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

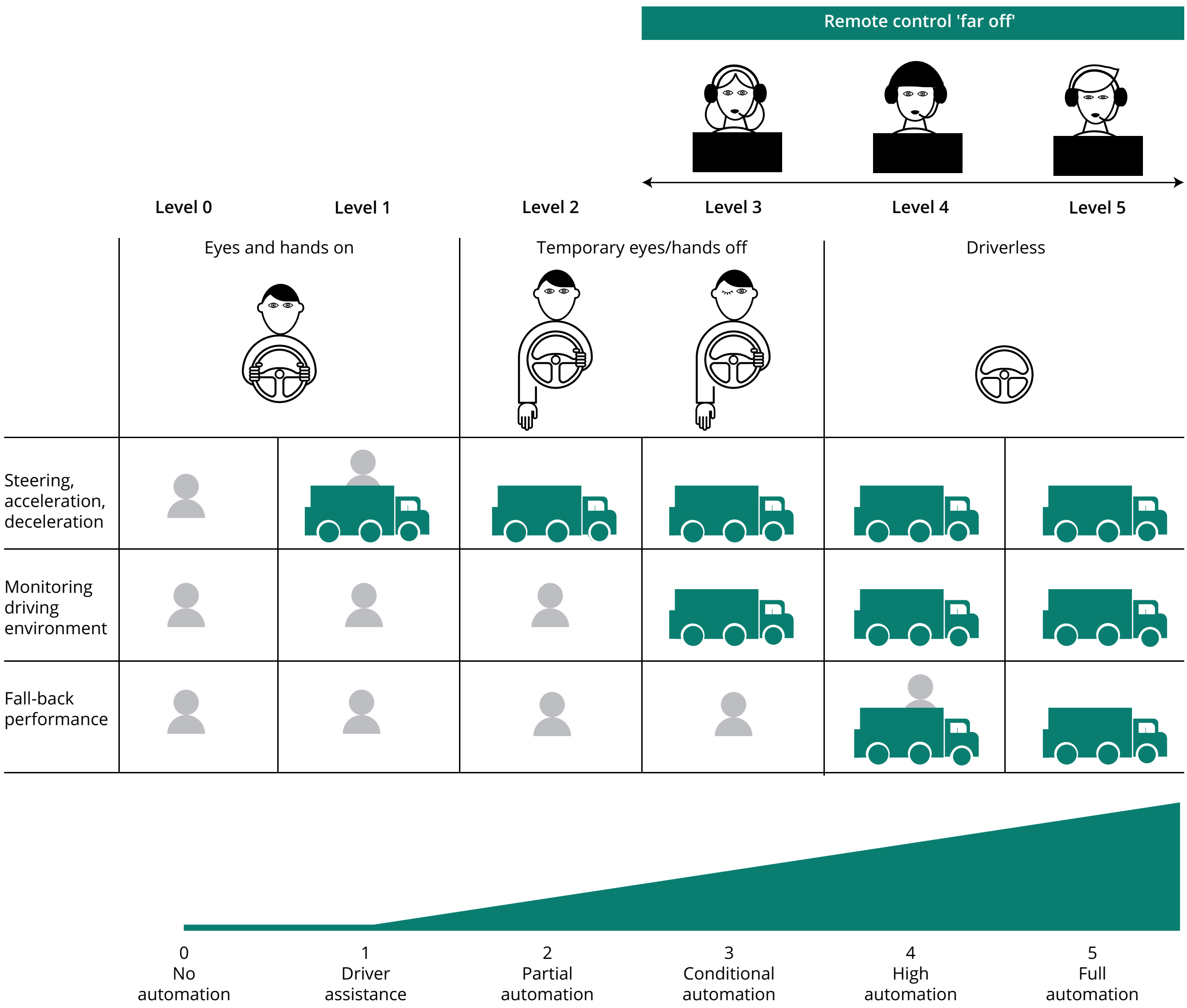
A3.1.1 Definition

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).

