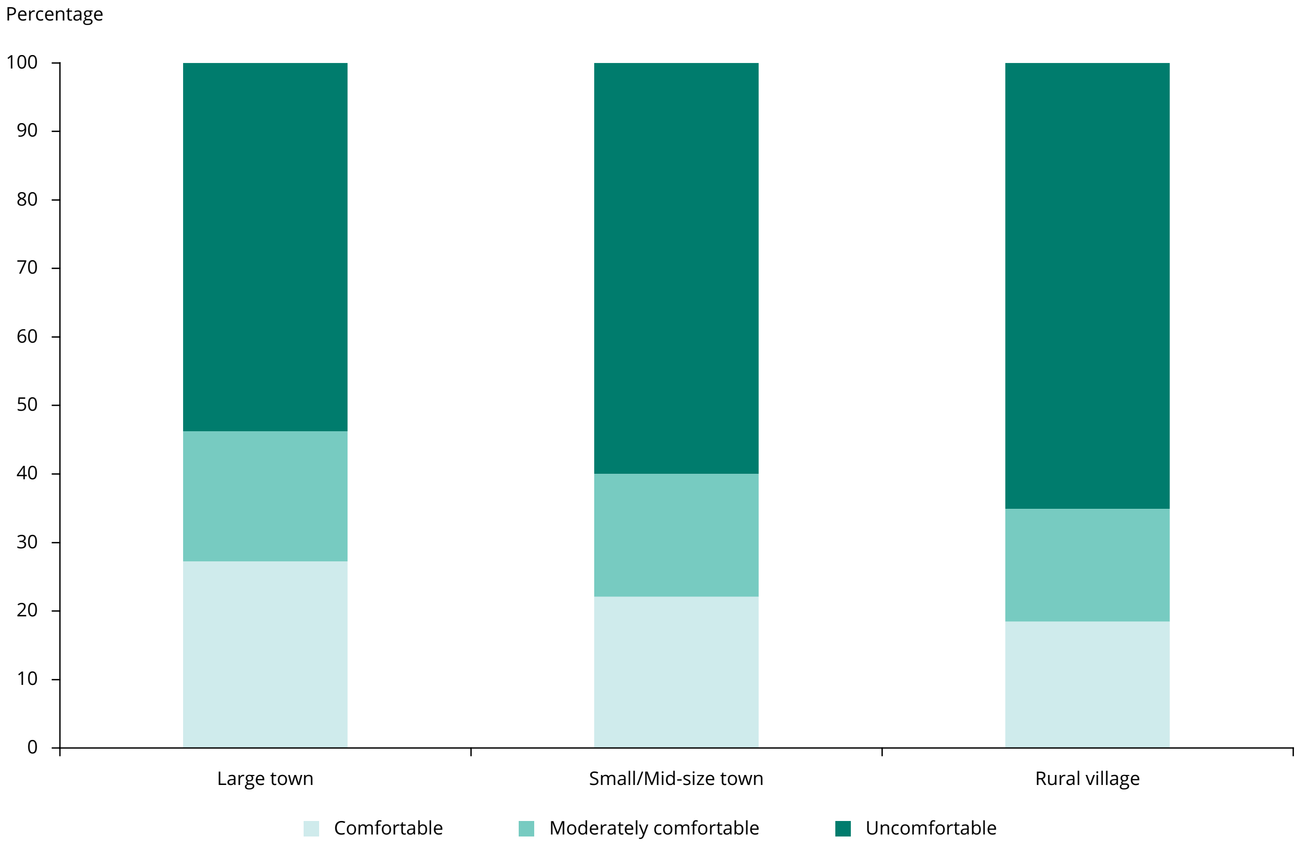
Apart from road safety, increasing the use of public transport in cities and shifting from privately owned cars to more sustainable transport modes are regarded as a high priority in Europe. Here, 75% of the population lives in urban areas, and this is predicted to increase by up to 84% by 2050 (Alonso Raposo et al., 2019). Although car ownership is typically lower in cities and other modes, such as public transport, cycling and walking, are used more than in non-urban areas, it remains a pressing concern because of the high environmental costs of individualised motorised transport modes (see additional details in Factsheets 4 and 7 and related annexes). An increasing modal shift is seen as necessary to achieve the environmental targets set by the EU and summarised in Chapter 4 (e.g. European Green Deal). Urban public transport, however, faces several challenges, such as a lack of flexibility and high operational costs, especially in cities with a low population density. SAVs are seen as a possible solution to these problems. In addition, in Europe the population is progressively ageing: in January 2021, the share of the European population at least 65 years old was 20.8%. This is projected to increase up to 29.5% by 2050 (Eurostat, 2022h). This implies that a growing share of people will be at risk of having limited mobility and an increased difficulty in accessing transport and other public services. Thus, it will become even more important to develop and guarantee an accessible and inclusive public transport system. SAVs have the potential to contribute to this, providing at the same time a less polluting, more efficient and safer transport system (Alonso Raposo, et al., 2017, 2019; Mäkinen et al., 2020).

The development and application of AVs is, however, challenging. The challenge varies greatly with the level of automation. Indeed, while level 2 AVs are more similar to conventional vehicles but with advanced safety features (e.g. lane assistant or adaptive cruise control), vehicles in the level 4 category will be able to operate in an almost completely automated way in environments with well-defined boundaries. Key enablers of this higher automation level are artificial intelligence and machine learning. The technical complexity associated with higher automation levels increases, however, in a non-linear way. Experts in the field often support an evolutionary paradigm, with a stronger diffusion of level 2 vehicles that can operate in less challenging conditions while gathering extensive data sets on users' behaviour and realistic driving scenarios. These will be then used to improve their performance. As anticipated, due to the technical complexity associated with the handling of all possible scenarios arising while driving, there are still significant uncertainties associated with level 5 automation. Indeed, it is still unclear whether it will be technically feasible at all (Schmidt et al., 2021). Even lower levels of automation remain challenging, as level 4 automation requires additional infrastructure to be successfully implemented and, depending on the situation (e.g. urban driving), a detailed mapping of the surrounding environment. The former is the so-called V2X infrastructure and requires high bandwidth and low latency wireless connections, sensors and communication devices (Alonso Raposo et al., 2019; Schmidt et al., 2021).

Equally important for the deployment of AVs is the existence of a legal framework. Policymakers are actively developing the legislation to lower the associated uncertainties and increase acceptability. A recent amendment to UN Regulation No 157 has extended the maximum speed for level 3 AVs up to 130km/h on motorways and allowed other automated systems such as lane changing (UNECE, 2022). In Europe, in July 2022, the EU General Safety Regulation came into force (EC Regulation 2019/2144), which sets a legal framework for the approval of level 4 AVs in Europe. It sets technical rules to ensure that the vehicles are safe and that the technology is mature before entering the market. Based on this new regulation, the EU is planning to align its legislation with the new UN rules mentioned above (EC, 2022m).

Lastly, user acceptance is essential, not only from direct passengers but also from other road users. According to recent surveys, a significant share of people would still feel uncomfortable using a high-level automation vehicle in both urban and rural environments. As noted in the Commission's strategy for the mobility of the future (EC, 2018b), 'in order for automated mobility to gain societal acceptance only the highest safety and security standards will suffice'. A large majority of people are still uncomfortable with driverless vehicles (Figure A2.3). Although acceptance is higher in urban areas, more than half of the participants are still uncomfortable about travelling in a driverless vehicle.

Figure A2.3 **Answers to the question 'How comfortable would you feel being driven in a driverless car in traffic?'**



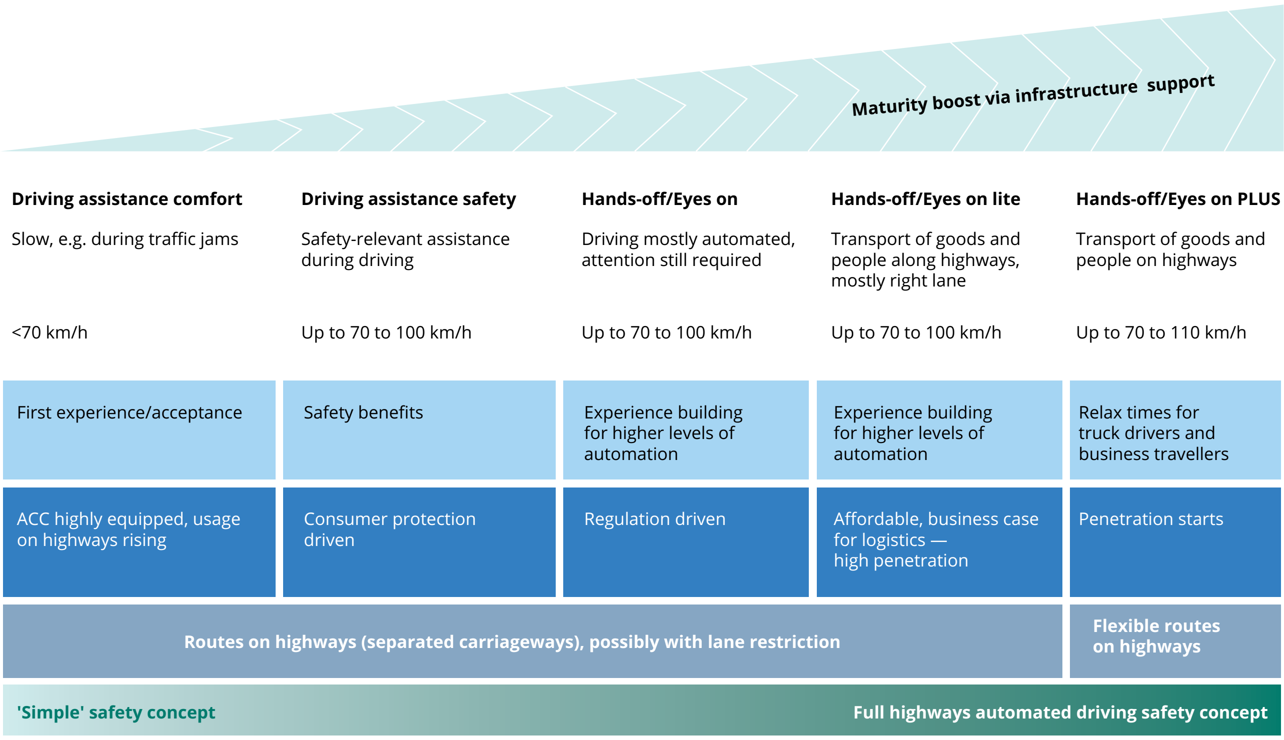
Source: Alonso Raposo et al. (2019).

A2.3 Time frame

There are several challenges to be overcome before vehicles with a high level of automation will be widely available and present in daily life. The market share of vehicles with an automation level equal to 3 or higher is currently negligible and, according to the estimates reported, future uptake will also remain very limited, at least until 2030 (Schmidt et al., 2021). There are large uncertainties about the speed of market penetration, especially for higher levels of automation. Litman (2015) projects that AVs will be commercially available by the 2030s but that, due to the cost and the long life cycle of cars, market penetration will remain fairly low at the beginning. The percentage of vehicle-km driven by AVs would be around 40% by 2050, with 30% of the fleet consisting of AVs by 2050, including those with low levels of automation (e.g. level 2). When looking at the projected penetration rate of level 4 and level 5 AVs by 2050 in Germany, they vary between 17% (Trommer, et al., 2016) and 36% (Krail, 2021).

Given the potential of AVs for the automobile sector, the EU is actively supporting a coordinated rollout of AV and SAV initiatives. The European Road Transport Research Advisory Council (ERTRAC) has published a roadmap for connected, cooperative and automated mobility (ERTRAC, 2022). It includes an agenda to 2030 and a vision for 2050, which includes a roadmap for deploying AVs in different domains. Four types of domains are described, in increasing order of complexity: highways and corridors, confined areas, urban mixed traffic and lastly rural roads. In the context of highways and corridors, it is expected that the share of vehicles up to level 2 automation will increase, with higher automation levels possible depending on regulation and the maturity of the technology. Level 3 pilot projects, (see also the example in case study 2.1) are being undertaken, and assisted corridors that can meet the requirements for deploying AVs are currently being identified. Figure A2.4 gives an overview of the outlook for highways.

Figure A2.4 ERTRAC outlook on highway automation



Source: ERTRAC (2022).

Confined areas are considered well suited for the early introduction of level 4 vehicles, such as valet parking services or buses and shuttles. From a societal point of view (increased safety, efficiency of transport system, accessibility and social inclusion) urban mixed traffic is a high priority, but the challenges of integrating AVs into the intermodal mobility system are considerable. Therefore, an incremental approach is suggested. It is believed that the introduction of AVs in restricted applications should be possible within a decade, while more complex applications will need more time. The relevant cases are level 4 applications such as bus-like or taxi-like applications. Figure A2.5 presents the deployment outlook for low-speed vehicles in confined and urban mixed traffic domains.

Figure A2.5 ERTRAC outlook on low-speed automation

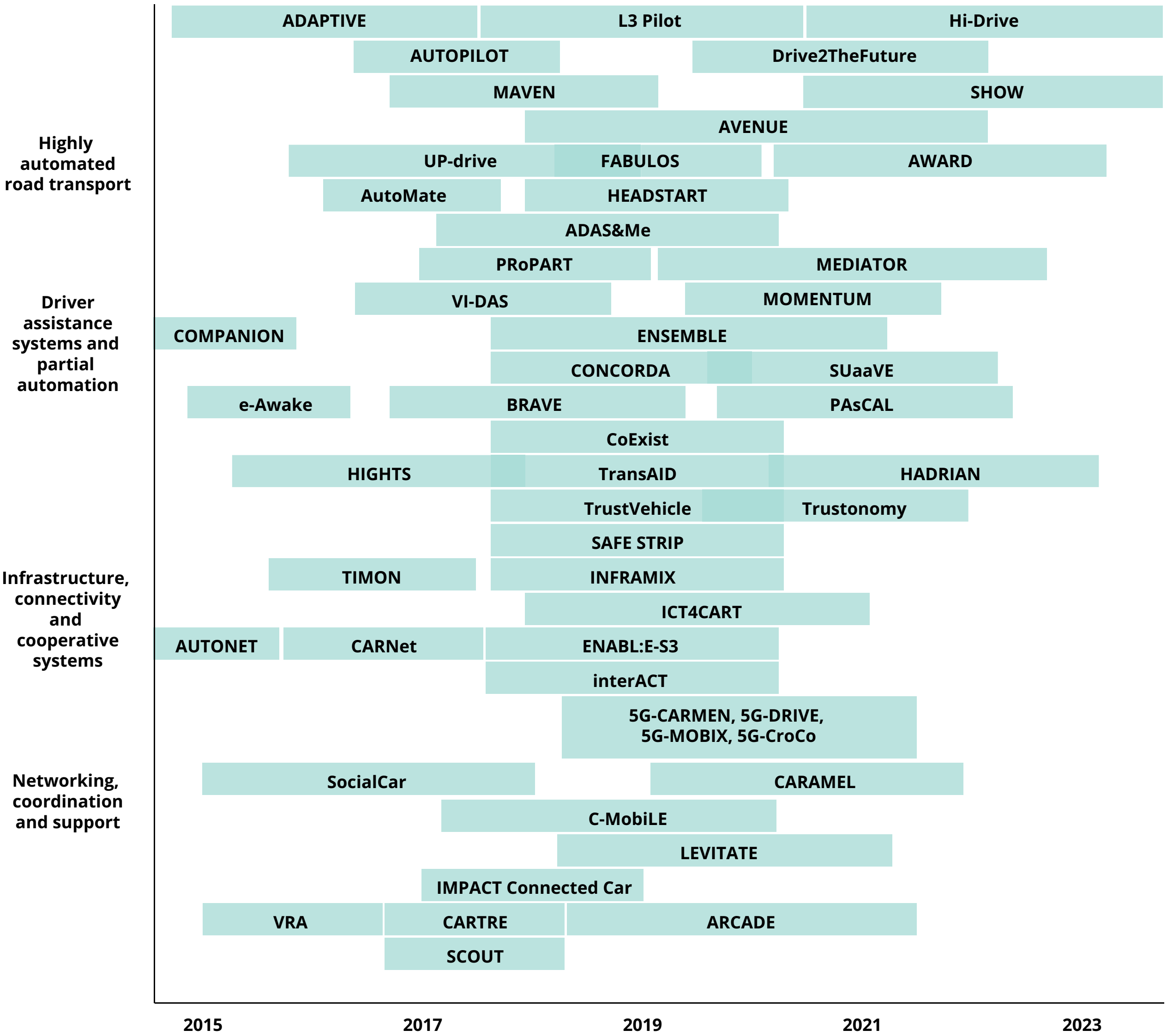
Level of maturity → Level 4

Restricted	Red carpet	Residential	Bus-like	Taxi-like
Transport of goods, parking	Transport of goods	Last mile transport of goods and people	Transport of goods and people on predefined routes	Transport of goods and people in urban areas
<25 km/h	25 up to 50 km/h	Up to 30 km/h	Up to 50 km/h	Up to 50 km/h
Private, gated area, one-lane road — valet parking (today limited 10 km/h)	Dedicated lane on primary road	Well structured residential lane that guarantees lane driving	Mixed traffic lane on primary and well-structured secondary roads	Complex urban road net
Convenience and productivity	Improved network efficiency	Convenience and productivity	Transport operator driven	Convenience and productivity
In 2040 highly available at terminals/hubs/parking	Partly depending on needs and regulation	User/Market driven	In 2040 in use depending on cost/benefits/needs/ regulation	User/Market demand driven
Predefined routes				**Flexible routes on defined net**
'Simple' safety concept			**Full high-complexity/low speed automated driving safety concept**	

Source: ERTRAC (2022).

The most complex environments are rural roads, as they are used by traffic travelling at higher and widely variable speeds. In addition, the quality of the road and support infrastructures (e.g. 5G coverage, GPS signal) can vary a lot. This significantly increases the difficulty of introducing high-level AVs in rural settings. The EU and its Member States are actively supporting R&D in the domain of AVs and SAVs to address the technical and legislative barriers discussed, as illustrated in Figure A2.6 which gives an overview of projects funded by the EU.

Figure A2.6 **Overview of a subset of EU-funded projects that support the development of connected, collective and automated mobility**



Source: ERTRAC (2022).

Several pilot projects in Europe (Fabulos (2021), Avenue (2021), SHOW (2022), Sohjoa (2020), L3Pilot (2021b); see also case studies 2.1 and 2.2 for more details about the last two projects) and the Mcity Driverless Shuttle in the United States (Kolodge et al., 2020)) have been successfully completed or are still in progress. Since June 2016, two 'smart shuttles' have been operating in Sion, Switzerland (Eden et al., 2017). People can book them via an app or at the railway station. The shuttle does not operate on a fixed route but adapts according to the demand along the 17 virtual stops.

A2.4 Expected environmental impacts

Using the taxonomy set out in Chapter 3 the following higher order environmental impacts of automation can be identified.

A2.4.1 Indirect effects — efficiency effects

It is generally expected that AVs could operate with higher fuel efficiency than traditional vehicles. There is, however, considerable uncertainty about the magnitude. A lot depends on the assumptions made about the level of penetration of AVs, the level of automation and which optimisation systems are being used. Milakis et al. (2017) and Massar et al. (2021) both give an extensive overview of studies reporting the potential fuel savings of various automation systems influencing the driving style and behaviour of the driver. Some of the examples cited include driving simulator experiments done in urban contexts. These are reported in Wu et al. (2011), where a 31% decrease in fuel consumption was estimated, thanks to an automated system that provides the driver with advice on acceleration and deceleration values for optimal fuel efficiency. Khondaker and Kattan (2015) calculate 16% fuel savings for their variable speed limit algorithm if 100% of vehicles were using their system. In conclusion Milakis et al. (2017) note that fuel savings of up to 31-45% can be achieved, depending on which automation system is used. The higher the penetration rate of the system, the greater the potential savings. Taiebat et al. (2018) list other results with efficiency gains from 5% to 20%, depending on the specific automation and operational systems used in the vehicles.

AVs are also believed to be able to reduce emissions in city centres by reducing the time spent searching for parking. Indeed, in city centres this causes between 2% and 11% of the greenhouse gas (GHG) emissions according to Shoup (2006). If driver can be directly and accurately informed about parking space availability, Brown et al. (2014) estimate that a 5-11% of emissions could be saved. Shared AVs could decrease the need for parking even more and reduce the time spent looking for parking to nearly zero (ITF 2015) and Fagnant and Kockelman (2015).

Compared to traditional public transport, SAVs have the benefit that they are more flexible and can better match specific vehicles to specific trips by using the right size of vehicle according to the demand. Therefore, SAVs can achieve better occupation levels per individual vehicle, reducing the number of vehicles needed. Fagnant and Kockelman (2015), estimate that if 3.5% of trips were made with SAVs, this could lead to a decrease of 5.6% in GHG emissions, as each SAV could replace up to 12 conventional vehicles.

Although there is a potential to reduce emissions, AVs will lead to an increase in energy consumption because of the additional requirements of the onboard systems, the mobile communication, the backend systems and the network infrastructure. A detailed study on this additional energy consumption has been performed by Krail (2021). That study uses the estimated energy savings potential for a mid-sized car across all automation levels from Krail et al. (2019) as a starting point. The savings potentials range from 493Wh/100km at level 1 to approximately 2,000Wh/100km at levels 4 and 5 in 2050. To estimate the extra energy consumption, the study considers two scenarios, with various degrees of complexity of the information and communications infrastructure. In the 'minimal networking' scenario, savings potentials remain substantial, albeit lower: 125Wh/100km in 2020 up to 1,617Wh/100km in 2050. Interestingly, in the 'efficient networking' case, however, there is an initial substantial increase of energy consumption up to 2,500Wh/100km. It is only in 2040, with the deployment of level 4 automation that energy savings can be achieved (579Wh/100km for level 4 and 631Wh/100km for level 5). It is also noted that this means that an increase of 2.6% in the vehicle-km travelled would render the overall effect of AVs negative in terms of energy efficiency.

A2.4.2 Indirect effects — substitution effects

SAVs can be a useful tool to address the first/last mile problem, to increase the accessibility of the existing public transport system and to reduce the use of private transport, as suggested in Lau and Susilawati (2021) and Moorthy et al (2017). Lau and Susilawati (2021) simulate the impact of integrating SAVs in the public transport network in Kuala Lumpur and find that public transport use increases by 3% and car-km travelled fall by 6%, suggesting a modal shift from private car to public transport. Moorthy et al (2017) find a 37% reduction in energy consumption when SAVs are used for the first/last mile rather than private cars. On the other hand, Alonso Raposo et al. (2019) and references therein, as well as Mäkinen et al. (2020), state that autonomous buses are more likely to be a substitute for walking or cycling rather than to reduce the number of car trips. The overall effect on emissions therefore remains uncertain. Moreover, autonomous taxi services, especially if not shared among different users, could also directly compete with the existing public transport systems, reducing their use. The impacts of this remain largely unknown.

A2.4.3 Structural and behavioural effects — direct rebound effects

AVs are expected to reduce travel costs through higher fuel efficiency. This reduction in the marginal cost of driving is expected to induce more travel. Moreover, travel is likely to become much more comfortable and thus more attractive. Taiebat et al. (2019) analyse the possible rebound effects and conclude that, assuming a 15% improvement in fuel efficiency and a 100% market penetration, AVs could potentially induce a 17.2% increase in fuel consumption. Other studies the authors reference also suggest considerable rebound effects on vehicle-km travelled but with considerable uncertainty, ranging between +2% and +341%, with a median of +43%, based on our own calculations. This underlines the importance of complementing such technological advances with measures aiming to internalise transport externalities, similar to those described in Factsheet 7. This is to avoid as much as possible the increase in vehicle-km travelled that could offset some of the environmental benefits mentioned above.

Other studies conclude that the use of SAVs will lead to fewer vehicles being needed to deliver the same number of trips but that the number of vehicle-km travelled is likely to increase. Dia and Javanshour (2017) use an agent-based model to examine the impact of SAVs from a pilot study on a small road in Melbourne, Australia. They model two scenarios, varying the passenger waiting time for the SAV. The results show a significant reduction in the number of vehicles needed (between 43% and 88%). However, the number of vehicle-km travelled would increase (+29% and +10%) and the overall effect on emissions would depend on the load factor of the SAVs. In a case study for Lisbon (ITF, 2015), it is estimated that SAVs (whether shared by several passengers at the same time or sequentially) could reduce the number of cars needed to deliver the same trips by 80-90%. The number of vehicle-km travelled would, however, increase by 6% if self-driving cars are shared by several passengers and high-capacity public transport is still available.

Apart from the rebound effect caused by a reduction in travel costs, SAVs create a mobility opportunity for people with disabilities, elderly people or other people with limited access to public transport. This creates new demand for mobility, increasing overall demand. Harper et al. (2016) estimated the potential increase in vehicle-km travelled at 14% due to an increase in mobility among the elderly and people with medical conditions.

A2.4.4 Structural and behavioural effects — economy-wide impacts

The cost structure for public transport can be expected to evolve, with lower operating costs (no drivers, more fuel efficient) but a higher capital cost. Currently, the final unit costs for SAVs are still uncertain, but it is likely that, especially in the short term, the purchase price of SAVs will remain higher than that of traditional vehicles because of the former's sophistication and their relatively low capacities. Removing the need for a driver can, however, have drastic implications for the operating costs. Differences can be expected across the EU, depending on the level of drivers' salaries. In Finland, staff costs are responsible for half of the total cost of public transport mileage (Mäkinen et al., 2020). Bösch et al. (2018) carried out a detailed comparison of the cost structures of conventional private cars and taxis with autonomous cars and taxis. They conclude that automation raises the purchase price but reduces the operating costs. For taxis, the main cost component is the driver's salary (up to 88% in conventional cases) which can be completely avoided in the case of an automated unit. Bösch et al. (2018) conclude that automation only marginally changes the cost of private cars (from CHF0.48/passenger-km for conventional cars to CHF0.5/passenger-km for AVs) and rail services (from CHF0.47 to CHF0.44/passenger-km); however, taxi services and buses can gain substantial competitive advantage through automation. The costs for taxis in an urban setting decreases from CHF2.73 to CHF0.41/passenger-km and buses could see their costs halved. A recent study investigated the impacts of autonomous taxis for the city of Zurich (Hörl et al., 2021).

The introduction of AVs in general (not only SAVs) is likely to have substantial impacts on the wider economy, with significant impacts on the labour market (Alonso Raposo et al., 2018, 2022). There will be a reduced need for professional operators but the demand for information and communications technology (ICT) professionals will increase, with a shift in the skills needed. In parallel, an increase in productivity in the electronic and software sector and the telecommunication, data services, automotive and freight transport sectors could be expected, while insurance and maintenance and repair sectors are likely to be negatively affected.

A2.4.5 Structural and behavioural effects — transformational changes

By transporting people door to door, SAVs can reduce the demand for parking and improve the allocation of space in city centres. A study performed in Lisbon (ITF, 2015) estimates that 80% of off-street parking could be removed and on-street parking would become obsolete following the introduction of SAVs. Fagnant and Kockelman (2015) estimate that 11 parking spaces per SAV in operation could be eliminated. This frees up space for other purposes such as designated bicycle lanes.

SAVs increase the accessibility of the transport system and this can also lead to a wider effect. Mäkinen et al. (2020) estimated from a simulation that the share of the population within 30 minutes of the centre of Helsinki would increase by 36% following the introduction of a shuttle service, illustrating the effect it could have on urban sprawl.

AVs can substitute for conventional cars without affecting the current business model centred on the ownership of the vehicle as long as lower automation levels (2 or 3) are predominant. Level 4 automation could enable the development of shared urban vehicles providing door-to-door services. This has the potential to significantly change the mobility system, first in urban environments and later also in rural-urban connections (Alonso Raposo et al., 2018, 2019; Schmidt et al., 2021).

A2.5 Policy corner

Progressive development of the automation technology and its wider diffusion is expected to take place in passenger transport, following the general trend towards digitalisation. It offers some possibilities to increase the environmental performance and safety of the transport modes. It reduces the time cost of travelling and can also reduce the monetary costs. It also facilitates travel for a number of groups in society who are served less well by the current transport system. The general increase in transport demand (both in general and for the modes that are automated), due to cost reduction, is beneficial to society only if the external costs that remain are fully internalised. Additional details on this can be found in Factsheet 7 and Annex 7. The regulatory framework around AVs is currently centred around safety. It is important that environmental considerations are also taken into account, especially considering the potential impact on public transport and the modal shift. The impacts of progressive automation will also depend on the environmental policies for the transport modes that are already in place in the baseline scenario without automation (e.g. emission standards, renewable energy targets).

Related to traffic safety, even with lower automation levels the interaction of the driver with a partially autonomous vehicle remains an important factor. For higher level AVs and driverless cars, liability issues may occur. Another point needing consideration are situations in which there are interactions between vehicles with different levels of autonomy. There also is a risk related to cybersecurity, also explored in Chapter 6.

A2.6 Bottom line

Although the effects of AVs on safety and mobility are promising, the environmental impacts remain uncertain as the gain in fuel efficiency arising from automated operations could be outweighed by the extra energy needed for the onboard systems and the broader ICT network infrastructure. Moreover, the rebound effect in terms of extra vehicle-km generated can be substantial. Shared autonomous urban vehicles that are well integrated into the existing public transport system are the most promising, but at present the interaction between SAVs and existing public transport is not yet clear.

A2.7 Case study 2.1: L3Pilot project

L3Pilot was a European research project aimed at testing and studying the viability of automated driving on public roads (L3Pilot Driving Automation 2021a, 2021b). The main focus was testing SAE level 3 functions, with additional assessment of some level 4 functions, on a large number of vehicles under a wide range of conditions. Indeed, the project involved 1,000 drivers, 100 cars and 34 different partners, including manufacturers, suppliers, research organisations, small and medium-sized enterprises, insurers, one local authority and one user group. The pilot lasted 4 years, from 2017 to 2021, and developed across 10 European countries, including driving on cross-border routes.

The project had four main objectives:

- to create a standardised Europe-wide piloting environment for automated driving;
- to coordinate activities across the piloting community to acquire the data required for evaluation;
- to pilot, test and evaluate automated driving functions;
- to innovate and promote automated driving to raise awareness and introduce it to the market.

In the testing phase, four different traffic scenarios were investigated: (1) traffic jams; (2) driving on motorways, including in traffic jam situations; (3) the parking environment; and (4) urban areas. In this way it was possible to collect a significant amount of data from various scenarios and to evaluate the behaviour of the automated driving system as well as to highlight areas for future development.

For the motorway scenario, the following observations were made. First, the AV drove at lower speed and allowing much greater leeway than in the baseline situation in which automation is deactivated. Second, the AV tended to remain longer in a stable driving scenario (i.e. free driving or following a vehicle). Similarly, lane-keeping behaviour was more stable than in the baseline case. Interestingly, the results indicated that, when the vehicle drove in an autonomous way, its energy consumption was reduced (up to 12% on average), probably due to the changes in driving behaviour (lower speed, more stable driving scenario, etc.). It should be noted, however, that the energy demand of the additional equipment was not considered.

In the urban driving scenario, because of its intrinsic variability, it was more complicated to evaluate the impact of autonomous driving. Nevertheless, some general points can be made. Urban AVs need more time to cross an intersection, suggesting more careful overall behaviour. No significant differences between the AV and the baseline situation could be identified when following a leading vehicle. This seems to suggest that deploying AVs would not interfere with the traffic flow. In general, autonomous driving reduced overall driving dynamics (i.e. longitudinal and lateral accelerations).

Lastly, in the parking environment, AVs were always slower than the baseline situation, taking more time to perform the task required.

In all scenarios, user acceptance evaluated through questionnaires was positive, although room for improvement in the overall experience was reported.

It is important to highlight that this pilot project was performed with individual cars in mind rather than urban shared vehicles. The study shows the extent to which travellers may be interested in switching from using public transport or active modes to an autonomous personal vehicle. More specifically, twice as many respondents expected to decrease their use of public transport (26-29%) than those expecting to increase their use of it (12-15%). This once again highlights the importance of policies encouraging a shift to collective and sustainable transport modes and the necessity of making public transport more attractive and accessible, also through automation, to avoid this unwanted modal shift.

A2.8 Case study 2.2: Sohjoa Baltic project

The aim of the Sohjoa Baltic project was to 'develop knowledge and competences required to organise environmentally friendly and smart automated public transport through research, promotion and piloting autonomous driverless electric minibuses as part of the public transport chain, especially for the first/last mile connectivity' (Mäkinen et al., 2020). During the Sohjoa Baltic project, which ran from to 2017 to 2020, autonomous minibuses were successfully piloted in six Baltic cities (Sohjoa Baltic Consortium, 2020). They identified situations in which autonomous minibuses could be part of the mobility solution (Mäkinen et al., 2020):

- First/last mile: especially for areas where the demand density for trips is low and first/last miles are distributed over a large area. On-demand services using autonomous shuttle buses are the most promising solution for this.
- Autonomous shuttle buses: these can also be deployed where there is a temporary high demand for transport (e.g. exhibitions, new residential areas that do not have a established public transport system).
- One of the more likely applications: in closed areas such as airports, hospital and campuses.

The project also identified the major impacts that can be expected after introducing SAVs:

- The role of SAVs can be seen as complementary to other public transport modes rather than a real substitute. The researchers therefore predict that it is not likely that SAVs will reduce the use of private cars but that they are more likely to be a substitute for cycling and walking.
- SAVs can replace traditional buses only in low-density residential areas, as currently they have a low capacity and operate at low speeds and thus are not suited for travelling long distances.
- SAVs can improve access to the existing public transport system and can make it more attractive, providing that the services are well synchronised.
- When used as feeders for trunk lines, SAVs can lead to a reduction in the number of stops on the trunk line and improve its efficiency.
- The cost structure of SAVs is still uncertain, but they are likely to have higher capital costs than traditional vehicles because of their sophisticated hard- and software. The operational costs are, however, likely to be significantly lower, as personnel costs are reduced.

In terms of acceptability, the overall user experience was very positive. The majority of the 837 respondents gave maximum scores when asked to rate their experiences (with 50% being the lowest score in Helsinki) and perceived the SAVs as safe, which is illustrated by the fact that between 40% and 60% of respondents considered the system suitable for children travelling alone to school.

Annex 3
Autonomous freight transport

A-S-I: improve

Context: freight transport

Time frame: mid- to long term

This factsheet explores the developments and impacts that progressive automation could bring to the freight transport sector, with a specific focus on its two most relevant sectors in terms of emissions, namely the road and maritime sectors, discussed in detail in Chapter 2. In these cases, the factsheet considers technologies that partially or entirely take over the role of human operator(s) onboard the vehicle, ship or vessel. In particular, it focuses on driverless trucks, maritime autonomous surface ships and autonomous vessels for inland navigation. Still, automation could also be an option for freight transported by autonomous delivery robots (e.g. Chen et al. (2021)), drones (e.g. Kellerman et al. (2020)), freight rail (e.g. Müller (2020)) or other modes.

A3.1 Driverless trucks

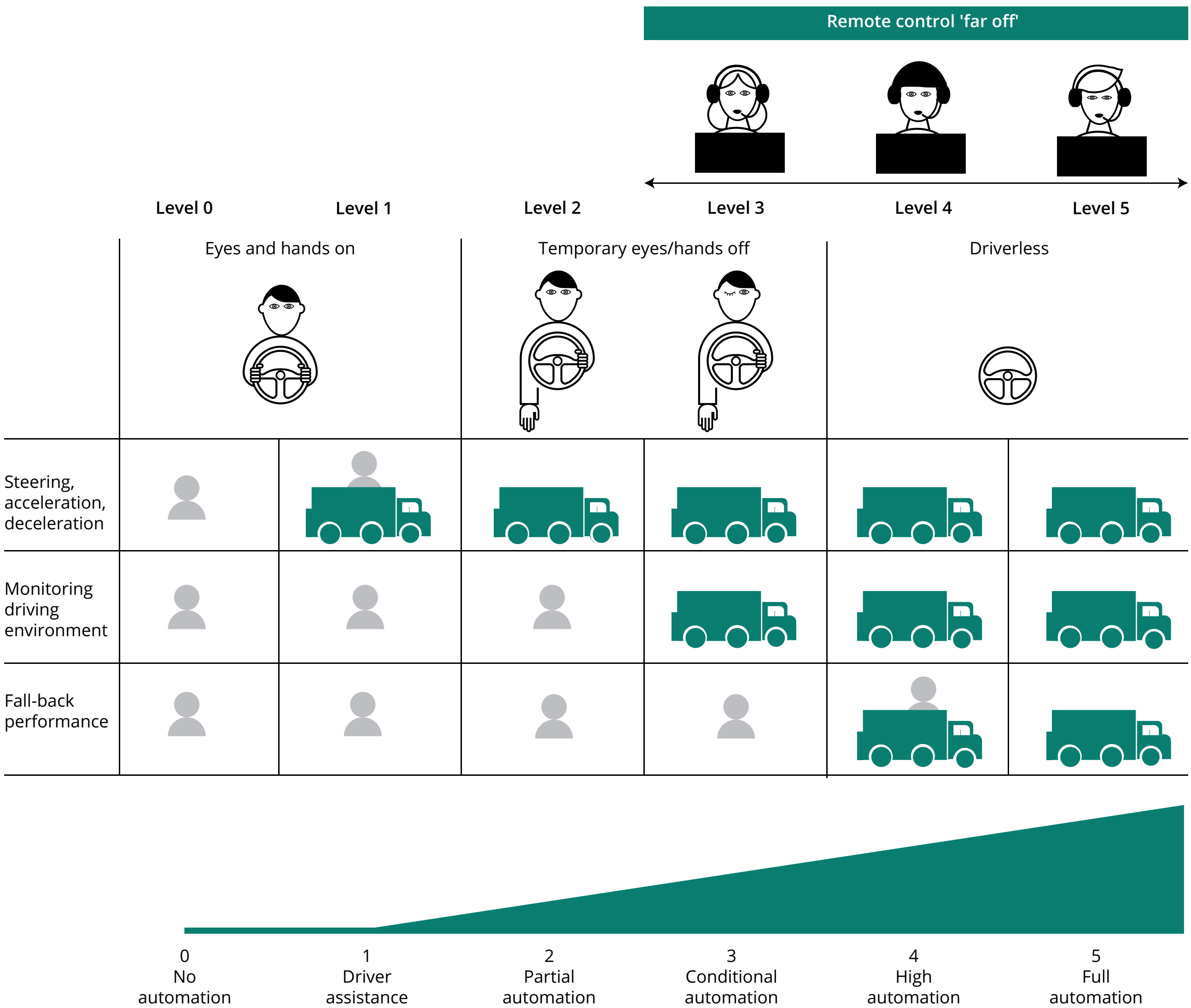
A3.1.1 Definition

Automated driving systems for road transport apply technology to partially or entirely replace the need for human intervention while driving a vehicle. The Society of Automotive Engineers (SAE) has developed a widely used classification system with six levels based on the level of human intervention (SAE International, 2021), starting from manual driving (level 0) up to full automation on all roadways and in all environmental conditions (level 5) (Figure A3.1). This is the same framework that is discussed for autonomous urban vehicles in Annex 2. To be categorised as 'driverless', trucks will need to attain SAE level 4 or 5. The systems can be set up and operated in different ways. As shown in Figure A3.1, for levels 3-5, having remote operators who can intervene when required is also envisaged. Similarly for the terms 'hands off' and 'eyes off', Mutzenich et al. (2021) refer to them as 'far off', as the remote operators would intervene from a location other than the road where the truck is driving. It is important to mention that driverless trucks will require different onboard systems, supporting infrastructure along the road network including information and communications technology (ICT), mobile and/or satellite connectivity compared to traditional vehicles (ITF, 2017).

This factsheet focuses on driverless trucks that operate at level 4, also with the assistance of a remote operator. The driverless truck may be platooning enabled or not. In the former case, two or more trucks are virtually linked in convoy, using automated driving support systems, and automatically maintain a short distance between each other (Atasayar et al., 2022). This method of operation is not restricted to driverless trucks in principle. It could also be applied, with lower performance levels, to trucks with a lower level of automation, although it is still debated in the literature whether this could be done by exploiting, for example, adaptive cruise control systems (Makridis et al., 2020). There could also be mixed forms in which the first truck in the platoon is manually driven while those following are either completely driverless or with drivers not actively controlling the vehicle (e.g. resting) (Bhoopalam et al., 2018).

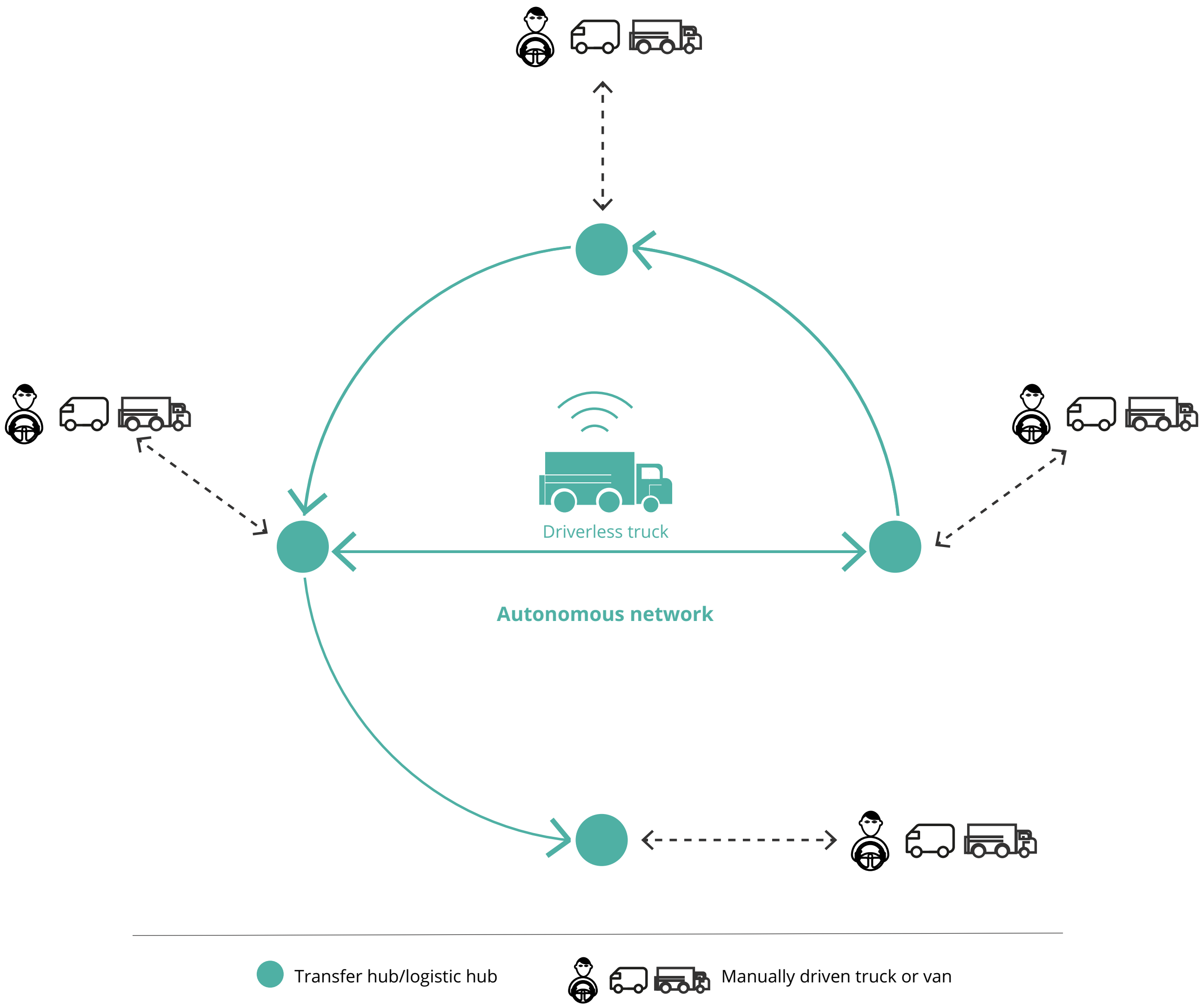
Level 4 driverless trucks can be used for so-called hub-to-hub transport. This can be defined as long-distance transport between logistics hubs, such as road terminals, distribution centres or ports. In a variant such services are rendered via transfer hubs along the main road network, as illustrated in Figure A3.2. Potentially these main roads could also be adapted with dedicated lanes for driverless trucks. Road transport in urban areas or other more complex traffic conditions, for which high SAE levels are currently more difficult to realise, is in this case still by manually driven trucks. These could of course also be automated to some extent. Only in the long run, depending on further technological development, could driverless trucks become an option for freight transport on all roads and in all traffic conditions (Engholm et al., 2021). For the delivery of small packages, drones or automated delivery robots could then also become an option (Vivid Economics, 2021).

Figure A3.1 Levels of automation in truck transport



Source: EEA compilation based on ITF (2017), European Parliament (2019) and SAE Internationl (2021).

Figure A3.2 **Hub-to-hub system on the road network with driverless and manually driven trucks**



Source: EEA compilation.

A3.1.2 Context

Road freight transport is the main mode of freight transport in the EU-27, accounting for 52% of the overall tonne-km travelled (EC, 2022a), as discussed in Chapter 2. In 2019, about 75% of vehicle-km were travelled over distances of at least 150km. 55% the transport was over a distance of at least 300km (Eurostat, 2022b). In this context, the hub-to-hub applications for long-distance transport introduced in Section A3.1.1 could target a large share of trucks. In 2019, heavy-duty vehicles (trucks and buses) accounted for 19.4% of the greenhouse gas (GHG) emissions of the total transport sector in the EU-27 (EEA, 2021a). By 2040 and 2050 the EU Reference Scenario 2020 projects further growth in the tonne-km travelled by road, although the impact on GHG emissions is expected to be at least partially counterbalanced by the improved environmental performance of trucks and using a larger share of sustainable fuels (EEA, 2022a).

In addition to environmental problems, accidents are an important external cost category for trucks (for a more detailed description of externalities in transport, see Factsheet 7 and Annex 7). In 2016 these costs were EUR 23 billion, or 30% of the total external costs of heavy-duty vehicles (EC, 2019a). In 2019, 3,040 people died in road accidents involving trucks, which corresponds to 14% of all road fatalities. For serious injuries, the share was 2%. In fatal accidents, only 12% of the fatalities were among trucks occupants. Most of the people who died in such accidents were car passengers (51%) or pedestrians (13%). Compared to other road transport modes, fatal accidents involving trucks are more likely to occur on highways (23% compared to 9% for all road modes) (EC, 2021t).

Labour accounts for 42% of total road freight transport costs (Persyn et al., 2020). Regulations are in place to ensure fair working conditions for drivers, with limited driving times and sufficient breaks and rest periods. This also improves traffic safety and ensures fair competition (EC, 2022n). However, in recent years, in spite of this, it is becoming progressively difficult to find drivers for long-distance transport (ITF, 2017). In principle, driverless trucks offer the opportunity to reduce the transport costs, to relax the constraints on driving times without jeopardising traffic safety, and at the same time to address the shortages in the labour market. These are the main drivers behind the developments in this field. In addition, it has been suggested that autonomous road freight could offer the potential, apart from improving road safety, to increase asset use, reduce congestion and achieve higher energy efficiency. Overall this would mean better environmental performance of trucks (ITF, 2017; Andersson, and Ivehammar, 2019). In general, although environmental considerations are mentioned as one of the drivers of the development of autonomous road freight transport, these are certainly not the sole or the main drivers.

A3.1.3 Time frame

While lower levels of automation are already in use in road vehicles (mostly up to level 2, in some cases moving towards level 3), the higher levels are still in a more experimental phase. Driverless trucks are in use in specific areas, such as the Port of Rotterdam, and are being used and tested on a small scale, for example in the following cases:

- Scania self-driving trucks on the E4 motorway between Södertälje and Jönköping in Sweden (Flaherty, 2021);
- a pilot project in Europe and China with the aim of validating and integrating the Plus autonomous trucking technology with an IVECO heavy-duty truck (Automotive World, 2021);
- a pilot project with Einride driverless electric freight transport trucks (so-called pods) on public roads in Tennessee, United States (Garsten, 2022);
- Gatik deliveries with autonomous trucks on fixed, short-haul, repetitive routes (Moto news today, 2022);
- test drives in Texas, United States, by Aurora Innovation Inc. (Black, 2022).

According to Engholm et al. (2021) the provision of hub-to-hub services with driverless trucks could be a reality before or during the 2030s. It is still much more uncertain whether and when driverless trucks of SAE level 5 will become operational, as also discussed for autonomous passenger vehicles in Factsheet 2 and Annex 2. Market outlooks by McKinsey and Accenture point to the transformational potential but also to significant challenges that still lie ahead (Chottani, et al., 2018; Schmidt, et al., 2021). Platooning is likely to be available before driverless trucks for manually driven trucks on highways. A McKinsey study expects it to be possible by 2025 (Chottani et al., 2018).

The revised General Safety Regulation (Regulation (EU) 2019/2144) (EU, 2019e), which entered into force recently, empowers the European Commission to complete the legal framework for autonomous and connected vehicles. Together with rules for automation level 3, the European Commission has proposed technical rules for the approval of fully driverless cars and vans (automation level 4), which will be the first international rules of their kind (EC, 2022o) and are likely to have a positive impact on the development of the sector.

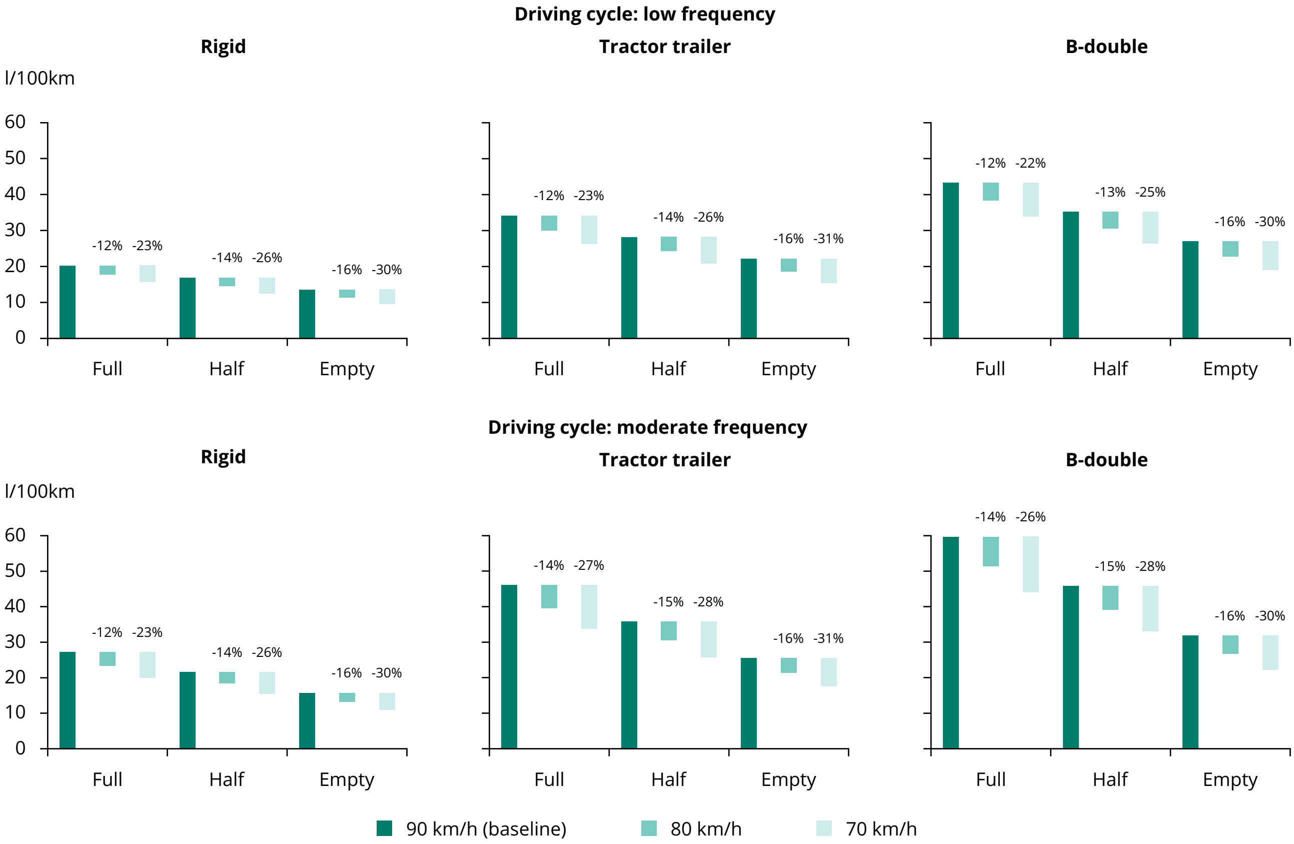
A3.1.4 Expected environmental impacts

Using the taxonomy set out in Chapter 3 the following higher order environmental impacts of automation can be identified.

Indirect effects — efficiency effects

It is expected that the fuel efficiency of trucks and thus their GHG emissions could improve thanks to automation. Although time is a crucial factor in the transport of goods, with driverless trucks it is less costly to drive more slowly to save fuel, due to the lower or negligible cost of labour. Figure A3.3 illustrates the simulated impact on fuel consumption of lower target speeds, for three types of heavy-duty trucks, three load factors and two highway driving cycles: 'low frequency' and 'moderate frequency'. The former refers to a driving cycle with brake events every 20km and an average speed for the 90km/h speed target of 87.3km/h. In the latter, braking takes place more frequently, at every 5km, and the average speed is 80.2km/h. Reducing the target speed from 90km/h to 80km/h leads to fuel savings of 12-16%, and reducing it from 90km/h to 70km/k leads to 22-31% lower fuel consumption (Bray, and Cebon, 2022).

Figure A3.3 Simulated impact of reducing average speed on truck fuel consumption



Source: EEA compilation based on Bray and Cebon (2022).

Additional fuel savings can be realised by changing the truck's design. As the driver is absent, the truck's cabin can be completely redesigned. This, together with other design modifications made possible by automation (such as the absence of heating and air conditioning on board) can contribute to lowering the weight and improving both the aerodynamics and the vehicle performance. Driverless trucks also offer more potential for eco-routing, i.e. optimising routes to minimise energy consumption, taking into account information on topology, real-time traffic, weather, location of charging stations, etc. (Engholm et al., 2020).

Fuel savings can be increased if the driverless trucks are operated in platooning mode. In general platooning reduces fuel consumption. This depends on various factors, including the spacing between trucks, the speed of the platoon and the increase in fuel consumption related to platoon formation and dissolution. Martínez-Díaz et al. (2021) note that the potential savings are larger for trucks than for cars, as the former have a lower aerodynamic efficiency. As air resistance increases with the square of the speed, Atasayar et al. (2022) point out that findings for the United States cannot be directly applied to Europe because of differences in the speed limits among the US states and EU Member States.

The expected fuel savings are higher on highways and increase when the gaps between the vehicles are reduced. The EDDI project, which investigated platoons on German highways under practical operating conditions, indicated fuel savings at a distance of 15m of 2.4% on average for a platoon of two trucks (reported by Neubauer and Schildorfer (2022)). In a study for Austria, Thonhofer et al. (2022) analyse fuel savings for platoons with three trucks on different routes. For example, on the highway between Pasching and Guntramsdorf, the maximum fuel saving is 4.8% (with a distance between vehicles of 0.5s, at a speed of 80km/h and with slow formation and dissolution of platoons) and the minimum fuel saving is 2.5% (same speed, distance of 1s and fast formation and dissolution). Compared to manually driven vehicles, driverless vehicles allow shorter gaps between the vehicles and therefore potentially lead to higher fuel savings. Compared to a truck platoon consisting of a manually driven leader truck and driverless followers, a fully automated platoon can drive closer and further contribute to fuel economy by allowing trucks to travel to different stops to form a platoon instead of returning to a fixed location to drop off the drivers (Zang et al., 2020).

In addition to these mechanisms leading to fuel savings by driverless trucks, the onboard automation system itself also consumes energy, depending on the specific technology used. This can partially offset the other effects (Engholm et al., 2020). In general, there is considerable uncertainty over the net effect on fuel efficiency. In their analysis of the operating costs of driverless trucks, Engholm et al. (2020) therefore consider three scenarios. In their base scenario, driverless trucks achieve a fuel saving of 10% thanks to eco-driving (higher fuel efficiency due to automation, lower speeds, etc.). In their pessimistic scenario fuel efficiency does not change, as the benefits of eco-driving are small and completely offset by the additional energy consumption of the onboard automation system. The third scenario is optimistic. A fuel saving of 20% is achieved thanks to eco-driving, lighter truck designs, high platooning rates and low energy consumption by the automation system. In a social cost-benefit analysis of autonomous trucks in Sweden, Andersson and Ivehammar (2019) assume an improvement in fuel consumption of 10% for long-distance trucks (six to seven axles and capacity of 40 tonnes), and no improvement for two smaller truck types, one for distribution and one for bulk transport for construction purposes.

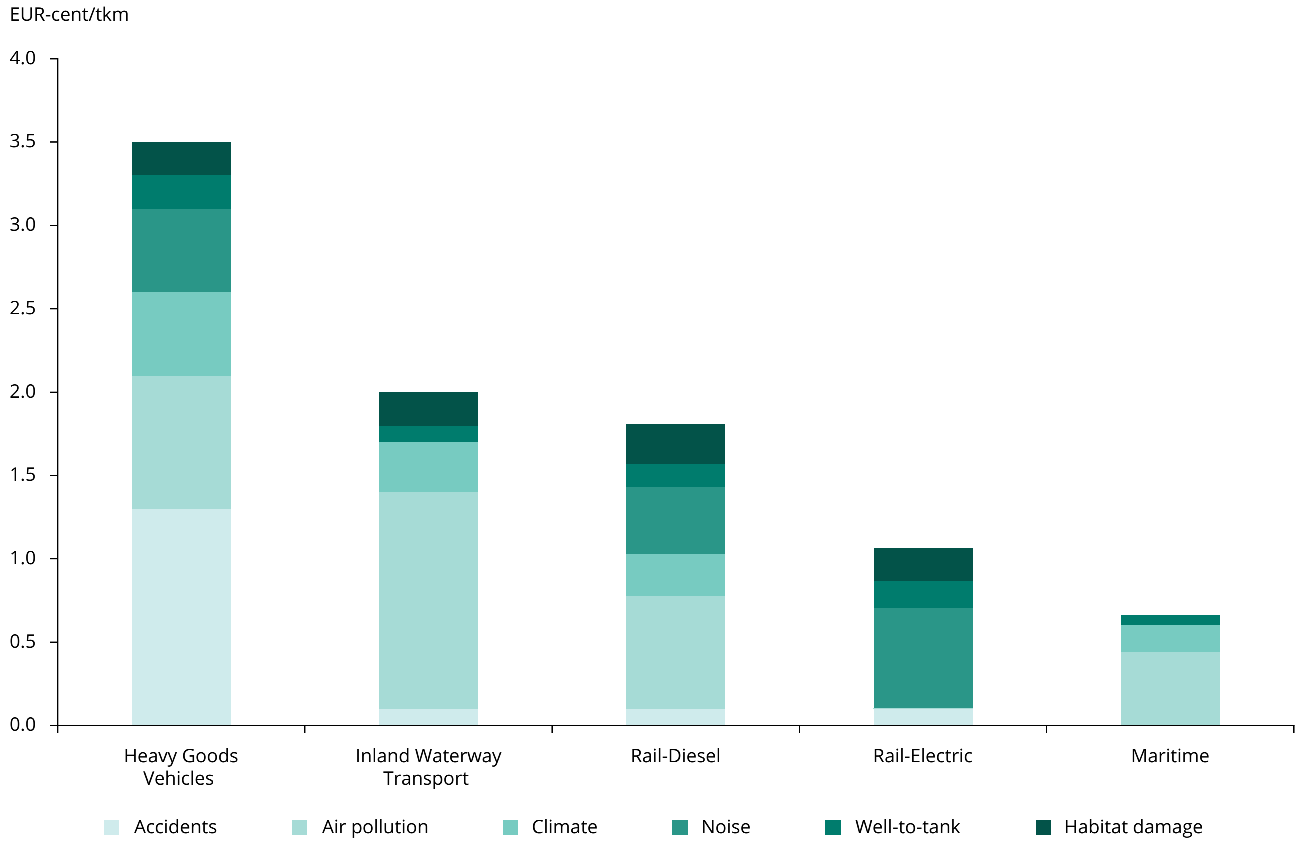
With diesel trucks the impact on fuel consumption will lead to the same percentage impact on CO_2 emissions. With battery electric trucks, road freight transport indirectly falls under the EU Emissions Trading System (ETS), via the power generation sector that produces the electricity. The total emissions under the ETS depend on the cap, and different energy efficiency levels of trucks will lead to shifts in the emissions of the sectors covered by the ETS cap. With hydrogen electric trucks the impact will depend on the way in which the hydrogen is produced, and which parts of the production process are included in the EU ETS.

Structural and behavioural effects — direct rebound effects

Driverless trucks can substantially reduce the costs of road freight transport. Given that the demand for transport reacts to changes in cost, in the absence of other control mechanisms, such as those described in Factsheet 7 and Annex 7, this can be expected to lead to higher freight transport demand and a higher share of road transport at the expense of other transport modes. Currently these modes have lower external costs per tonne-km travelled than road transport, as shown in Figure A3.4. The environmental external costs of road freight transport depend on the type of truck and fuel (combustion engine with fossil or renewable fuels, or electric engine), whose shares are expected to change in the future. Similarly, the environmental performance of the other modes is also likely to change in future, meaning that the impacts of the direct rebound will be influenced by this.

The impact on the transport costs can be relevant, as shown, for example in Engholm et al. (2020). They calculate the cost differences for four truck types under different scenarios (Figure A3.5). The relative cost reduction per 1,000 tonne-km is the largest for the smaller trucks, due to the comparatively higher cost of the driver. In all cases it is substantial. Their analysis considers various cost categories including fuel costs, driver costs, maintenance costs, tyres, depreciation, capital, taxes, insurance, remote operations, loading and unloading, and other costs. Any costs of infrastructure investments are not considered. In this case these should cover the additional investments that would be needed to support driverless trucks (and other driverless vehicles).

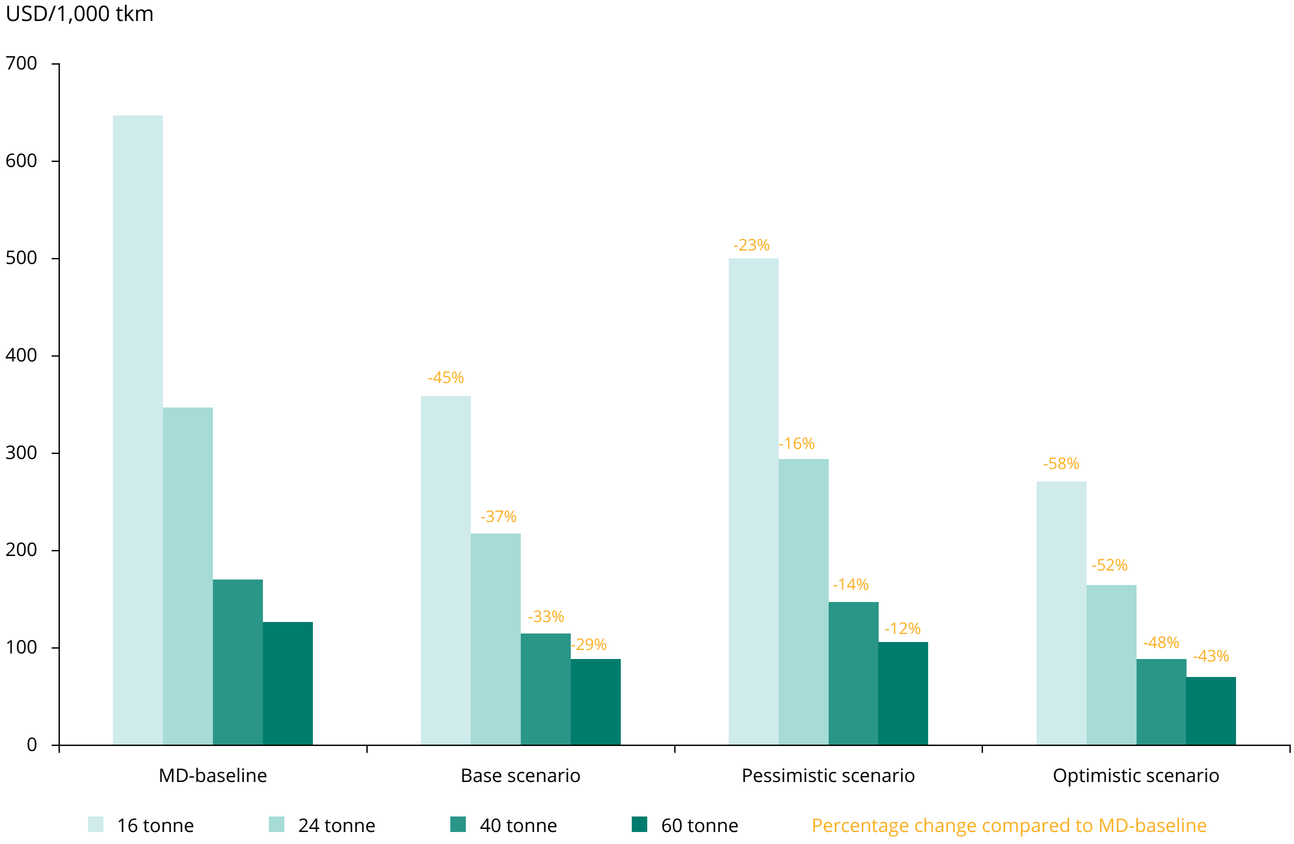
Figure A3.4 Average external costs of freight transport modes in 2016 (EUR-cent/tkm)



Note: Maritime refers to the average for selected EU-27 and UK ports.

Source: EC (2019a).

Figure A3.5 **Transport costs (US dollars per 1,000 tkm) for three cost scenarios for driverless trucks compared to the manually driven baseline scenario**



Note: The percentages represent the relative cost change from the MD-baseline.
MD, manually driven.

Source: Engholm et al. (2020).

Structural and behavioural changes — economy-wide effects

The value of travel time in road freight transport can change as a result of automation. This can have profound effects on the way in which freight transport is organised. In addition, depending on the time at which automated road freight is transported, there may be an impact on congestion and noise levels. Lastly, the social dimension should also be considered: automation will have an impact on the drivers' jobs. This should be accounted for, and actions to mitigate this issue and smooth the transition may be required.

Structural and behavioural changes — transformational changes

The decrease in transport costs and the change in the value of travel time can have an impact on firms' location decisions, thereby affecting the distances over which goods are transported.

A3.2 Automation in navigation: maritime autonomous surface ships and autonomous inland vessels

A3.2.1 Definition

The International Maritime Organization (IMO) defines a maritime autonomous surface ship (MASS) as 'a ship which, to a varying degree, can operate independent of human interaction' (IMO, 2021). It makes a distinction between four degrees of autonomy, which can be combined during a single voyage, as shown in Table A3.1.

Lloyd's Register proposes a more detailed classification with seven levels and the subcategories 'connected', 'digitalised' and 'autonomous', shown in Figure A3.6.

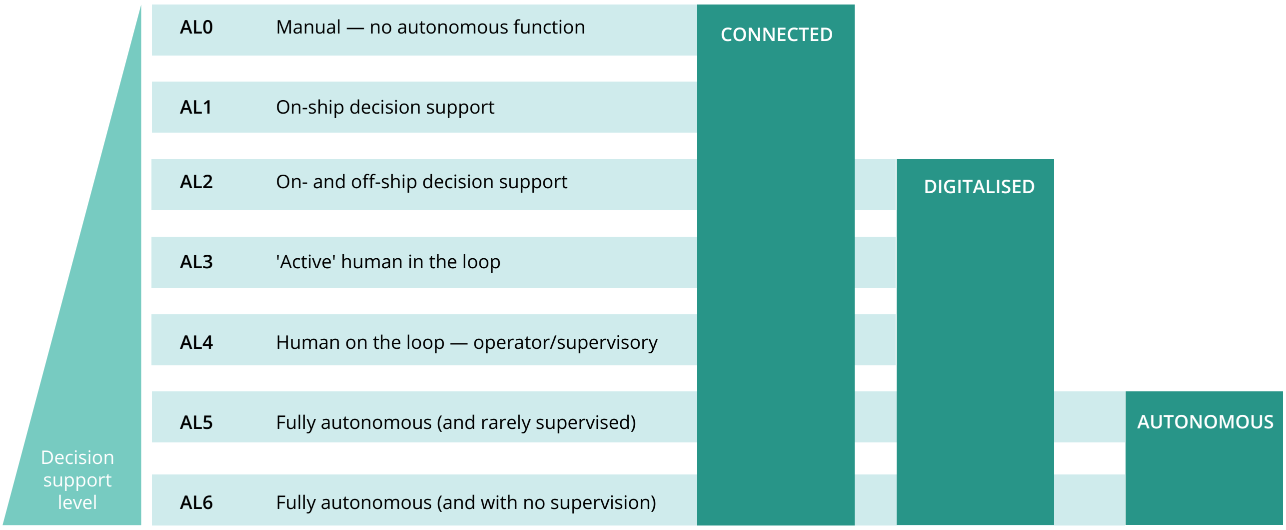
Table A3.1 IMO classification of maritime autonomous surface ships ([a])

	Description	Seafarers on board	Remote control
Degree 1	Ship with automated processes and decision support	Yes	No
Degree 2	Remotely controlled ship with seafarers on board	Yes	Yes
Degree 3	Remotely controlled ship without seafarers on board	No	Yes
Degree 4	Fully autonomous ship	No	No

Note: ([a]) It should be noted that discussions at the IMO are currently ongoing and the definition of a MASS and the corresponding degrees of autonomy may change in light of the development of the future MASS code.

Source: EEA compilation based on IMO (2021).

Figure A3.6 Lloyd's Register autonomy levels for maritime shipping

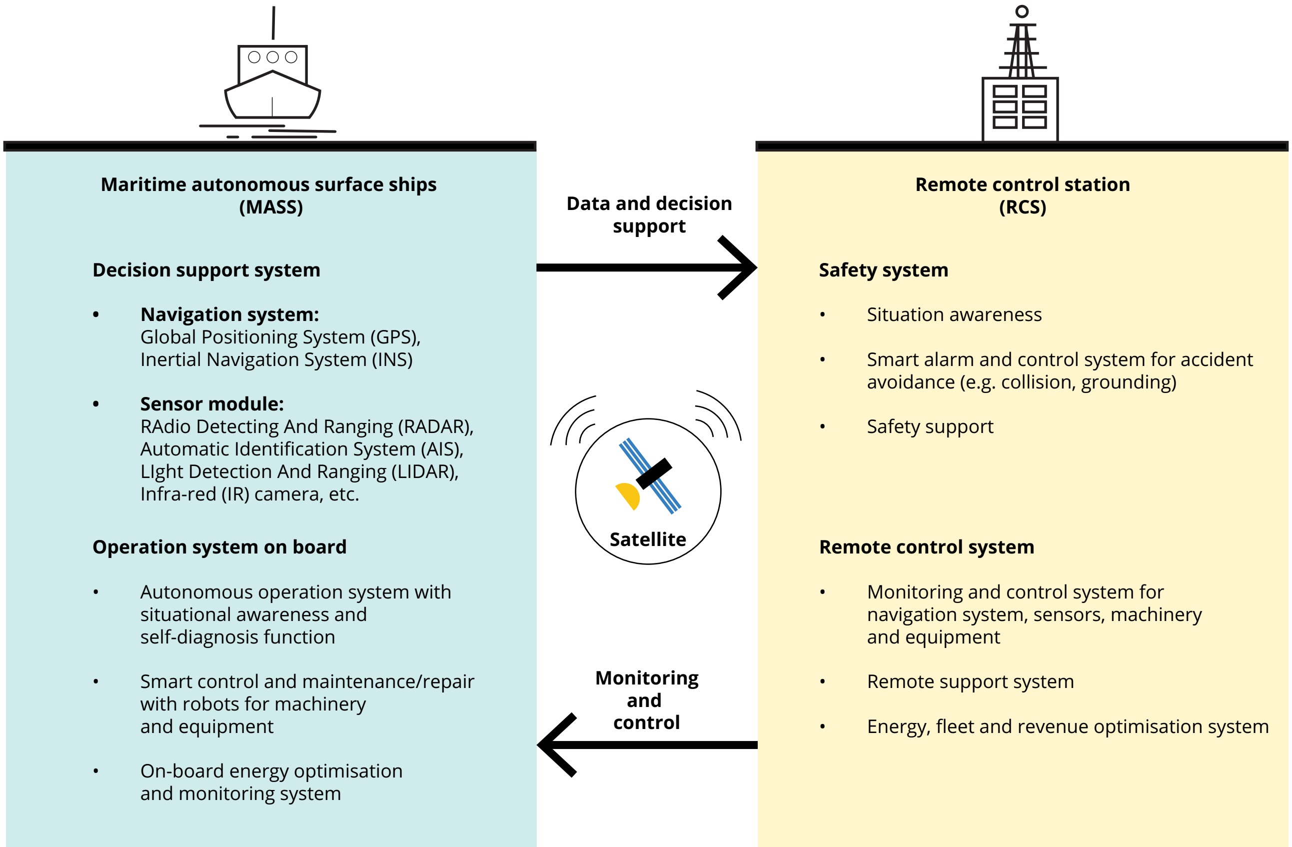


Source: EC (2020d) based on Lloyd's Register.

Figure A3.7 illustrates the main system components of a MASS with a remote control station, also know as shore control centre, i.e. a centre where operators can monitor and remotely control the MASS. It should be noted that communication systems based on terrestrial solutions could also potentially be used as duplication/redundancy of the space-based solutions shown in Figure A3.7.

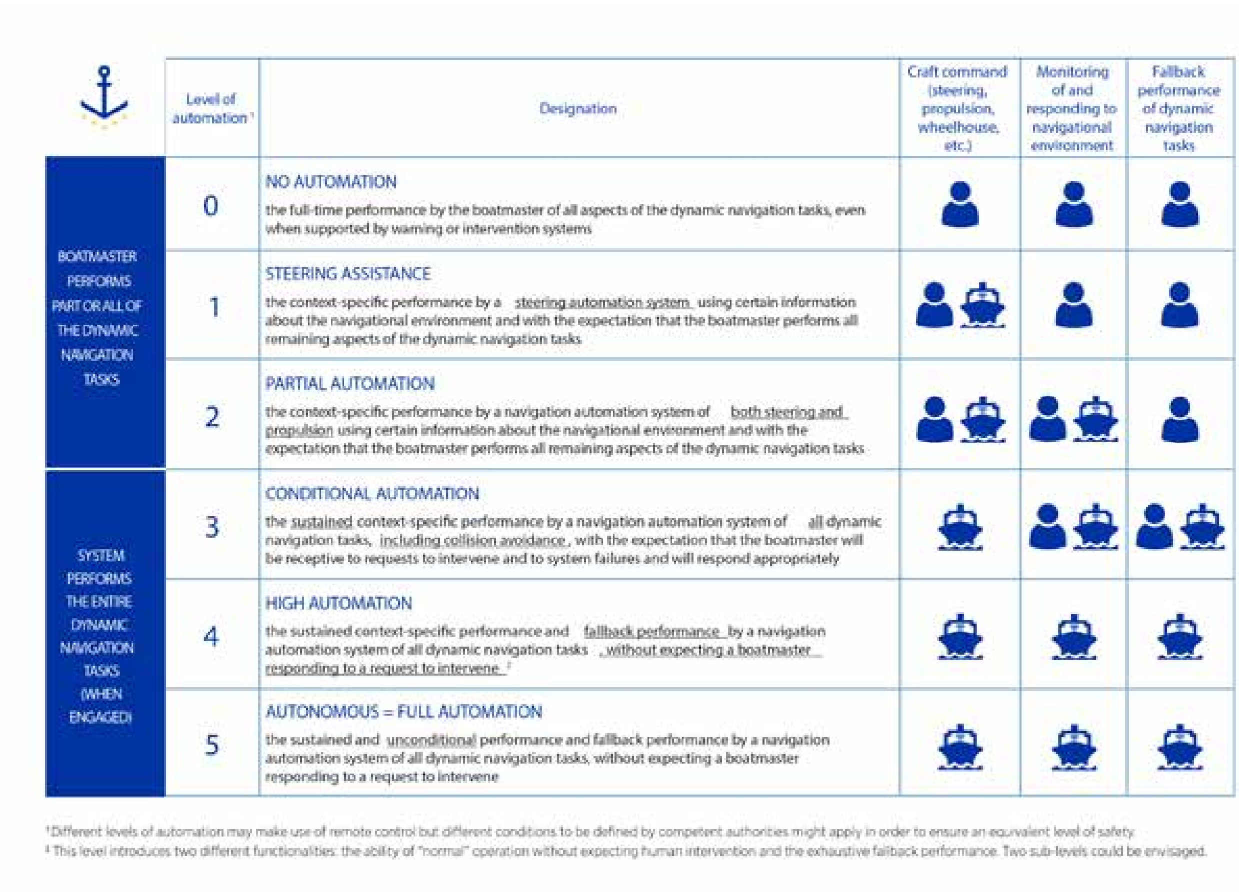
Similarly, in the case of inland navigation, progressive automation is expected to take place in future years. Like the classifications in road and maritime transport, the Central Commission for the Navigation of the Rhine (CCNR) has proposed a classification of the automation levels, reported in Figure A3.8

Figure A3.7 System components of a MASS with a remote control station



Source: Adapted from Kim et al. (2020).

Figure A3.8 CCNR classification for levels of automation in inland navigation



Source: CCNR, Central Commission for the Navigation of the Rhine.

Verberght and Vanhassel (2019) list the main components of the automated operating system (AOS) that will be required for level 5 vessels: 'The AOS integrates all scanners, devices, the automated engine room, automated docking stations ..., the automated helmsman, the on-board bunkering system ..., automated cargo management system ..., and maintains communication with the shore control centre (SCC), locks, bridges, ports, terminals, other ships and authorities'.

A3.2.2 Context

Maritime shipping accounted for almost 29% of the overall tonne-km transported in the EU-27 in 2019 and inland navigation for about 4% (EC, 2022a). Navigation was responsible for 14.1% of GHG emissions from transport in the EU-27 (EEA, 2021a), as discussed in detail in Chapter 2. At the global level, the IMO (2020) indicates that, in total, shipping emitted 1,076 million tonnes of CO_2e (CO_2 equivalent) in 2018, which corresponds to approximately 2.9% of the total global anthropogenic CO_2e emissions in that year.

Porathe et al. (2014) contributed to the EU project MUNIN (Maritime Unmanned Navigation through Intelligence in Networks) and present four main motivations for progressive automation in maritime shipping:

- With partial automation the improvement in the remaining crews' working conditions on board (e.g. more flexible working hours, other types of support from automation system) contributes to making the job more attractive in a sector that faces growing labour shortage problems (EC, 2020d). Full rather than partial automation could offer an alternative way to deal with this shortage, as no crew members are needed on board, although its feasibility should still be demonstrated before it is implemented. In this latter case, it will be important to consider the social dimension of the problem.

- Automation offers the potential to reduce transport costs in a sector that is highly competitive. The competition will take place not only within the sector itself but also across modes. In road transport, which competes with short sea shipping (SSS) or inland waterway transport (IWT), progressive automation is expected to take place. Automation of SSS/IWT is a way to remain competitive in the future compared to road transport. It should be mentioned, however, that the overall impact on costs will also depend on the cost of the automation system.

- Automation can lower the costs of fuel through savings and emission reductions, allowing cost-competitive operational changes such as slow steaming (as staff costs become less important). In this way, it also has the potential to reduce other environmental impacts of maritime shipping.
- An estimated 65-96% of shipping accidents are due to human error. Automation could help to increase safety in shipping by reducing the occurrence of human errors. It should be noticed, however, that human intervention is still likely to be necessary in MASSs, albeit in a different way. It is still uncertain how automated systems will behave in the maritime world in difficult circumstances.

Similar considerations apply for inland navigation. As discussed for the road sector, while environmental considerations play a role, they are not the sole or the main reason for progressive automation in the sector.

A3.2.3 Time frame

According to a survey reported in EC (2020d), in 2020 no maritime ships reached automation level 3 or higher of the Lloyd's Register scale (Figure A3.6). MASSs have been studied in a number of projects in Europe, Asia and North America. Examples of European projects are:

- The European Maritime Safety Agency SafeMASS project (EMSA, 2020) aimed to identify emerging risks and regulatory gaps posed by the implementation of the different degrees of MASS, to support policymakers at different levels. In parallel, EMSA is working on a risk-based assessment tool for MASS (RBAT MASS) which will be developed gradually over the coming years.
- The YARA Birkeland project led to the development of the first fully electric and autonomous container ship, currently in operation in Norway (Skredderberget, 2018).
- The MUNIN project (7th framework programme, 2012-2015) considered as a use case the automation of a dry bulk carrier operating in the intercontinental tramp trades (i.e. without a fixed schedule, itinerary or published ports of call) (MUNIN Consortium, 2016).
- The Autoship project (Horizon 2020 project: 2020-2022) aims to build and operate two different autonomous freight vessels, in order to demonstrate their usefulness for SSS and inland navigation (Autoship Consortium, 2022).
- The AEGIS project (Horizon 2020 project, 2020-2023) aims to develop a sustainable and highly competitive waterborne logistics system consisting of ships with more automation and automated cargo handling (AEGIS Consortium, 2022).
- The MOSES project (Horizon 2020 project, 2020-2023) focuses on SSS and aims to develop, among others, an autonomous vessel manoeuvring and docking scheme (MOSES AutoDock) as well as a digital collaboration and matchmaking platform (MOSES platform) that will use machine learning and data-driven analytics (MOSES Consortium, 2022).

CISMaRT (2020) notes that the European projects focus mainly on SSS, short-haul ferries and specialist vessels, such as tugs or dredgers, while the Asian projects also concern large ocean-going ships. In North America, projects on transport on the Great Lakes and specialist vessels are ongoing. The European Commission (EC, 2020d) predicts that conventional ships will continue to be used for the next 30 years, together with smart conventional ships (with more digital equipment and digital integration of the fleet operation) and fully autonomous ships. Ship renewal rates are around 3% (Economist Impact, 2022). The European Commission (EC, 2020d) indicates that the lifespan of ships is 15-30 years. Therefore, the uptake of autonomous shipping is projected to be slow. Moreover, considerable time will pass before the regulatory framework is set up. Until then, CISMaRT (2020) expects that autonomous shipping will be restricted to specific projects operating within strict conditions. The need to adapt the regulatory framework also holds for inland navigation (Nzengu et al., 2021). Several pilot studies have been carried out or are still ongoing in this area too (CCNR, 2022).

A3.2.4 Expected environmental effects

Using the taxonomy set out in Chapter 3 the following higher order environmental impacts of automation can be identified.

Indirect effects — efficiency effects

MASSs can contribute to reducing environmental pressures from the sector in several ways. First, by reducing the possibility of human error, environmental disasters and oil pollution could potentially be reduced because of lower accident risks, although uncertainties exist, especially in the period in which MASSs will coexist with traditional vessels. Oil pollution from accidents accounts for about 10% of oil spills. The extent to which the accident risk is reduced will depend on the quality of the system, and the training of the (remote) operators (Zanella, 2020). Porathe et al. (2014) point out that, even with MASSs, human errors in remote operation are likely to remain a challenge.

Second, if fewer or no crew members are needed, MASSs also lower the costs of operational measures such as reducing speed. Indeed, lower speeds permit less fuel consumption, and hence lower CO_2 emissions, but also imply longer voyages with higher salary costs, as well as longer stays on board, which reduces the attractiveness of the job (Porathe et al., 2014). These negative effects of reducing speed can be mitigated by MASSs. Fuel savings from slowing down can be substantial. Cariou (2011) estimated that slow steaming by container ships led to an 11% decrease in CO_2 emissions between 2008 and 2010, taking into account the additional shipping required to compensate for slower ships. Conventionally, fuel consumption by ships is estimated to vary according to the third power of speed. In actual operating conditions, the fuel savings can even be higher. However, even assuming that the cubic law holds, a 6% reduction in speed would offer 17% fuel savings for typical slow ships (Pastra et al., 2021). For container ships in the Mediterranean Sea, Degiuli et al. (2021) found a reduction in fuel consumption and CO_2 emissions of about 31% for a reduction in speed of 13.6% for an engine powered by low-sulphur marine gas oil (LSMGO). They found that, for a ship powered by natural gas, the reduction in CO_2 emissions may be 49% compared to an LSMGO-powered ship operating at design speed, although this will depend on the engine technology and the resulting methane slip on a well-to-wake basis. The impact on the GHG emissions depends on the carbon intensity of the fuel that is used and on the pollutants with a global warming potential that will be emitted. If less CO_2-intensive fuels are used in the future, the effect on the CO_2 emissions of MASSs in combination with slow steaming will be lower.

Third, compared to the average conventional ship, MASSs will be newer and will therefore produce less noise and be more energy efficient and cleaner. To a large extent their environmental performance in this respect will be similar to other newer ships. However, they could perform better because automation allows more efficient operation and/or because they are more likely to integrate newer propulsion technologies (Zanella, 2020).

Fourth, thanks to the smaller crew or its absence, the dumping of garbage and sewage is reduced or eliminated. The average amount of sewage is estimated to be 0.01-0.06m^3 per person per day. If mixed with other wastewater, it ranges between 0.04m^3 and 0.45m^3 per person per day (EMSA et al., 2021). While most sewage is discharged by passenger ships, freight ships also generate sewage, the amounts of which can be reduced with fewer crew members. Studies indicate that pollution from dumping by ships contributes 10% of the pollution of the marine environment (Zanella, 2020), and that ships are responsible for 14% of the plastic entering the marine environment, of which part is garbage from the crew members (EMSA et al., 2021).

Structural and behavioural effects — direct rebound effects

In the case of autonomous ships that operate at lower speeds, it is expected that more ships will be needed to provide the same service, which will lead to lower fuel savings (Porathe et al., 2014).

By reducing or even abolishing the crew on board, the labour costs can be reduced. According to the Dutch cost barometer for freight transport in 2018, staff costs accounted for 9-11% of costs in maritime transport, depending on the type of ship (bulk carrier, tanker or container ship). Askari and Hossain (2022) report that labour accounted for 17% of total cargo costs. In inland navigation the share of staff costs was even more important: 19% for push barges, 60-64% for small ships, 34-49% for medium ships and 35-46% for large ships (van der Meulen et al., 2020). This implies that staff cost savings from automation can be important. These need to be balanced against the costs of the automation system. The system can be expected to be taken up on a large scale only if it allows cost reductions and higher competitiveness compared to alternative modes. Cost reductions will have an impact on total freight demand and increase the modal share of navigation, everything else being equal.

Structural and behavioural effects — indirect rebound effects

There are indications that prolonged operation at slow speeds can adversely affect engine efficiency and has implications for engine maintenance (Dere et al., 2022). This aspect may be relevant in the design of autonomous ships.