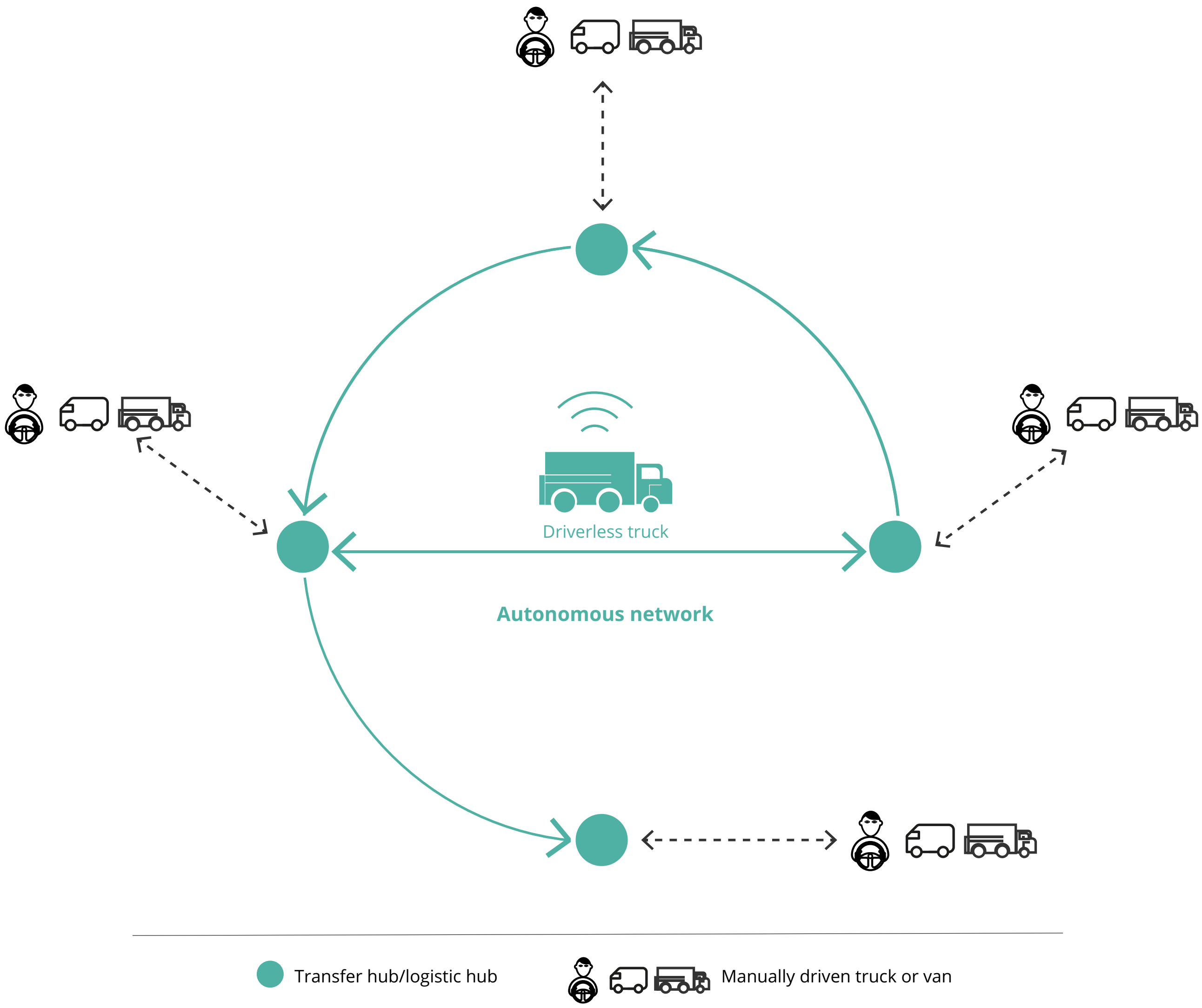
Level 4 driverless trucks can be used for so-called hub-to-hub transport. This can be defined as long-distance transport between logistics hubs, such as road terminals, distribution centres or ports. In a variant such services are rendered via transfer hubs along the main road network, as illustrated 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.