There are also environmental risks related to MASSs (Zanella, 2020), which also apply to autonomous inland vessels:

- In the event of emergencies, there is only a small crew or no crew on board who can take immediate action, which can increase the environmental impacts of such emergencies.

- In the case of freight containing unstable, flammable and explosive products, the required safety level cannot be met without regular human inspection or intervention, unless very advanced types of automation are available.

- Accident risks and associated environmental impacts in the event of cyberattacks.

Structural and behavioural effects — transformational changes

If progressive automation reduces the costs of navigation, this can potentially change the set-up of the logistics system and lead to systemic transformation.

A3.3 Policy corner

Progressive automation is expected to take place in freight transport, following the general trend towards digitalisation. While it offers some opportunities to increase the environmental performance of the transport modes, one of the main motivations is to increase safety, to reduce transport costs (alongside other motivations) and to deal with shortages in the labour market.

The general increase in transport demand (both in general and for the modes that are automated), due to cost reduction, is beneficial to society only if the external costs that remain are fully internalised.

The environmental impacts of progressive automation also depend on the environmental policies for the transport modes that are already in place in the baseline scenario without automation (e.g. emission standards, renewable energy targets). This environmental perspective should guide the development of the new regulatory framework for automation in the sector.

Regarding the environmental consequences of accidents, the impact of automation on accident risk is a point to consider, as the human factor is not necessarily avoided with remote control and it introduces a cybersecurity risk. Another point to consider is situations in which there are interactions between vehicles or vessels with different levels of autonomy.

A3.4 Bottom line

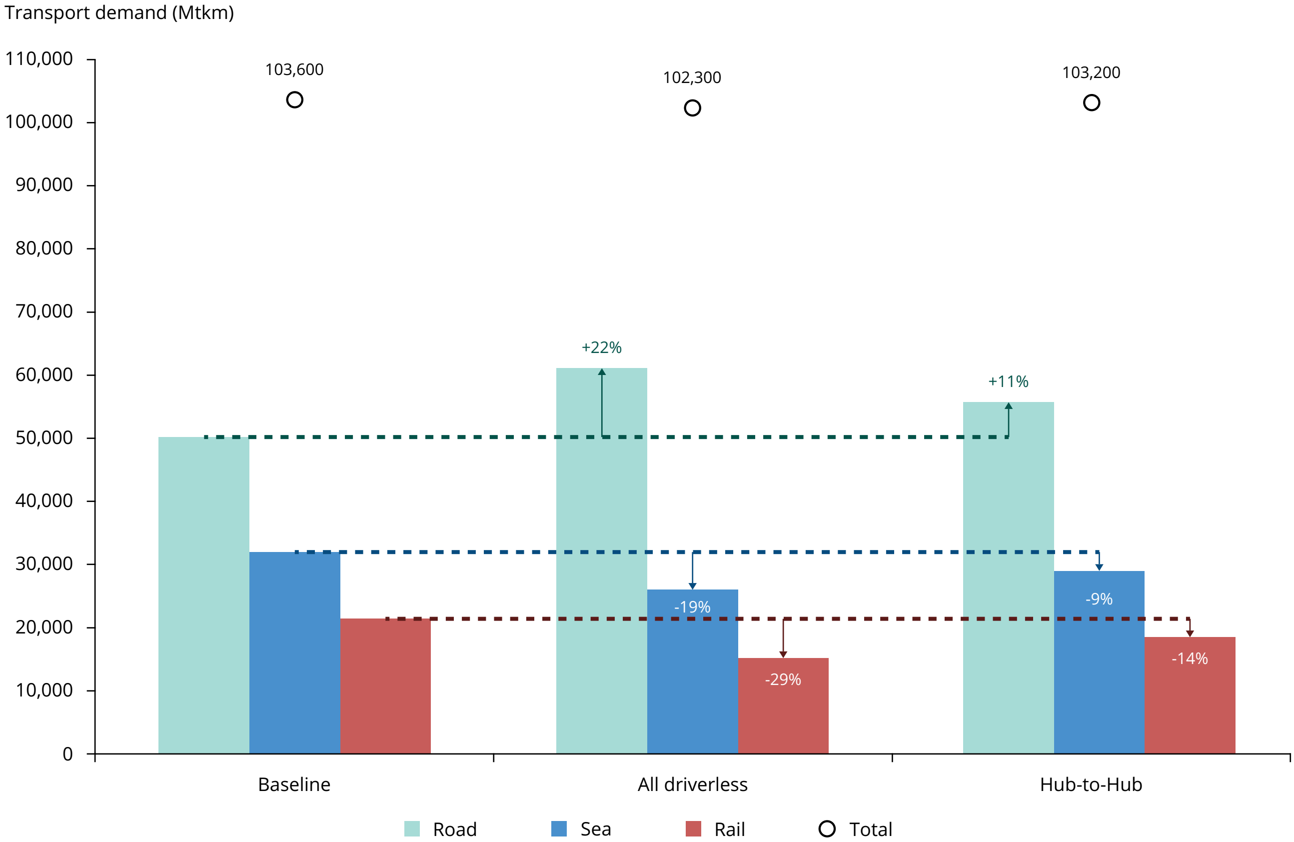
Driverless trucks and automation in navigation offer some potential to increase the environmental performance of transport modes. They are also likely to lead to cost reductions. As transport volumes respond to changes in transport costs, this can be expected to increase transport volumes in general and affect modal choice to favour the modes that become relatively cheaper. Both these effects must be considered carefully since they could have significant environmental impacts. In general, it is important that the external costs are fully internalised and transport demand is managed.

The environmental performance of freight transport modes is expected to improve in the future even without automation. On the one hand, this will reduce its positive environmental effects. On the other, it will decrease the negative effects brought about by the increase in transport volumes that result from the lower transport costs.

A3.5 Case study 3.1: Driverless trucks in Sweden

Engholm et al. (2021) use the freight transport model Samgods to simulate the potential impact of driverless trucks in Sweden. In the first scenario, driverless trucks completely replace manually driven trucks in the Swedish territory. Below, this is referred to as 'All driverless'. In the second scenario, called 'Hub-to-hub', 40 tonne driverless trucks are used only for freight transport between logistics hubs. In this case, the driverless trucks are combined with manually operated trucks in urban areas and other complex traffic environments. Both scenarios are compared to the baseline, which represents the freight transport situation in Sweden in 2017. For rail and sea transport, no automation is considered to happen in this simulation.

Figure A3.9 Impact of two scenarios for driverless trucks on freight transport in Sweden (Mtkm and percentage change compared to baseline)



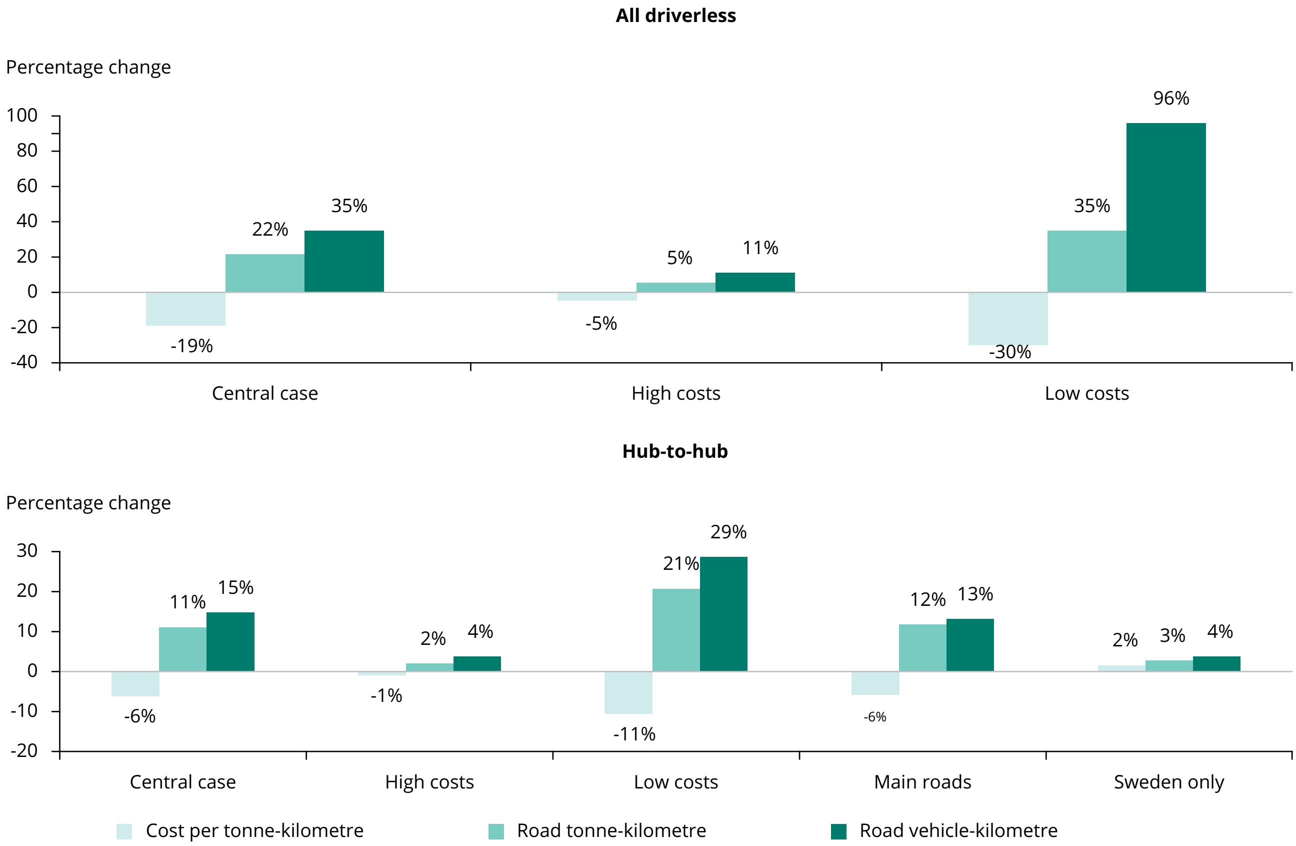
Note: The percentages represent the relative changes in tonne-km transported by the three modes in comparison with the baseline scenario.

Source: EEA compilation based on Engholm et al. (2021).

Figure A3.9 shows that, in both scenarios, there is a substantial increase in road transport at the expense of rail and sea transport. The authors also performed a sensitivity analysis, reported in Figure A3.10, to investigate how the tonne-km transported by road depend on the assumptions that are made about the costs of driverless trucks, and the transport by driverless trucks in the hub-to-hub scenario. In the central cases medium costs are assumed, and for hub-to-hub transport, transport flows with an origin and/or destination outside Sweden can use driverless trucks. In the hub-to-hub scenario 'Sweden only' driverless trucks can only be used for transport flows with an origin and destination in Sweden. In the 'Main roads' scenario hub-to-hub transport by driverless trucks is only possible between transfer hubs along the main roads, both within and outside Sweden.

Compared to the central case, the sensitivity analysis show that, as expected, the growth in road freight increases as the transport costs fall and vice versa. The highest increase in road freight is simulated with all driverless trucks and low costs. In the case of hub-to-hub transport 'Sweden only' the average transport cost is somewhat higher than the central case, which suggests that hub-to-hub transport is most interesting from a cost perspective for international flows. It could also be because domestic transport flows in Sweden use a lot of 60 tonne trucks, and the scenario does not consider the possibility of driverless 60 tonne trucks.

Figure A3.10 Impact of scenarios for driverless trucks on freight transport in Sweden — sensitivity analysis



Source: EEA compilation based on Engholm et al. (2021).

Considering the combined effect of the higher fuel efficiency of driverless trucks and the growth in road freight, the authors make a rough calculation of the impact on CO_2 emissions. The domestic emissions from trucks increase by 18% in the 'All driverless' scenario and by 13% in the 'Hub-to-hub' scenario, under the assumption that the trucks have internal combustion engines and for the central cost estimate. The relatively greater attractiveness of trucks in these scenarios will make it more difficult to realise a modal shift to rail and sea transport.

As shown in Figure A3.4, the average environmental costs of road freight are higher than those of maritime transport and electric rail freight and lower than those of diesel rail freight. Based on the external cost estimates in the European Commission handbook (EC, 2019a) for Sweden, the external environmental costs of freight transport increase by 7.7% in the 'All driverless' scenario and by 4% in the 'Hub-to-hub' scenario when the trucks replace electric rail. Based on the share of diesel in rail energy consumption in Sweden (about 6%, based on the Eurostat energy balances for Sweden) the increase would be 6.8% and 3.6%, respectively. In future years the environmental effects will depend on the changes in the relative environmental performance of the transport modes. A social cost-benefit analysis for driverless trucks in Sweden in 2025 and 2040 indicates that they provide a net societal benefit (Andersson et al., 2019), which increases over time as traffic grows and the share of autonomous vehicles without drivers grows (Table A3.2). The reduction in labour costs would account for about 90% of these net benefits.

Table A3.2 Example calculation of social costs (-) and benefits (+) of driverless trucks in Sweden (EUR million)

Social cost or benefit	2025	2040
Saved driver costs for long-distance transport *(Assumption: 15% of long-distance transport by autonomous vehicles is driver free in 2025 and 50% in 2040)*	+31.4	+706.8
Saved driver costs for other transport by trucks *(Assumption: 10% of distribution vehicles and 20% of construction vehicles are driver free in 2025 and 50% in 2040)*	+13.4	+287.6
Saved fuel due to platooning *(Assumption: platooning accounts for 10% of long-distance transport in 2025 and 50% in 2040; 10% fuel saved)*	+0.9	+34.9
Saved environmental costs due to platooning	+0.6	+25.3
Increased traffic safety *(Assumption: 10% fewer accidents in 2025 and 30% in 2040 compared to current level)*	+1.7	+44.0
New traffic *(Assumption: price elasticity: -0.8 long distance and -0.5 other)*	+1.2	+30.6
Adjustment post: difference between consumer price and marginal social cost *(Assumption: price 20% over marginal social cost)*	+0.5	+12.2
Added cost: transferred traffic from rail *(Assumption: 5% of new long distance transport transferred from rail)*	-0.5	-2.6
TOTAL	**+49.2**	**+1,138.9**

Source: Andersson and Ivehammar (2019).

Annex 4
Multimodal digital mobility services in passenger road transport

A-S-I: shift. Promote a modal shift to public transport by simplifying access to services and trip planning.

Context: urban, extra-urban passenger transport

Time frame: short to medium term. Digital technologies to better integrate public transport modes and improve accessibility to information on and ticketing of public transport are already available and are likely to improve and spread in the future.

A4.1 Definition

Multimodal digital mobility services (MDMS) can be defined as 'systems providing information about, inter alia, the location of transport facilities, schedules, availability and fares, of more than one transport provider, with or without facilities to make reservations, payments or issue tickets' (EC, 2021u). This definition is similar to that of mobility-as-a-service (MaaS), given by given by Heikkilä (2014) and Smith and Hensher (2020). Most of the considerations about MaaS hold for MDMS. With time, however, the former term has assumed more than one meaning, identifying either a specific service, the different actors providing such services or its effects on the system (e.g. an induced modal shift). Currently, an unambiguous definition is lacking in the scientific domain (Smith, and Hensher, 2020). In the following, for these reasons and to be consistent with the Commission legislative initiative currently being prepared (EC, 2022p), we will use the term MDMS.

Generally speaking, MDMS aim to facilitate the realisation of multimodal journeys, helping passengers and/or other intermediaries to compare different travel options, choices and prices, and to ease the sale and resale of mobility products from different operators, whether they are private or public or within one or across multiple modes. This is normally achieved through a single digital interface or platform (e.g. a smartphone application or a website). In this sense, MDMS are not the sum of different transport services but rather a unified and simplified way to access them (Smith, and Hensher, 2020). Importantly, MDMS per se will not create a service if there is none available. MDMS can potentially operate at different geographical scales and for all different passenger transport modes. This means, for example, road, rail, water and air transport at urban, interurban and rural scales. In addition, they can offer various types of payment options ranging from customisable subscription packages to pay-per-use options (Smith, and Hensher, 2020). In addition, the level of integration of MDMS can differ. The KOMPIS project (Smith, and Hensher, 2020; KOMPIS, 2020), involving the Swedish Government's collaboration group for next generation travel and transport, Drive Sweden and Vinnova, categorises these services according to the following progressively higher levels of integration and types of offer:

- Level 0: mobility services operate separately; there is no integration between the services.
- Level 1: informational services are available, for example on possible routes like web mapping services.
- Level 2: integrated booking and payment is available; users can pay for different services via a platform.
- Level 3: individual mobility services are bundled by a third party.
- Level 4: the mobility system fulfils societal goals, for example by incentivising individual users to choose more sustainable modes of transport.

MDMS are enabled by different digital technologies, also presented in Chapter 3, such as the internet, broadband connectivity, smartphones, cloud computing, big data and integration of information technology (IT) systems.

A4.2 Context

Chapter 2 showed how privately owned vehicles remain dominant in the passenger transport system, not only outside the cities but also in urban areas. These are particularly affected by the externalities caused by individual motorised transport modes, as discussed in more detail in Factsheet 7 and Annex 7. In this context, a modal shift to more sustainable and collective transport modes such as buses or trains has been often mentioned as a necessary measure (EEA, 2019a) to achieve the ambitious policy objectives identified in the European Green Deal. However, recent data show that this is currently not happening, with the share of travel by buses and passenger trains in the total transport demand steadily decreasing over the past 20 years, as shown in Chapter 2 and in EEA (2023).

Among the different connected factors that can explain this trend, it is worth considering the greater accessibility (real or perceived) of privately owned cars in comparison with public transport services, even in urban areas where such services are well developed (Becker et al., 2020; Storme, et al., 2020). This is even more relevant in rural areas, as shown in Aapaoja et al. (2017) and Eckhardt et al. (2018). Indeed, planning and buying tickets for multimodal journeys using public transport is often a challenge for travellers in the EU. MDMS can improve this by helping both passengers and/or other intermediaries to compare different travel options, choices and prices. In addition, they can facilitate the sale and resale of mobility products from different operators, whether they are private or public or within one mode or across modes. In this sense, MDMS can promote a modal shift to public transport by increasing its attractiveness and accessibility for the end users, especially in rural areas, without offering an additional means of transport. Indeed, the ITS4C workshop cites a Creafutur study stating that 'MDMS can help to solve the crucial last mile problem to make public transport attractive, but therefore, an offer of flexible last mile transport needs to be offered' (ITS4C Congress, 2019). Apart from making public transport more attractive, MDMS, especially when coupled with other measures aiming to discourage the use of individual cars (Factsheet 7), may contribute to reducing greenhouse gas and air pollutant emissions, traffic congestion, the need for parking spaces and the number of fatalities (Smith, and Hensher, 2020).

Despite these potential benefits, MDMS trials are still very limited and, as a consequence, there is a scarcity of experimental evidence in the scientific literature (Smith, and Hensher, 2020). This contributes to considerable uncertainty about the potential societal or environmental benefits that such services can actually deliver. For example, it is currently largely unknown how the different MDMS business models will affect mobility and the environment. According to Smith et al. (2018), the development of MDMS will require the introduction of two new roles in the transport system: MDMS integrators and MDMS operators. The former will gather the offers available from different transport providers and make them available to the operators (also providing technical integration), while the latter will package the offers and deliver them to the final users. Three different general scenarios for the future development of MDMS can be envisaged (Smith et al., 2018):

1. Market driven development. In this situation the MDMS are provided by private entities at both the integrator and operator levels. This scenario will require a viable business case for the private player, while the role of public transport providers will remain essentially unchanged, with only the additional requirement to allow third-party ticket reselling.

2. Public-controlled development. In this case MDMS are aggregated and operated by a public entity. This scenario is motivated by the fact that public and private actors can have mutually conflicting interests. This is particularly relevant if the main goal of MDMS would be to realise societal or environmental benefits. To achieve this, public transport must remain a backbone of MDMS as the main viable and sustainable alternative to extensive individual car use.

3. Public-private development. In this scenario the role of the MDMS integrator is assumed by the (public) transport service provider, while the role of operators is taken by private companies. It has been argued that this could lower the initial investment costs for MDMS operators, facilitating the integration process. In addition, by acting as a buffer between MDMS operators and transport service providers, the publicly controlled MDMS integrator could mitigate the risk of any of the MDMS operator becoming too dominant.

Depending on the development models that will be followed and the pricing schemes that will be proposed, specific MDMS could end up having different priorities and objectives not necessarily in line with the environmental goals highlighted at the beginning of this section. It is unclear whether a purely market-driven approach could be compatible with the sustainable transition sought. Indeed, profits are normally not the main focus of a well-developed and fair public transport system. At the moment, there is no evidence that MDMS alone will be able to shift the existing paradigm of incremental change to one of fundamental transformation of our transport system, critical for reaching the EU sustainability goals (EEA, 2019a).

A4.3 Time frame

Multimodal digital mobility services are based on digital technologies that are already widely available, as discussed in detail in Chapter 3. Indeed, some examples of MDMS are already available such, as Jelbi in Berlin, described in more detail in case study 4.1 (Section A4.7), Citymapper in London or Whim in Helsinki, which started operations in 2017. All allow the use of several public transport services provided by different operators with a single subscription. Although the digital technologies for a successful large-scale introduction of MDMS are already available, some barriers may still be present in specific contexts. In particular, the development of and the acceptance among the different players of standardised communication protocols, open APIs (application programming interfaces) and the use of interoperable formats for data exchange are seen as a key step to enabling MDMS (Smith, and Hensher, 2020; Polydoropoulou et al., 2020). In general, big data and algorithms will play a significant role in MDMS. This must be properly accounted for by regulatory entities. The remaining technological barriers are often minor compared to the relational one between different parties (Rudzinski and Van Schijndel, 2022). The more mobility providing parties participating in MDMS, the more added value MDMS can provide. Indeed, the greater the participation, the more services and combinations of them can be provided and the more attractive the offer can be. However, the parties involved can anticipate the risks of participating in MDMS such as losing their position in the mobility market or being overtaken by a bigger player. Building trust between parties (and among users) is crucial. The large investment needed to build the platforms and integrate the data are another barrier for the development of MDMS (Rudzinski et al., 2022).

From a policy perspective, MDMS are currently under discussion at different levels. First, the revision of the Intelligent Transport Systems (ITS) Directive (EC 2021v) envisages a streamlined recording and reporting of data (see Chapter 4). Its revision will support multimodal ticketing. A dedicated regulation on MDMS is in preparation. Its objective is to create optimal conditions for the creation of MDMS, implementing action 37 of the smart mobility strategy. Its main drivers are (1) to address the opaque conditions for combining and reselling mobility products in land-based, waterborne and maritime transport; (2) the difficulty of ensuring that incumbent MDMS do not adopt anti-competition practices or that deployment of MDMS is not limited by anti-competition practices; and (3) the difficulty of ensuring that MDMS support sustainability. The revised directive is indicatively planned for Q2 2023 (EC, 2021o; European Parliament, 2022c).

Policy can promote the future development of MDMS through a series of initiatives. Particularly relevant is the obligation for transport service providers to allow third-party resale of their tickets, as for example in the new Finnish transport regulation for single journey tickets (Smith, and Hensher, 2020). Similarly, Denmark has decided to release public transport data and tickets for third-party resale (Qvartz, 2018; Smith, and Hensher, 2020). In the framework of the MaaS4EU project, a review of existing policies and whether these act as enablers of or barriers to the development of such services has been undertaken. In particular, it is worth mentioning that, in the context of the EU passenger rights regulation (EU, 2004; Brunagel et al., 2019; European Parliament, 2022d), multimodal trips are still not covered. Additionally, the roles and responsibilities of MDMS actors are not yet clearly defined. For example, it is not clear if and how a multimodal trip purchased through an MDMS operator will be reimbursed if the final user misses a plane due to a train delay or vice versa.

Several research projects in the MDMS domain are ongoing or have been financed recently. An example is the above-mentioned EU-funded project MaaS4EU, which aimed to provide 'quantifiable evidence, frameworks and tools, to remove the barriers and enable a cooperative and interconnected EU single transport market for the mobility as a service (Maas) concept, by addressing challenges at four levels: business, end-users, technology and policy' (MaaS4EU Consortium, 2020). Similarly, in Sweden, KOMPIS, a collaboration programme to support the development of combined mobility by reducing initial barriers and creating favourable conditions, has been realised. The feasibility of MDMS has also been explored in pilot projects such as SMILE in Austria (Audouin, 2019) and in multiple other trials both in Europe and worldwide, as reviewed by Kamargianni (2016).

Despite the favourable technical conditions and the ongoing legislative initiatives, barriers still exist in the collection, interoperability and sharing of data among the established transport operators and MDMS actors. As explained above, the reasons for this are not necessarily technological but often relational or economic. Moreover, such systems will have to demonstrate their scalability across different transport modes and geographical areas and for a large number of users.

A4.4 Environmental impacts

To estimate the environmental benefits of MDMS, is important to evaluate the impact of MDMS on modal choices such as reducing personal car use in favour of public transport or other mobility services, such as shared and pooled transport. Similarly, it is relevant to understand how pedestrians and cyclists will be influenced. The literature provides some evidence, although it is not sufficient to draw clear conclusions. The indications reported here therefore need to be considered preliminary and treated with caution.

Using the taxonomy set out in Chapter 3 the following higher order environmental impacts of MDMS can be identified.

A4.4.1 Indirect impacts — substitution effects

MDMS are likely to have environmental impacts, as they will offer new combinations of existing modal alternatives to satisfy mobility needs. Depending on the modal choices these new combinations will replace, the overall result could be either positive or negative for the environment.

In general, studies show that the shift from active modes to public transport is easier than from individual car use to public transport (EEA, 2020b). To reduce car use, measures that discourage it are necessary, such as internalising its external costs. A study performed for the city of Zurich simulated the impacts of the introduction of MDMS, including different transport modes such as cars, public transport, free-floating car-sharing and ride-hailing services, personal bikes, free-floating bike-sharing services and walking. The results indicate that the presence of large car-sharing and bike-sharing fleets can decrease the overall energy consumption of the simulated system by up to 7% by attracting users from other modes. However, the most relevant reduction is achieved when the total cost of private cars is charged in the model simulations instead of considering the cost of car use only (see also Factsheet 7 and Annex 7). This reduces transport-related energy consumption by approximately 25% (for trips within the service area). In addition, the study indicates that the only shared mode that has a negative impact on energy consumption is ride-hailing, because it tends to compete with public transport and active modes. Interestingly, on a system level, the benefits in other domains such as travel time savings or the generalised costs of the system were marginal (Becker et al., 2020).

Storme et al.(2020) question the potential of MDMS to significantly substitute for the use of private cars in urban areas. In their pilot project in Ghent, Belgium, none of the alternatives was close to completely substituting for the use of private cars, especially for leisure trips. However, car use in commuting trips was significantly reduced, although the sample used in the study mostly consisted of highly educated and motivated employees of Ghent University.

A study on Whim in Helsinki shows that MDMS users travel more frequently by public transport and shared modes than other city inhabitants. It is, however, unclear how the mobility behaviour of Whim users was influenced by Whim compared to the situation before Whim existed (Ramboll, 2019).

The MDMS pilot Ubigo was carried out in Gothenburg. The study shows that the participants in the trial already used public transport and bicycles more and car less than the average Gothenburg resident. The results were similar to the findings in Helsinki. After the trial participants stated that they travelled more by public transport and bicycle and less by private car than before. Private car use among the participants decreased by 50% and their perception of the other modes became more positive (Sochor, et al., 2014). See also case study 4.2 (Section A4.8).

It is still unclear whether car drivers will adapt their behaviour. Alyavina et al. (2020) state that this could be difficult, and there is the risk that future MDMS users could substitute public transport trips with car trips and ride-sharing services. Another challenge is the digital divide. A Belgian report from the King Baudouin Foundation finds that 46% of Belgians are digitally vulnerable. This is also true for 45% of youngsters with a low education level (Faure, et al., 2022). A general discussion of this is also available in Chapter 6.

Trials of MDMS and surveys of users suggest that the typical early adopter is likely to be young, live in a dense urban area, have high digital competence, tend to travel multimodally already and have relatively high levels of public transport use (ITF, 2021). To maximise the impact of MDMS it is important that those services can be easily accessed by a wider variety of final users.

It is difficult to draw a conclusion on the impact of MDMS on modal choice based on the above studies. Although they seem to suggest that such services could reduce car use, especially for digitally skilled young people who are open to alternatives, it is complex to assess the exact quantitative impact and how MDMS will influence the modal choices of other societal groups.

MDMS are likely to be used more where the offer of existing mobility solutions is dense and they meet the users' mobility needs. This holds especially for occasional short trips and, in particular, when two or more transfers between modes are necessary. Indeed, in the case of several mobility solutions, users may not be aware of all the different possibilities and make a choice ignoring a potentially interesting non-car solution. In the case of longer or frequent trips, it is more likely that users will try to optimise their transport solution, even without using MDMS, in this way partially offsetting the benefits of MDMS. However, the transport system is dynamic and optimal solutions may change over time depending on, for example, congestion levels. Moreover, final users are often unaware of the external costs of their modal choices, as described in Factsheet 7 and Annex 7. Both dimensions can be accounted for in MDMS, which has the potential to make such externalities transparent to individual users and nudge their individual choices towards more sustainable transport modes.

Regular urban trips, such as commuting for work and education, count for between 30% (Germany) and 50% (Croatia) of urban trips (Eurostat, 2021e). In addition, half of personal business, leisure, accompanying and shopping trips are regular trips. Irregular trips, for which MDMS could have most impact, account for 25-45% of urban trips (Eurostat, 2021e). As urban mobility accounts for 40% of CO_2 emissions from road transport (Cepeliauskaite, et al., 2021), MDMS could potentially influence between 10% and 20% of the emissions. A 1% or 2% reduction in car use could thus reduce the emissions of the road transport sector by 0.1-0.2%.

As discussed, the main feature of MDMS is to facilitate access to the transport system, without creating additional services if those are not available. For example, if there are no mobility options apart from the private car, MDMS will not be able to provide an alternative apart from a carpooling solution. However, such solutions are not very popular, except for longer distances with apps such as BlaBlaCar. The environmental gains are limited: CO_2 emission reductions are estimated at only 12% as a trip with BlaBlaCar often replaces a train journey or is a new journey (Mayeres, et al., 2018).

It is also the case that the way in which the MDMS scheme is developed will influence its environmental impacts and attractiveness. As described in Section A4.2, MDMS could be developed according to various general schemes that are likely to influence the final objectives and environmental benefits of such services. Similarly, the proposed pricing structures will differ, which will affect the overall system. It has been argued that modal choices are often based on actual costs of use rather than on overall figures that also account for sunk costs (Becker, et al., 2020) (e.g. in the case of a private car the purchase price, insurance, etc.) or, even better, the externalities generated. This topic will be extensively explored in Factsheet 7 and Annex 7, but it is also relevant for MDMS. Indeed, Hörcher and Graham (2020) show that flat rate subscriptions can generate market distortions because they do not include the marginal costs of use. This induces overconsumption by owners of a subscription passes and a modal shift to private cars by infrequent travellers, due to the increased congestion of the system and the higher access costs. In contrast, non-linear pricing is found to be less harmful from a social welfare perspective, allowing revenue generation at the same time.

A4.4.2 Structural and behavioural effects — direct rebound effects

By freeing up personal resources or by making the available transport modes more attractive, MDMS will also lead to new trips if no additional measure to contain the demand is in place (Ringenson, and Kramers, 2022). Although new trips respond to a need and therefore have a societal benefit, from an environmental point of view new trips have a negative impact. If travellers are not confronted with the full external costs of their travel, the societal costs of their trips can be higher than the societal benefits, as is widely discussed in Factsheet 7 and Annex 7. Active mode trips nearly always have a positive impact thanks to their positive health impact.

A4.4.3 Structural and behavioural effects — indirect rebound effects

MDMS could promote a modal shift to collective transport modes by making access to public transport easier and more attractive. This could also lead to a decrease in traffic in congested areas because of a reduction in traffic volumes. This will have a positive impact on public transport in the short and mid-term (Honey-Roses et al., 2020). At the same time, however, the reduction in congestion will attract new traffic. It is therefore important that such rebound effects are properly controlled using, for example, the tools described in Factsheet 7 and Annex 7.

MDMS could have impacts on location patterns and urban structures in the long term. Areas around public transport hubs will develop more and/or certain transport or mobility lines will develop more. An efficient and attractive public transport system could promote relocation outside the city centre, promoting urban sprawl (Ringenson et al., 2022). Copenhagen is a well-known example of transit-oriented growth since 1947 with its 'Finger plan' (Knowles, 2012).

A4.5 Policy corner

MDMS are an important tool that can contribute to promoting modal shift to collective transport modes and public transport. However, it is important to stress that MDMS alone will not provide the structural changes in our transport system that will make it sustainable. MDMS improve access to the urban and potentially peri-urban transport system, mostly for the digitally literate. Investment in the physical infrastructure for active transport modes, investment in public transport services, a pricing system internalising external costs for all transport modes, including private cars, and a strategy for digital inclusion are fundamental building blocks in the transition to a sustainable transport system. MDMS will make that transport system more accessible. It is also fundamental for scaling up and developing MDMS that dynamic and static data (also real-time) from transport providers are made accessible and comply with harmonised standards.

To fully harvest the potential environmental benefits of MDMS, developing a global transport system framework will thus be necessary, with the following characteristics:

- Active modes and public transport are the backbones of the transport system (and MDMS). Both must be supported by public engagement. Public transport should offer high-quality and accessible services. Active modes should be able to rely on high-quality and safe infrastructure.
- Active modes, electrically assisted for longer distances, are encouraged as a flexible and healthy mode on their own or as a first and last mile option in combination with public transport. A shift away from active modes to public transport, private car or other MDMS is avoided.
- Transport pricing schemes, such as those described in Factsheet 7 and Annex 7, that can fully internalise transport externalities are a third building block of sustainable transport systems. MDMS can make the application of pricing policies for the services they provide easier and approach optimal economic marginal cost pricing (ITF, 2015).
- The transport system framework is developed in dialogue with traditional urban planning (Creutzig et al., 2019). This also applies to MDMS and other digitalised services.
- MDMS complete the transport system framework. Digital platforms provide seamless integration of all mobility services and service providers. The framework also ensures, again through government involvement, that suboptimal

monopolistic situations are avoided, as digitalisation can facilitate their occurrence (Vij, and Dühr, 2022).

- The transport system guarantees access to digitally illiterate people via (digital) inclusion strategies or strategies that guarantee access to the transport system in another way.

A4.6 Bottom line

It is hard to draw clear conclusions on the potential environmental impacts of MDMS. One reason for the difficulty of making a thorough assessment is that fully integrated MDMS are still rather rare, and the integration of the ticketing and services from different providers is often difficult.

A number of the above-mentioned studies and communications state that MDMS have the potential to be environmentally beneficial. To fully harvest that potential, it is important that MDMS comes at the top of an integrated transport system with the following characteristics:

- Active modes and public transport are the backbone of the system.
- Transport pricing schemes are in place to internalise external costs.
- The system is coherent with traditional planning.
- It pays attention to (digital) inclusion.

In isolation, MDMS will hardly be sufficient to realise important environmental benefits.

A4.7 Case study 4.1: Jelbi, Berlin

This case study describes the Jelbi system in Berlin and the impacts the COVID-19 had on it. Research on the impacts on modal share is still ongoing. Therefore, case study 4.2 also provides some information from user groups in a pilot study in Gothenburg, which give an idea of the mobility impacts.

Jelbi is an integrated system of mobility services. Where previously different mobility solutions existed separately, each with a different app, with Jelbi all kinds of mobility solutions are integrated into one app. This means that all public transport, bus and local trains but also several services for car sharing, bike sharing, sharing e-mopeds, e-scooters and taxis and ride sharing are part of it (Cepeliauskaite et al., 2021). The service started in June 2019 as a limited pilot project. By October 2021, 250,000 people had already downloaded the app in a city of 3.5 million inhabitants. The project also envisaged creating 72 Jelbi stations or hubs by the end of 2021, where different mobility solutions would be brought together to make easy transfers between mobility solutions possible.

A study investigating Jelbi's impact on modal shares is ongoing, but results are not yet available. However, the results of a study on the impact of COVID are available. They show that the use of public transport fell dramatically (by 80%) during COVID, while the use of other sharing services grew modestly (by 6%). Before the crisis, public transport made up 80% of Jelbi use, whereas during the crisis it fell to 20% of Jelbi use, while other sharing services moved in the opposite way. Once normal life was re-established, the use of public transport grew more rapidly among Jelbi users than among traditional public transport users. The study therefore concludes that integrating different mobility solutions keeps users closer to public transport (Mobility Institute Berlin and Jelbi, 2020).

A4.8 Case study 4.1: UbiGo pilot, Gothenburg

UbiGo is an example of an MDMS provider developed and tested for 6 months (November 2013 to April 2014) in the framework of the Go:Smart project in Gothenburg, Sweden (Sochor et al., 2015, 2016). UbiGo was developed for urban households that already have access to existing transport modes, such as public transport and car sharing, and with mobility needs sufficiently large for the service to be competitive with their already available solution. In the testing phase, 195 participants tried the new service through 83 customer subscriptions (173 adults and 22 individuals under 18 years of age at the start of the trial). The base UbiGo subscription was set at approximately EUR 135 per month at the time of the trial, although users were able to purchase additional services. Indeed, the average subscription expenditure was approximately 150% of this value.

The sample tested was young (38 years old on average) and digitally skilled: more than 88% used the internet and applications on computers, tablets and smartphones on a daily basis. In the questionnaire before the start of the trial, approximately 54% of the sample interviewed stated that they did not own a car, although in case of need 42% of this group could borrow one. Interestingly, the vast majority were neither car-sharing (69%) nor bike-sharing scheme members (81%). Most of the participants owned a bicycle (81%) and had a public transport card (88%).

The preliminary results obtained through the pilot suggest that the participants were able to reduce the use of private car by 50% while increasing their use of other modes such as car sharing by 200%, express buses by 100% and conventional buses by 35%. Train use increased by 20% and tram use by 5%. Among the active modes there was a slight decrease in walking (by 5%) but a significant increase in the use of private bikes (by 35%). The fact that during the project the participants purchased approximately 30% more car hours than the amount that they actually used, indicating that the perception of mobility needs is a relevant variable to take into account, is important. It is interesting to note that not only the use of but also the attitude towards the various travel modes changed during the trial, with participants becoming less positive about the private car (23%) and more positive about other modes (e.g. car sharing 61%; bus or tram 52%; bike sharing 42%). Although these results are not straightforward to quantify in terms of environmental benefits, they suggest that, when properly implemented, MDMS have the potential to contribute to mitigating the impacts of the transport sector on the environment.

It is worth noting that, from the interviews held during and after the trial, users believed that their accessibility to and the flexibility they have in using the transport system increased following the introduction of the MDMS.

The authors underline the importance of MDMS targeting a specific segment of users and the necessity of developing services in line with the demand and the expectations of the chosen group. In this context, the importance of adequate packaging, simplicity, improved access, flexibility and economy is essential to promote a behavioural shift in users and should not be underestimated.

Another relevant aspect to take into account in the design of MDMS is the complex interaction between public and private actors. For example, the authors argued that car sharing and car rentals are profitable for the MDMS providers, but that extensive use of such modes will clash with the objective of reducing car use, which is relevant for the public stakeholders.

Annex 5
Smart logistics

A-S-I: improve, by allowing more efficient organisation in the logistics sector by, for example, simplifying the administrative burden. Shift, induced by the relative difference in the benefits that improvements in efficiency can bring in transport modes.

Context: transport of goods, all different modes

Time frame: short to medium term. Significant developments are already ongoing; digitalisation is a continuous process.

A5.1 Definition

Logistics is a term that can be used in different contexts. In the business sector, with specific reference to the shipment of goods, it can be defined as 'the process of planning, implementing and controlling procedures for the efficient and effective transportation and storage of goods, including services and related information from the point of origin to the point of consumption for the purpose of conforming to customer requirements and includes inbound, outbound internal and external movements' (CSCMP, 2022). In simpler terms, the logistics sector comprises all operations linked to the flow of goods from a point of origin (e.g. a factory) to a point of consumption (e.g. the final user) to meet different set of requirements.

The application of digital technologies such as those presented in Chapter 3, and in particular information and communications technology (ICT), to the logistics sector has been often identified with the term 'smart logistics' (Geiger, 2016), although that term, as discussed for other technologies, has progressively acquired a more articulated and multifaceted meaning, and a widely agreed definition is still missing (Uckelmann, 2008). Korczak and Kijewska (2019) compiled a detailed review on the topic, and identified three key features of smart logistics: (1) the multiplicity of services that it entails; (2) the different sales channels driving deliveries; and (3) the synchronisation of planning, people, policy and infrastructure. In general, the use of ICT in logistics allows data to be recorded at the source, then be processed and transferred to successive systems in real time and made constantly available (Scheer, et al., 2001). This, by monitoring current states and identifying deviations, can form the basis for better steering of logistics flows.

In the following we use the term smart logistics in line with the definition reported by BCI Global, i.e. 'the effective use of data to improve the efficiency of traffic and logistics' (BCI Global, 2022).

A5.2 Context

Freight transport, as extensively discussed in Chapter 2, is a key sector in the EU economy. The transport and storage sector alone employs approximately 10.4 million people and records an added value of EUR 510.3 billion, excluding satellite activities. This represents 7.9% of those working in the non-financial business economy and 7.4% of the wealth generated in that part of the economy (Eurostat 2022c).

EU-27 demand for freight transport continues to increase, at approximately the same pace as the gross domestic product (GDP). In 2019, approximately 3,392 billion tonne-km were transported, 23% more than in 2000. This corresponds to a compound annual growth rate of 1.8%. By comparison, in the same period overall GDP in the EU-27 increased by 31% in real terms (after removing the effect of price changes; this corresponds to a compound annual growth rate of 1.4%). In 2019, 52.0% of tonne-km were transported by road, 28.9% by sea and 12% by rail. The share of the other transport modes was 4.1% for inland navigation, 3.0% for oil pipelines and 0.1% for air. Meeting such demand has significant environmental impacts, as discussed in Chapter 2, and external costs (see Factsheet 7). For this reason, understanding the effect of applying digital solutions to the logistics sector is of interest: eliminating inefficiencies and administrative burdens can on the one hand bring environmental benefits (e.g. reducing greenhouse gas (GHG) and air pollutant emissions or congestion) and on the other hand further increase the demand for services due to the lower costs.

The logistics sector is complex and includes many actors and processes, with a wide geographical scope and different transport modes involved. A key element of interest in this factsheet is the transport of goods across different nodes of a network or of a supply chain. These movements are associated with the need to exchange a significant amount of information, not only for business purposes but also to demonstrate compliance with transport rules and contractual agreements. Today, according to the European Commission, the vast majority of this information is printed on paper: for example, only 1% of cross-border operations in the EU territory can be carried out in a completely digital manner, i.e. not requiring a physical document at some stage of the transport process. Differences exist if we make comparisons across single modes (i.e. not considering multimodal transport), with aviation being the one with the highest uptake (approximately 40%) of electronic information exchange. By comparison this share is approximately 5% for rail, 1% for road and virtually zero in the maritime sector (Ecorys et al., 2018).