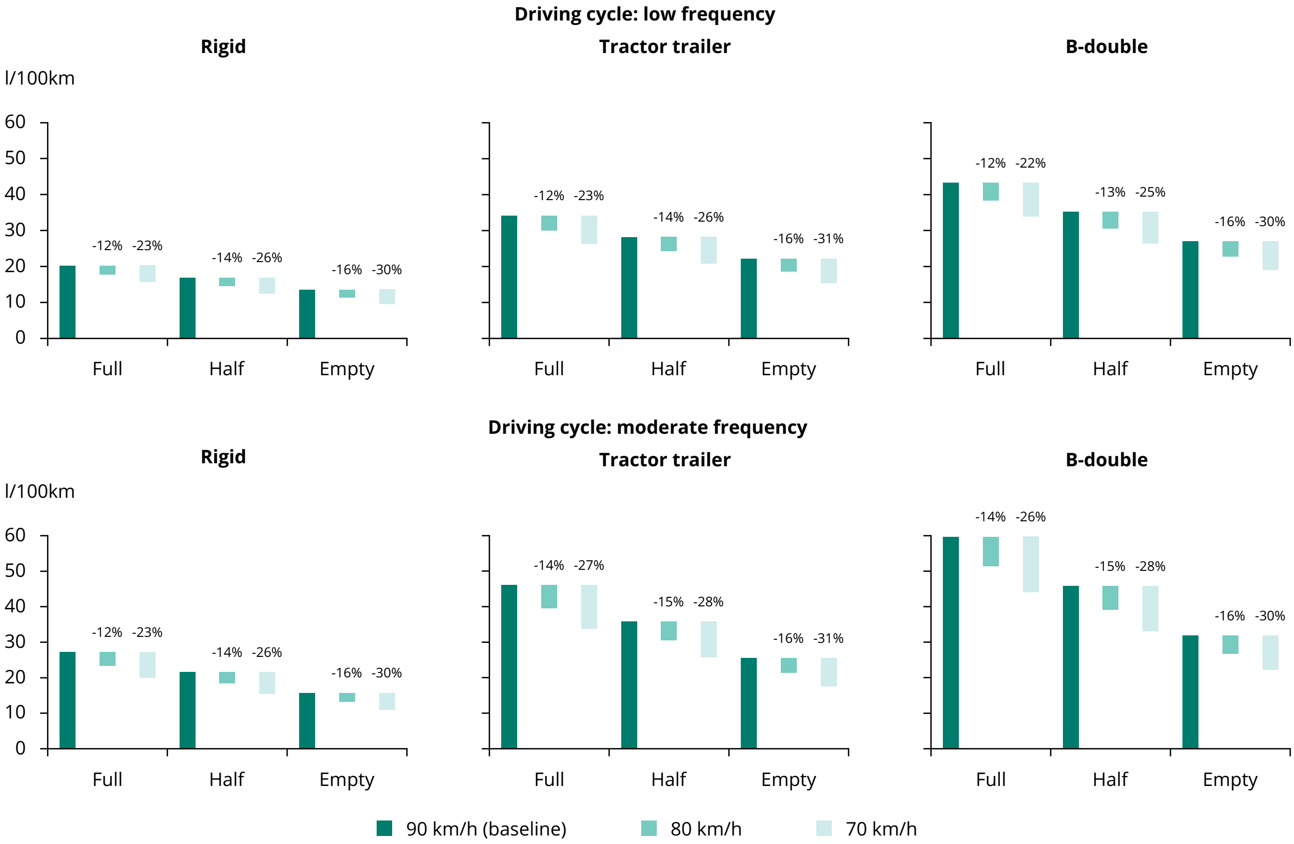
A3.1.4 Expected environmental impacts

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.

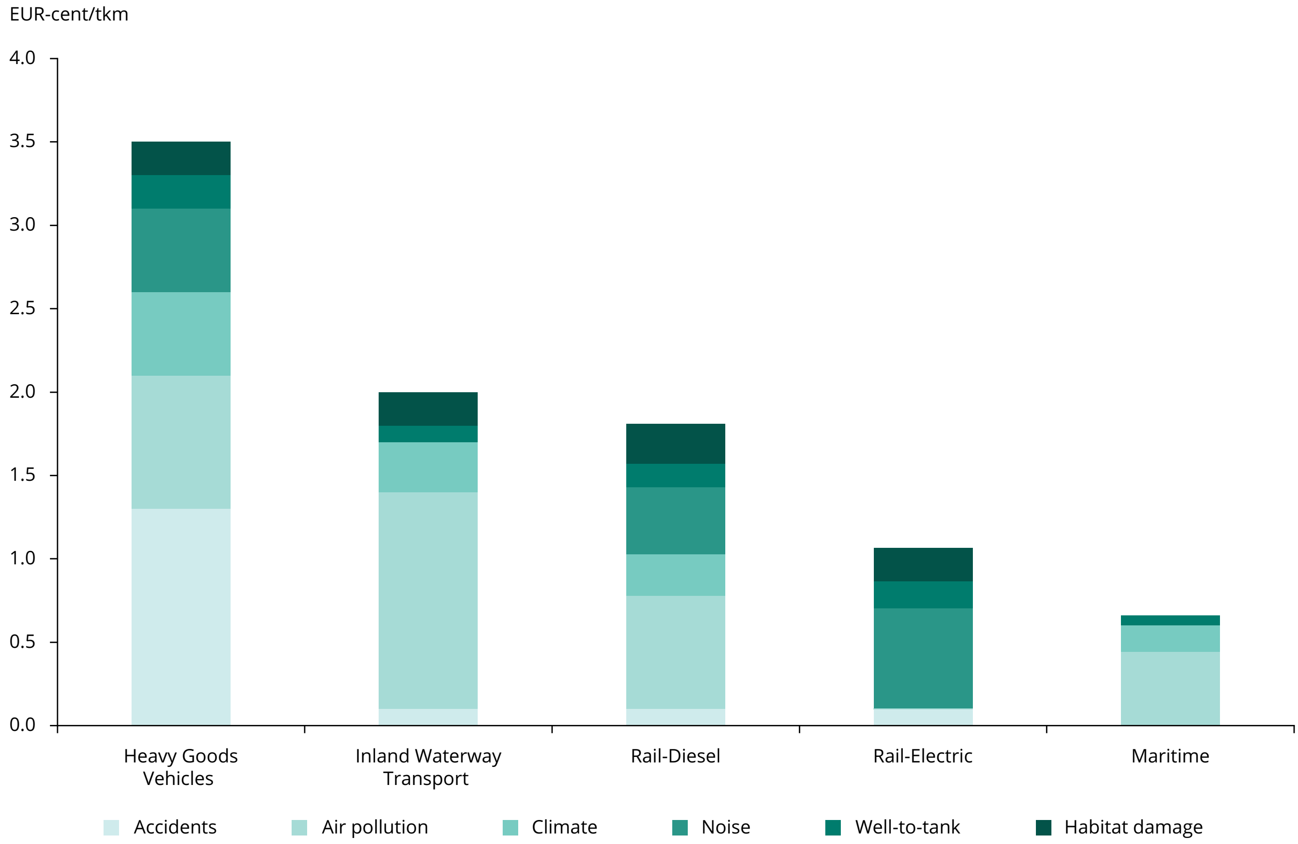
With diesel trucks the impact on fuel consumption will lead to the same percentage impact on CO_2 emissions. With battery electric trucks, road freight transport indirectly falls under the EU Emissions Trading System (ETS), via the power generation sector that produces the electricity. The total emissions 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).