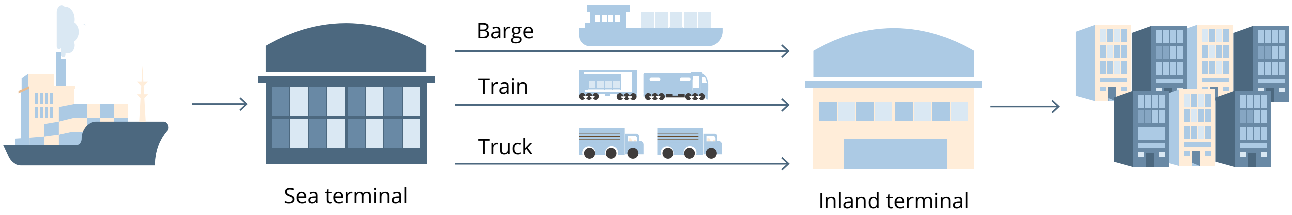
The reasons for this situation lie in the legal and technical barriers preventing an efficient and secure exchange of information based on trust between operators and authorities. Indeed, legal provisions in some Member States require that, in order to fulfil regulatory requirements, transport documents requested by public authorities need to carry handwritten signatures (e.g. Belgium, Bulgaria, Italy Luxembourg, Slovenia and Spain). More generally, there is no consistent rule across modes and for all EU-27 Member States on the acceptance of electronic transport documents (Ecorys et al., 2018) indicating a fragmented legal framework. From a technical standpoint the situation is similar. Although, for some modes, protocols for electronic documents exist (e.g. UNECE electronic consignment notes: e-CMR for road transport and e-AWB for air transport), for others the situation is less clear and no accepted standard yet exists. Moreover, how these protocols will work across modes is still unclear. The situation becomes even more complicated when the digital solutions implementing such protocols are considered. Indeed, in the past 20 years, many public or private platforms to support the sharing of data for business or compliances processes have been developed. In general, although these have certainly contributed to local efficiency gains in specific modes, there is a significant concern among stakeholders about the lack of interoperability and interconnectivity across these tools. Indeed, it should be mentioned that the costs of switching from one platform to another are likely to be high. Most efforts in this digitalisation domain remain mode specific and this is also due to historically separate regulations.

Since 2015, the European Commission has organised and coordinated the Digital Transport and Logistics Forum (DTLF), a platform where policymakers and the stakeholders in the transport and logistics sector can interact and cooperate to support the development of relevant legislative initiatives and programmes. Its main target is achieving full-scale digital interoperability and data exchange in a shared, secure and trusted transport and logistics data space (EC, 2022q). One of the main outcomes of the work done in the forum was the preparation of Regulation (EU) 2020/1056 on electronic freight transport information (eFTI) (EU, 2020). This regulation entered into force in 2020 and will become fully applicable from 2025. It establishes a legal framework for information exchange across the whole sector. The DTLF supports the implementation of the eFTI Regulation across four different domains: (1) the data requirements (e.g. which data are necessary to collect and exchange); (2) the rules and procedures for access to data and platforms (e.g. how authorities will be able to obtain information and where/how operators will make this available); (3) definition of the technical architecture of the system; and (4) the certification of platforms and service providers (e.g. for security reasons). This initiative will build upon and work together with others such as the EU maritime single window environment (EU, 2019f) and the EU single window environment for customs (EC, 2020e). The first establishes the legal and technical framework for electronic transmission, through harmonised interfaces, of the information necessary to comply with reporting obligations for ships calling at an EU port, while the latter aims to streamline customs control and facilitate trade across EU borders, also by means of improved digital tools and cooperation.

Another relevant initiative under the DTLF is the realisation of 'corridor freight information systems', aimed at creating a common ground for information sharing across multiple modes and logistics chains. The idea is to realise a federated network in which it will be possible to integrate existing or new platforms for data exchange in logistics. This will be structured in line with the following principles: (1) to allow stakeholders to connect and share data according to predefined agreements and procedures, in a 'plug and play' manner; (2) to ensure interoperability across different platforms within the federation even if built on different technologies; and (3) to be trusted, safe and secure (EC, 2022q). This initiative is supported by two different EU-funded projects: Federated and FENIX, described below.

The advances brought by digital technologies are not only limited to the transition to a fully digital transfer of information but digitalisation can also intervene at different levels in the logistics system. RIS and ERTMS are examples at the single mode level. RIS (River Information Service) provides information on how and where inland ships navigate on the network. This, among other things, facilitates the invoicing of sail duties and reduces waiting times. ERTMS (European Railway Traffic Management System) improves interoperability between EU rail systems via a European automatic train protection system that replaces the national systems and a communication system between train and track or central operators. It has been estimated that such a system can increase capacity on the rail network by up to 30-40% (Alstom Transport et al., 2022).

Figure A5.1 Illustration of synchromodality



Source: Karimpour and Ballini (2018).

At a broader level, synchromodality is a typical example (Figure A5.1). It can be defined as the 'provision of efficient, reliable, flexible, and sustainable services through the coordination and cooperation of stakeholders and the synchronisation of operations within one or more supply chains driven by information and communication technologies (ICT) and intelligent transportation system (ITS) technologies' (Giusti, et al., 2019). It is based on the real-time sharing of information between different stakeholders and across transport modes (Acero et al., 2021), and it is ultimately achieved by assigning shipments to a multimodal network in real time, depending on the conditions (ACEEE, 2021).

A5.3 Time frame

The development of digital technologies for logistics applications is a continuous process. As discussed, this has led in recent years to the realisation of many different platforms and technologies to support data exchange, strategic planning and optimising the flow of goods. For example, transport as a service (TaaS) in freight road transport, a concept similar to mobility as a service, explored in detail in Factsheet 4 and Annex 4, is based on digital load matching, i.e. the process of matching shipping demands with transport capacity via digital technologies. In the US it is projected to grow from USD 1.2 billion in 2019 to USD 79.4 billion in 2025, a growth rate of approximately 39% per year. TaaS could represent more than 10% of the US trucking industry market share within a few years (ACEEE, 2021).

Digitalisation and automation are expected to bring changes to the freight transport sector that, as we have discussed in Factsheet 3 and Annex 3, will have to face the double challenge of the sustainable transition and, at the same time, the shortages in the labour market. Cimini et al. (2020) reviewed some of the technologies expected to bring changes to the sector in the future, although the impact these will have on the environment is yet to be understood. Policy will play a key role in this context.

The push for a modal shift away from road and towards less GHG-intensive transport modes should be accompanied by a progressive improvement in air pollutant emissions standards in these other transport modes (e.g. maritime and inland waterways shipping). This is to mitigate externalities caused by increased emissions of nitrogen oxides (NOx) and particulate matter, including black carbon.

Lastly, the policy framework is, as described, evolving rapidly and with the ambition of enabling easy and effective data sharing across the whole freight transport sector. This is explored through two different pilot projects described below: Federated and FENIX.

A5.4 Expected environmental effects

Using the taxonomy set out in Chapter 3 the following higher order environmental impacts of smart logistics can be identified.

A5.4.1 Indirect effects — efficiency effects

It is generally complex to evaluate quantitatively the environmental benefits that digital technologies applied to logistics can deliver. This is due to the variety of the potential applications discussed above and to the significant rebound effects associated with gains in efficiency. Ideally, smart logistics will have a positive effect on the environment the moment it will be able to (1) promote a modal shift to the more sustainable transport modes such as rail and short sea shipping and (2) eliminate inefficiencies and administrative burdens that cause congestion, delays and additional emissions. However, while it is true that shipping has generally lower CO_2 emissions per tonne-km transported, NOx and particulate emissions, including black carbon, are higher than those of other transport modes, with effects on global warming effects (EC, 2017b; EEA, 2022e). If a significant portion of freight transport traffic is to be shifted to shipping, improved emissions standards should be developed in parallel to handle these additional pressures.

Through the eFTI Regulation the Commission estimates that the administrative costs in the transport and logistics sector can be reduced by EUR 27 billion over a period of about 20 years (2018-2040), compared to a baseline scenario in which no action is taken. Smaller scale initiatives in the passenger transport sector have demonstrated that the transition to electronic documents and certificates can reduce the administrative burden and realise cost savings. An example is the e-Albania platform: among other things, it simplifies Albanian citizens' access to public administration services in transport through the transition to digital documentation. Estimated savings in 2021 are in the order of EUR 16 million (Albania, 2022; Albania GDRTS, 2022).

Karam et al. (2021) highlight that, due to the high degree of market fragmentation typical of the freight sector, transport inefficiencies are relevant. In 2018, trucks were running empty for 12.3% of the total distance travelled between EU countries. This reached 15-30% in some Member States. This has significant environmental impacts, such as air pollutant and GHG emissions, noise and congestion.

A5.4.2 Indirect effects — substitution effects

The increase in efficiency likely to be induced by the eFTI Regulation, is expected to facilitate multimodal transport, with the net effect of inducing a modal shift away from road transport. This has been quantified to be in the order of 0.2-0.3%, corresponding to a reduction of 1.3 billion tonnes of CO_2 in the 2018-2040 period and compared to a baseline in which no action is taken. This is equivalent to a EUR 74 million saving of external costs and up to EUR 300 million saving of congestion costs. These figures account for the increase in NOx and particulate matter externalities induced by an increase in waterborne transport (EC, 2017b).

A5.4.3 Structural and behavioural effects — direct rebound effect

As discussed, digitalisation in logistics has the potential to realise significant efficiency gains, especially if a fully integrated system across modes becomes a reality. However, this is likely to induce a further increase in demand. This, if not properly managed, risks counterbalancing if not completely offsetting the environmental benefits realised through the implementation of the technology. The European Commission has estimated that this effect could be in the order of 0.3-0.4% in 2030 compared to a baseline in which there is no coordinated uptake of digitalisation in logistics (EC, 2017b).

A5.4.4 Structural & behavioural effects — transformational changes

Digital innovations in logistics can also have relevant consequences for the wider economy, with for example, significant impacts on the labour market. Full-scale deployment of electronic documentation is likely to impact the large number of jobs nowadays related to the processing and acceptance of paper documents. At the same time, it is expected that the demand for ICT professionals, ICT providers and IT platforms will increase, with competition leading to reductions in system costs for the transport operators, and possibly for the authorities.

A5.5 Policy corner

At the EU level, a policy framework to enable the creation of 'a seamless European transport system' is under development (EC, 2022q). Digitalisation has the potential to enhance cooperation across supply chains, improve their visibility and realise the real-time management of cargo flows. This is likely to reduce the administrative burden and improve the efficiency of existing infrastructure and resource use. However, it is important that such innovation will not translate into an increase in the demand for transport that will ultimately erode any environmental benefit achieved through efficiency gains. Implementing measures to internalise external costs, similar to those described in Factsheet 7 and Annex 7, will be complementary to the deployment of smart logistics tools. Promoting the conditions for data sharing and horizontal collaboration will be key conditions for realising the benefits discussed in the factsheet. Cooperation with competitors will require a new way of thinking, focused on trust and the advantages of cooperation instead of competition (Karam et al., 2021).

The digitalisation of the freight transport sector and the transition to a paperless way of exchanging information will require the prevention of cyberattacks and the capability to ensure the continuity of operations and disaster recovery. Ensuring cybersecurity and the privacy of commercially sensitive data remains complex (EC, 2018d). Some of these challenges are further detailed in Chapter 6.

Digitalisation in freight transport has the potential to realise a modal shift to less GHG-intensive modes such as railway and maritime or inland waterway shipping. However, ships have generally higher emissions of air pollutants such as NOx and particulate matter, including black carbon, with adverse effects on both human health and the environment. For this reason, it will be important to support the technological evolution of logistics with more stringent emission standards and advanced monitoring techniques such as those described in Factsheet 9 and Annex 9.

For society, the automation and digitalisation of the logistics sector will bring further challenges, as also discussed in Factsheet 3 and Annex 3. Changes are expected in the type and number of jobs required. The mechanism through which workers could be redeployed in higher value tasks is, however, uncertain. This will largely depend on the way each company is structured.

A5.6 Bottom line

Digitalisation has the potential to make logistics more efficient, facilitate multimodal transport, promote a modal shift away from road transport, and realise both environmental and economic gains. However, it is of utmost importance that this does not translate into a significant increase in the demand for transport, which would be likely to nullify any benefit for the environment. This will require appropriate management measures such as those discussed in Factsheet 7 and Annex 7. It is also important to mention that, although there is a significant interest in shifting goods always from road transport, some of the alternative modes, such as maritime shipping, have higher emission factors for some relevant pollutants such as NOx, particulate matter and black carbon. These not only have an impact on health and air quality but also may have direct or indirect effects on global warming that will require attention.

If policymakers succeed in putting in place a framework (fiscal and regulatory) to avoid efficiency gains being used only to cut prices and increase volumes (rebound effect), smart logistics will be able to provide environmental gains.

A5.7 Case study 5.1: Federated and FENIX projects

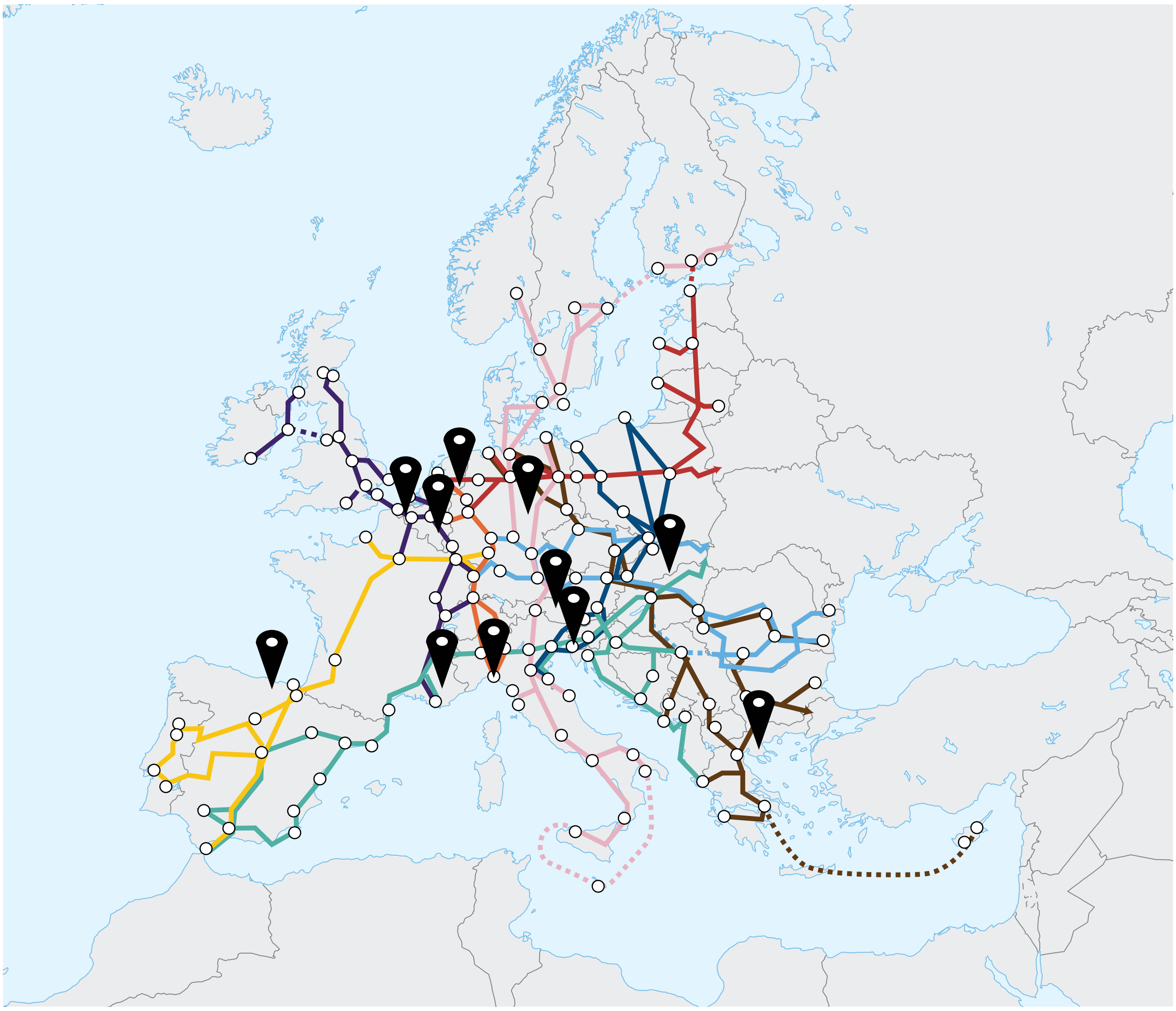
The Federated (FEDeRATED 2022) and FENIX (FENIX Consortium 2022) projects are EU Connecting Europe Facility-funded projects, aiming to support the work done in the DTLF to develop and validate technical solutions for corridor freight information systems, and to support the implementation of the eFTI Regulation.

Federated involves 15 partners located across six EU Member States from both private sector and public administration. The main objective is to develop future-proof federated networks of platforms that will enable seamless data sharing throughout the freight transport sector. This is achieved by practical experimentation on the ground, in the form of living labs in which approaches and technologies can be tested in real-world small-scale conditions. The project will run until 2023, when a final report is expected to be delivered.

FENIX involves 45 members, two implementation bodies and two Member States, with the objective of developing the first EU federated architecture for data sharing serving the European logistics community of shippers, logistics service providers, mobility infrastructure providers, cities and authorities. Map A5.1 shows the 11 pilot sites on the Trans-European Transport Network (TEN-T) that have been identified and will be used to demonstrate the operational feasibility and benefits of the technology.

As a part of this project, a survey to identify gaps and future opportunities in multimodal freight transport has been performed. Most of the respondents from the European transport industry identified the following three aspects among the most desirable for intermodal logistics: (1) less paperwork and more exchange of digital information (79%); (2) increase efficiency, agility and real-time exchange of information (75%); and (3) a wider application of existing standards (70%). Interestingly, only slightly more than half of the participants (56%) identified increased horizontal collaboration between manufacturer and retailers as a desirable aspect. The main barrier identified in a wider implementation of existing standards is the lack of knowledge about the standard itself and the perception of the risks associated with the change.

Map A5.1 The 11 pilots of the Fenix project



FENIX pilot site

Baltic — Adriatic corridor

North Sea — Baltic corridor

Mediterranean corridor

Orient/East Mediterranean corridor

Scandinavian — Mediterranean corridor

Rhine — Alpine corridor

Atlantic corridor

North Sea — Mediterranean corridor

Rhine —Danube corridor

Source: FENIX (2022).

A5.8 Case study 5.2: Smart ports

Digitalisation of ports is seen as an important measure to increase the resilience of our logistics system and crucial supply lines. Smart port logistics will increase efficiency and improve the allocation of resources (UNESCAP, 2021) and are expected to become not only logistics hubs but also energy hubs (SEArica Intergroup, 2022).

The main characteristics of smart ports can be summarised as follows:

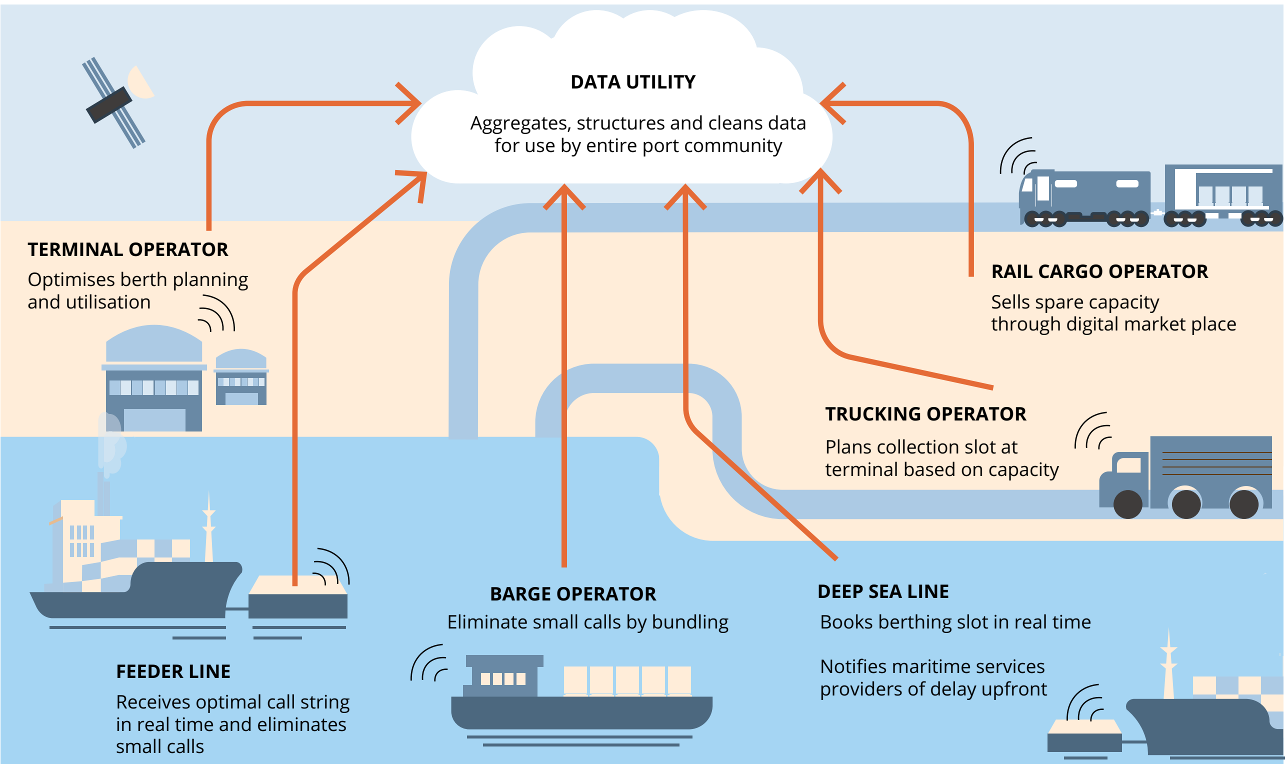
- The combination of technology and the collection and distribution of data and information helps the management of operations inside and outside the port.
- Information is shared with operators, the port community and stakeholders.
- The port is integrated with the territory surrounding it (city, region, country) and with smart transport (roads, rail, rivers) and energy infrastructures (for the distribution of new energy carriers).

Smart ports can realise benefits in different ways (Figure A5.2). By improving port operations, they can speed up of the transit time for goods, reducing costs and the time required for cargo loading, unloading, stowage or storage. They can reduce the administrative burden and facilitate compliance checks through the exchange of digital information. At the same time, by providing real-time data about, for example, the status of cargo and the working condition of the port facilities, they can facilitate strategic planning and communication with customers and stakeholders.

Different examples of development smart port capabilities can be identified throughout Europe. Rotterdam is the largest European port. Its smart port programme has three focus areas: smart logistics, smart energy and industry and future-proof port infrastructure. It aims to create a digital twin of the whole port to optimise its actual, near future and future use. It has been estimated that, by reducing ship waiting times and cargo handling times and streamlining the use of terminal yards, shipping companies using the Port of Rotterdam could save about USD80,000 per call (UNESCAP, 2021). The ambition of the Port of Rotterdam is to evolve to a fully automated port with automated ships, smart containers and autonomous cranes (Port of Rotterdam, 2022).

The Port of Hamburg is the third biggest port in Europe, after Rotterdam and Antwerp. It handles 20% of European exports. Through its smart port programme, it plans to reduce the cost of port operation by 75% and port congestion by 15% (UNESCAP, 2021).

Figure A5.2 Some benefits of digitalisation in maritime port areas

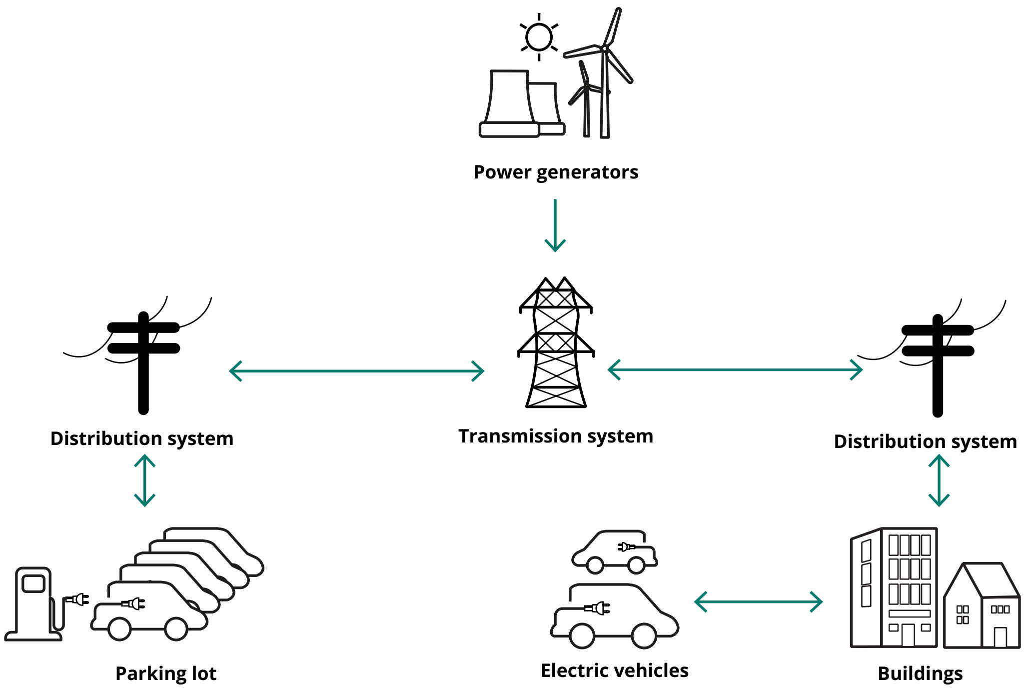


Source: Courtesy NxtPort in DocksTheFuture Consortium (2020).

The European Corealis project carried out an energy assessment for the Port of Pireas. The study conclusions were that it would be possible to supply energy at competitive prices of EUR 60/MWh including battery storage to cope with load demand and renewable energy production peaks (see also Factsheet 6 and Annex 6). The overall load of the port, including electric vehicles and onshore power supply, is approximately 55GWh and could be covered through 46MW of renewable energy generation and 30MWh battery storage. Self-sufficiency would exceed 85% with renewable energy that emits 25g CO_2/kWh compared to the current levels of 1,167g CO_2/kWh. Furthermore, substituting the entire fleet of diesel-powered yard vehicles with electric vehicles could save a significant amount of fuel annually, while the impact on electricity consumption would be limited. The additional need is estimated to be equal to 10% of the current electricity demand. Indeed, the port could even become a net exporter of renewable electricity due to excess generation (Cardone, 2019; Corealis Consortium, 2021).

Annex 6
Vehicle-grid integration

Figure A6.1 A simplified scheme showing the vehicle-grid integration concept



Source: Ala et al. (2020).

A-S-I: improve (lower carbon content electricity generation and lower costs of and emissions from electric vehicles)

Context: integration between electric vehicles for road transport and the power grid

Time frame: medium to long term. Up until now, vehicle-grid integration has mainly been studied in field tests and research projects. The system still requires a greater uptake of vehicle-to-grid-enabled electric vehicles, the roll-out of the necessary infrastructure and further research, including on battery degradation.

A6.1 Definition

The term vehicle-grid integration (VGI) covers the systems in which electric vehicles (EVs) can communicate with the power grid and, in this way, render unidirectional or bidirectional services to it. The technology is also often called vehicle-to-grid or V2G (Elia 2022).

In the case of unidirectional vehicle-to-grid services or V1G, also known as 'managed (or smart) charging', the charging of EVs is controlled. This can involve, for example, delaying EV charging to avoid times of high power demand on the grid or throttling the charging rate to better accommodate grid needs (e.g. in the event of excess power generation by intermittent renewable energy sources).

In bidirectional vehicle-to-grid, or simply V2G, the EVs can return electricity to the grid in a controlled manner by means of specifically enabled bidirectional chargers. In this way, EVs can render additional services to the grid, such as frequency regulation, which is further described below. VGI could also be applied at a local scale, in vehicle-to-home (V2H), vehicle-to-building (V2B) or vehicle-to-everything (V2X) applications. In this case, the EV battery is used to store electricity produced on site or as a back-up power supply in the event of possible power failures.

VGI can be realised not only with battery electric vehicles (BEVs) and plug-in hybrid electric vehicles (PHEVs, albeit to a limited extent given the comparatively small capacity of their battery) but also by fuel cell electric vehicles (Oldenbroek et al., 2017). In the last case, the energy transfer is unidirectional, from the vehicle to the grid, with the former operating as a controllable power generator. To provide services to the electricity system, a minimum capacity is generally required. To achieve this, different assets can be pooled in a so-called single virtual power plant. This is enabled by digitalisation in the form of aggregators. These combine power electronics and control algorithms to collect data on connected EVs and the status of the grid and take or schedule charging and discharging decisions in real time for each connected vehicle based on grid needs and the boundary conditions in place (e.g. residual charge) (Krueger, and Cruden, 2018; Rancilio et al., 2022).

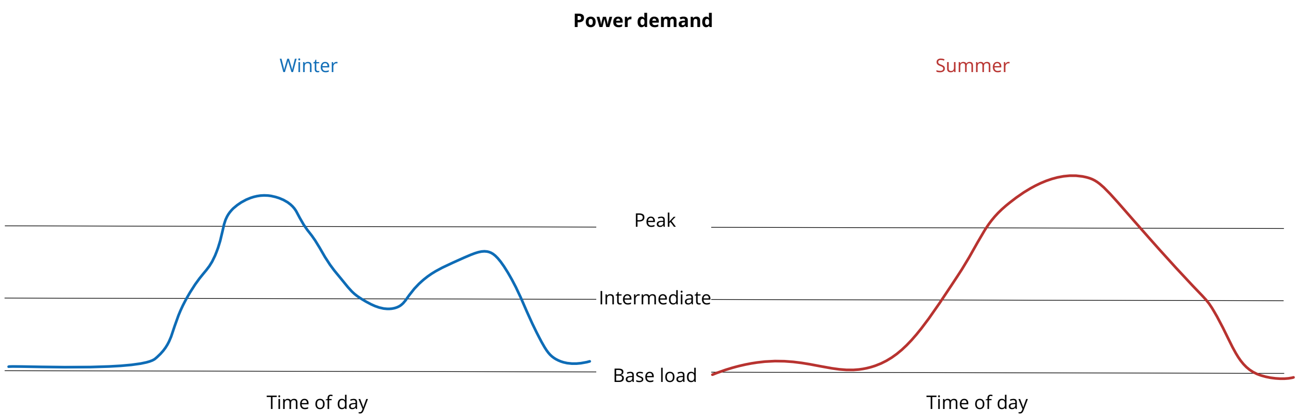
A6.2 Context

To better understand how VGI could impact the environment, it is necessary to have some understanding of the energy generation and distribution system and of the interactions between this and the ongoing electrification of the transport sector.

A6.2.1 The electricity system

Electricity is an energy carrier and is normally obtained from the conversion of other primary sources (e.g. solar and wind energy or nuclear and chemical energy in fuels) realised in centralised, large-scale power plants or in distributed smaller scale installations. This electricity can be immediately consumed, in the case of distributed installations (e.g. a photovoltaic (PV) panel mounted on the rooftop of a residential unit), or sold in an electricity market and distributed through an interconnected network often called a grid or power grid. In general, on a given grid over a span of time, it is possible to distinguish three different levels of demand: baseload, intermediate and peak load, as shown in Figure A6.2. The baseload is the minimum level of demand on an electrical grid over a span of time. This demand can be met by so-called baseload power plants, which run at almost constant output round the clock, or a combination of dispatchable power plants (which control their output within a specific range and that can be either renewable or non-renewable) and variable renewable electricity (VRE) sources (Ueckerdt, and Kempener, 2015). The above-base power demand (intermediate and peak demand) can be met by VRE sources and dispatchable generators, including energy storage. Peak power plants are often constituted by gas turbines operating on natural gas at lower efficiencies (approximately 30-40%) than those achievable in combined cycle gas turbine plants (approximately 64%). Electricity supplied during peak periods is sold at a much higher price per kilowatt-hour than that supplied to cover base load demand.

Figure A6.2 Example of the daily variation in power demand

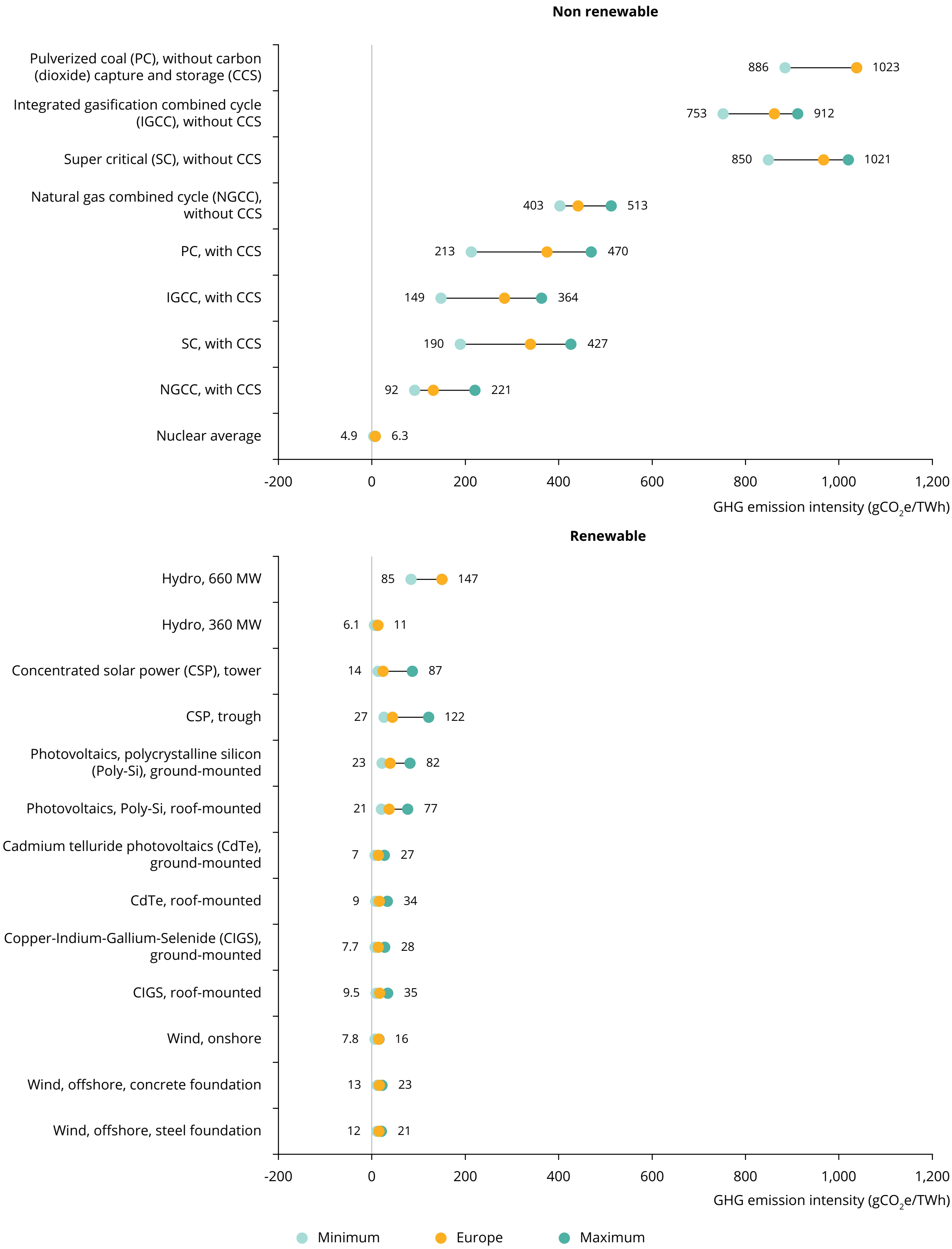


Source: Fedkin (2020).

Apart from providing electricity, actors operating within the grid can provide additional services. These are normally called ancillary services and are 'provisions necessary for the proper operation of a transmission or distribution system' (Electricity Directive, Directive (EU) 2019/944; (EU, 2019g)). These maintain grid reliability, balance supply and demand, and support the transmission and distribution of electricity from the seller (producer) to the buyer (consumer). With the growing share of VRE sources such as wind and solar PV the challenge of ensuring the stability of the power system increases. Given their variability, VRE need to be combined with dispatchable back-up capacity. The need for this could be reduced when a mix of solar and wind power is used, as their production time patterns can be different, or when energy storage is available. With VRE sources, deviations also occur between forecast and actual generation, which requires balancing the available power at short notice (Ueckerdt et al., 2015). The ancillary services thus become even more critical with a high share of VRE in the power generation mix.

In 2020, 37.5% of total gross electricity consumption in the EU-27 was from renewable energy sources (EC, 2022r). Wind accounted for 36% and solar for 14% of the renewable electricity production. Among other renewable sources, hydropower accounted for 33%, solid biofuels for 8% and the remaining 9% was from a range of other sources (Eurostat, 2022i). The average greenhouse gas (GHG) emission intensity of this power generation mix in the EU-27 was 230.7g CO_2e/kWh in 2020, which was 54% lower than in 1990 (EEA, 2022f). With the policies that were in place at the end of 2019, the share of renewables in electricity generation is projected to increase to about 60% in 2030 and 75% in 2050. In 2030, about half of renewable electricity should come from wind and one fifth from solar energy (EU Reference Scenario 2020, reported in EC (2021a)). With the RePowerEU plan, the European Commission puts forward a higher 2030 target at EU level for renewable energy (45% compared to 40%, as proposed in the revision of the Renewable Energy Directive) and the further strengthening of wind and solar energy (EC, 2022b). On 30 March 2023 the European Parliament, the European Commission and the EU member reached the provisional agreement on a legally binding target to raise the share of renewable energy in the EU’s overall energy consumption to 42.5% by 2030. EU countries that choose to do so can complement this target with an additional 2.5% indicative top-up that would allow reaching 45% The potential of renewables to reduce GHG emissions by electricity generation is evident as shown in Figure A6.3. The United Nations Economic Commission for Europe has derived CO_2 emissions/TWh based on a life cycle analysis of different power generation technologies (UNECE, 2021). It is expected that, if the above-mentioned target is achieved, the overall average GHG emission intensity of power generation in the EU-27 will further decrease in the coming years. With the RePowerEU plan, the renewable energy share in the electricity sector would reach 69% in 2030 (EC, 2022s).

Figure A6.3 **Life cycle greenhouse gas emissions of power generation technologies in different regions of the world (gCO_2e/TWh), 2020**



Source: UNECE (2021).

A6.2.2 Electric vehicles in the EU-27

In 2022, about 12% of the newly registered cars and vans in the EU were BEVs, and 9.5% were PHEVs. The current share of EVs in the EU is still small (1.2% for BEVs and 1.1% for PHEVs in 2022) and distributed unevenly across Member States (EAFO 2023) , with only high-income countries in the top five in terms of EV share in the fleet (Sweden, Denmark, Netherlands, Luxembourg, Germany), while the share of EVs is very small in the countries with the lowest income per capita. In 2022, the highest share of EVs in the car fleet was recorded in Sweden: 9.7%. Outside the EU, Norway recorded a share of 25.7%. With the EU policy framework that was in place at the end of 2019 for the decarbonisation of road transport, the EU Reference Scenario 2020 projected a share of electricity in road transport of 2.7% by 2030 and about 12% in 2050 (EC, 2021a).

In the meantime the EU has further strengthened the CO_2 emission standards of cars and vans. By 2035 all new passenger cars and vans should have zero CO_2 emissions per kilometre at the tailpipe. It is expected that the regulation will further strengthen the uptake of EVs (Erbach, 2022; Goulding Caroll, 2022). However, the EC have also committed to prepare proposals to enable the registration of cars and vans exclusively running on carbon-neutral fuels after 2035. The impact assessment of the revised regulation indicated that the share of light-duty vehicles in electricity consumption could increase from 2.8% in 2030 to 11% by 2040. Over the period 2030-2050 the cumulative savings in petrol and diesel would amount to 1,100Mtoe (megatonnes of oil equivalent) compared to the baseline (EC, 2021w).

A6.2.3 Interactions between electric vehicles and the grid

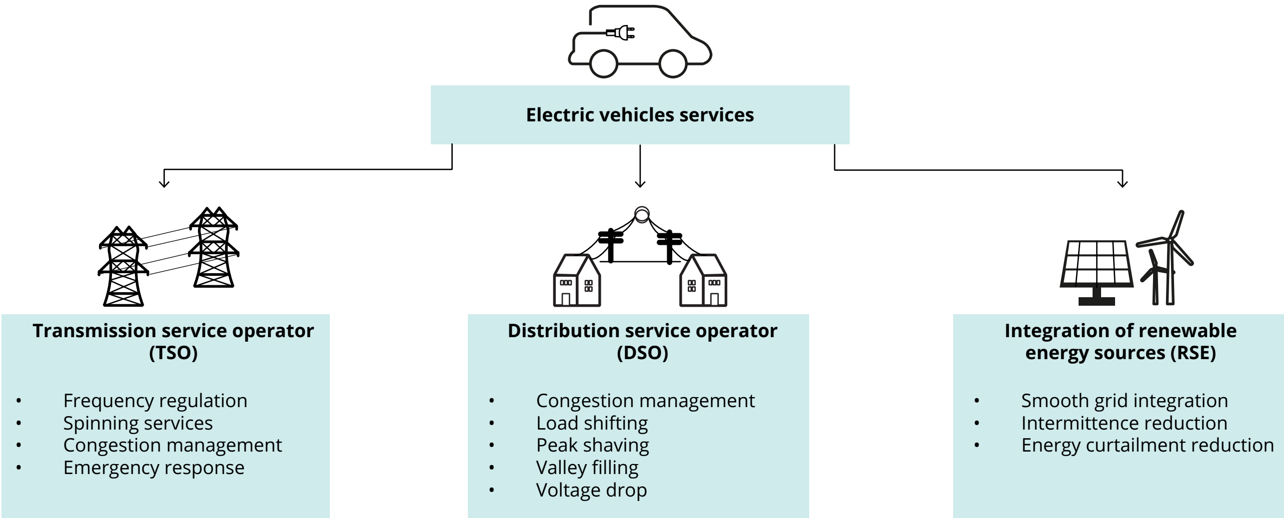
While contributing to the decarbonisation of road transport, the electrification of the road vehicle fleet will significantly increase the demand for electricity. The impact assessment of the CO_2 emission performance standards of cars and vans indicates that, with a high penetration of EVs, their electricity consumption could reach around 11% of total electricity consumption in 2040, compared to a share much below 1% in 2020 (EC, 2021w). If EV charging is unmanaged or managed incorrectly when the fleet becomes large, this can create additional challenges for the electricity system, including distribution grids (RTE, 2019). Most risks could be caused by two factors: the simultaneous charging of a large number of vehicles in the same area and/or coinciding with a peak in the electricity demand. Indeed, in a situation in which charging is unmanaged, it could be expected that many EV drivers will plug in their vehicles when arriving home in the late afternoon/early evening, when electricity demand is already high, thereby causing a substantial increase in peak load and saturation of the infrastructure. This could require the development of additional peak power capacity, nowadays less efficient and more GHG intensive, and the realisation of supplementary investment in the grid to accommodate the increasing peaks in the energy flows. Other impacts could be, for example, reduced voltage, overloaded electrical equipment and possibly power outages. Such impacts become larger when fast chargers are used rather than regular chargers (Cleary, and Palmer, 2019).

It is important to state, however, that EVs are used for only part of the day. Based on a big data analysis for a selection of European cities, Paffumi et al. (2018) conclude that the share of private vehicles that are being driven at the same time is never larger than 12%. During the day, the use of private vehicles peaks at three times: in the morning, at noon and in the evening, although the pattern is more prominent in some cities than others. A large majority of the private vehicles studied were driven less than 100km per day. This creates the possibility of using the batteries of EVs parked and connected to the grid as distributed storage and generator units. In this way, it is possible to support the power system and mitigate some of the challenges associated with considerable penetration of both VRE sources and EVs.