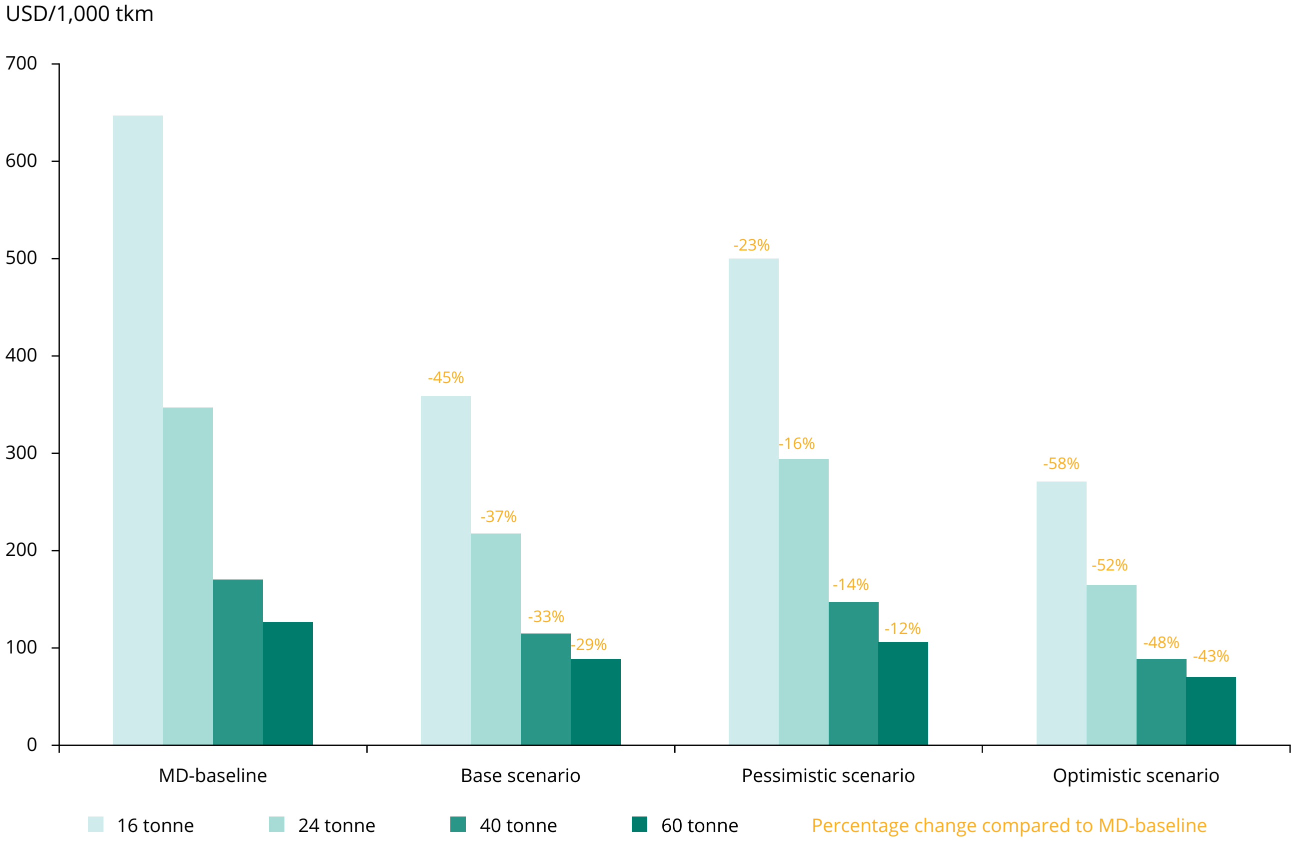
Figure A3.4 Average external costs of freight transport modes in 2016 (EUR-cent/tkm)



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.

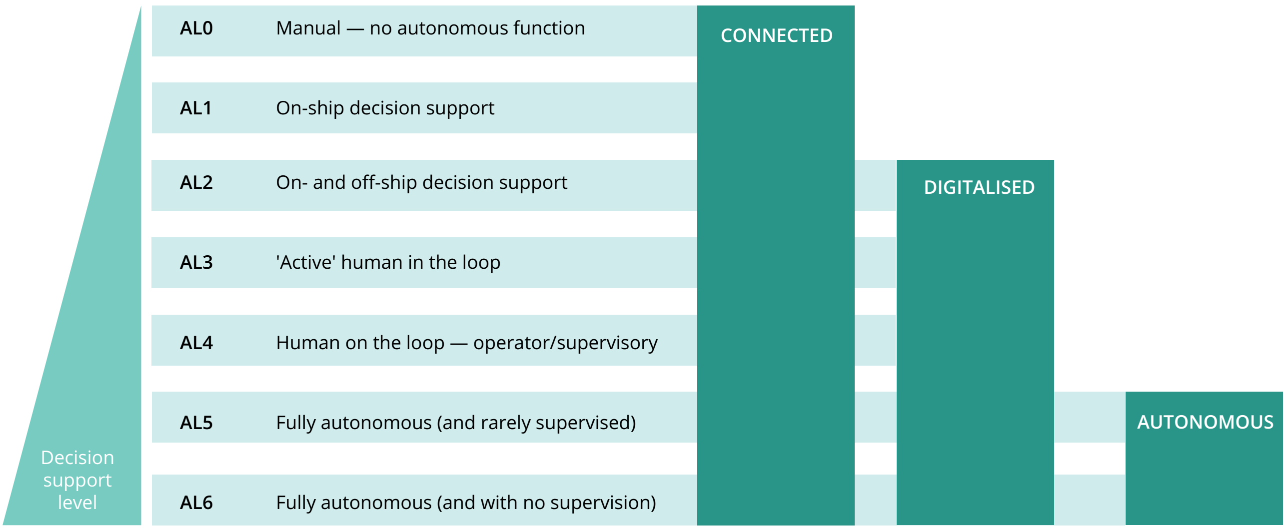
Table A3.1 IMO classification of maritime autonomous surface ships ([a])