Figure A6.4 gives a general overview of the different services that EVs can provide through VGI. A distinction is made between services to transmission system operators (TSOs) and distribution system operators (DSOs) and services contributing to the integration of renewable energy sources. The TSOs manage electricity transmission, dealing with high-voltage grids, while DSOs manage electricity distribution (mostly dealing with medium- and low-voltage supplies to consumers' meters) (Prettico et al., 2021). Although it goes beyond the scope of this factsheet to dive into the details of each of these services, it is worth mentioning that Thompson (2018) indicates frequency regulation, i.e. the process of ensuring the balance of electricity supply and demand at all times, as one of the most attractive services that can be provided by VGI. This is because it requires an almost instantaneous response and little energy, while the market prices can be relatively high. EV batteries are well suited for this, as they can respond within seconds and have only limited capacity to provide energy to the grid (since their primary use is for driving). VGI services can also be provided by fleets of vehicles with known and regular schedules (Tomić, and Kempton, 2007), such as school buses (Horrox et al., 2022).

Figure A6.5 gives another overview of the services that can be rendered by VGI and also provides information on the timescale of these services (Muratori et al., 2021).

Figure A6.4 Electric vehicle services that can be provided to partners in power systems



Source: Reproduced with permission from Bañol Arias et al. (2019). © IEEE, 2019.

Figure A6.5 Summary of opportunities for EVs to provide demand-side flexibility to support power system planning and operations across multiple timescales

Smart electric vehicle-grid integration can provide flexibility — the ability of a power system to respond to change in demand and supply — by charging and discharging vehicle batteries to support grid planning and operations over multiple time-scales

Power system application	**Generation capacity and transmission/ distribution planning**	**Resilience to extreme events**	**Seasonal planning (Hydro/long-term storage dispatch)**	**Commitment and dispatch decisions**	**Balancing and power quality**	**Support end customers**
Time scale	Multi-year	Years (planning), hours (real-time response)	Months	Days and hours and sub-hours	Seconds to sub-seconds	Years (planning), hours (real-time response)
Vehicle-grid integration value	Ability to reduce peak load and capacity requirements and defer distribution systems upgrades if reliable EV charging flexibility is available	Load responses to natural events (heat waves, tornados) or human-driven disasters, load postponement over days, and support microgrid management and grid restoration (V2G)	No role for EVs	Leverage EV charging flexibility to support supply dispatch and load-supply assignement (tariff management), variable renewables, inegration, operating reserves, energy arbitrage (V2G)	Provide voltage/ frequency regulation and support distribution system operations	Tariff management (e.g. mitigate retail demand charges), complement other distributed energy resources (smart load, generation and storage), and minimise equipment ageing/upgrades

Source: Reproduced with permission from Muratori et al. (2021). © IOP Publishing Ltd 2021.

A6.3 Time frame

VGI is expected to contribute to decarbonisation in the medium to long term, although the possibilities offered by the technology have been already extensively demonstrated at the pilot scale. This is mostly because currently the number of EVs is still limited and the VGI-enabled infrastructure is lacking, but the potential of VGI increases as the number of EVs increases. In addition, to facilitate acceptance among final users, the range of EVs needs to be sufficiently large or not significantly affected by the provision of VGI services.

In Denmark, in the framework of the Parker project (Andersen et al., 2019) which ran from August 2016 to July 2018, the following main results were demonstrated: (1) the EVs studied in the project (PSA, Mitsubishi and Nissan) and the infrastructure and digital technology used were able to support V2G and to provide advanced services to the grid; (2) the technology can be brought to the market to provide frequency regulation; (3) the battery degradation experienced by the EVs used and under the project conditions was limited; and (4) providing VGI services can be economically attractive for the end user. Further steps need to be taken to put in place a system that can cover all EV brands, standards and markets. The system cost also needs to be brought down.

In 2021, the *Vehicle to grid Britain* report, aiming to assess the long-term viability of VGI in the United Kingdom, was published (ElementEnergy, 2021). One of the findings of this Energy Systems Catapult project is that residential V2G charging can be economically viable in the short term if a number of conditions are met: high plug-in rates, lower installation costs of the metering equipment, the combination of revenues from different services, and the potential to switch easily between these revenue streams.

In 2021, a stated preference survey about the willingness of vehicle owners to participate in V2G in Belgium (Vanpée, and Mayeres, 2022) showed that unfamiliarity with the concept still represents a barrier. Moreover, the respondents were found to be unresponsive to the financial compensation that was presented to them in the choice experiment: annual savings in their electricity bill ranging between EUR 25 and EUR 120 in combination with a one-time compensation that ranged from zero to EUR 1,000. The only contract specification that was found to be statistically significant was the minimum driving range guaranteed by the V2G contract, which positively influences the likelihood of supplying V2G services. VGI is currently being actively researched outside the EU, with examples such as the Los Angeles Air Force Base vehicle-to-grid pilot project (Black et al., 2018) and the METI project in Japan (Nuvve, 2019).

A6.4 Expected environmental effects

Using the taxonomy set out in Chapter 3 the following higher order environmental effects of VGI can be identified.

A6.4.1 Indirect impacts — efficiency effects

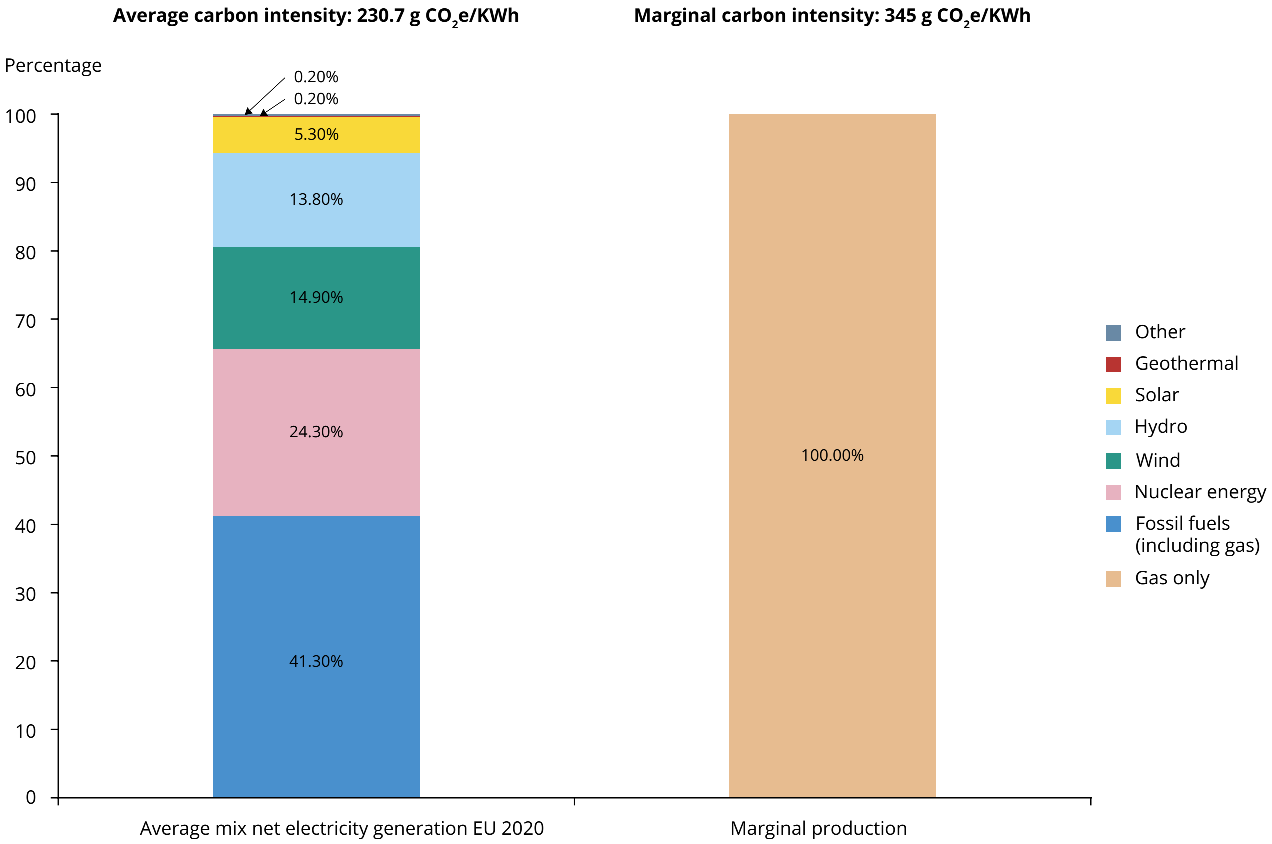
VGI can help to reduce the environmental impacts of the transport sector in various ways. It can promote the uptake of EVs by reducing their total ownership costs and their well-to-tank emissions. In addition, it can increase the use of VRE sources and better exploit existing infrastructure in the electricity system.

Various pilot projects have shown that VGI could decrease the cost of ownership of an EV by providing an economic benefit to the end user willing to provide ancillary services to the network. Total estimates vary considerably, depending on the number and magnitude of services provided to the network and on the local policies in place and the market structure. In Denmark (Andersen, et al., 2019), for example, estimated yearly revenues for providing bidirectional frequency regulation for 14 hours a day through a 10kW charger may vary between EUR 1,700 and EUR 2,500 per car. In the case of unidirectional regulation, such revenues decrease to EUR 680-700 yearly per car. In the United States, the pilot project led by the University of Delaware indicated that the yearly gross revenues generated from selling frequency regulation services for 19 hours a day to the network at 10kW could be up to USD 2,000 per car (Kempton, et al., 2008). In the US context, where diesel prices are relatively low, the results from a Blue Bird Corporation project indicate that VGI can reduce the total ownership costs of electric school buses to levels comparable to the diesel buses (Moore, 2021). VGI thus has the potential to significantly reduce the overall expenses associated with owning an EV. In parallel, a successful implementation VGI will require a diffused bidirectional recharging infrastructure to achieve effective EV participation. Both these aspects are regarded as essential to increase the uptake of EVs. It should also be noted that, with an increase in the uptake of VRE sources, the availability of frequency regulation services, as well as other ancillary services normally provided by conventional installations, will be reduced. The first case study below indicates that in order to successfully provide this service the EV fleet needs to be sufficiently large and that the benefits increase as the share of VRE sources increases and fall if the initial level of flexibility in the system is already high.

VGI can be used to optimise the charging time of EVs to minimise their well-to-tank emissions of both air pollutants and greenhouse gases. In the short term, an uptake in electrification of vehicles could, if not well managed, potentially lead to an increase in the peak power demand, which is normally covered by fast reacting gas power plants operating at suboptimal efficiency. In this framework, consuming an additional unit of energy will have a different impact depending on the moment at which that unit is produced, as shown in Figure A6.6.

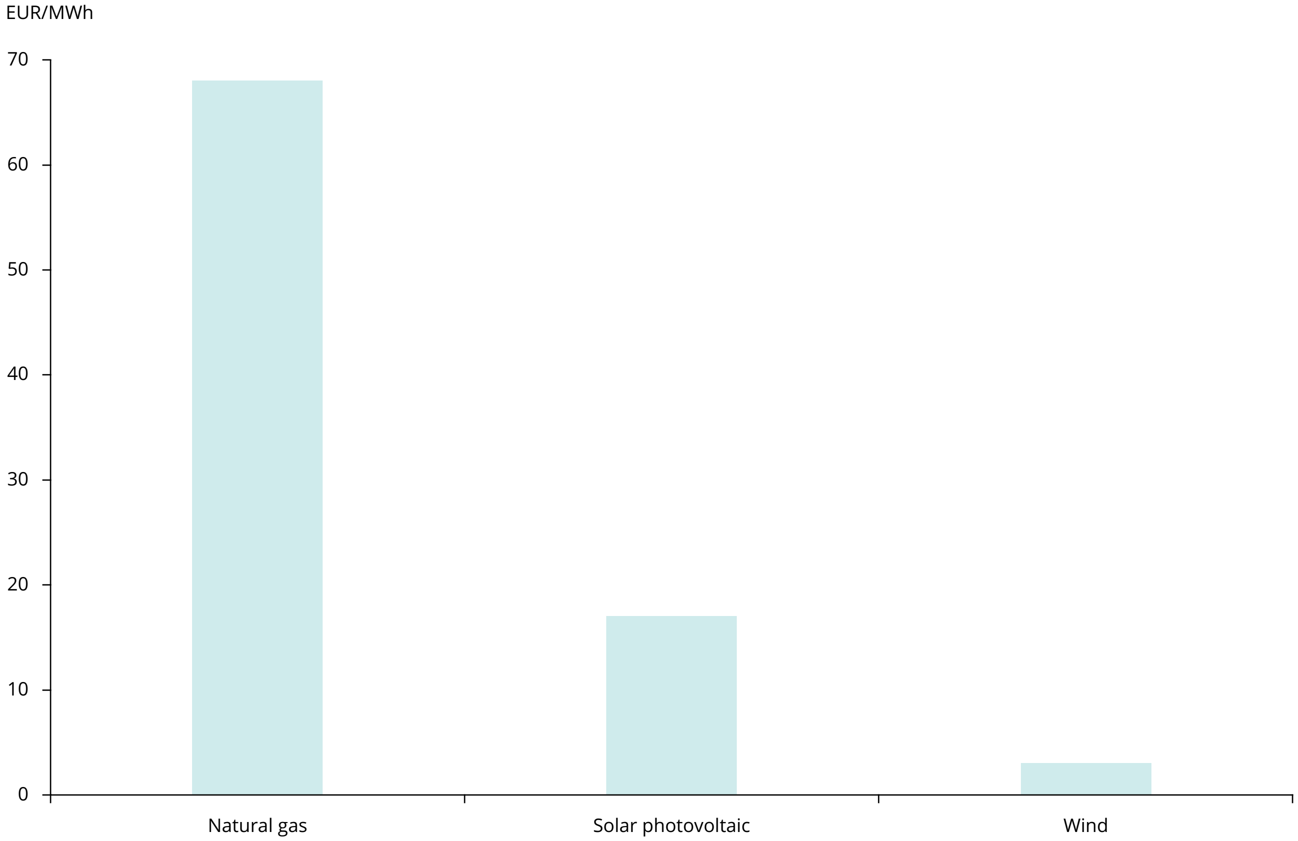
In the ideal case, in which it is possible to shift 1MWh of energy produced during peak hours from natural gas to the same amount but produced from renewables, by managing EV charging well, significant environmental benefits could be achieved, as shown in Figure A6.7.

Figure A6.6 Average versus marginal greenhouse gas emission factors for electricity generation



Source: EEA compilation based on EEA (2022f), Eurostat (2022j) and Scarlat et al. (2022).

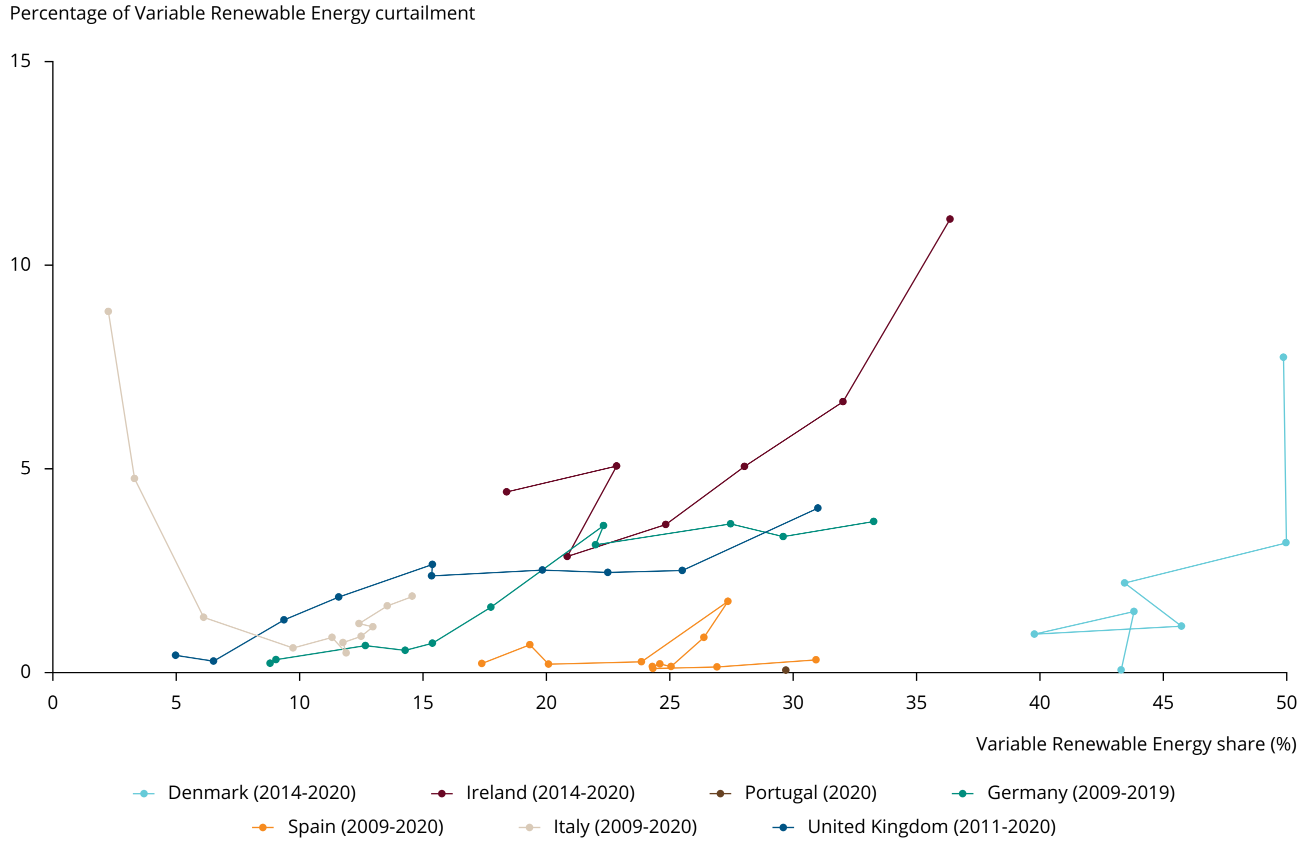
Figure A6.7 Environmental costs of electricity production (EUR/MWh)



Note: Natural gas is a combination of combined cycles and open gas turbines. Wind is both on shore and off shore.
Source: EC (2020f).

Figure A6.8 gives an overview of the curtailment rate (i.e. the deliberate reduction in the power output of a power generator in order to balance supply and demand or due to transmission constraints) in a selection of European countries and its evolution over time, together with the trend in the share of VRE. The curtailment rate is presented for a combination of wind and solar sources. In general, the solar curtailment rate is smaller than that of wind, as wind power plants are larger and easier to control. The curtailment rate varies between the countries considered, depending upon their energy mix, grid conditions, policies and regulations, operational practices, and the evolution of these factors over time. In some countries, the curtailment rate is non-negligible, indicating that there is potential for VGI to reduce the GHG emissions from electricity by improving the use of the intermittent renewable electricity sources. Generally speaking, by adjusting the charging of EVs it is possible to better exploit the availability of such sources by closely matching production and consumption profiles. In this framework, EV batteries could be used as controllable loads and could be charged at moments where an excess of energy is available. This could in principle reduce the curtailment rates of renewable forms of energy, increasing their use and possibly reducing transmission bottlenecks (CAISO, 2022). This could also be used to increase the self-consumption of energy generated by rooftop PV or other distributed VRE installations, reducing congestion and grid-related costs. Ultimately this would lead to a reduction in the GHG emissions from electricity generation. Indeed, the renewable energy stored in the EV battery could be either used for driving (thus with very low emissions, as also shown in Figure A6.3) or returned to the grid during periods of peak demand or to deal with the intermittent nature of solar and wind power generation, thereby reducing the need for electricity sources with a higher environmental impact.

Figure A6.8 Curtailment rate: energy share map of variable renewable electricity sources in selected European countries



Source: Yasuda et al. (2022).

Lastly, it is important to state that with the EU Emissions Trading System (EU ETS), any changes in the GHG emissions of power generation will be compensated for by the other entities under the EU ETS, while the cap — which decreases over time — must be respected. When the GHG emissions from power generation drop, thanks to V2G deployment, this means that emission rights become available to other entities covered by the EU ETS.

A6.4.2 Indirect impacts — efficiency effects related to battery degradation

The environmental benefits of VGI may be counteracted by the environmental costs related to battery degradation. EV batteries slowly degrade over their lifetime as a result of two phenomena: calendar ageing and cycling ageing. The first mechanism takes place when the battery is at rest. It mainly depends on temperature and state of charge (SOC). The higher the ambient temperature and the SOC, the more relevant it becomes (Wang et al., 2016). The second mechanism takes place when the battery is being used. Here temperature, charge/discharge rate and energy throughput are the relevant parameters (Wang, et al., 2016; Thompson, 2018).

It is conventionally assumed that EV batteries will reach their the end of their life and be no longer suitable for driving applications once they have lost 20-30% of their original storage capacity (Wang, et al., 2016). However, other research has challenged this assumption, showing that driving performance will not be significantly impacted even at 30% residual capacity (Saxena, et al., 2015). It should also be considered that, once batteries are no longer suitable to meet driving needs, they can still be used in stationary applications before being recycled or decommissioned (Zhao, and Baker, 2022).

In general, unidirectional VGI, in which charging periods are adjusted according to the needs of the grid, is expected to have a very limited additional effect on battery degradation (Wang et al., 2016). Several studies have provided quantitative estimates of the additional degradation induced by providing bidirectional VGI services and, in particular, frequency regulation and peak shaving.

Wang et al. (2016) showed that the extreme case of providing systematic peak shaving services to the grid, every day between 19.00 and 21.00 for 10 years, could result in significant additional degradation of the battery, up to 5-14% more than the baseline case and depending on the charger used (1.44kW vs 7.2kW). In the worst-case scenario, total battery degradation could be above 45% after 10 years. 30% battery degradation could be reached after 6-7 years in this case, depending on the conditions. However, in a more realistic situation in which V2G services are supplied only on a limited number of days when the grid needs them most, the additional battery degradation is minimal. In the case of frequency regulation, assuming that the service is provided daily between 19.00 and 21.00 for 10 years, the simulated additional loss of capacity will be approximately 3.6% compared to the baseline under the hypotheses used (Wang et al., 2016).

A modelling study based on the environmental conditions, driving patterns and network performances recorded during a whole year in Bornholm, Denmark, indicates that the additional battery degradation due to the provision of 14 hours of frequency regulation with a ±9kW bidirectional charger every day for 5 years is 2% (Thingvad, and Marinelli, 2019).

In the Danish Parker project, Thingvad et al. (2021) studied the evolution of the battery capacity of 10 Nissan e-NV200 electric vans that have provided frequency regulation with 10kW chargers for 5 years. After 2 years the usable battery capacity was reduced by 10% and after 5 years by about 18% due to the combined effect of driving and providing the service. A battery degradation model assigns one third of this capacity loss to the additional cycling due to VGI and the rest to normal ageing.

The literature also suggests that the degradation of batteries supporting VGI can be limited if certain conditions are satisfied (Wang et al., 2016; Uddin et al., 2018; Zhao et al., 2022). According to Uddin et al. (2018), a smart control algorithm could be developed that controls access to the energy stored in the EV battery such that the longevity of the battery is not reduced. Good battery prognostic models are essential for this, and further research is needed on the factors playing a role in battery degradation.

If VGI leads to faster degradation of batteries, then the environmental impacts of earlier replacement of batteries needs to be taken into account. These environmental costs include GHG emissions, but also other costs such as human toxicity, ecotoxicity and material depletion (Díaz-Ramírez et al., 2020). Case study 6.2 on the environmental impacts of EV batteries illustrates the potential magnitude of such effects. Other uses of EV batteries could also help lower the environmental impacts, such as battery swapping and reusing end-of-life EV batteries (Mobilize, 2021; Zhao et al., 2022), as discussed in the same case study.

A6.6 Policy corner

In the Parker project, Andersen et al. (2019) provide a general assessment of the barriers to V2G in Europe and national barriers in four European countries, using the Pestel framework as shown in Figure A6.9, which considers the political, economic, social, technical, environmental and legislative dimensions.

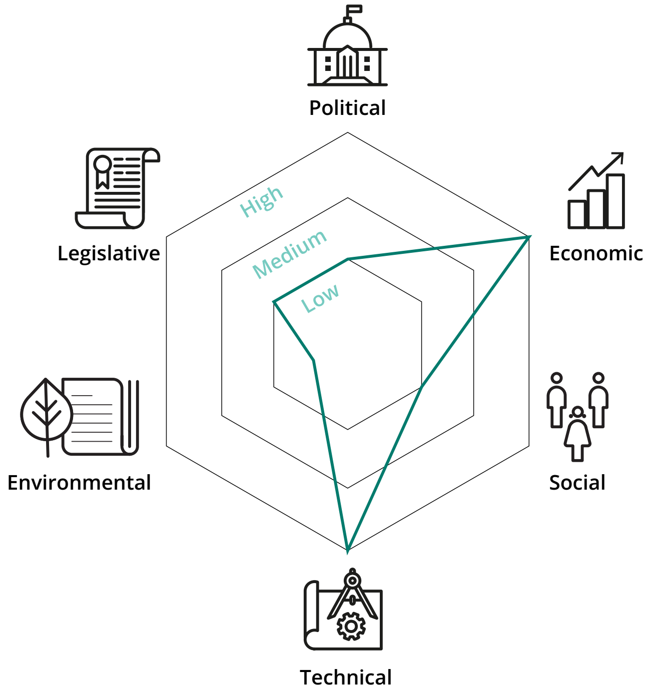
For Europe as a whole, the most important barriers identified in 2019 were economic and technical, while others were assessed to be of lower importance. The main general barriers are the lack of V2G infrastructure and its cost (Andersen, et al., 2019; ElementEnergy, 2021), the uncertainties about the extent of battery degradation, and the still limited number of V2G-capable EVs.

At the national level, the type of barriers and their magnitude varies widely across European countries. Additional obstacles to the large-scale adoption of VGI could be:

- the uptake of other systems that provide similar services (e.g. stationary battery storage);
- regulatory barriers, the lack of a market framework and international standards, and also aggregator services (Bañol Arias et al., 2019);
- possible conflicts of interest between TSOs and DSOs (Bañol Arias et al., 2019);
- the general public's lack of familiarity with V2G (Vanpée, and Mayeres, 2022).

The existing and proposed policies for decarbonising road transport and power generation in Europe have consequences for the potential of and the need for VGI: the number of EVs is expected to increase substantially and further growth in VRE sources will increase the need for grid-supporting services. By targeting regulatory barriers and possible conflicts between different actors in the electricity system, policymakers can create a policy framework for overcoming them. There is also a need for an appropriate policy framework for creating a market for V2G services. To bring down the system costs and understand and resolve issues regarding battery degradation due to VGI will also need further R&D financing.

Figure A6.9 Barriers to the provision of V2G services in Europe — Parker project, 2019



Source: EEA compilation based on Andersen et al. (2019).

A6.6 Bottom line

VGI can support both considerable EV penetration and a large deployment of VRE sources, contributing to the decarbonisation of both the transport (by reducing the well-to-tank emissions of EVs) and the electricity system. VGI has the potential to strengthen the link between the energy and transport sectors, creating opportunities for synergies and underlining the need for the sustainable transition of both sectors to progress in parallel. This potential increases with the increasing share of VRE sources but becomes smaller when other providers of such services are present. In addition, the compensation that EV owners can earn by providing VGI services reduces the total cost of ownership of EVs, which can contribute to the uptake of these vehicles. VGI systems should, however, be operated in such a way that battery degradation is minimised, when compared to the situation in which no VGI services are provided, and the environmental costs associated with earlier battery replacement are avoided as much as possible.

A6.7 Case study 6.1: E4Future project

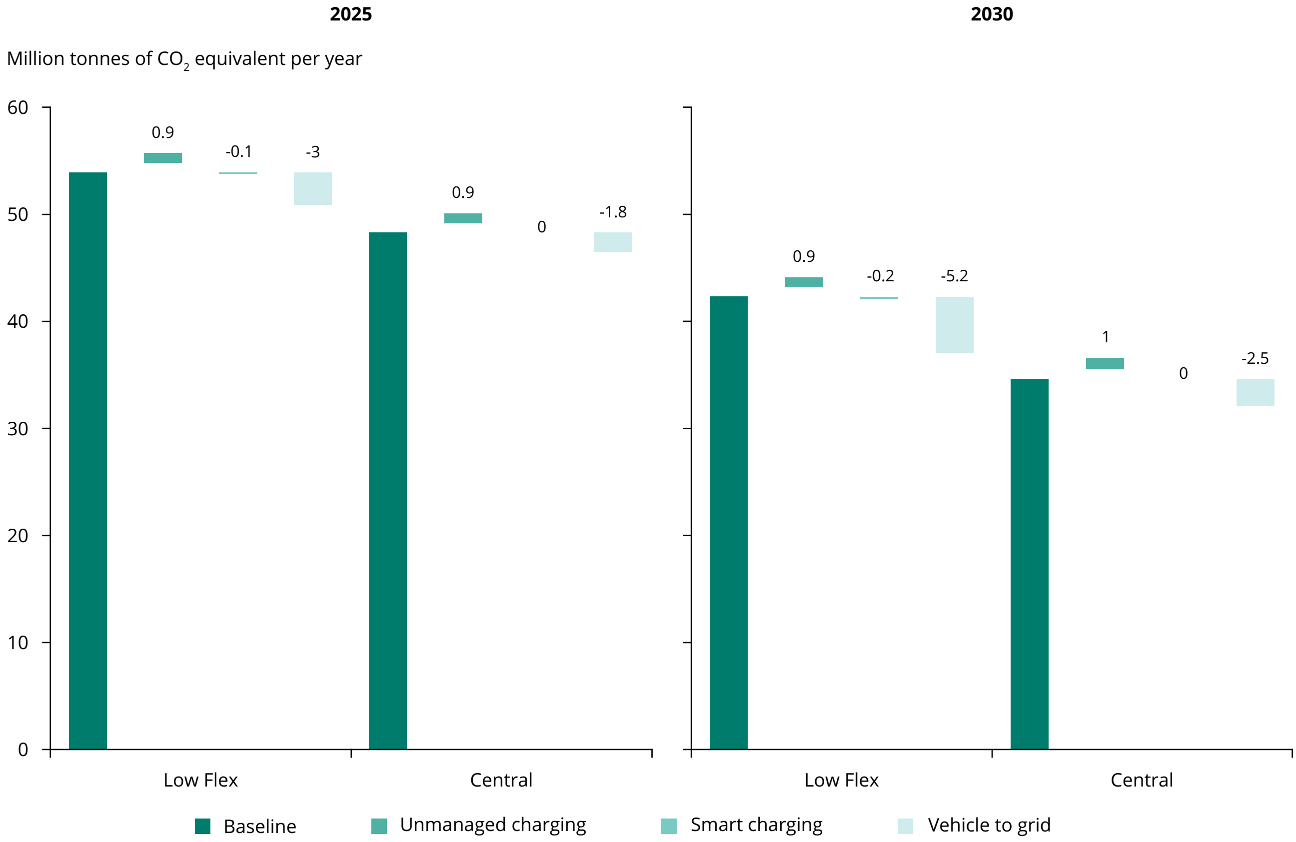
Aunedi and Strbac (2020) simulate the carbon emissions of the UK power system in 2025 and 2030 using the WeSIM model. They consider two different cases for system flexibility, in terms of the importance of energy storage and demand-side response (DSR). The former is expressed as the share of electricity generated that can be stored, while the latter refers to changes in electricity consumption patterns by users following a signal or incentive. In particular, the authors assume:

- low flex case: storage limited to 3-4% of power generation and no use of DSR;
- central case: storage equals 10% (2025) to 13% (2030) of power generation and the penetration of DSR is 25%.

For these two cases, the study compares the baseline, in which there are only private EVs and no fleet EVs, with three scenarios with a large number of fleet EVs in addition to the same number of private EVs as in the baseline. Fleet EVs are studied because their schedules are more regular than those of individual private EVs. All three scenarios assume 1 million fleet EVs, but consider different charging regimes: unmanaged charging, smart charging and V2G operation. With smart charging (also known as unidirectional vehicle-to-grid, V1G) the electricity demand from EVs is shifted from the peak period to the night-time, taking account of constraints on the state of charge. In the V2G regime vehicles also provide frequency regulation services to the grid.

Figure A6.10 shows the simulated impact of the different charging regimes on annual CO_2 emissions from the power system. In the baseline scenario the emissions fall between 2025 and 2030 due to the higher penetration of renewable electricity sources, with an almost constant level of electricity demand. The baseline emissions are lower in the central case than in the low flex case because of the higher flexibility of the latter to make better use of the renewable electricity sources.

Figure A6.10 Carbon emissions in the UK power system in 2025 and 2030 under different flexibility and EV charging scenarios



Source: Reproduced with permission from Aunedi and Strbac (2020). © IEEE 2020.

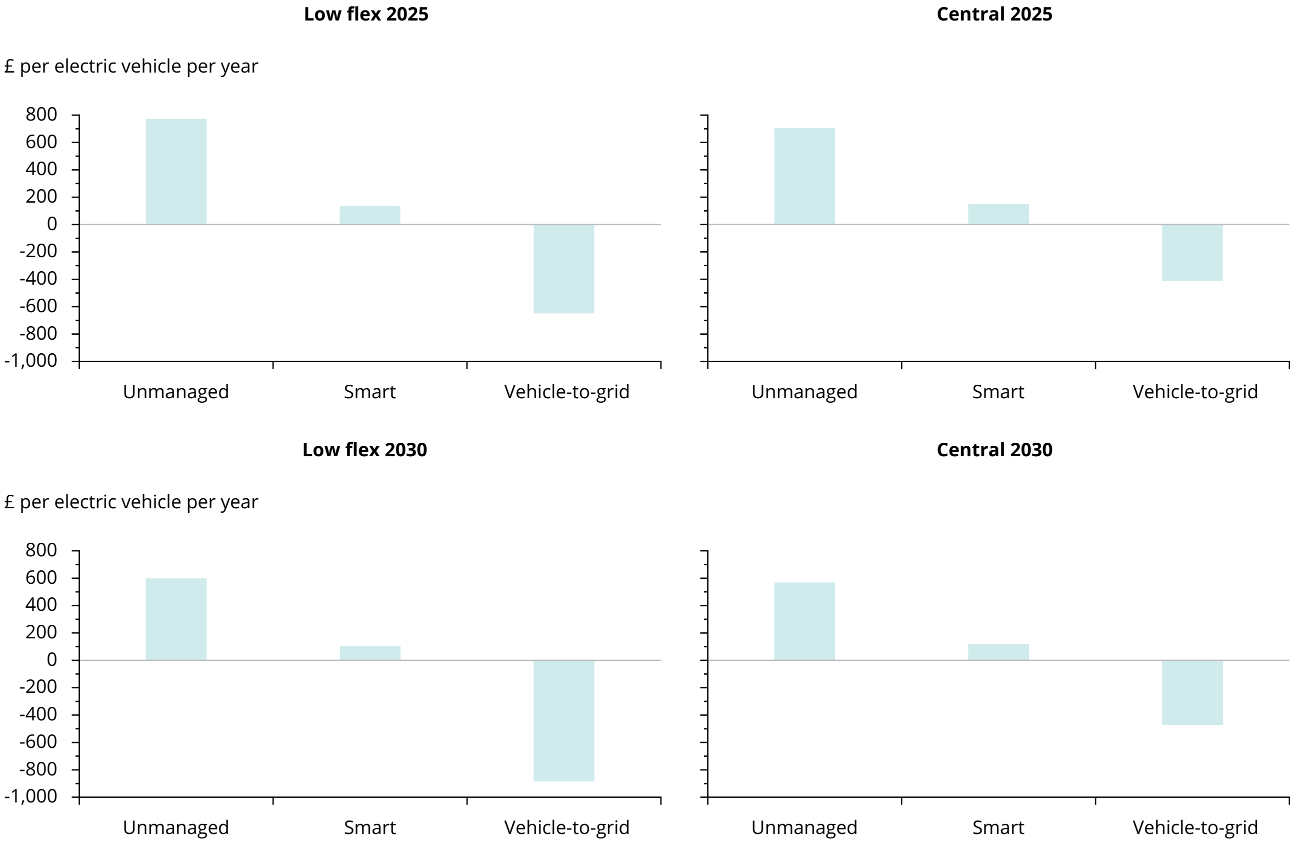
Unmanaged charging of the fleet EVs leads to an increase in carbon emissions. Charging EVs leads to higher peak demand, which is met by additional peak gas power plants. With smart charging this increase can be essentially avoided. With V2G carbon emissions can be further reduced below the level of emissions without fleet EVs. This is because V2G allows the carbon emissions from frequency regulation to be reduced by reducing the need for more CO_2-intensive generators and allows better integration of renewable electricity sources (less curtailment of these sources). In 2030 the potential reduction in carbon emissions is higher, as the share of renewable electricity sources is higher.

In a power system with central flexibility (central case) the reduction in carbon emissions thanks to V2G is about half that with lower flexibility (low flex case). This is because in the former case there is less opportunity to support the power system, as other sources of flexibility are also available.

The carbon emission reductions realised by V2G also mean that fewer renewable electricity installations need to be built to meet the decarbonisation targets of the power system.

Considering the costs, accommodating 1 million fleet EVs with unmanaged charging leads to significant additional system costs as shown in Figure A6.11, with the main share being due to the additional generation capacity that is required. Moreover, more distribution capacity is needed, and the operational costs also increase. With smart charging these costs are reduced substantially: only a small increase in generation capacity is needed and no extra distribution capacity. With V2G the system cost is lower than in the baseline. This is because even less generation and distribution capacity is required. Moreover, the operational costs are reduced, as 50% of frequency regulation is no longer provided by fossil fuel plants and there is also less curtailment of renewable electricity sources.

Figure A6.11 Additional system cost of supplying electricity to fleet EVs in the United Kingdom in 2025 and 2030



Source: Reproduced with permission from Aunedi and Strbac (2020). © IEEE 2020.

The life cycle environmental benefits of the above-mentioned changes in investment and operational costs are not considered in the study, nor does it consider the additional costs and environmental impacts of the V2G system itself or those related to battery degradation.

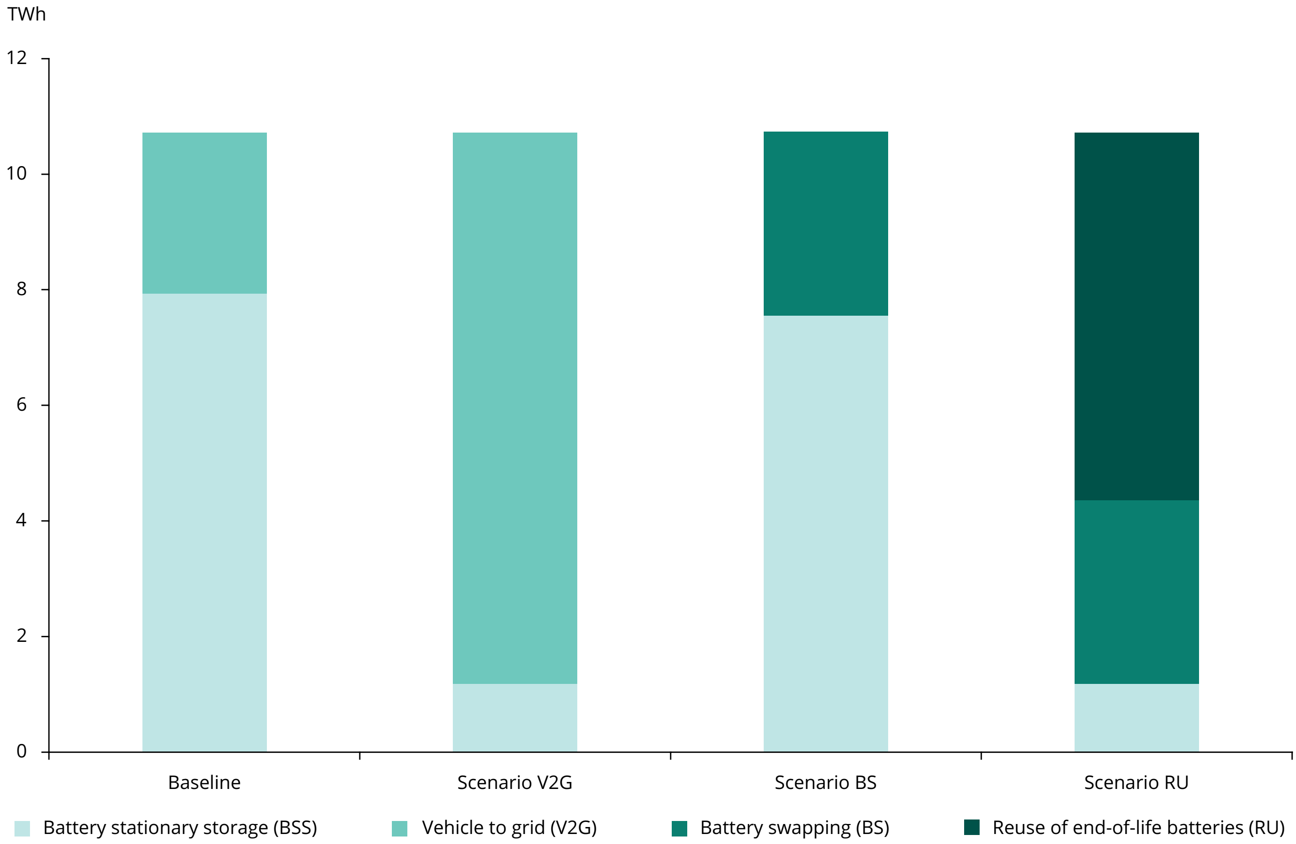
A6.8 Case study 6.2: Environmental impacts of using EV batteries as storage — a case study for the United Kingdom

Zhao and Baker (2022) shed light on the life cycle impacts of GHG emissions of VGI provision and the role of battery degradation. They study EV battery degradation using the model of Wang et al. (2014) and a model using stationary batteries for storage by Schimpe et al. (2018). Zhao and Baker's study is a life cycle analysis of different energy scenarios for the United Kingdom in 2050.

The baseline scenario is a low-carbon scenario for 2050 in which solar and wind energy are combined with storage to balance supply and demand. In this scenario the share of fossil fuels is only 2%. Smart charging applies for 78% of EVs (for a total of 31.7 million EVs) and 14% of EVs render V2G services. Battery storage accounts for 2.4% of electricity demand, delivering 10.7TWh, with the main share provided by stationary batteries, as shown in Figure A6.12. Zhao and Baker consider three other scenarios for 2050, as shown in Figure A6.12: in the V2G scenario most of the battery storage is provided by V2G, without reusing end-of-life batteries for storage. In the battery swap scenario stationary batteries are combined with battery swapping. In the battery reuse scenario end-of-life EV batteries are reused to provide the main share of storage services. No V2G is assumed in this scenario.

The upper panel of Figure A6.13 shows that in the baseline, GHG emissions per kilowatt-hour are projected to be substantially lower than in 2018. Part of the remaining GHG emissions is linked to V2G. Increasing the role of V2G in 2050 as in scenario SV2G, increases the GHG emissions from a life cycle perspective by 16% compared to the baseline. With battery swapping and reuse of end-of-life batteries, the GHG emissions per kilowatt-hour are 2% lower than in the baseline.

Figure A6.12 Battery storage in the different scenarios for the United Kingdom in 2050



Source: EEA compilation based on Zhao and Baker (2022).