	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

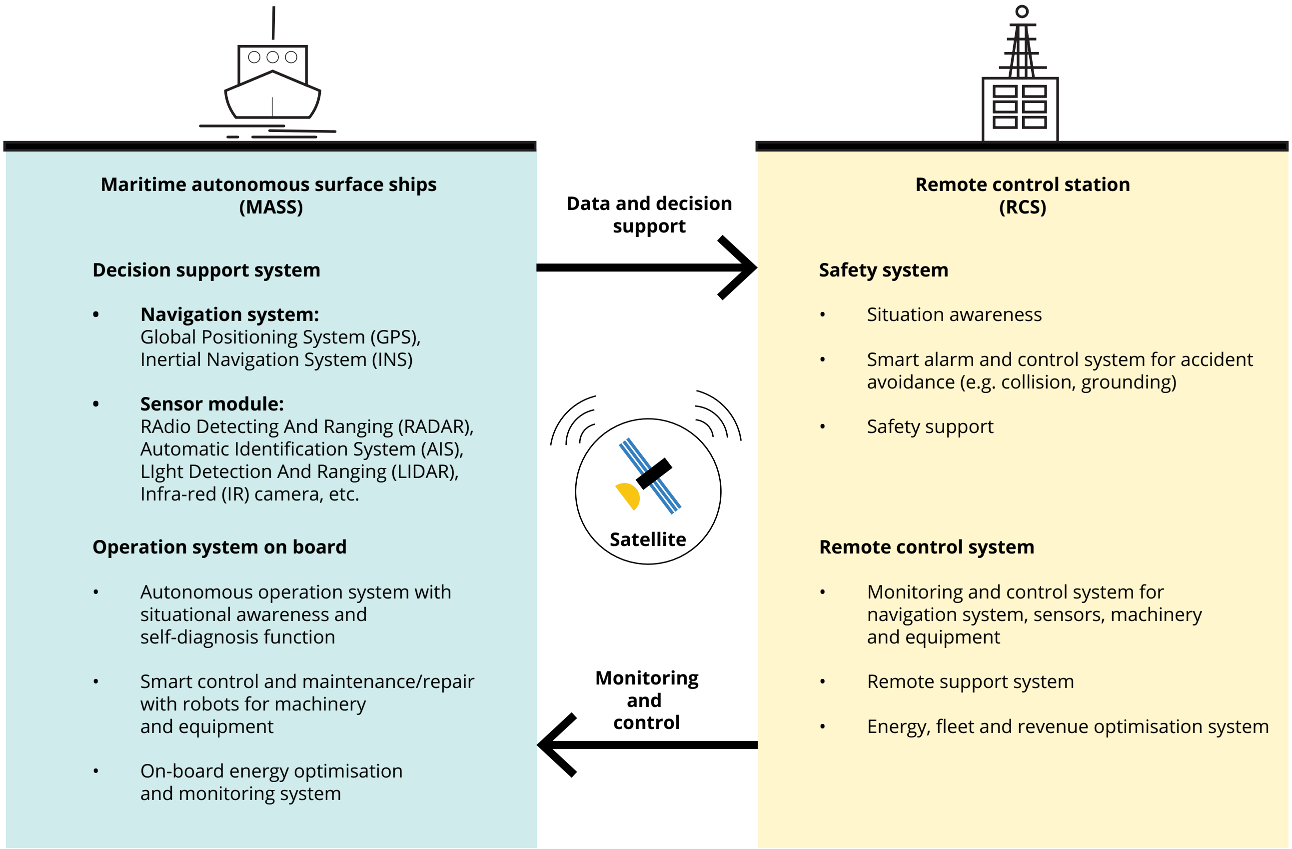


Source: EC (2020d) based on Lloyd's Register.

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.

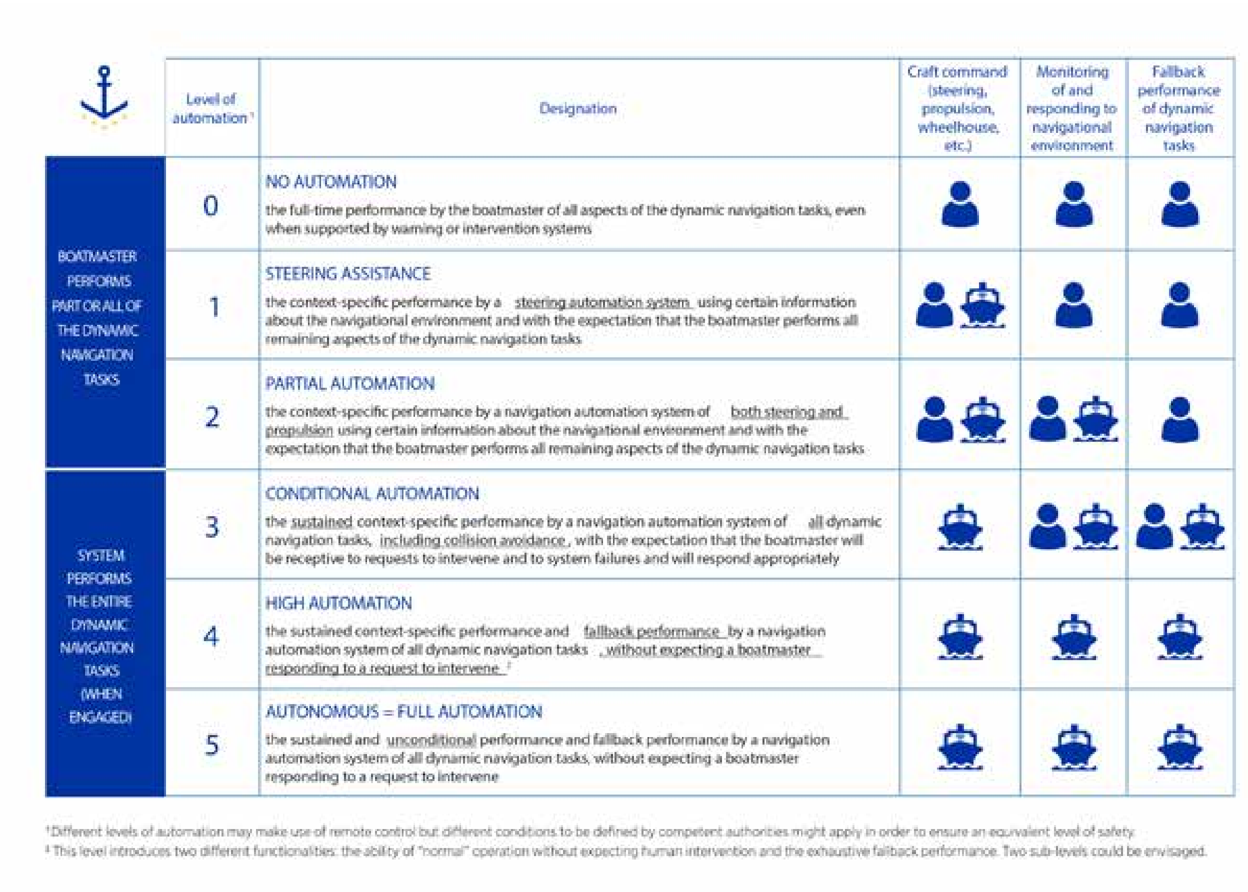
Similarly, in the case of inland navigation, progressive automation is expected to take place in future years. Like the classifications in road and maritime transport, the Central Commission for the Navigation of the Rhine (CCNR) has proposed a classification of the automation levels, reported in Figure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



	Level of automation[1]	Designation	Craft command (steering, propulsion, wheelhouse, etc.)	Monitoring of and responding to navigational environment	Fallback performance of dynamic navigation tasks
BOATMASTER PERFORMS PART OR ALL OF THE DYNAMIC NAVIGATION TASKS	0	NO AUTOMATION the full-time performance by the boatmaster of all aspects of the dynamic navigation tasks, even when supported by warning or intervention systems			
	1	STEERING ASSISTANCE the context-specific performance by a steering automation system using certain information about the navigational environment and with the expectation that the boatmaster performs all remaining aspects of the dynamic navigation tasks			
	2	PARTIAL AUTOMATION the context-specific performance by a navigation automation system of both steering and propulsion using certain information about the navigational environment and with the expectation that the boatmaster performs all remaining aspects of the dynamic navigation tasks			
SYSTEM PERFORMS THE ENTIRE DYNAMIC NAVIGATION TASKS (WHEN ENGAGED)	3	CONDITIONAL AUTOMATION the sustained context-specific performance by a navigation automation system of all dynamic navigation tasks, including collision avoidance, with the expectation that the boatmaster will be receptive to requests to intervene and to system failures and will respond appropriately			
	4	HIGH AUTOMATION the sustained context-specific performance and fallback performance by a navigation automation system of all dynamic navigation tasks, without expecting a boatmaster responding to a request to intervene[2]			
	5	AUTONOMOUS = FULL AUTOMATION the sustained and unconditional performance and fallback performance by a navigation automation system of all dynamic navigation tasks, without expecting a boatmaster responding to a request to intervene			

[1] Different levels of automation may make use of remote control but different conditions to be defined by competent authorities might apply in order to ensure an equivalent level of safety.
[2] This level introduces two different functionalities: the ability of "normal" operation without expecting human intervention and the exhaustive fallback performance. Two sub-levels could be envisaged.