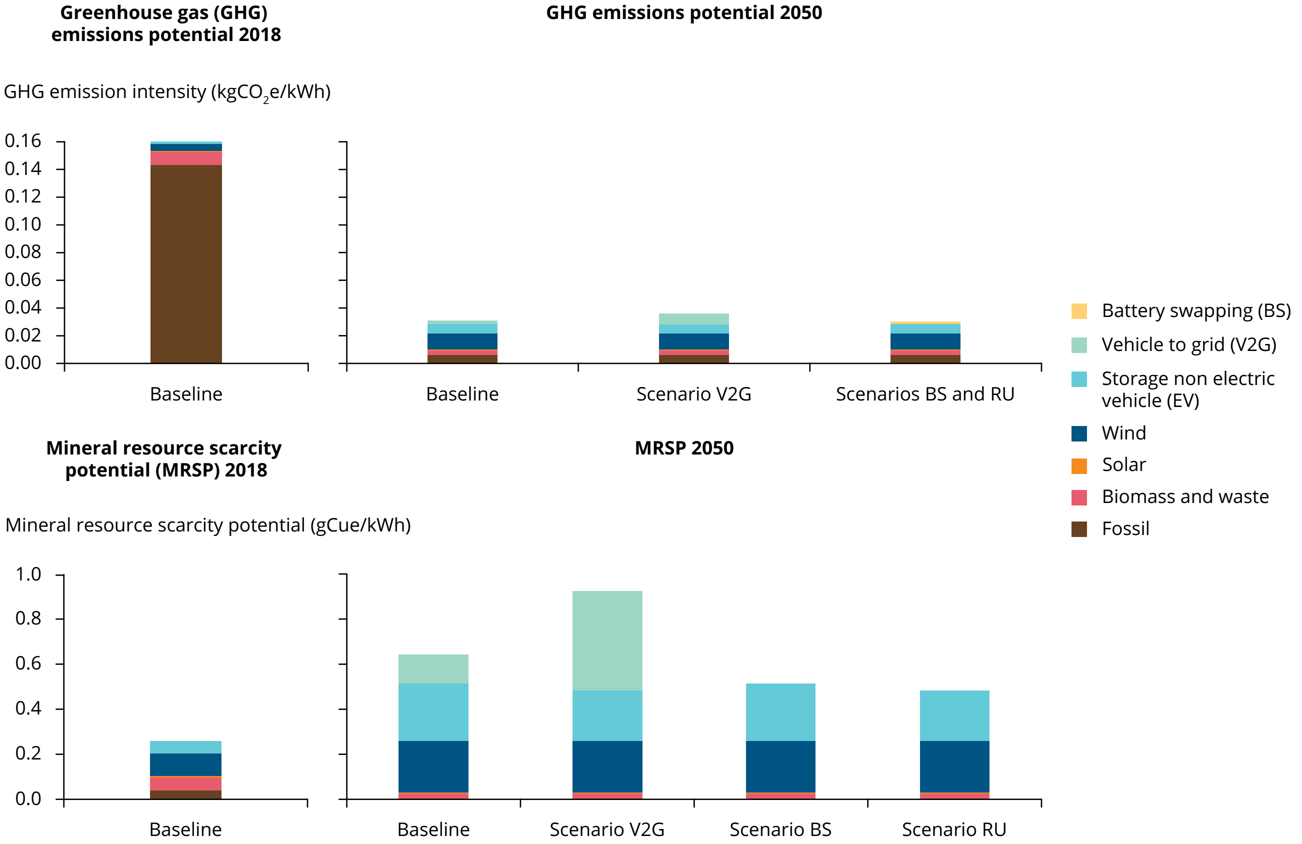
In 2050, some environmental costs counteract the reduction in GHG emissions, due to the materials that are required for the renewable energy installations and the storage facilities. This is the case, for example, for the indicator for mineral resource scarcity potential ([14]), one of the 11 indicators considered in the study, as illustrated in bottom panel of Figure A6.13. Providing V2G services is contributing to this impact, as it leads to faster battery degradation. As the share of V2G increases, this degradation impact increases further. With battery swapping this effect is much smaller, because in that case EV batteries are stored under better conditions while not in use for driving. A small additional reduction can be realised in the case of reusing end-of-life EV batteries.

However, based on a sensitivity analysis the authors indicate that the additional battery degradation due to V2G can be reduced if EV owners do not supply a lot of energy to the grid and do not keep the battery in a state of high charge. With high ambient temperatures these recommendations become even more important. The authors also point out that, for EV owners with low mileage, V2G could even reduce battery degradation.

A second lesson that can be drawn from the study is that reusing end-of-life EV batteries can also be environmentally beneficial.

([14]) The mineral resource scarcity potential gives an indication of the amount of mineral resources consumed both directly and indirectly.

Figure A6.13 GHG emissions (top) and mineral resource scarcity potential (bottom) per kilowatt-hour in the different scenarios



Source: EEA compilation based on Zhao and Baker (2022).

A6.9 Case study 6.3: Energy storage from electric vehicles and pumped hydro in La Palma, Canary Islands

Ramirez-Diaz et al. (2016) study the potential of two possible energy storage systems on the island of La Palma: pumped hydro energy storage (PHES) and bidirectional VGI. Table A6.1 presents the projected results for 2024, when there are assumed to be 3,400 EVs on La Palma with a total battery capacity of about 101MWh.

In scenario 1A no storage is available and the charging of the EVs is unmanaged. In that scenario the share of renewable sources is about 28%, and almost half of the renewable energy is curtailed, i.e. not available on the grid. Scenario 1B introduces smart charging of the EVs, which allows an increase in renewable energy sources and a substantial reduction in the share of curtailment. The CO_2 emissions from the power system are reduced by 5.7% compared to scenario 1A. The introduction of PHES enables a larger reduction in emissions and in the curtailment, when compared to scenarios 2A and 2B. In scenarios 3 and 4, very similar results can be achieved with the highest benefits in terms of reduction in CO_2 emissions. In scenario 4, the installed capacity of renewables is more than doubled (an increase by 25MW), with the support of 20MW from PHES and VGI services provided by about 3,400 EVs. A minimum state of charge of the EV batteries of 40% is assumed. The renewable share then increases to about 49%. The estimated reduction in CO_2 emissions compared to scenario 1A is almost 23%. In all scenarios with storage, the share of renewable energy that is lost is reduced substantially compared to scenario 1A, with the largest reduction in scenario 4, while the levelised cost of energy ([15]) is lowest in scenario 3.

([15]) The levelised cost of energy is 'an indicator for the price of electricity or heat required for a project where the revenues would equal costs, including making a return on the capital invested equal to the discount rate' (Badouard, et al., 2020).

Table A6.1 Impacts of electricity storage and vehicle-grid scenarios in La Palma in 2024

Scenario	Storage	EV charging	Renewable share (%)	Curtailment (%)	Electricity mix LCOE (EUR/MWh)	Electric power system emissions ($ktCO_2$)
1A	No	Unmanaged	28.2	47.3	125.7	141.3
1B	No	Smart	33.3	22.6	118.8	133.2
2A	PHES	Unmanaged	42.8	3.6	113.3	121.4
2B	PHES	Smart	43.9	1.8	111.9	117.4
3	VGI	VGI	47.1	3.2	109.4	109.0
4	PHES+VGI	VGI	48.8	0.7	111.7	108.9

Notes: In scenario 3 all EVs are used for storage; in scenario 4 priority is given to pumped hydro energy storage (PHES), with the help of VGI. LCOE, levelised cost of energy.

Source: Ramirez-Diaz et al. (2016).

Annex 7 Digitalisation in road transport pricing

Context: road/urban transport; internalisation of the external costs of transport

A-S-I: general. Digitalisation supports the development of more comprehensive transport pricing schemes and facilitates their implementation, as well as the implementation of other transport policies.

Time frame: short to medium term. Digital tools are available and several pilot or full-scale projects are already ongoing.

A7.1 Definition

Digitalisation can enable various types of policies for transport. This factsheet focuses on policies on road pricing, urban access restrictions and smart parking.

A7.1.1 Road pricing

Road transport incurs various marginal external costs. External costs or negative externalities are costs imposed on uninvolved third parties that originate from the activity of one or more different actors, while the actors causing them are not confronted with them in any way. The term 'marginal' indicates that the costs arise from an additional trip or kilometre travelled. The external costs of transport include environmental costs (air pollution, noise, climate change) as well as accident costs and congestion caused by traffic (EC, 2019a). These marginal external costs can be internalised through transport taxes. In this way, the final users can take them into account when deciding on the number of trips, the distance travelled, the modal choices, the environmental performance of their vehicle, the timing of their travel, the route selected, etc. The concept of externalities and the use of corrective taxes to internalise them originated in the work of Pigou (1920). Hence such corrective taxation is also called 'Pigouvian taxation'. Notably, pricing these externalities also reflects the 'polluter pays' principle.

Different pricing instruments exist for road transport, such as vehicle taxes, fuel taxes, parking charges and road user charges. Economic theory indicates that it is best to use pricing instruments that are closely related to the factors that determine the external cost levels. For example, congestion problems vary according to the time and location of travel. Therefore, an instrument such as road pricing, which can be differentiated across these dimensions, is best, as it gives incentives to travel less in the peak periods or in areas with a lot of traffic. In contrast, fuel taxation is only a rough instrument for tackling congestion, as it does not allow transport users to make this differentiation, but it can give good incentives to reduce CO_2 emissions if it takes into account the differences in CO_2 emissions per litre of the different fuels.

In general, a distinction can be made between different types of road pricing that can be further differentiated according to the determinants of the external costs (vehicle type, environmental characteristics, location, time of day, road type, etc.):

- Distance based charges: an amount is paid per kilometre driven. It can be due on all roads or a selection of roads, in a country or region or only in certain zones.
- Cordon pricing: drivers pay a charge when they drive through a cordon around a certain area. People who drive only in the area within the cordon do not pay. A cordon system can consist of several cordons.
- Area licence/time-based toll: a fee to be paid when one wishes to drive within a certain area during a certain period.
- High occupancy toll lanes: lanes on which vehicles with a minimum number of occupants and other exempt vehicles can drive free of charge. Other vehicles can use the lanes if the drivers pay a toll. Tolls are set at a level that ensure a speed advantage for toll lanes over unmanaged lanes.

A7.1.2 Urban access restrictions

Various European cities and towns regulate or impose restrictions on vehicles driving in all or part of their territory. This can serve various purposes such as improving liveability or air quality or reducing congestion.

Aside from urban road pricing, which was discussed in the previous section, the regulations can also take the form of low-emission zones (LEZs) or other entry restrictions. The latter cover, for example, access only during certain times or for certain vehicles.

A system with automatic number plate recognition (ANPR) cameras is also used for the implementation of such regulations. For example, the LEZs of Antwerp, Ghent and Brussels in Belgium use number plate recognition to check whether vehicles are conforming with the LEZ prescriptions.

Digitalisation can also help to implement other types of policy. For example, Arnd and Cré (2018) discuss the role of digitalisation in parking policies. Sant et al. (2021) present research on a smart parking system in Malta that is based on green internet of things (IoT) devices to manage unused garage spaces.

A7.2 Context

Worldwide, the interest in road user charging is growing in order to deal with congestion problems as well as to attain environmental goals. In addition, road pricing, in contrast to other instruments such as fuel taxation, can be easily differentiated across multiple dimensions (e.g. congestion problems that differ according to the time and location of travel). The need is for an instrument that is closely related to the factors that determine the external cost levels, as this will give transport users a direct incentive to adapt their transport choices and thereby reduce their externalities (Mayeres, 2003).

The European Commission handbook on external costs (EC, 2019a) indicates that the external costs of road transport are substantial: EUR 820 billion in 2016. The largest impact categories are accident costs (38%) and congestion costs (32%), followed by the environmental impacts: climate change (10%), noise (7%), air pollution (6%), habitat damage (4%) and the costs of well-to-tank emissions (3%).

In the 2011 White Paper *Roadmap to a single European transport area — Towards a competitive and resource efficient transport system* (EC, 2011), the European Commission called for 'the full and mandatory internalisation of external costs (including noise, local pollution and congestion) on top of the mandatory recovery of wear and tear costs for road and rail transport'. The Eurovignette Directive (EU, 1999) set the framework for the charging of heavy-duty vehicles (HDVs). In February 2022 a revision was adopted (Directive (EU) 2022/362) (EU, 2022d) containing new rules on road charging on the Trans-European Transport Network (TEN-T) for HDVs, as well as extending some of its principles to passenger cars and light commercial vehicles if countries wish to apply charges for these vehicles as well. Existing time-based vignettes for HDVs on the TEN-T network should be phased out by 2030 and replaced by distance-based charging to conform with the 'user pays' principle. To support the environmental sustainability of road transport, road charging rates will have to be differentiated based on CO_2 emissions for trucks and buses and based on environmental performance (i.e. air pollutants and CO_2 emissions) for vans and minibuses, as of 2026. Zero- or low-emission vehicles should be charged less. In addition, Member States can apply 'tolls and user charges on other roads, provided that the imposition of tolls and user charges on such other roads does not discriminate against international traffic and does not result in the distortion of competition between operators'. Road pricing can therefore be implemented at local or regional/country scale and for all roads or for part of the road network.

While the concept of road pricing is not new (Pigou, 1920; Vickrey, 1963), digital technologies make it much easier to implement than before, especially if one wants to apply differential pricing. De Ceuster and Mayeres (2021) give an overview of the available technologies. Short-range and microwave communication are widely applied, with dedicated short-range communication the most popular standard. Vehicles are equipped with a tag that can be identified by roadside equipment. Each time a vehicle passes this equipment, it is charged. The system is easy to use and cheap for simple road networks. However, it is less suited to large networks, as a lot of roadside equipment would need to be installed. Urban systems, such as the cordon tolls in Sweden and the London congestion charge, and some motorway systems make use of ANPR cameras. In this case, no device is needed in the vehicle. Cameras at the roadside register every passing vehicle. Vehicles that are registered must pay the toll.

The implementation of area-wide charging schemes on a large scale requires the use of a global navigation satellite system (GNSS). Each vehicle is equipped with a device that is used to determine its position and that is connected to a central system. The charges are calculated by the device itself or by the central system, based on the location of the vehicle, the time of driving and other elements included in the charge formula. Such a system was introduced in Germany in 2005 for charging HDVs on motorways and main roads, followed by other European countries. Singapore is preparing the roll-out of a similar system for all vehicles. Also in global satellite-based systems, there is a role for ANPR cameras, namely for enforcement purposes to check that vehicle drivers pay the road user charges.

Urban access restrictions such as LEZs or other restrictions are used to address local air pollution and noise or to improve the liveability of cities and towns. Solutions for parking also work at the local scale.

A7.3 Time frame

Various types of road charging schemes are already applied across the world. Currently, most charging schemes are a time-based vignette, a highway toll or a distance-based charge for HDVs on main roads. The latter applies in several European countries: Austria, Belgium, Bulgaria, Czechia, Germany, Hungary, Poland, Slovenia, Slovakia and Switzerland (Impargo, 2021). There are also some examples of urban charging systems: cordon tolls in Norway (Bergen, Oslo, Trondheim), Sweden (Stockholm, Gothenburg), Italy (Milan) and the electronic road pricing system that was introduced in Singapore in 1998. Examples of area licensing schemes were used in Singapore between 1975 and 1998 and the congestion charge that was introduced in London in 2003.

General (i.e. for all vehicle types) area-wide road pricing over larger areas has been studied in a number of countries or regions (e.g. the Netherlands, Flanders, Brussels Capital Region). However, no examples of such systems covering all vehicles and roads yet exist. Still, there is a continued interest in road pricing for the purposes of mitigating congestion and reducing emissions. With the greater uptake of electric vehicles that is expected in future years and the fact that they are more energy efficient and that electricity is taxed less than conventional fuels, the need to control the other external costs will remain or even grow. In addition, road pricing offers an alternative source of revenue for governments instead of fuel taxation during times when electrification is taking off.

GNSS-based road pricing now commonly uses onboard units in vehicles. Examples are the systems for HDVs in Belgium, Bulgaria, Czechia, Germany, Hungary, Poland and Slovakia. Denmark, Lithuania and the Netherlands are planning to introduce such systems for HDVs (GNSS Consulting, 2022). An alternative could be to use drivers' own mobile phones and/or in-vehicle telematics as a device instead, thereby reducing the system costs. Various market players are working on this new development (Grosche et al., 2022). For example, the use of smartphones is being considered in the SmartMove system that is under investigation for the Brussels Capital Region (Brussels Capital Region, 2021). The certification process and privacy concerns are two very important points to consider.

A7.4 Expected environmental impacts

Given the broad scope of this factsheet, its structure and assessment of environmental impacts are different from the previous ones, and it showcases examples covering different approaches. Indeed, digitalisation enables the development of diverse road pricing tools.

A7.4.1 Road pricing

While road pricing is often implemented or considered an instrument to mitigate congestion, or to raise revenues, it can also contribute to reducing the environmental costs of road transport in the areas where it is implemented. Indeed, several variants of the above-mentioned general categories of road pricing exist, as well as combinations of the different systems (e.g. combination of a kilometre charge with an area licence). For this reason, in the following, and at variance with previous factsheets, the expected environmental impacts will be discussed from a general standpoint and with the help of existing examples.

Table A7.1 presents a general overview of the environmental impacts observed for three urban pricing schemes in Europe (Croci, 2016): the London congestion charge, the cordon toll in Stockholm and the Ecopass system in Milan, which evolved from an LEZ to Area C, a road pricing scheme. The schemes have reduced emission levels. It should be noted that road pricing was not the only measure introduced. For example, in London and Stockholm the schemes were accompanied by improvements in the availability of public transport.

An analysis by Green et al. (2020) confirms that the London congestion charge did indeed significantly reduce the emissions of a range of air pollutants. By mitigating congestion the charge led to reductions in emissions that went beyond what could be expected from the reduction in traffic volumes alone by reducing the emissions per kilometre, thanks to less traffic jams. However, because exemptions were given to buses and taxis, and because the congestion charge was accompanied by an increase in bus services, nitrogen oxide pollution increased. The authors conclude that the parameters of such charges must be set carefully to avoid unwanted effects.

For the Stockholm congestion charge, Eliasson (2009) estimates that the investment and start-up costs were 'recovered' in terms of social benefits in around 4 years. The environmental benefits related to the reduction in greenhouse gases are estimated to be SEK 64 million per year and those related to lower air pollution SEK 22 million per year. This compares with a social benefit (excluding investment and operational costs) of SEK 683 million per year. At the time of the study SEK 10 was equivalent to about EUR 1.1.

According to Danielis et al. (2012), the Ecopass in Milan achieved a net social benefit of between EUR 5.7 million in 2008 and EUR 9.6 million in 2010. The congestion and accident costs were the main externalities that were reduced. The environmental benefits, which were the official political motivation for the system, were considerably smaller. They equalled EUR 0.45 million in 2008 to EUR 1 million in 2010. Considering the change in air pollution levels in Milan and the surrounding region, after a court order suspended Area C in Milan in 2012, and transferring the US monetary value of the unit cost of air pollution to Italy, Gibson and Carnovale (2015) arrive at an environmental benefit of USD 3 billion, which is substantially higher than the previous estimate.

It is important to mention that in all three cases a significant modal shift to more sustainable public transport modes was realised. More advanced pricing schemes could potentially deliver additional benefits. For example, it could be expected that, with road charges that are differentiated according to the environmental characteristics of the vehicles, there would be an incentive to shift to cleaner vehicles, changing the composition of the vehicle fleet and promoting the use of cleaner vehicles over more polluting ones. Moreover, schemes that increase the price per kilometre within a certain area, give an incentive to increase the occupancy rate of passenger vehicles or the load factor of goods vehicles. If the price signal is also differentiated on the basis of the location, it could reduce the number of people who are affected by air pollution and noise in particularly affected areas.

Under the influence of EU emissions legislation, first, the environmental performance of the road fleet will improve substantially, especially when more electric vehicles enter the fleet. In that case the benefits of road pricing in terms of the reduction in exhaust emissions will become smaller. However, even with electrification other environmental costs of transport remain (non-exhaust emissions, well-to-tank emissions, noise pollution). Second, other factsheets have pointed to the risk that the beneficial environmental effects of digitalisation will be reduced or even completely offset by the so-called digital rebound. Third, congestion is expected to increase in both the EU Reference Scenario 2020 with existing policies and in the policy scenarios underlying the European Commission's Fit for 55 proposals. Electric vehicles do not offer a solution to this problem and might even make it worse if they lead to lower driving costs. An increased demand for transport by electric vehicles might also make it more difficult to decarbonise the electricity sector. For these different reasons, it is important to optimise transport levels by internalising the external costs of transport. Road pricing can contribute to this goal, together with other instruments.

The case studies below present the results of simulations for the SmartMove system in the Brussels Capital Region and a pilot-scale implementation of Pigouvian taxation in Switzerland.

Table A7.1 Impacts of urban road pricing schemes in London, Stockholm and Milan

	London	Stockholm	Milan
Change in all traffic volumes compared to (reference year)	-14% (2003) -16% (2006) -21% (2008)	-21% (2006) -19% (2007) -18% (2008) -18% (2009) -19% (2010) -20% (2011)	Ecopass: -20.8% (2008) -17% (2009) -19.3% (2010) Euro IV diesel charged -10.8% (2011) Area C: -38.5% (2012) -37.6% (2013) -36.8% (2014)
Modal shift	Switch by car drivers to public transport (about 10% increase in underground and bus passengers with destinations in the area)	99% of commuters renouncing car use switched to public transport	Switch by car drivers to public transport (about 12% increase in passengers exiting subway stations inside the area)
Change in emissions in the area	-13% NOx, -15% PM_{10}, -16% CO_2	-13% PM_{10}, -13% CO_2	-15% PM_{10} in 2011 compared to pre-Ecopass period. Further 18% PM_{10} in 2012 (first year of Area C) compared to 2011

Note: NOx, nitrogen oxides; PM_{10}, particulate matter with a diameter of 10μm or less.

Source: Croci (2016).

A7.4.2 Low-emission zones

The environmental benefits of LEZs arise because the most polluting vehicles can no longer drive in the zone or only under a number of conditions. Drivers of such vehicles can adapt in different ways: by replacing their vehicle with one that is allowed to enter, by switching modes for their trips in the LEZ, by changing destinations or by no longer making the trip by car. The environmental benefits depend on several factors:

- The share of the vehicles that are no longer allowed in traffic within the LEZ — the higher this share, the higher the potential improvement in air quality when the vehicles are banned.
- The difference in environmental performance between the vehicles that are allowed and those that are not — the larger this difference, the higher the potential environmental benefit.
- The extent to which the traffic within the area of the LEZ contributes to the level of air pollution in the LEZ and surrounding areas — if the air pollution is influenced to a large extent by other sources, the environmental benefit of the LEZ will be smaller.
- The population density and its composition in the area that benefits from the LEZ — the larger the population density and the larger the share of people that are vulnerable to air pollution, the larger the benefit of better air quality.
- The fate of the vehicles that are no longer allowed in the LEZ — their destination is of relevance.

Aside from access restrictions, other initiatives can discourage the use of cars in urban areas. Indeed, increasing the monetary costs of parking makes car transport less attractive and more sustainable modes more attractive.

Discouraging the use of cars in city centres can have additional positive environmental effects. It can reduce the land needed for parking spots, freeing up land that can be used for infrastructure for sustainable transport modes such as walking or cycling, making them more attractive, or that can be used to create more green areas in the city and increase the water permeability of surfaces. It can also reduce the amount of cruising in search of a parking spot. Hampshire and Schoup (2018) estimate that 15% of traffic in central Stuttgart is cruising. Eliminating this traffic will, however, not reduce the traffic volume by 15% because of rebound effects in congested cities.

A7.5 Policy corner

The digital technologies to implement road transport pricing schemes already exist. Nevertheless, the number of road pricing schemes in urban areas is still limited, and while a number of countries have introduced road user charges for HDVs on a large scale, there are no examples yet of such systems for light-duty vehicles. One of the main obstacles to their full-scale application lies in the lack of public acceptance. Several different motivations have been reported in the scientific literature (De Borger, and Proost, 2012; Börjesson et al., 2016; Schade, 2017):

- the public's lack of familiarity with new types of pricing schemes, resulting in uncertainty about the costs of changing transport choices and about the benefits of road pricing;
- the perception of road pricing as just another tax that comes on top of existing taxation;
- distrust about how the revenues will be used;
- concerns about equity across different income groups, people with different professional activities, people with different access to public transport, etc.;
- privacy concerns;
- difficulty in understand charging systems if the tariff schemes contain a lot of differentiation and if the charging systems differ by country or city.

In addition, the current economic climate, with high energy prices and inflation, makes the acceptance of road pricing even more difficult.

In general, parking policies are more readily accepted, which explains why many cities already charge high prices for on-street parking. New digital solutions, however, can increase the performance of such systems.

Some future developments are expected to make implementing the policies more attractive:

- further technological developments that are expected to lower the costs of digital solutions and increase their usefulness;
- the loss of fuel tax revenue as a consequence of the electrification of the vehicle fleet;

- the need to internalise the additional external costs that will arise if electrification will lead to lower driving costs;

- the need for a policy framework that can address any unwanted digital rebound due to the ongoing digitalisation of road transport.

A7.6 Bottom line

Digitalisation can enable the development and implementation of road pricing schemes that allow transport costs to be fully internalised. Such approaches have demonstrated the ability to effectively promote a modal shift to more sustainable transport modes, albeit at pilot scale. Despite not being a new concept, its implementation was impractical without the support of digital technology. Lastly, road pricing schemes can help to mitigate the unwanted rebound effects of digitalisation.

A7.7 Case study 7.1: SmartMove Brussels

Through a modelling study, the Brussels Capital Region analysed the effects of introducing road pricing for light-duty vehicles in its territory, in parallel to the per kilometre charge that already applies for HDVs. Compared to existing urban road pricing schemes in Europe, this system would apply to a much larger area, namely about 161km^2.

The charge consists of a per kilometre charge and a daily access charge. Both apply only during the working week. The per kilometre charge is higher during peak than off-peak periods and zero in the evening and over night. The daily access charge depends on the vehicles' fiscal power and powertrain technology (electric or not) and on the time of the day (peak vs off-peak). Several charge levels were studied. Here the results are reported for a daily access charge with a weighted average level of EUR 0.66 during the off-peak period only and double that amount for travels during the peak period. The kilometre charge is EUR 0.2/km in the peak period and EUR 0.08/km otherwise. For Brussels residents, the existing car purchase and annual vehicle taxes are abolished in the scenario.

Under these conditions model simulations indicate that SmartMove leads to the following results (De Ceuster et al., 2020):

- a reduction in the number of vehicle-km travelled by cars, vans and motorcycles of 7.7%;

- a reduction in congestion: the extra travelling time per kilometre compared to free flow speed is reduced by 30%;

- a reduction in passenger-km travelled of 2% (for all modes taken together) and a fall in the number of car passenger-km travelled of 6.7%;

- based on the 2020 vehicle fleet composition, CO_2 emissions decreased by more than 5%, and the decrease in emissions of air pollutants ranged between 4.8% and 5.3%, depending on the pollutant.

Car users who travel less by car are expected to adapt as follows: by making fewer trips or reducing the length of their trip in Brussels (53% of car passenger-km are expected to disappear, as drivers switch to bus-tram-metro (20%), train (14%) or cycling or walking (12%). For commuting and business travel there also is a shift to more carpooling. Overall, the environmental benefits are estimated to equal EUR 9.8 million.

This simulation does not yet consider the effect on the vehicle stock of differentiating the SmartMove charge according to the vehicle's fiscal power (giving an incentive to drive less powerful vehicles) and the type of propulsion. This is likely to lead to underestimating the impact. However, the environmental performance of the vehicle fleet in future years is expected to improve, partially reducing the impact of SmartMove on air pollutant and greenhouse gas emissions.

A7.8 Case study 7.2: Pigouvian transport pricing in Switzerland

The Swiss Competence Center for Energy Research, the Swiss Federal Roads Office and the Swiss Federal Office of Transport jointly financed a study on the impacts of a Pigouvian transport pricing scheme in Switzerland. The empirical work was conducted by ETH Zürich, the University of Basel and the Zurich University of Applied Sciences (Axhausen et al., 2021). The main objective of the project was to investigate the impact of a pricing scheme on behavioural shifts towards optimised and more sustainable travel patterns. In addition, the effectiveness of increasing the awareness of citizens through soft measures was explored. These do not involve an increase in transport costs but include measures such as sharing targeted information on the external costs associated with transport. The study took place in urban agglomerations in the German- and French-speaking parts of Switzerland from September 2019 to January 2020.

It involved a sample of 3,700 participants, selected through an initial survey among 21,800 individuals. Participants were identified based on a set of criteria such as living in a metropolitan area, being between 18 and 65 years old, travelling by car (either their own or shared) at least twice a week, and being able to use a smartphone and to walk without assistance. The last points were to ensure that participants have a free choice of mode and unimpeded access to the transport network. The study was 8 weeks long overall (from September 2019 to January 2020). It was divided into an observation period of 4 weeks followed by a 'treatment' period. Participants were enticed to actively participate in and complete the study through an incentive of CHF100 per person to be paid at the end of the treatment period. During this second period, participants were divided into three groups: a control group for which no additional action apart from monitoring was taken; an information group to which specific information about the impact of the participants' transport choices was provided; and a pricing group in which, in addition to receiving information, the Pigouvian scheme was also implemented. In that scheme, the external costs of transport due to climate change, health effects (i.e. air pollution, road accidents) and also congestion and crowding on public transport were internalised in the final user price. The set-up allowed, through the control group, decoupling the effect of the pricing scheme from the effects occurring for other reasons in the sample (e.g. general traffic volume, road repairs, weather) during the period of testing. In addition, by analysing the behaviour of the second group, it was possible to see how an increased awareness of transport externalities can influence transport choices.

The participants were tracked with a dedicated application installed on their smartphones, using the smartphone's location services. The app used machine learning algorithms to correctly identify not only trip parameters, such as duration, distance or the route followed, but also the mode of transport. This is an example on how digital technologies could promote the realisation of such pricing schemes that would otherwise be very difficult to implement in practice.

The study demonstrated that a time- and location-based transport pricing scheme that internalises the external transport costs can effectively reduce the external costs in the pricing group by approximately 5%, with a short-term elasticity of -0.31. This means that an increase in the transport price of 10% causes a decrease in the external costs of 3.1%. The researchers point out that this is largely in line with previous before-and-after studies of urban road pricing schemes and with the effects induced, for example, by an increase in the fuel price.

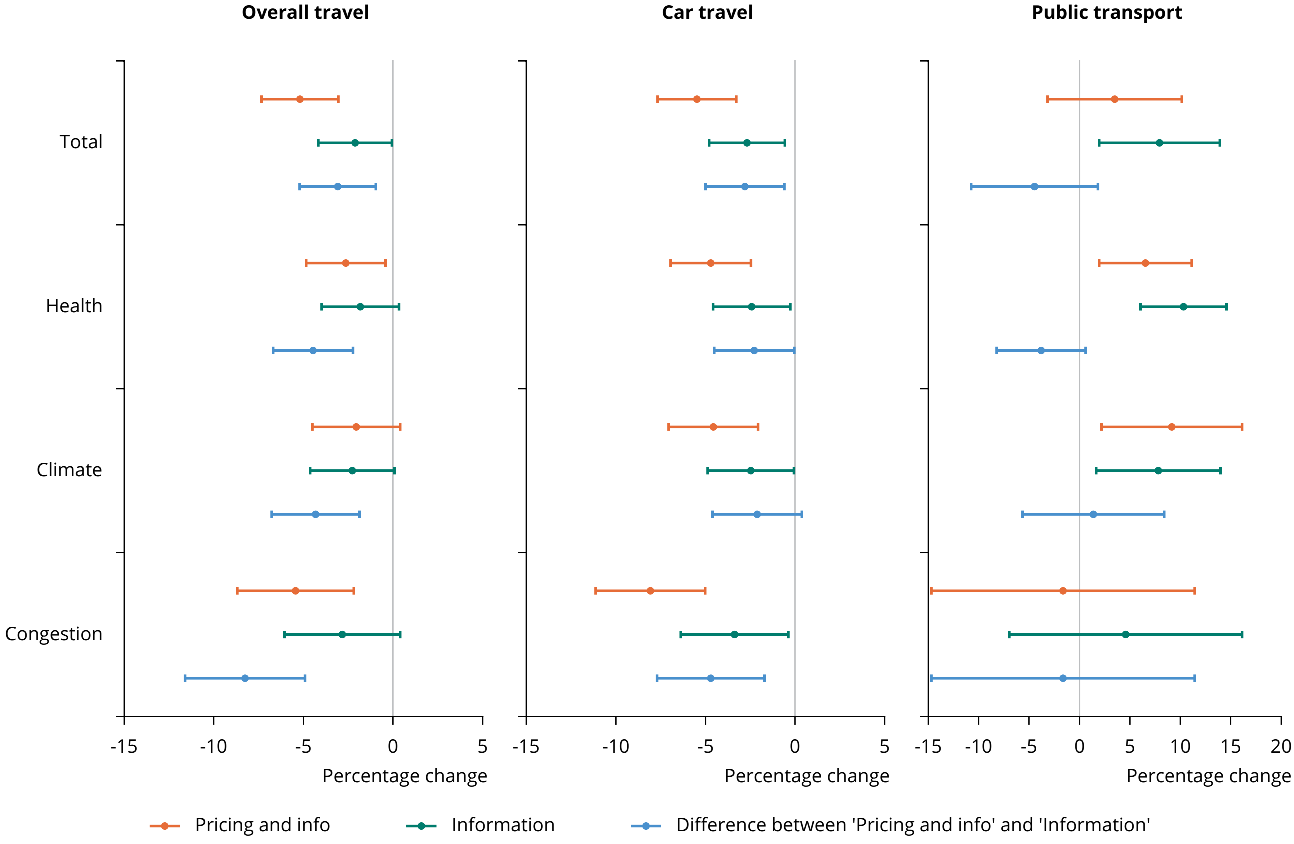
Figure A7.1 shows that, in general, it is possible to reduce the externalities associated with transport. This result can be achieved, albeit to different extents, not only by applying a Pigouvian pricing scheme, which confronts users with the external costs they impose, but also providing people with information on their external costs. Indeed, if information provided were the only relevant aspect, the relative bars would have been identical to those associated with the treatment including pricing and information. On the other side, if the information component were completely irrelevant, the relative bars associated with it would have been zero. To summarise, this suggests that providing information alone has a more limited effect than providing the combination of both measures. Interestingly, it can also be noted that, for congestion, the monetary component is relatively more important than for the other types of external costs, possibly because people understand it better than other environmental costs.

The middle and right panels of Figure A7.1 show that the reduction in external costs achieved is mainly due to a modal shift from car to public transport. Indeed, the reduction in the distance travelled by car is statistically significant and in the order of 3%. The share of public transport and active modes such as biking and walking increases.

The effects of applying this transport pricing scheme did not vary significantly with education level, age group or income level. The effects on congestion were significantly higher for men than for women. Preliminary data suggest that lower income households may be less sensitive to pricing (although the difference is not significant at conventional levels). Although this may look counter-intuitive, it is consistent with the hypothesis that people with high incomes tend to have jobs that are more flexible in terms of working hours.

Lastly, it should be mentioned that the number of participants in the study was limited, and this should be taken into account when considering the results reported here. An extensive transport modelling study or a full-blown experiment (such as that done in Stockholm before the official introduction of the cordon toll) can help to better understand these effects on large scale and to achieve the optimal design of a future pricing scheme.

Figure A7.1 **Treatment effects on the external costs of transport: overall travel (left), car travel (middle), public transport (right)**



Note: The bars denote the 80% confidence intervals.

Source: Axhausen et al. (2021).

Annex 8
Air traffic management

A-S-I: improve (reduce emissions and noise through optimisation of operations)

Context: passenger and freight air transport

Time frame: short to medium

A8.1 Definition

Air traffic management (ATM) is the term normally used in the aviation sector to indicate all the systems that assist an aircraft and its crew during the different phases of the trip, including departure, the flight through the airspace and landing at the airport of destination. ATM is one of the many systems that enables air mobility (Steffen Liebig et al., 2021). It has specific tasks and responsibilities, mainly related to the infrastructure and its safe operation and it includes three main services: air traffic services (ATS), including air traffic control (ATC); air traffic flow management (ATFM); and airspace management (ASM). ATS assists aircraft in real time to ensure their safe travel by providing necessary information to the aircraft crew throughout the entire flight. This service is facilitated by ground-based air traffic controllers who follow the flights through specific sections of the airspace. To ensure efficient use of the airspace, ASM controls the allocation of airspace to different users (civil and military, although it should be noted that, in some EU countries, civil and military airspaces and ATM are segregated) and the way the airspace is structured. The air traffic flows are regulated by ATFM, which ensures that airspace and airport capacities are not exceeded to avoid congestion (SKYbrary, 2022; Wikipedia, 2022). The ATM is provided by air navigation service providers (ANSPs), which also provide other services such as meteorological, surveillance and communication services.

With the expected growth in urban air mobility the ATM system will need to integrate seamlessly with U-space, a set of new services relying on a high level of digitalisation and automation of functions and specific procedures designed to support safe, efficient and secure access to airspace for large numbers of drones (SESAR Joint Undertaking, 2022a). This includes standard urban flights departing from airports.

A8.2 Context

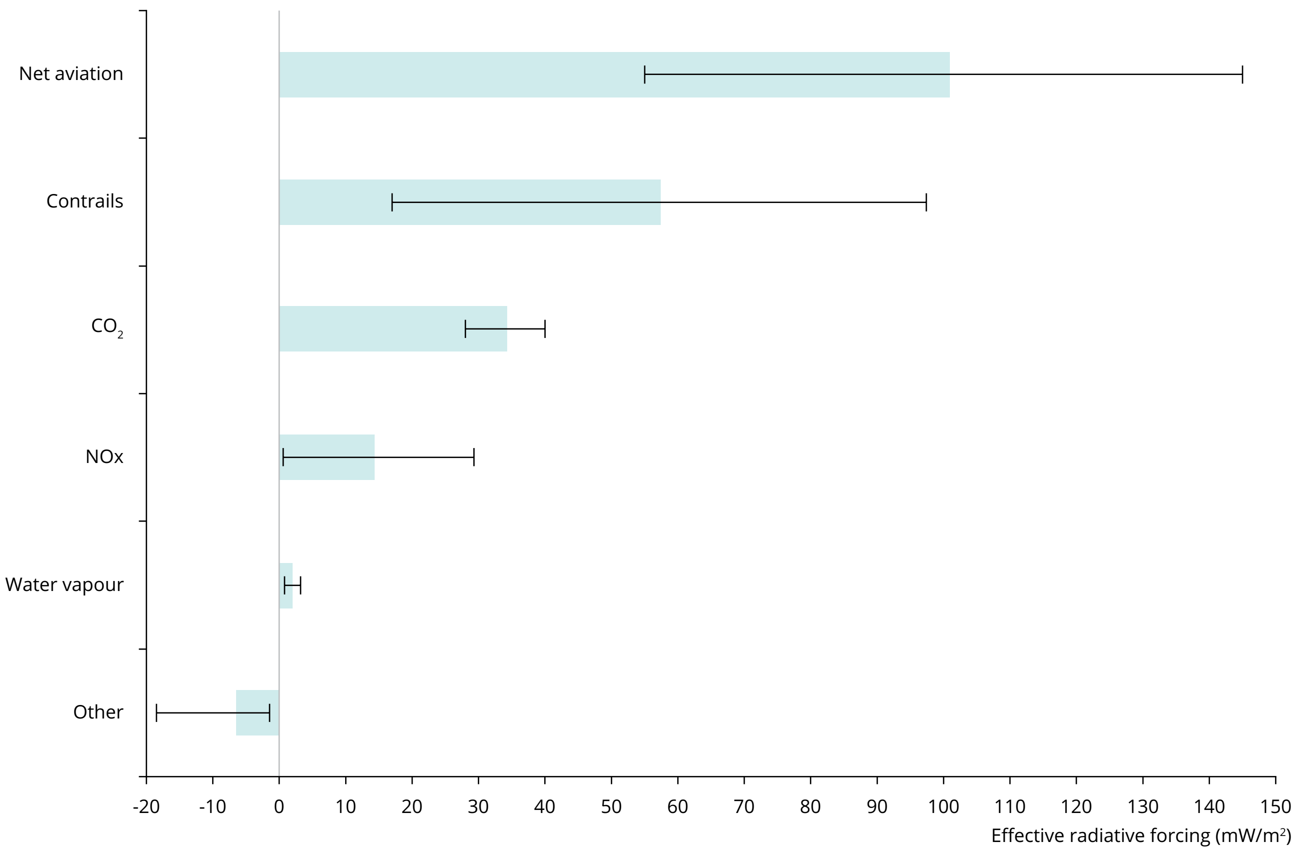
In 2019, aviation produced 3.6% of the total EU-27 and UK greenhouse gas (GHG) emissions and was responsible for 14.1% of the GHG emissions from transport (EASA et al., 2019; EEA, 2021a). The sector contributes to climate change in different ways, the most important being: (1) direct emissions of GHGs such as CO_2; (2) the formation of contrail cirrus clouds; and (3) emissions of nitrogen oxides (NOx), due to chemical reactions they induce in the atmosphere. Water vapour, soot particles and sulphur-containing aerosols can also have an effect. To estimate the impact of both CO_2- and non-CO_2-related phenomena on climate change, effective radiative forcing (ERF) is often used. This metric captures the influence that a factor (e.g. a compound released in the atmosphere) has in modifying the incoming and outgoing energy fluxes in the Earth-atmosphere system (IPCC, 2007). ERF is measured in W/m^2 and is positive when a substance has a warming effect on the Earth's atmosphere and negative when it has a cooling effect. For the aviation sector, it is estimated that CO_2 emissions contribute 34% of the total ERF while non-CO_2 effects are responsible of the remaining 66% (Lee, 2021; Brazzola et al., 2022). Among these, the most relevant mechanism is believed to be that induced by contrail generation.

Contrails are mostly formed from water vapour already present in the atmosphere, which can freeze, in specific conditions, when an aircraft flies through it. This phenomenon occurs when temperatures are sufficiently low and humidity sufficiently high and is triggered by the aeroplane emitting soot particles around which the vapour can solidify. The ice crystals formed can then expand into a contrail. Contrails can either quickly disappear or become a cirrus cloud, reflecting radiation and contributing in this way to global warming. It should be noted, however, that there is still considerable uncertainty on the overall impact of such phenomena, as demonstrated by the variation in the data reported in Figure A8.1. This is also due to their dependence on atmospheric conditions, which makes it much harder to predict. It should also be noted, however, that, while the impacts of CO_2 on climate change are well understood, the situation for non-CO_2 effects induced by contrail formation is more uncertain. It is still unclear what the overall long-term effect of implementing actions that will reduce non-CO_2 effects may be if this reduction is counteracted by an increase in CO_2 emissions (Lee et al., 2021).

NOx is the third largest contributor and accounts for approximately 20% of the total ERF from aviation. NOx has both a warming and a cooling effect on the climate, depending on the chemical compounds it reacts with. The overall net ERF is positive, though, meaning that it contributes to warming the atmosphere of the Earth.

As discussed in Chapter 2, the continuous increase in transport demand has significant environmental impacts, leading to a progressive increase in GHG and air pollutant emissions, often so large that they partially or totally counteract technological advancements. This is true also in the case of the aviation sector. Indeed, between 2005 and 2017, the number of passenger-km flown by commercial flights departing from within the EU-27 plus EFTA and the UK ([16]) increased by 60% (EASA et al., 2019) and the number of passenger-km is predicted to grow by 42% according to EASA et al. (2019), or by 44% by 2050 (Eurocontrol, 2022a). Despite a decrease in average fuel consumption (-24% between 2005 and 2017), CO_2 emissions have increased by 22%, as shown in Figure A8.2 (from 110 million tonnes in 2005 to approximately 134 million tonnes), and are forecast to grow by another 2-40% by 2040 in the base traffic scenario (EASA et al., 2019). Other estimates anticipate an increase of 67% by 2050 in a business-as-usual scenario, reaching approximately 315 million tonnes of CO_2 (NLR and SEO Amsterdam Economics, 2021).

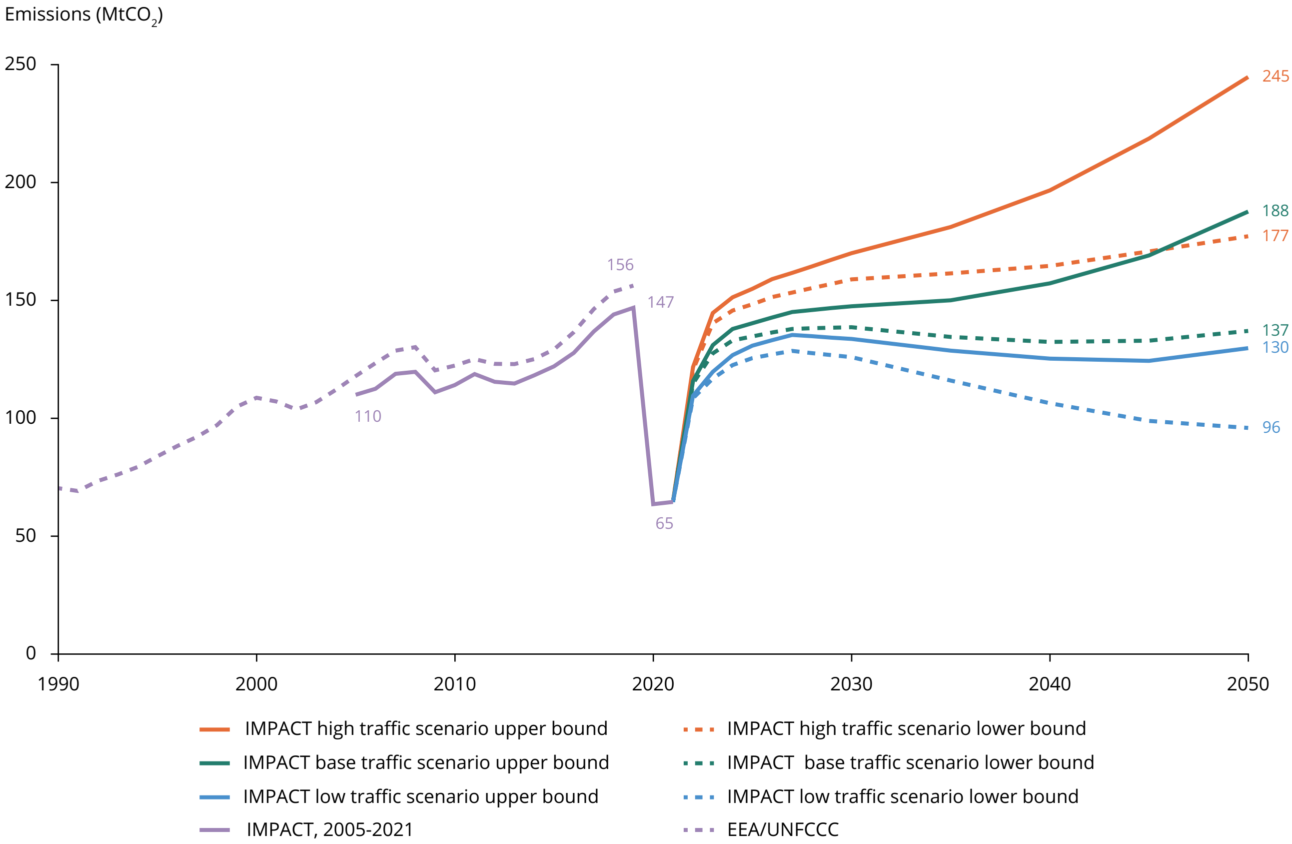
Figure A8.1 Global aviation effective radiative forcing



Source: EEA compilation based on Lee et al. (2021).

([16]) EU-27 plus EFTA comprises the 27 EU Member States plus Norway, Switzerland, Liechtenstein and Iceland.

Figure A8.2 **Historical trend and long-term outlook for the CO_2 emissions from aviation in Europe**

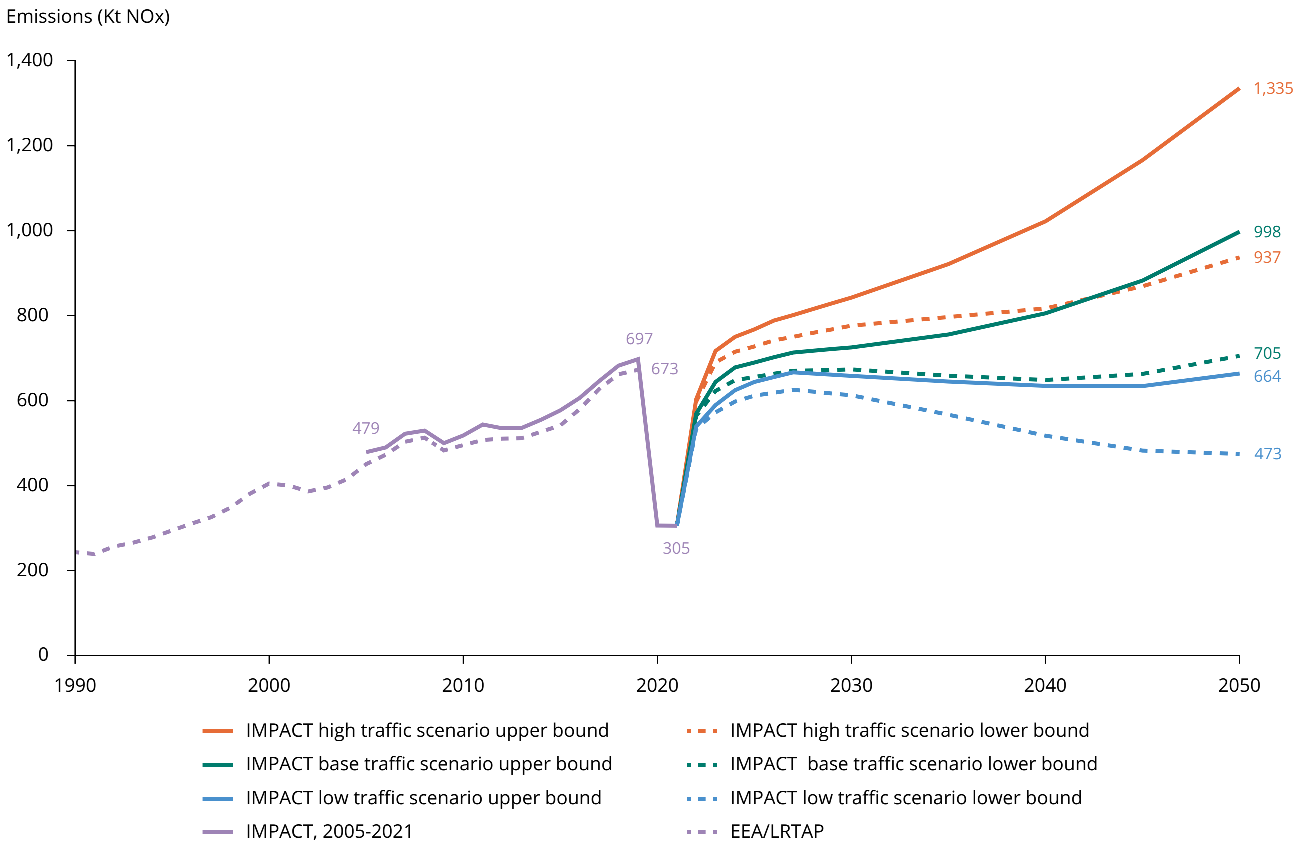


Source: EASA et al. (2022); estimates computed using the IMPACT model.

Similarly, NOx emissions are also predicted to grow by 2050. For the base traffic scenario the estimate growth by 2050 is projected to lie between 1.2% and 43%, as shown in Figure A8.3 (EASA et al., 2022). Other emissions, such as unburned hydrocarbons and carbon monoxide are more stable, and carbon monoxide emissions have even decreased (by 2% between 2005 and 2017) and are believed to have decreased even further. Particulate matter emissions are also believed to have risen (volatile particulate matter by 61%).

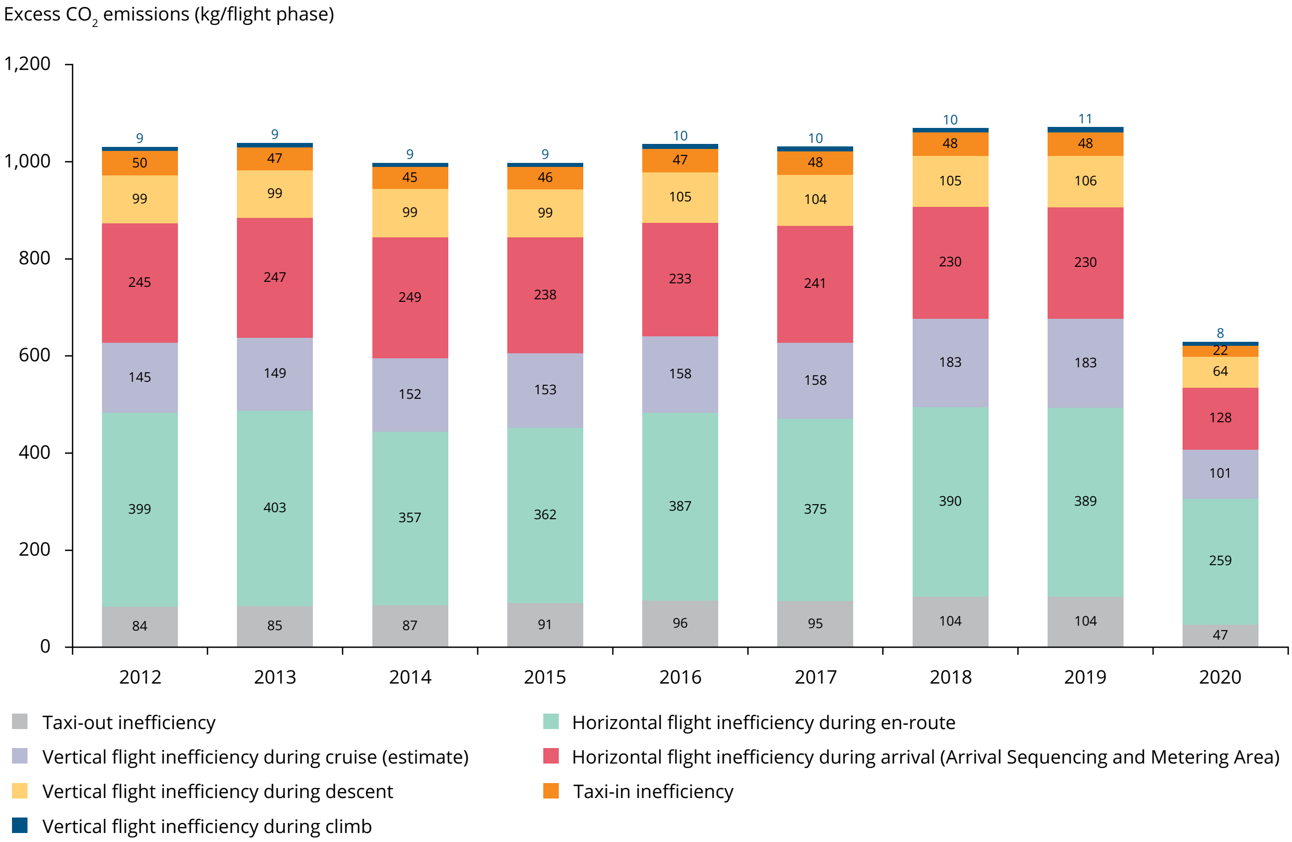
Emissions from aviation are highly correlated with the number of flight-km flown and, although the demand for flight-km is mainly dictated by the demand for air travel, inefficiencies in flight routes contribute to excess kilometres travelled and thus emissions. Today, the inefficiencies are captured through two key performance indicators (KPIs), measuring the difference between the shortest route between the origin and the destination and the last filed flight plan (also known as the KEP) or the actual trajectory flown (known as the KEA). The difference between these two KPIs is also called the horizontal flight efficiency. Non-optimal trajectories are not, however, the only source of inefficiency and, according to some authors, KEP and KEA indicators may not be an adequate measure of environmental performance, as, for example, the speed at which the trajectory is flown is not considered. In addition, horizontal flight efficiency does not account for the cruising altitude, which has a relevant impact on fuel consumption. It should also be mentioned that a high value for horizontal flight efficiency within a given airspace does not necessarily correspond to an optimal overall trajectory from origin to destination. Currently, values for these indicators are between 98% and 94% (Fricke, et al., 2021), and based on these alone there seems to be little room for improvement. Several authors argue (Edard, and Sitova, 2021; Fricke et al., 2021; Jarry, and Delahaye, 2021) that other indicators that also account for fuel efficiency should be adopted. For example, Eurocontrol network manager is developing a tool to assess fuel burn with a wheels-up/wheels-down approach (Eurocontrol, 2014). This could potentially help to better understand the environmental impact of flight trajectories and related choices. Aside from the in-route inefficiencies, they also occur around airports with non-optimal take-off and landing trajectories (which can be accounted for in the vertical flight efficiency (or VFE indicator), in which non-optimal arrival times cause unnecessary airborne holding and long taxi times at airports. The arrival sequencing and metering area (ASMA) time measures the additional taxi-out time and additional transit time within a radius of 40 nautical miles around an airport compared to the time during periods of low demand. Altogether these factors contribute to significant excess CO_2 emissions, shown in Figure A8.4, and to additional emissions of other pollutants (e.g. NOx).

Figure A8.3 Historical trend and long-term outlook for the NOx emissions from aviation in Europe (EU-27 plus EFTA and the UK)



Source: EASA et al. (2022).

Figure A8.4 Breakdown of gate-to-gate excess CO_2 emissions for an average flight in Europe

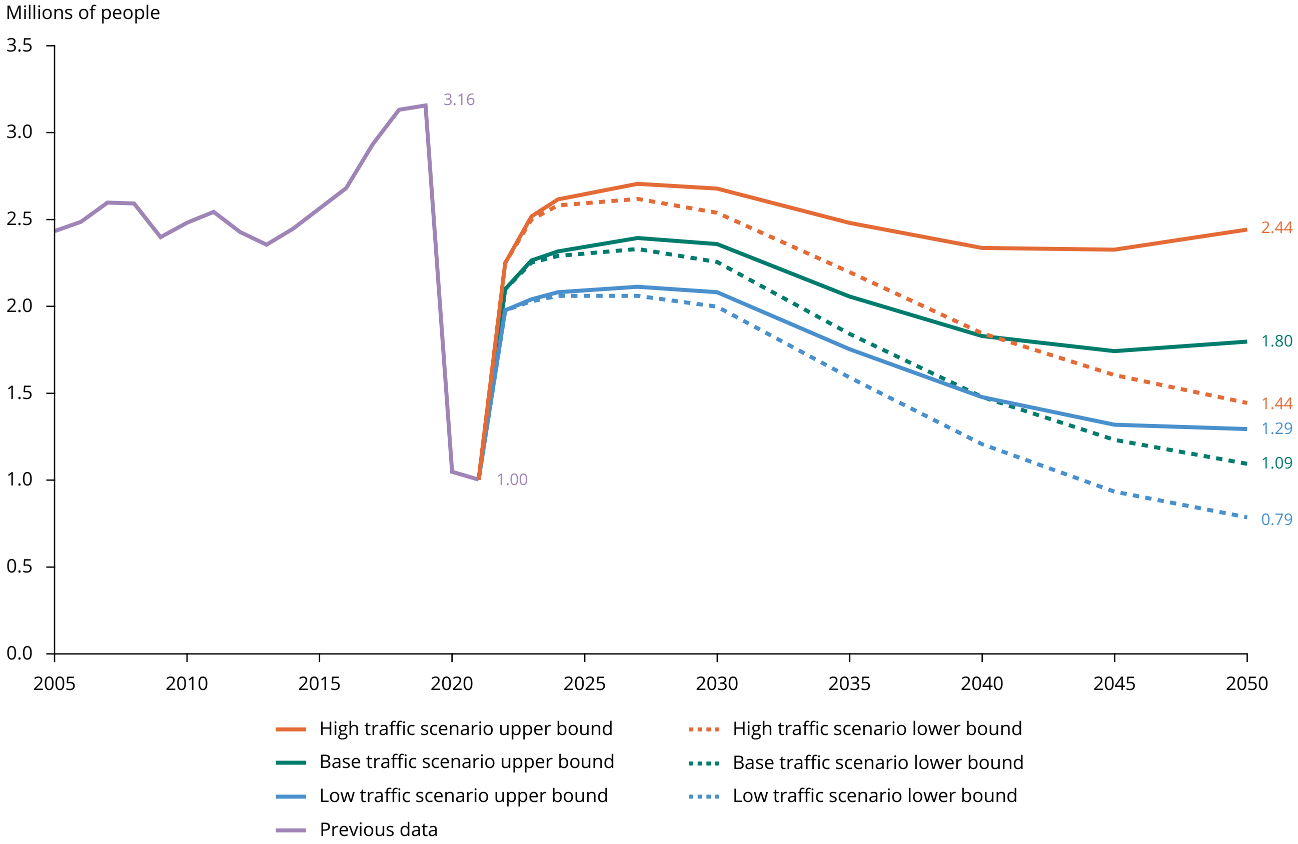


Source: EASA et al. (2022).

There are many reasons for the in-flight inefficiencies (Edard et al., 2021). First, since safety is a priority, traffic segregation is implemented, leading sometimes to longer routes. Second, aircraft are sometimes prohibited from using part of the airspace used for military purposes, etc., and need to circumvent some areas, increasing the length of their route. Sometimes airlines deliberately choose environmentally inefficient long routes to avoid delays or costs (e.g. high route charges). Lastly, weather can be another reason why the most efficient route cannot be followed. Climate change itself will have an impact on future weather patterns and will affect delays and flight efficiency (Eurocontrol, 2021a). The overall impacts will vary across Europe and, although delays due to major storms are expected to increase, the expected changes in high-altitude winds could lead to a reduction in fuel burn.

Aside from climate change impacts, aviation is also responsible for noise pollution. The noise impact of air traffic is mostly experienced around airports where the population is subjected to the noise of aircraft landing and taking off. It is estimated that in Europe in 2017, approximately 3 million people were subjected to day-evening-night average noise levels (L_{den}) equal to at least 55dB due to aircraft noise in urban areas and an additional 1 million people were affected in rural areas (EEA, 2020a). New landing and take-off procedures facilitated by ATC can reduce noise around airports (see case study 8.2). At variance with other impacts, the outlook for noise pollution is more favourable, as also shown in Figure A8.5. In the base load scenario the number of people living close to the 47 major EU airports and exposed to L_{den}≥55dB is projected to decrease by approximately 43% to 65% of the population by 2050 compared to 2019 (EASA et al., 2022).

Figure A8.5 **Historical trend and long-term outlook for the number of people in the L_{den}≥55dB noise contours at 47 major European airports**



Source: EASA et al. (2022).

To mitigate this increase in emissions and achieve the targets set out in the Fit for 55 package, improvements to ATM and aircraft operations are an important short- to mid-term step alongside other instruments such as demand management, sustainable fuels, improved aircraft technology and economic and policy measures. One of the main pillars for increasing the efficiency of ATM is the development of new digital solutions to optimise air traffic, both in-route and in airports. This resulted in the launch in 2004 of the Single European Sky initiative (SES) and the corresponding research projects (enabled by the SESAR Joint Undertaking, created in 2007). Initiatives include: (1) the integration of airport collaborative decision-making (A-CDM) systems to decrease ASMA time, (2) continuous climb and descent operations to optimise taking-off and landing trajectories and (3) the introduction of free route airspace allowing airlines to freely plan their route between origin and destination (see Sections A8.7-A8.9 for more information about these three initiatives).

A8.3 Time frame

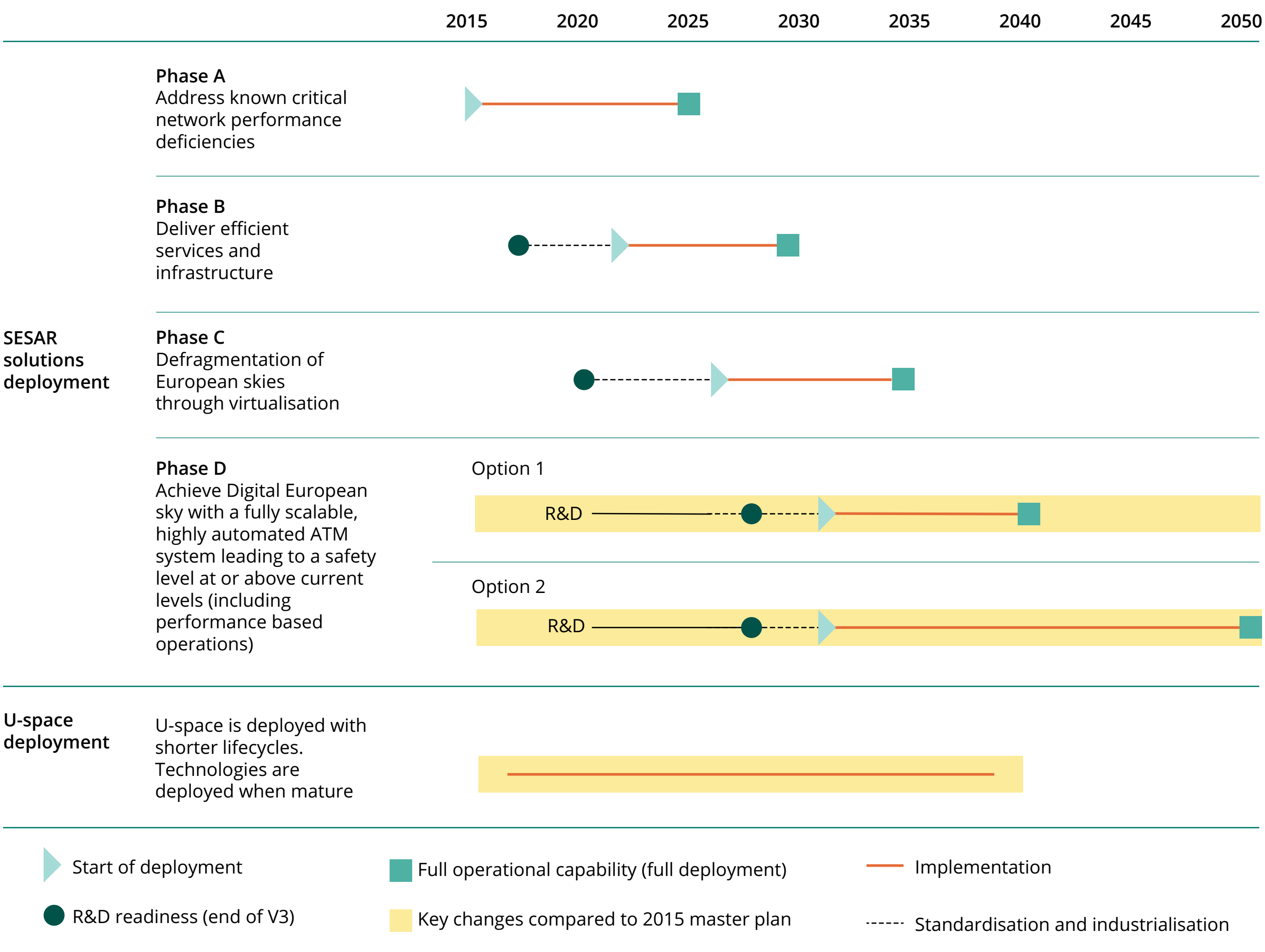
In 2004 the SES initiative was launched. The SES Framework (Regulation (EC) No 549/2004) laid down the framework for a single European sky. Initially, it was meant to provide solutions to excessive delays through a more integrated European ATM system, and the main goals were to defragment the European airspace and increase collaboration between the many ANSPs controlling it (Regulations (EC) No 550/2004, 551/2004 and 552/2004). For this to be possible, new technologies and a greater level of digitalisation were deemed necessary, and in 2007 the SESAR research programme was launched to coordinate EU research and development activities in ATM. In 2009, The SES II Regulation ((EC) No 1070/2009), amending the SES I Regulations, was approved. This set binding performance targets on safety, environment, capacity and cost-efficiency on the air traffic service providers. In addition, to improve the synchronisation of the deployment of the digital solutions developed under the SESAR framework, the SESAR Deployment Manager was created (SESAR Deployment Manager 2022). In 2013, the SES II+ proposal was made, which aims to increase competition between ANSPs and reinforce the role of the network manager in the hope of accelerating the rate of digitalisation in ATM.

The SESAR solutions are defined in the European ATM masterplan, in which the roadmap for implementation is set out until 2050 (Figure A8.6). The ambition is to reduce additional gate-to-gate flight time and CO_2 emissions by 3.2% and 2.3%, respectively, by 2035 (EASA et al., 2022).

A detailed catalogue of digital SESAR solutions can be found in SESAR Joint Undertaking (2021) (see also case studies 8.1-8.3). Despite the high ambitions, it should be noted, however, that only 26% of SESAR solutions have been deployed (SESAR Joint Undertaking, 2020), demonstrating the difficulties of introducing operational changes in the sector.

To achieve the timeline set out in the masterplan, it was recognised that there is a need for a review of the incentivisation programme. Rewarding actors who implement innovative solutions, strengthening the synchronisation and coordination efforts already made by the SESAR Deployment Manager and promoting the deployment programme are among the proposed mitigation actions (SESAR Joint Undertaking, 2020). Via calls for digital sky demonstrators by the European Climate, Infrastructure and Environment Executive Agency (CINEA) under the Connecting Europe Facility, the SESAR Joint Undertaking targets early movers to accelerate the delivery of SESAR solutions (SESAR Joint Undertaking, 2022b).

Figure A8.6 Target roll-out of SESAR solutions



Source: SESAR Joint Undertaking (2020).

A8.4 Expected environmental impacts

Using the taxonomy set out in Chapter 3 the following higher order environmental impacts of ATM improvements can be identified.

A8.4.1 Indirect effects — efficiency effects

It is estimated that CO_2 emissions savings from ATM improvements could range between 13 million tonnes and 25.5 million tonnes by 2030, achieving 8.3-12.4% of potential CO_2 reductions (Eurocontrol, 2022b). In the long run, the potential ATM improvements will become slightly less pronounced but could still contribute 6-9% of overall CO_2 emission reductions by 2050 (Figure A8.7) (NLR et al., 2021; Eurocontrol, 2022b).

Others estimate that the SESAR programme could deliver a reduction of 5.6% in CO_2 emissions by 2035 and an extra 2% by 2040 compared to emission levels in 2020. Improved flight planning has the potential to reduce CO_2 emissions by 1.5% (NLR et al., 2021; see table 39). For contrail formation, Teoh et al. (2020) estimated that rerouting 15.3% of flights can reduce the impact of contrails significantly but that this comes with an increase in fuel consumption of 0.70%. It should also be noted that diversions come with a modest loss of airspace capacity, which is normally a scarce resource. Avila et al. (2019) show that in the United States, on average 15% of flights produce contrails, and an increase in flight altitudes can reduce the radiative impact by 92% with little impact on fuel consumption. All this requires improved ATM services to be able to communicate accurate weather forecasts and compute optimal flight routes. The use of sustainable aviation fuels could further help reduce the formation of contrails, as such fuels produce less soot particles when burned, which leads to reduced formation of ice crystals. However, the extent of this reduction is still subject to research (Lee, 2021).

Due to the complexity of air travel, there are a lot of interdependencies between externalities, and trade-offs are numerous. Although the optimisation of flight routes and airport operations have an important potential for reducing CO_2 emissions, they can have negative impacts on other externalities. The report by NLR and SEO Amsterdam Economics (2021) and references therein list some examples:

- Noise versus emissions (GHG and pollutants): a particular departure or landing trajectory might reduce noise for the surrounding population but might be less fuel efficient. Flights that avoid highly populated areas to reduce noise nuisance may increase the distance flown and fuel consumption.

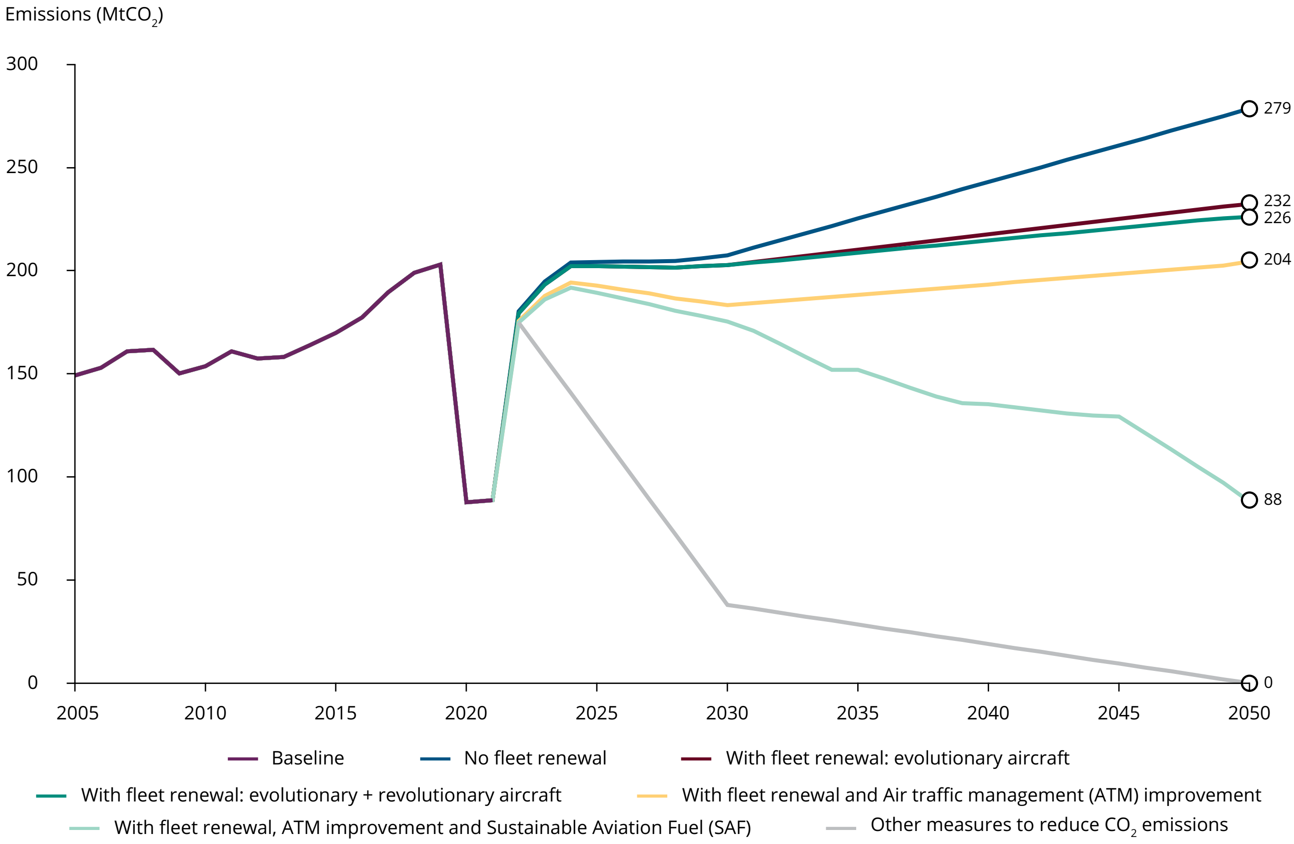
- Safety versus emissions (GHG and pollutants): guaranteeing separation limits the capacity of a given airspace, creating congestion and might lead to aircraft choosing a non-optimal flight trajectory.

- Contrail formation versus emissions (GHG and pollutants): it is sometimes better to take longer routes or fly at different altitudes to avoid areas where contrails form more easily. This, however, may imply following less fuel-efficient routes and increasing CO_2 emissions.

- Capacity versus emissions (GHG and pollutants): if airlines follow optimised routes, this could increase the use of some airspace, leading to capacity problems and congestion with longer delays for aircraft and passengers.

The quantification of these trade-offs is not straightforward, as pointed out in various contributions during the research workshop 'Climate change and the role of air traffic control' (Baltic FAB et al., 2021). There is a need for more and diverse data and new metrics to be able to evaluate the impacts of technological advances on emissions and to quantify their interdependencies.

Figure A8.7 **Estimated CO_2 emissions of aviation between 2005 and 2050 in Europe, base case scenario**



Source: Eurocontrol (2022a).

A8.4.2 Structural and behavioural effects — direct rebound effects

Flexibilities and improvements in the use of the airspace can lead to positive effects such as an increase in the efficiency of asset use and a decrease in the costs of delays. However, this will always be limited by overall capacity: a CO_2 emission-optimal route choice can lead to increased use of some sectors of the airspace, increasing congestion.

A8.4.3 Structural and behavioural effects — indirect rebound effects

As mentioned before, airlines sometimes choose a longer, non-optimal route to avoid airspaces with high air navigation service charges. If airlines are constrained to follow the CO_2 emission-optimised routes, this could lead to a change in revenues for both the airlines and the ANSPs.

Changes in fuel burn costs and in air navigation service charges will be passed on, at least partially, to passengers through reduced or increased airfares. Changes in delays will also affect passengers directly and might encourage or discourage air travel, directly impacting the demand for it.

It should be noted that a delayed flight could be the more environmentally friendly solution, depending on the situation.

A8.5 Policy corner

The complexity of ATM operations can lead to a slow uptake of new technologies as reported in Delhaye et al. (2021). Some of the main challenges identified relate to the numerous stakeholders with different objectives (revenues, increasing capacity, safety) that are not always aligned. This leads to an articulate decision-making process, in an environment in which stringent safety requirements are of paramount importance. Other issues are that ATM investments are often very expensive and budget constraints can hinder their uptake, certainly when the investing party will not directly benefit from them (the 'split incentive problem'). In general, it is important to clearly signal the priorities for the whole sector. These must include environmental concerns.

Despite the numerous barriers, Delhaye et al. (2021) also identify ways that can encourage the aviation sector to implement further digitalisation technologies. They explore a number of policy options that could be adopted to promote investments in the sector, such as: (1) a flexible charging regulation that allows agents to charge different rates to their service users according to the technologies implemented, (2) giving subsidies to ANSPs when investment costs are very high but the technology is of more benefit to the airlines, and (3) introducing a 'best equipped-best served' charging mechanism that allows agents (ANSPs, airports, etc.) to provide a better service to airlines using a particular technology. A need for more and better demonstration of technologies to show their potential and the involvement of all stakeholders was also identified as necessary to ensure a good uptake of innovative technologies. The SESAR Deployment Manager and the SESAR Joint Undertaking digital European sky demonstrators are examples of tools that contribute to solving these issues.

Similar to what happens in other sectors, internalising transport externalities and managing demand could help to reduce the environmental impact of the sector and avoid some of the distortions currently seen in the market discussed above.

A8.6 Bottom line

Digitalisation potentially improves the overall operational efficiency of air traffic by reducing taxi time at airports and by optimising flight routes and landing and take-off trajectories. This will reduce emissions through a decrease in the fuel burned and the potential to avoid contrail formation. Due to the complexity of air travel, there are numerous trade-offs and reducing one externality can exacerbate another. Other technological innovations and the use of sustainable fuels in aviation are expected to have a greater impact on reducing GHG emissions. However, to achieve significant results, collaboration between the various actors is necessary and the creation of a digital single European sky is an important tool for this. As extensively discussed in other factsheets (e.g. Factsheet 7), internalising the externalities and managing the constantly increasing demand are necessary and complementary actions to reduce the environmental impact of the sector and avoid neutralising the benefit of other technological advancements.

A8.7 Case study 8.1: Airport collaborative decision-making

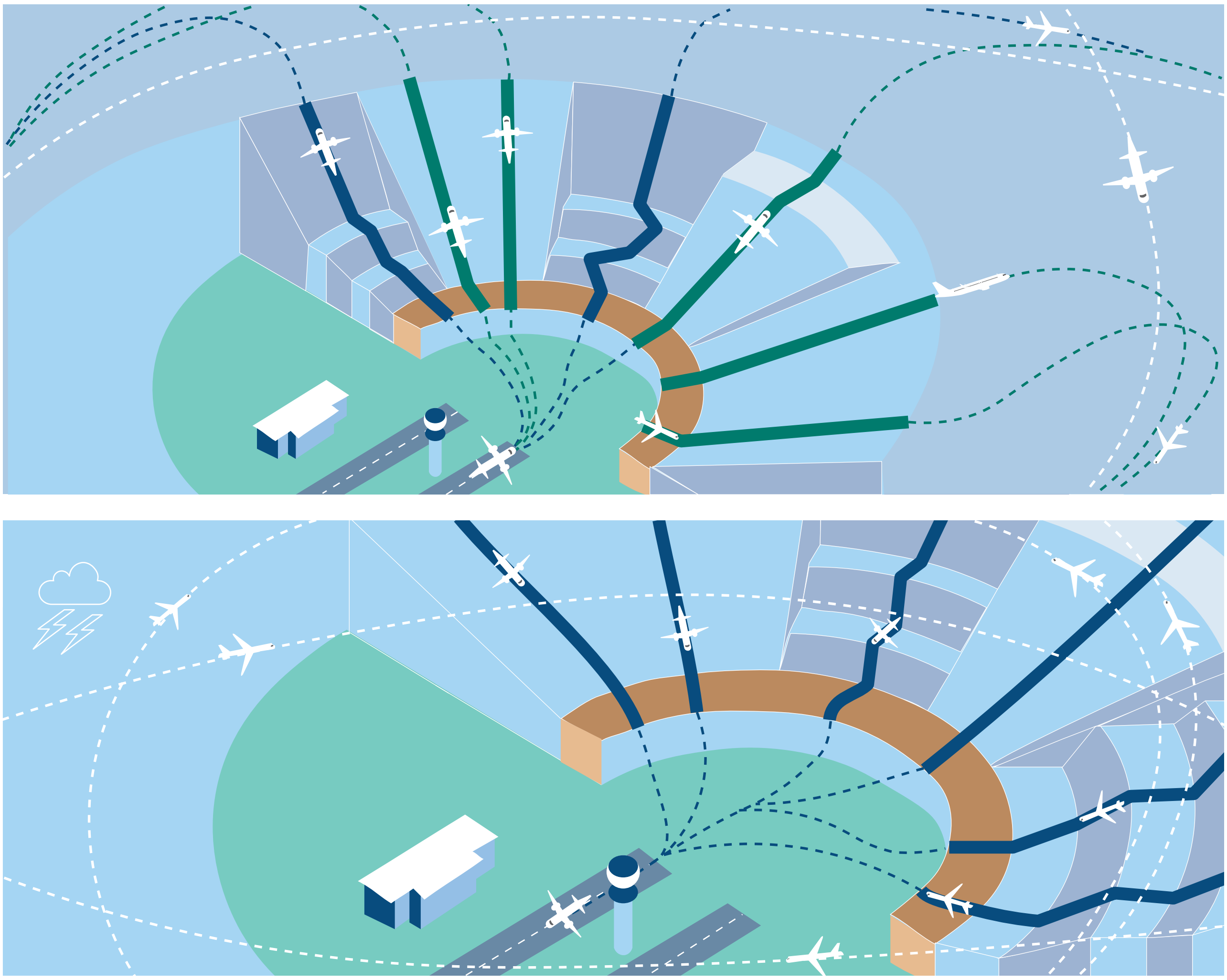
The objective of A-CDM is to improve data and information exchange, which is essential to improve operational efficiency, to optimise the use of resources and to improve the predictability of air traffic. Increased predictability can significantly improve traffic flow management, decreasing taxi times and related fuel burn.

A-CDM is currently fully implemented in 33 airports across Europe (Eurocontrol, 2023). In 2016, Eurocontrol performed an impact assessment of 17 A-CDM airports and identified a reduction in taxi minutes of 7% and in ATFM delay minutes of 10.3%, resulting in a reduction in CO_2 emissions of 102.7 kilotonnes and a reduction in sulphur dioxide emissions of 28.7 tonnes, which represent an overall 7.7% of reduction in emissions (Eurocontrol, 2016).

A8.8 Case study 8.2: Continuous climb and descent operations

Continuous climb and descent operations (CCO/CDO) allow aircraft to optimise their flight path when taking off and landing, leading to environmental benefits, thanks to reduced fuel burn and noise (Figure A8.8). In 2018, Eurocontrol conducted a European Civil Aviation Conference-wide study of the current implementation of CCO/CDO. The study concluded that CCO has the potential to save 48kg CO_2 per flight, while CDO saves a potential 145kg CO_2 per flight. Deployment throughout Europe could reduce CO_2 emissions by up to 1.1 million tonnes. Furthermore, the study concludes that CCO/CDO also has a positive impact on noise and could reduce noise levels by 1-5dB. It is, however, important to note that a full-scale deployment is probably not likely because of safety issues, weather, and capacity or air traffic controllers' workload. At the moment, this is a decision commonly taken by the pilot and the controller (Eurocontrol, 2018).

Figure A8.8 Schematic representation of continuous climb and descent operations



Source: FABEC (Functional Airspace Block Europe Central).

A8.9 Case study 8.3: Free route airspace

The free route airspace (FRA) concept allows airlines to freely plan routes between origin and destination, taking into account variables such as weather and wind speeds. This could allow aircraft in principle to take a more direct and fuel-efficient route and to reduce delay times and make more efficient use of the airspace. In 2017, 20% of flown flight times in the EU flew in FRA, and it is estimated that the fuel saved since 2014 due to FRA has reduced CO_2 emissions by 2.6 million tonnes. Once fully implemented in the EU, FRA could save up to 20 million tonnes of CO_2 (EASA et al., 2019; Eurocontrol, 2022c).

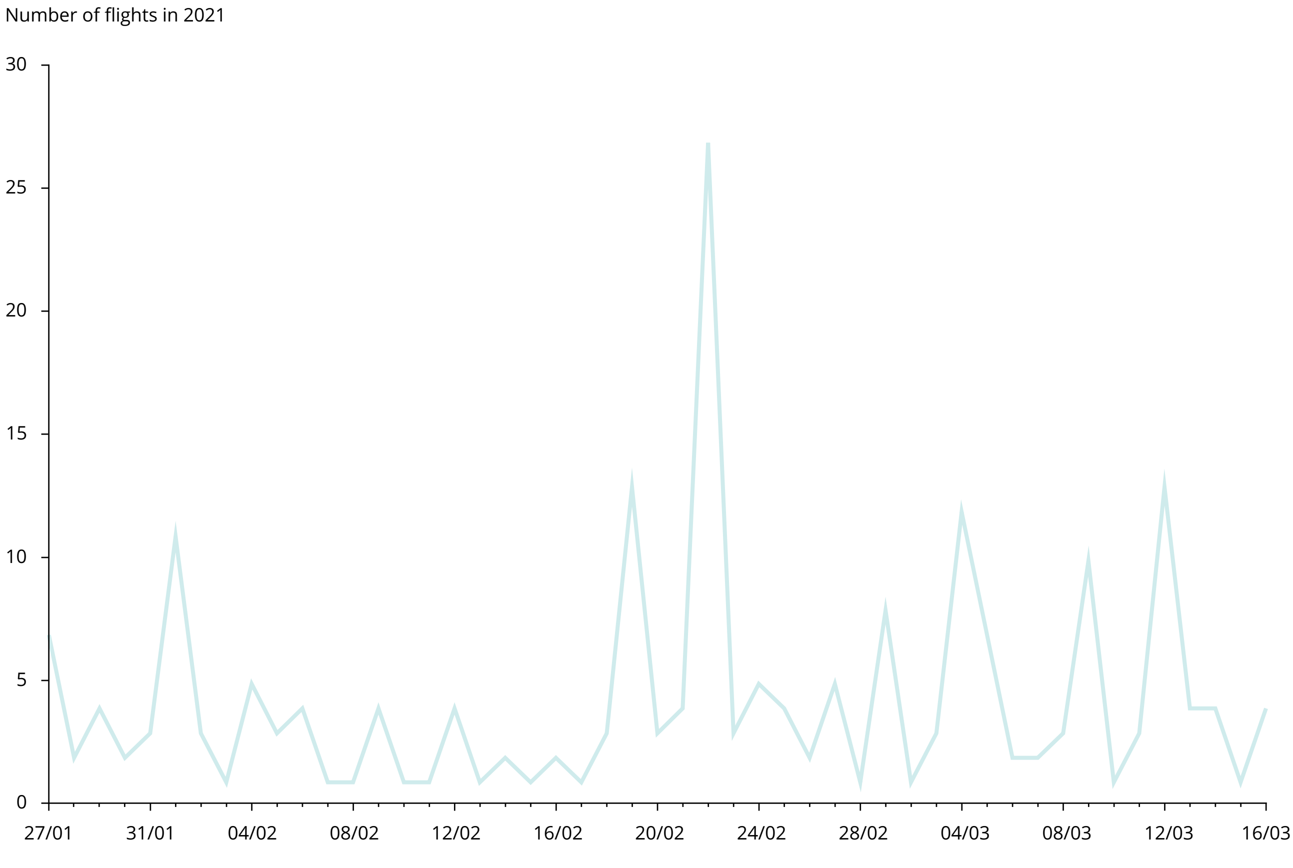
A8.10 Case study 8.4: Mitigating contrail formation — Eurocontrol live trial 2021

Non-CO_2 effects such as those generated by contrail formation can have a significant effect on climate change. Eurocontrol's Maastricht Upper Area Control Centre is currently running a pilot project aiming to investigate the operational feasibility of mitigating such effects though ATC. The main idea is as follows: by implementing minor operational changes such as diverting from the normal flight trajectory by 2,000 feet up or down to avoid flying planes through regions with a high probability of developing stable cirrus clouds or contrails (i.e. ice-supersaturated regions). Among other things, this involved creating a reliable persistent contrail prediction algorithm, developed in partnership with DLR, the German Aerospace Centre.

The trial started at the beginning of 2021 and, in the first 10 months, 209 flight trajectories were included in the project (Figure A8.9). It was operational on selected dates, after 18.00 local time and during the night, when contrail formation can have a warming effect.

The net assessment of environmental effects is still not available, but the project has highlighted a number of challenges and opportunities. An accurate model to forecast the location of ice-supersaturated regions is necessary as well as models to evaluate the usefulness of contrail prevention in specific weather contexts. These models can be supported by sensors mounted on the aircraft, ground-based cameras or satellite imaging, but these options are currently under investigation and not implemented . Aside from accurate weather forecast models, the trade-off between the reduction in non-CO_2 effects and the additional CO_2 emissions due to modifying aeroplane trajectories must be carefully evaluated, taking account of the different uncertainties affecting the two impacts. This is also challenging because the time horizons of the two are significantly different and comparing them on a common base is not necessarily easy. Despite the challenges, interest in this trial has been considerable among the large variety of stakeholders in the aviation sector, including policymakers.

Figure A8.9 Daily number of flights recorded during the trial



Source: Eurocontrol (2021b).

Annex 9
Digitally-enabled monitoring tools

A-S-I: general. In-use real-time monitoring can be a useful tool to better inform policymakers, fill knowledge gaps and support the enforcement of environmental policies.

Context: all transport modes, all environmental impacts

Time frame: short/medium term

A9.1 Introduction

This factsheet focuses on the possibilities enabled by digitalisation in the field of real-time monitoring of the transport sector. In-use monitoring is an appealing option for policymakers, allowing us to fill knowledge gaps and better inform the development of new legislative initiatives, while supporting the enforcement of existing ones. Ultimately, this is expected to have a positive impact on the effectiveness of the process. Monitoring is only one of the possible ways in which digitalisation could support policymakers. For example, Factsheet 7 discusses innovative policy instruments made possible by digital technologies. The digitalisation of administrative processes and documents currently ongoing in various EU Member States will not be discussed here, despite their significant benefits for the citizens and institutions involved.

Given the broad scope of this factsheet, its structure is different from the previous ones, and it showcases several examples covering different sectors. Indeed, digitalisation enables the development of several diverse monitoring tools across multiple transport modes and for different environmental impacts. The next sections will discuss a representative selection of these, including both fixed and mobile technologies:

- remote sensing, plume chasing and onboard monitoring for pollutant emissions in road transport;
- onboard monitoring of fuel consumption and CO_2 emissions in road vehicles;
- remote sensing of marine oil spills from vessels;
- remote sensing of pollutant emissions in maritime transport.

Digitally enabled monitoring tools are not only relevant for policymakers but can also make easily available to the general public empirical data about their local environment, the factors contributing to it and on the impact of their modal choices, as also discussed in Factsheet 7. For this reason, the factsheet also discusses an example of a tool for empowering citizens and increasing their awareness of the environmental impacts of transport.

A9.2 Digitally-enabled tools for the monitoring and enforcement of air pollutant emissions from road vehicles

A9.2.1 Context

Vehicles are expected to comply with pollutant emission limits both at type approval and throughout their normal useful lifetime and under normal real-world operating conditions (EU, 2017c). Real-world emissions of road vehicles are a complex function of many variables. These include the age of the vehicle and its standard of maintenance, the proper functioning of the exhaust after-treatment system (ATS), the tyre pressure, the driving style, the weather conditions, the road gradient and the altitude.

Exhaust ATS can be subject to malfunctioning or they can be deliberately tampered with to reduce the total cost of owning a vehicle or to improve its performance (Giechaskiel, Forloni, et al., 2022). An internet review in 2017 identified 87 separate sites supplying Europe with tampering devices for Euro IV, V, and VI vehicles (Godwin, 2017). The phenomenon is believed to be more common for heavy-duty vehicles (HDVs) equipped with a selective catalytic reduction unit, which requires a diesel exhaust fluid (commercially known as AdBlue in Europe) to operate. This is estimated to costs operators up to approximately EUR 2,000 per heavy-duty vehicle on a yearly basis (at an annual mileage of 150,000km). If major servicing and repair is needed, the costs can be even higher (Frandsen, 2018; Janssen, and Hagberg, 2020). AdBlue emulators are devices that send a signal to the engine emission control, confirming that the exhaust ATS is working properly even if no fluid has been injected into the system. Such systems are becoming progressively more sophisticated and difficult to identify, especially because they can be easily deactivated by the user for an inspection.

Currently, ATS are verified on a regular basis during mandatory periodical technical inspections. Notably, however, the systems controlling some of the most relevant pollutants (e.g. nitrogen oxides (NOx) and solid particle number >23nm (SPN_{23}) for diesel engines) are currently not verified. The scope of the periodical technical inspections and the techniques used for the verification of ATS performance are currently under revision by the European Commission (EC, 2021x). To guarantee the effectiveness of air pollutant emission standards and of area restrictions based on the emission characteristics of the vehicles, it is important that the real-world emissions of road vehicles are monitored in real time. This will allow both better enforcement of the current policies but also the collection of an extensive set of data on the performance of the vehicle fleet. This can be used to develop new legislative initiatives and to fill knowledge gaps such as how to account for the deterioration in catalytic ATS.

A9.2.2 Environmental impacts

The magnitude of the problems caused by malfunctioning or manipulated after-treatment devices (e.g. deNOx units or particulate filters) is largely unknown and a comprehensive EU statistic is currently lacking. The number of malfunctioning or manipulated vehicles circulating in the EU-27 is not straightforward to determine. This is due in part to the absence of systematic monitoring but also to the cross-national dimension of the problem. Indeed, long haulage HDVs systematically drive in several Member States in addition to the one where they are registered and for which most of the statistics are available.

It is not uncommon for modern light- and heavy-duty diesel vehicles with a malfunctioning or manipulated deNOx after-treatment unit to have exhaust emissions that are 40 times higher than vehicles with a properly functioning unit. However, in some cases this difference could exceed two orders of magnitude (Janssen et al., 2020; Pöhler, 2020; Giechaskiel, Forloni et al., 2022; Selleri et al., 2022).

A similar situation holds for malfunctioning or deliberately manipulated particle number filters. Melas et al. (2021, 2022) report that studies have estimated that 10% of high emitting light-duty vehicles can contribute to 85% of the entire fleet's emission of particle numbers. Approximate estimates show that assuming that just 1% of diesel particulate filters are severely damaged or have been removed would increase the SPN emissions of a filter-equipped diesel vehicle fleet more than 10 times.

Switzerland carries out continuous testing of HDVs driving through the country. For 2017, it reported that 0.7% of 15,500 vehicles inspected showed evidence of tampering (Frandsen, 2018). In Norway it is estimated that 10-20% of trucks are equipped with emulators, while acknowledging the difficulty in providing sound estimates (Frandsen, 2018).

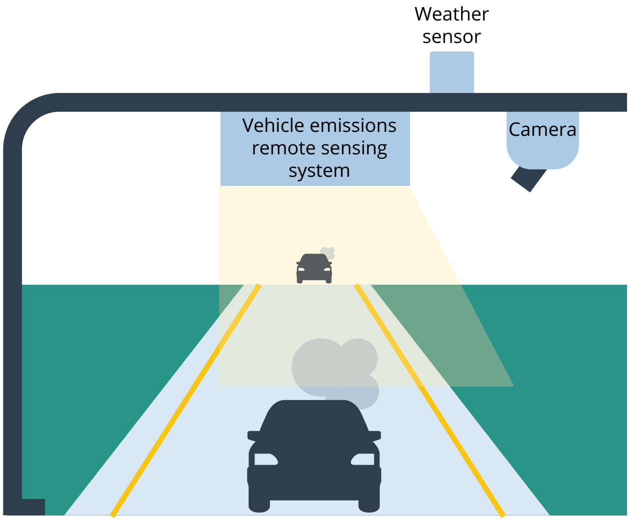
A9.2.3 Examples of monitoring tools

Various methods are available to determine the real-world air pollutant emissions from road vehicles. In the following, remote sensing, plume chasing and onboard monitoring are briefly described. A description of portable emissions measurement systems (PEMS), the reference instruments for the in-use verification of real-world vehicle emissions can be found elsewhere (Bonnel et al., 2022).

Remote sensing

Remote sensing is a well-known technology that has been applied in the United States since 1989 (Bishop et al., 1989) but has developed significantly in recent times due to the evolution of digital technologies and sensors. A remote sensing installation typically consists of a source and detector module, a sensor for speed and acceleration, a weather station for monitoring ambient conditions, and an automatic number plate recognition system for identifying vehicles and their characteristics, as shown in Figure A9.1. With this technology it is possible to monitor, at fixed positions, a large number of vehicles in a short time and in an unobtrusive way (Yang et al., 2022). The large amount of information collected by such installations is then transmitted over the internet and processed by a back-office system.

Figure A9.1 Example of a remote sensing installation for road vehicles



Source: Borken-Kleefeld and Dallmann (2018).

Remote sensing instruments generally use absorption spectroscopy to measure several pollutants such as carbon monoxide (CO), unburned hydrocarbons, NOx (including nitrogen oxide, nitrogen dioxide), N_2O, sulphur dioxide and ammonia. Particulate emissions can also be measured by complementary systems, for example dedicated instruments such as opacimeters, or by gas sampling and filter analysis. Usually, the measure is expressed as a ratio between the concentration of the pollutant and the CO_2 concentration, since that quantity remains fairly constant even at high dilution ratios (Dallmann, 2018). To translate this into the more commonly used emission factors per kilometre, the measurements need to be combined with additional information. For example, Davison et al. (2020) develop an approach based on vehicle specific power (power demand on the engine during driving).

These installations can record pollutant emissions for many vehicles but only at the moment they drive past the remote sensing location. This is at variance with what happens in other systems such as those using onboard sensors, PEMS or plume chasing approaches in which a vehicle is continuously monitored for a whole trip or a part of it.

Remote sensing installations have already been used in several situations, with interesting results.

A remote sensing campaign in Warsaw during autumn 2020 shows that imported second-hand vehicles, which make up more than 30% of the vehicles in the city, have NOx and particulate matter (PM) emission rates that are more than two and three times as high as those from domestic vehicles (i.e. vehicles only registered in Poland). This is due to their older emission technologies. The study concludes that a clean transport zone that bans older vehicles could improve air quality in Warsaw (Lee, et al., 2022).

In Hong Kong the remote sensing enforcement programme, which has been operating since September 2014, aims to detect high-emitting petrol and liquefied petroleum gas vehicles. It is combined with a subsidy for fitting exhaust reduction equipment for certain vehicles. The owners of the high-emitting vehicles identified are notified and must repair and have their vehicles tested within a specified period of time. If they fail to do so or fail the test, they are delicensed and not allowed to drive their vehicle on the road. Huang et al. (2022) conclude that the combination of the replacement programme and enforcement has been effective, while pointing out that the remote sensing system does not yet monitor all lanes in multilane roads and does not yet cover diesel vehicles.

Hooftman et al. (2020) report on a remote sensing campaign in the Flemish region in Belgium in 2019. Some 10% of the 'high-emission events' arising from diesel cars are found to be responsible for 80% of the cumulative PM_{10} (PM with a diameter of 10µm or less) emissions of Euro 5 and 6 diesel cars. For petrol cars, about 7% of high-emission events cause approximately 40% of the observed NOx emissions. It is estimated that 9.5% and 4.8% of Euro V and VI trucks, respectively, are driving with either damaged or intentionally manipulated exhaust ATS. This is reckoned to result in 24% and 67% additional NOx emissions, respectively. On motorways, the NOx emissions of the most recent Euro VI trucks are found to be very low.

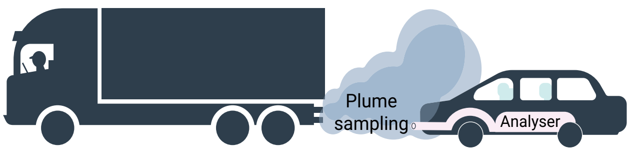
Research is also ongoing on identifying potentially problematic vehicles with remote sensing data, for example within the CARES project (Rushton et al., 2021; Qiu, and Borken-Kleefeld, 2022; Yang et al., 2022). Remote sensing is also at the core of the NEMO project (2021), aimed at facilitating the enforcement of low-emission zones and the monitoring of noise pollution levels in cities.

Plume chasing

In plume chasing, an instrumented vehicle is used to sample gas directly from the exhaust plume of the vehicles inspected, as shown in Figure A9.2. This can be done without informing the vehicle's driver and at a random location during a normal driving situation. This is different from inspection at fixed remote sensing locations, making the approach very suitable for identifying vehicles that are not only malfunctioning but have also been deliberately tampered with.

From a technical point of view the measurement concept is similar to that of remote sensing. It exploits the fact that the ratio between NOx and CO_2 is fairly constant, including at high dilutions. The method appears tolerant of different driving patterns and distances from the chased vehicle.

Figure A9.2 Example of the plume chasing approach for road vehicles



Source: CARES project (Sjödin, 2011).

The measurements are not sensitive to weather, such as rain, moderate wind or fog, and the rate of false-positive detection is generally low (Janssen et al., 2020), confirming the potential of plume chasing for enforcement purposes for the Danish Road Traffic Authority, although the system could benefit from further refinement. The data collected are processed in real time using dedicated software that helps the inspector to immediately identify problematic vehicles. The data collected can be subsequently downloaded and further analysed.

Plume chasing is already systematically used for inspections, and reports mention that up to 25% of the vehicles inspected could have had their devices tampered with (Pöhler et al., 2019; Vojtisek-Lom et al., 2020), although more conservative estimates exist.

An HDV plume chasing campaign in Denmark showed that around 2% of Euro V and Euro VI trucks were high emitters, with malfunctioning or tampering confirmed through subsequent dedicated technical inspection. Of the overall sample tested, only 55% of the vehicles were registered in Denmark (Pöhler, 2020).

Two similar experimental HDV campaigns on German and Austrian motorways showed a higher share of high-emitting vehicles. However, in these cases, the HDVs identified as high emitters were not subsequently inspected to confirm the presence of a faulty or manipulated device (Pöhler et al., 2019). A summary of the results of recent plume chasing campaigns is reported in Table A9.1.

Table A9.1 Results of plume chasing campaigns for heavy-duty vehicles in Denmark, Germany and Austria

Campaign details	Share of high-emitting vehicles		Comment	Source
	Euro V	Euro VI		
Denmark (2020)	2.1%	2.2%	Confirmed by inspection	(Pöhler, 2020)
Germany (2016)			Potentially manipulated	(Pöhler et al., 2019)
German trucks	0%	6.9%		
Non-German trucks	26%	19%		
Austria (2018)	35%	25%		

In the United States, the Air Enforcement Division of the Environmental Protection Agency estimated that more than 550,000 diesel pickup trucks were tampered with in the last decade, constituting approximately 15% of the national fleet. As a result, it is expected that these vehicles will emit more than 570 kilotonnes of excess NOx and 5,000 tonnes of excess PM over their lifetime. Due to their high emissions, these trucks have an air quality impact equivalent of more than 9 million additional circulating diesel vehicles (compliant, non-tampered with) (US EPA, 2020).

Onboard monitoring systems

Modern vehicles are nowadays equipped with multiple onboard sensors which allow real-time detection of several parameters and checking that the vehicle is functioning properly . There is a growing interest in the possibility of using such sensors and the information already available on board the vehicle not only for diagnostics but also to monitor its emissions for environmental purposes (California Air Resources Board, 2018; Zhang et al., 2020; CLOVE, 2021; Winther, 2021; Selleri, Gioria et al., 2022; Selleri et al., 2022). This approach is sometimes referred to as onboard monitoring (OBM).

A potentially interesting application that is less complex to implement is that for diesel vehicles. Indeed, in both modern light (Euro 6) and heavy (Euro V and Euro VI) duty diesel vehicles, onboard NOx sensors are widely already available to control the status and the proper functioning of deNOx ATS such as selective catalytic reduction units. These could be used, for example, to monitor NOx exhaust emissions.

To obtain a real-time measure of vehicle emissions, accurate measurements of both the vehicle exhaust flow rate and the concentration of pollutants are needed. In a recent Joint Research Centre study on two light-duty commercial diesel vehicles, in the specific case of NOx, both quantities were acquired from currently available onboard sensors and compared to reference laboratory and PEMS instruments, with fair agreement. This allowed accurate estimation of NOx emissions in both laboratory and real-world driving tests. Sensors were able to detect both high and low NOx concentrations, indicating that a malfunctioning after-treatment unit could be easily identified (Selleri et al.,2022). Similar results were obtained in previous studies performed on an HDV (Mendoza-Villafuerte et al., 2017; Selleri, Gioria et al., 2022).

In principle, such data could be stored in the vehicle and periodically downloaded (e.g. during periodical technical inspections) or directly transmitted over the air. In the latter case, the information could conceivably allow real-time detection of malfunctioning and rapid intervention. In addition, the data from the onboard system could be used to monitor the trend in the average emissions of the fleet during its whole lifetime, building evidence on the different ageing phenomena affecting the vehicles and their ATS. All this could ultimately facilitate the design of emission limits and their systematic enforcement.

To carry out real-time monitoring of pollutants from vehicles through onboard sensors some technical hurdles still need to be surmounted and are actively being researched. Indeed, currently available sensors are not designed for real-time monitoring but rather for diagnostic purposes. They can take up to 15-20 minutes to reach the operating temperature, meaning that, in their present form, they cannot be used to monitor short trips. In addition, although the quantification of NOx emissions has been demonstrated under research conditions, additional sensors and efforts will be needed to cover other pollutants and to reduce their cross-sensitivity (Selleri, et al., 2022).

The real-time monitoring of NOx through OBM is a consistent part of the new proposal for a Euro 7 regulation, recently put forward by the European Commission (EC, 2022h).

A9.3 Onboard devices for monitoring fuel consumption of road vehicles

Regulation (EU) 2019/631 (EU, 2019a) sets CO_2 emission standards for new passenger cars and new light commercial vehicles. CO_2 emissions subject to targets are determined in laboratory testing. Up until 2020, the officially reported CO_2 emissions of cars and vans were based on measurements using the New European Driving Cycle (NEDC). Research, however, showed that real-world fuel consumption and CO_2 emissions are significantly higher than the NEDC levels, and that this gap increased over time, from 8% in 2001 to 39% by 2017. Hence, the average real-world CO_2 emissions in 2017 were 39% higher than the test value (Dornoff et al., 2020). For this reason, a new testing procedure, the World Harmonised Light Vehicle Test Procedure (WLTP), was introduced to better represent real-world driving conditions. In 2018 countries started to report CO_2 emissions based on the WLTP. From 2021 onwards, compliance assessment is fully based on the WLTP data. However, WLTP-tested and real-world emission levels reported by drivers show that there is still a gap (Dornoff et al., 2020), although it is smaller than with the NEDC.

To prevent the gap between real-world and tested emissions increasing, Regulation (EU) 2019/631 includes the provision that as of 1 January 2021 onboard fuel and/or energy consumption monitoring (OBFCM) devices are mandatory for new types of passenger cars and most light commercial vehicles. As of 1 January 2022, this is mandatory for all new cars and light commercial vehicles. Table A9.2 reports the information collected (EU, 2021b).

The following entities are responsible for reporting the information collected to the European Commission: (1) manufacturers, based on either direct data transfers from the vehicles to the manufacturer or on data collected by their authorised dealers or authorised repairers; (2) Member States, with data collected by bodies or establishments responsible for roadworthiness testing (e.g. periodical technical inspections). The entities responsible for the data collection have to ensure that secure means of communication are used for the collection of the VINs and respect the General Data Protection Regulation specifications (EU, 2021b).

Based on the anonymised OBFCM data the European Commission plans to publish annually the average real-world CO_2 emissions, and the gap between those and type-approval CO_2 emissions, by manufacturer, vehicle category and fuel type. This will provide information on the trends in real-world emissions to vehicle owners and potential vehicle buyers. Using data for 2021-2026 the Commission will evaluate the future development of the gap between real-world and type-approval emissions. To prevent an increase in the size of the gap it will assess in 2027 how this might be counteracted by further regulation. The OBCFM data will also be used to determine the average real-world utility factors of plug-in hybrid electric vehicles. These parameters are used to calculate the official CO_2 emission values of these vehicles at type approval and are a complex function of the vehicle electric range (Melas et al., 2022; Selleri, Melas, Ferrarese et al., 2022; Selleri, Melas, Franzetti et al., 2022; Tansini et al., 2022).

The Regulation on CO_2 standards for new HDVs, Regulation (EU) 2019/1242 (EU, 2019b), also mandates the introduction of OBFCM devices for the monitoring and recording of fuel and energy consumption, payload and mileage in HDVs. The technical and legal framework for the OBFCM devices for HDVs is currently under discussion.

Table A9.2 Information collected in the scope of real-world CO_2 monitoring

Vehicle type	Information collected
All vehicles	Reporting period (year of data collection)
	Manufacturer's name (as provided in the certificate of conformity)
	Vehicle identification number (VIN)
	Total fuel consumed (lifetime) (litres)
	Total distance travelled (lifetime) (km)
Plug-in hybrid vehicles	Distance travelled (lifetime) in charge-depleting operation with engine off (km)
	Distance travelled (lifetime) in charge-depleting operation with engine running (km)
	Distance travelled (lifetime) in driver-selectable charge-increasing operation (km)
	Fuel consumed (lifetime) in charge-depleting operation (litres)
	Fuel consumed (lifetime) in driver-selectable charge-increasing operation (litres)
	Total grid energy into the battery (lifetime) (kWh)

Source: Source: EC (2021e).

A9.4 WeCount project: involving citizens in local transport and environmental policies

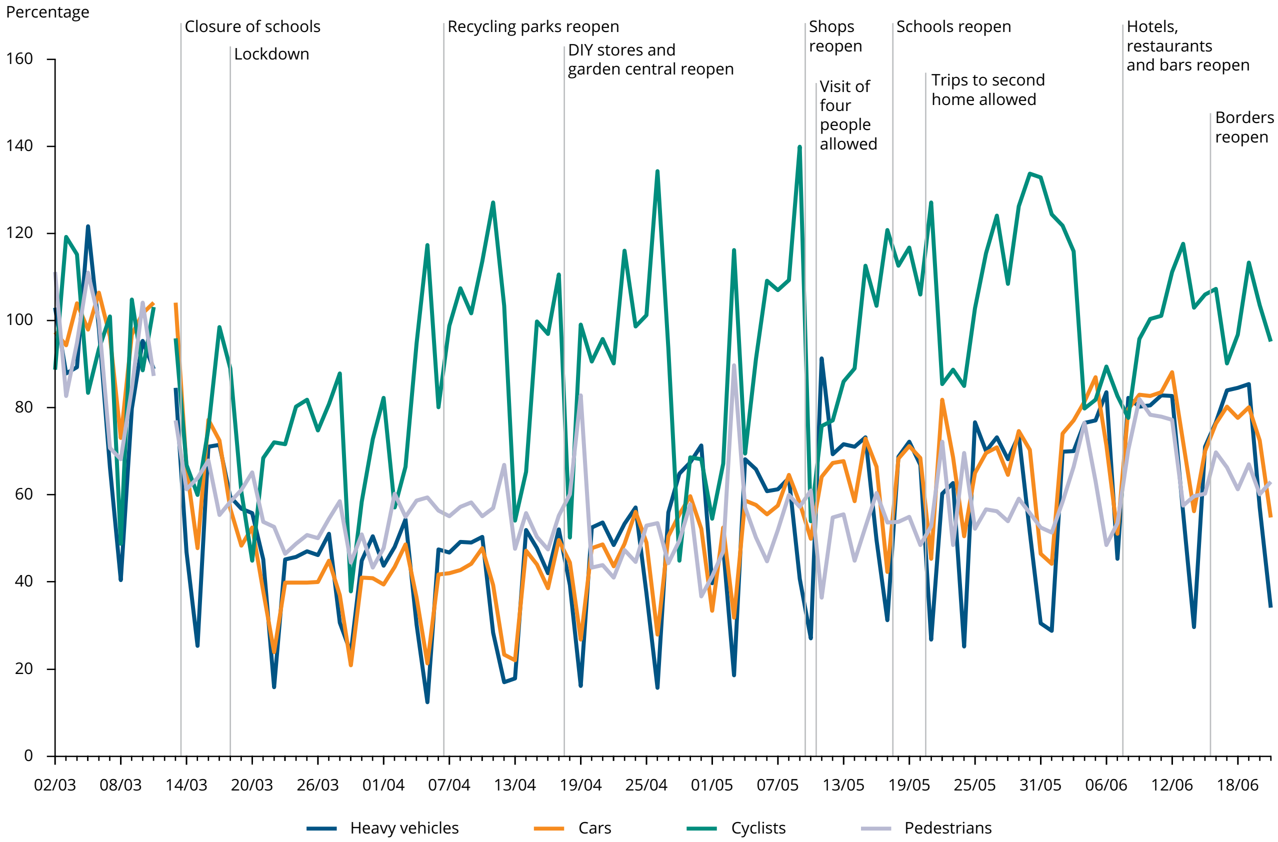
Traffic counts, i.e. the quantification of vehicular, bicycle or pedestrian traffic, are important instruments to support local environmental policies and develop a better understanding of local mobility patterns. These counts are normally realised automatically by installing electronic traffic recording devices. However, nowadays classic traffic counts are limited in time, geographical coverage and scope, e.g. the transport modes to which they apply. In addition, they are often expensive and the data collected may not be readily available.

To overcome these limitations, the WeCount project (TML et al., 2022) collaboratively developed and deployed an innovative, low-cost automated traffic counting sensor and multi-stakeholder engagement mechanisms in five European cities: Leuven (Belgium), Madrid and Barcelona (Spain), Cardiff (United Kingdom), Dublin (Ireland) and Ljubljana (Slovenia). It was funded by Horizon 2020 and it is an example of public participation in scientific research (citizen science). The traffic counting sensor, called 'Telraam', is a combination of a Raspberry Pi microcomputer, sensors and a low-resolution camera. It is mounted on the inside of an upper-floor window with a view over the street. Compared to classic devices it covers a wider range of modes: cars, heavy goods vehicles, public transport vehicles, cyclists and pedestrians. Figure A9.3 presents traffic monitoring per mode by devices in Leuven during the first 14 weeks of the COVID-19 pandemic, highlighting the impact on traffic of changes in the pandemic containment measures.

In all participating cities, WeCount showed that the availability of local mobility data promoted a number of initiatives such as speed bumps, lower speed limits and changes to traffic circulation.

Although the quantification of environmental impacts was not the main focus of the project, the increased knowledge of the local traffic situation can be a driver for new initiatives that can also have positive environmental impacts.

Figure A9.3 Traffic registered by Telraam in the first 14 weeks of the COVID-19 pandemic, Leuven, Belgium



Source: Pápics et al. (2020).

A9.5 Remote sensing of marine oil spills

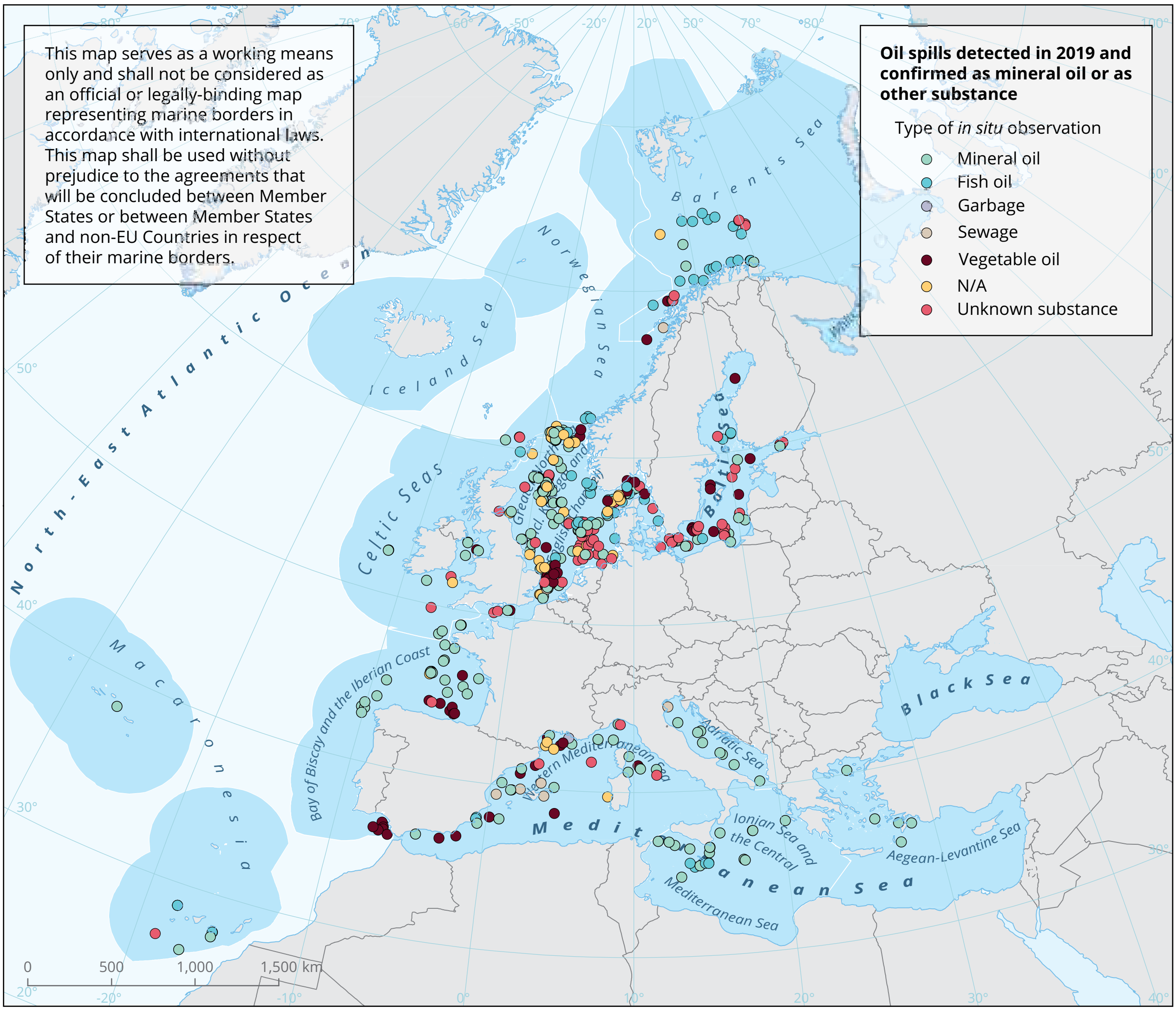
Digitally enabled monitoring solutions could also be applied to non-road transport modes, with similar benefits. For example, in the maritime sector, oil spills are one of the most concerning sources of pollution, as they are difficult to clean up and can remain for long periods in the marine environment. Almost two thirds of them are due to vessels, followed by offshore installations, fish farms, accidents and other causes. Oil spills can severely pollute marine and coastal habitats, causing damage to the natural environment and the economy (EMSA et al., 2021). It is therefore of relevance to have tools for the detection of the spills and for the enforcement of the policy measures taken to address them.

Since 2007 the European Maritime Safety Agency (EMSA) has operated CleanSeaNet, the European satellite-based oil spill monitoring and vessel detection service. The service provides monitoring on a regular basis. Satellite images from both synthetic aperture radar (SAR) and optical satellite missions are analysed with the aim of detecting oil pollution, identifying its possible source and gathering information on the spread of oil spills. An important challenge in detecting oil spills using SAR is the high share of false detections, or so-called 'oil look-alikes'. Research on improved interpretation approaches is ongoing (Cantorna et al., 2019; Bianchi et al., 2020; Rousso et al., 2022). In the event of potential oil spill being detected the coastal states involved receive an alert within 20 minutes. EMSA's web interface allows it to acquire further information on the spill, ships identified and vessel traffic information (EMSA et al., 2021). This system complements monitoring by aerial surveillance (for example in the Baltic Sea area by the Helsinki Commission contracting partners (Helcom, 2020)). It allows coverage of a larger area and optimising the effectiveness of the surveillance flights.

According to the *European maritime transport environmental report 2021* (EMSA et al., 2021) CleanSeaNet monitors more than 3 million km^2 per day. In the period 2010-2019 there were three large oil spill accidents (>700 tonnes) in EU waters and five medium-sized accidents (7-700 tonnes). In addition, many smaller oil spills (under 7 tonnes) took place. In 2019 more than 7,700 satellite images were produced, leading to the identification of over 7,900 possible oil spills. 5% of the *in situ* verifications in 2019 took place within 3 hours of the satellite observation. In 42% of these cases pollution by mineral oil and other substances (such as fish oil or vegetable oil) was subsequently confirmed.

In the Baltic Sea, the combination of aerial surveillance of the Helsinki Commission countries and satellite surveillance has led to a substantial fall in the number of confirmed oil spills: from 472 in 2000 to 72 in 2019, and this is despite the higher shipping density. The estimated volume of the oil spills has fallen throughout the period (Map A9.1). In 2019, 89% were smaller than 0.1m^3 (100 litres) and 97% were smaller than 1m^3 (Helcom, 2020).

Map A9.1 Oil spills detected in 2019 confirmed by CleanSeaNet users as mineral oil and/or other substances



Reference data: ©ESRI

Source: EMSA and EEA (2021).

A9.6 Remote sensing of emissions in maritime transport

Monitoring of air pollutant emissions is relevant for the maritime sector too. Ships emit various air pollutants, including SOx, NOx, PM, CO, non-methane volatile organic compounds and ozone-depleting substances. These ship-generated emissions can sometimes be significant in areas of heavy maritime traffic and can also travel long distances (EMSA et al., 2021).

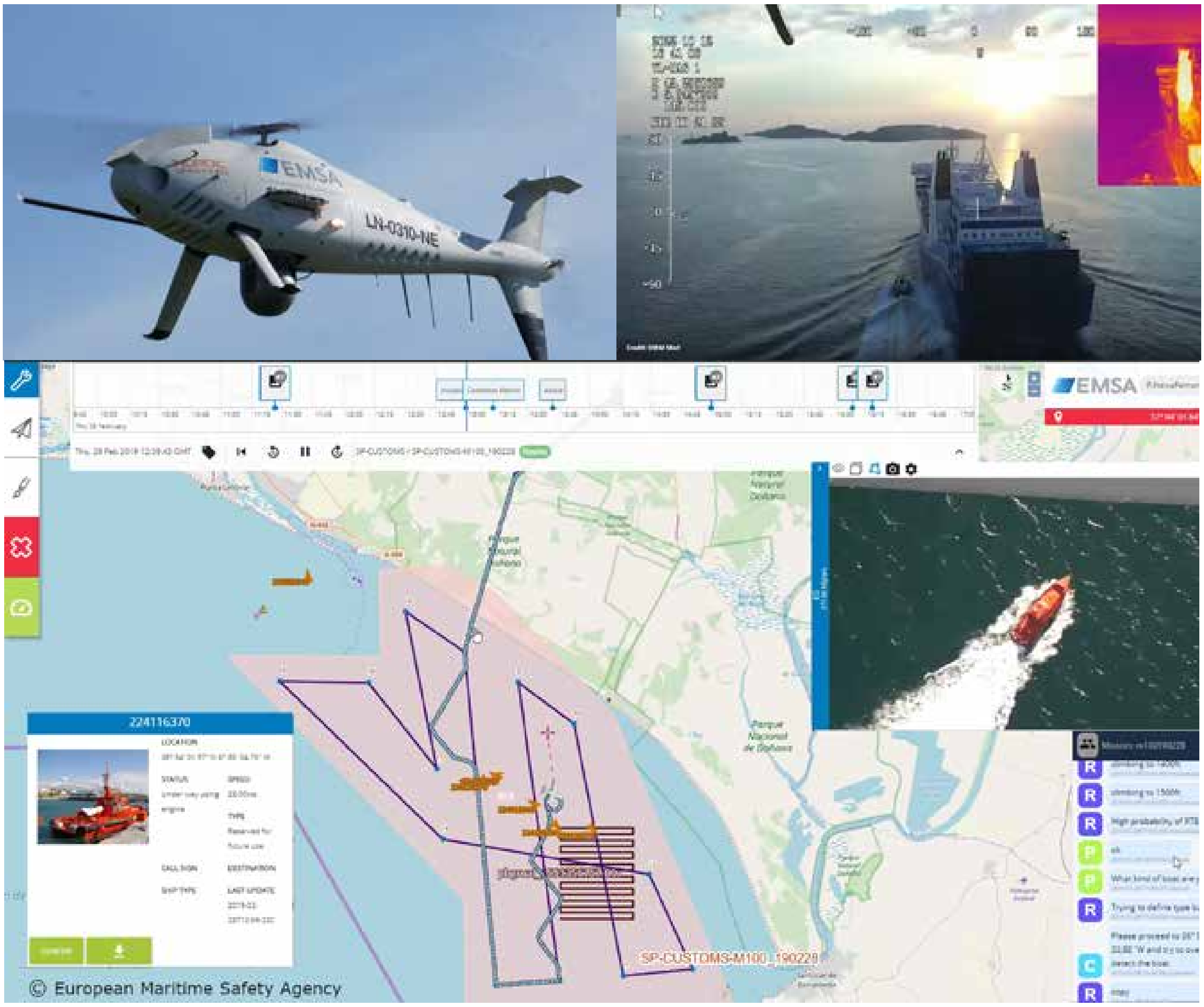
In 2019 international maritime transport was responsible for almost 85% of SOx emissions by transport in the EU-27 (EEA data reported by Eurostat (2021a)). In order to reduce the resulting environmental impacts the Baltic Sea, the North Sea and the English channel are designated as SOx emission control areas (SECAs) pursuant to Annex VI of MARPOL (International Convention for the Prevention of Pollution from Ships (IMO 2022)). In these areas EU Member States must ensure that the sulphur content of fuels used by ships does not exceed 0.1%. This level has been in force since 2015. Higher sulphur contents are allowed only on condition that exhaust systems are installed on board. While the SOx emissions from maritime transport in European seas remained fairly stable between 2014 and 2019, they fell substantially in the North Sea and Baltic Sea SECAs but not in the Mediterranean Sea, which accounts for the largest share of SOx emissions and where no SECA applied at the time (EMSA et al., 2021). Since 2020, EU Member States must ensure that the sulphur content of fuel does not exceed 0.5% for ships in all EU waters outside the SECAs. The same requirement also holds at world level, as decided in 2016 by the International Maritime Organization (IMO, 2022).

EMSA contributes to the enforcement of the sulphur regulations by providing remotely piloted aircraft systems (RPAS) that measure the SOx and CO_2 emissions from individual vessels and based on the relationship between the two, the sulphur content can be determined and compared with the legal limits. These systems are based on similar principles of the remote sensing and plume chasing ones already described (Section A9.2.3). In addition, information about the ship's identity is recorded. This service is provided for free to interested countries, in addition to their own enforcement methods. Through EMSA's RPAS data centre historical and real-time data can be accessed, and new tasks or points of interest can be defined. There is the possibility of real-time interaction with the pilot and sensor operator (EMSA, 2017).

On a mission in the Strait of Gibraltar in 2021, 10% of the ships monitored were found to be potentially above the legal limits (Maritime Executive, 2021). In the first half of 2022, campaigns started in the Baltic Sea and Denmark (Maritime Executive, 2022; Safety4Sea, 2022). The system can also be deployed for NOx emission monitoring in the North Sea and Baltic Sea nitrogen emission control area, which was put in place in 2021.

Remote sensing of maritime emissions is also used in research. An example is the Fugitive Methane Emissions from Ships (FUMES) project, started in March 2022. The project focuses on methane emissions from ships fuelled by liquefied natural gas (LNG). It will monitor emissions using in-stack continuous monitoring, drones and helicopters, with the aim of better understanding the potential of LNG-powered ships to reduce greenhouse gas emissions in maritime transport (ICCT, 2022).

Image A9.1 Example of remotely piloted aircraft system for measuring SOx emissions



Source: EMSA.

A9.7 Policy corner

Digitally enabled solutions for monitoring are useful for supporting the design and enforcement of environmental policies in transport. These could address knowledge gaps, ensure a more thorough enforcement of existing legislation and obtain data at the local scale. Accountability and identifying responsibility in cases of violation is a delicate topic that will require a clear and robust framework. Privacy concerns are a point of contention and should be adequately addressed.

By means of research and development funding the performance and cost-effectiveness of these systems could be improved, ensuring that the social benefits exceed the costs. The latter include, for example, the system costs, or the costs incurred by the inaccuracies remaining in the monitoring systems, leading to either false positives or negatives.

A9.8 Bottom line

Monitoring has the potential to support the design of environmental policies and their subsequent implementation, contributing to their effectiveness. A good incentive for improving and developing monitoring systems is the growing public awareness of the problems caused by environmental pollution. The magnitude of the environmental benefits depends not only on the quality of the monitoring systems but also on the quality of the policies and on the environmental problem that is addressed. When they are used for enforcement purposes, the impact also depends on the quality of the next steps in the enforcement process: the extent to which violations that are identified lead to sanctions and the size of these sanctions.

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