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

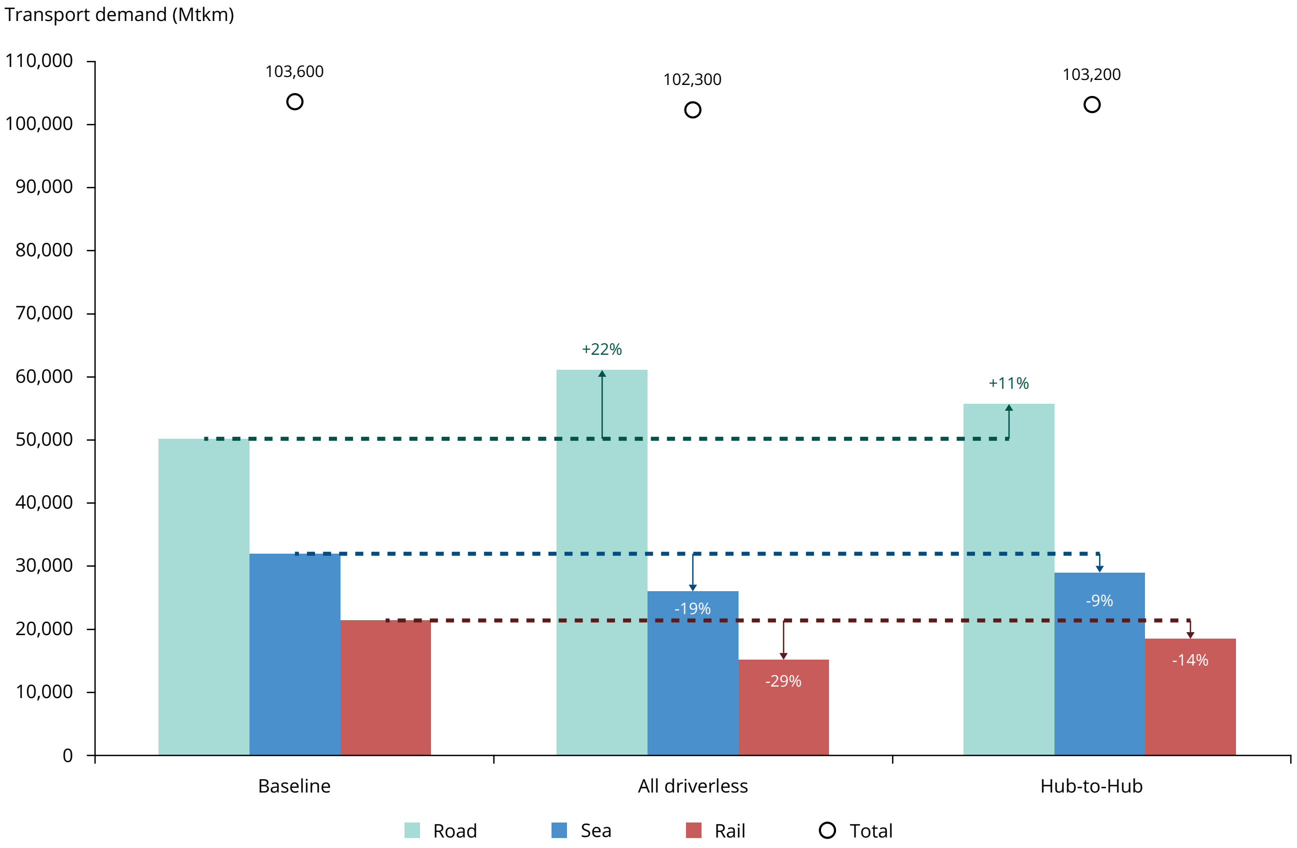
Driverless trucks and automation in navigation offer some potential to increase the environmental performance of transport modes. They are also likely to lead to cost reductions. As transport volumes respond to changes in transport costs, this can be expected to increase transport volumes in general 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)



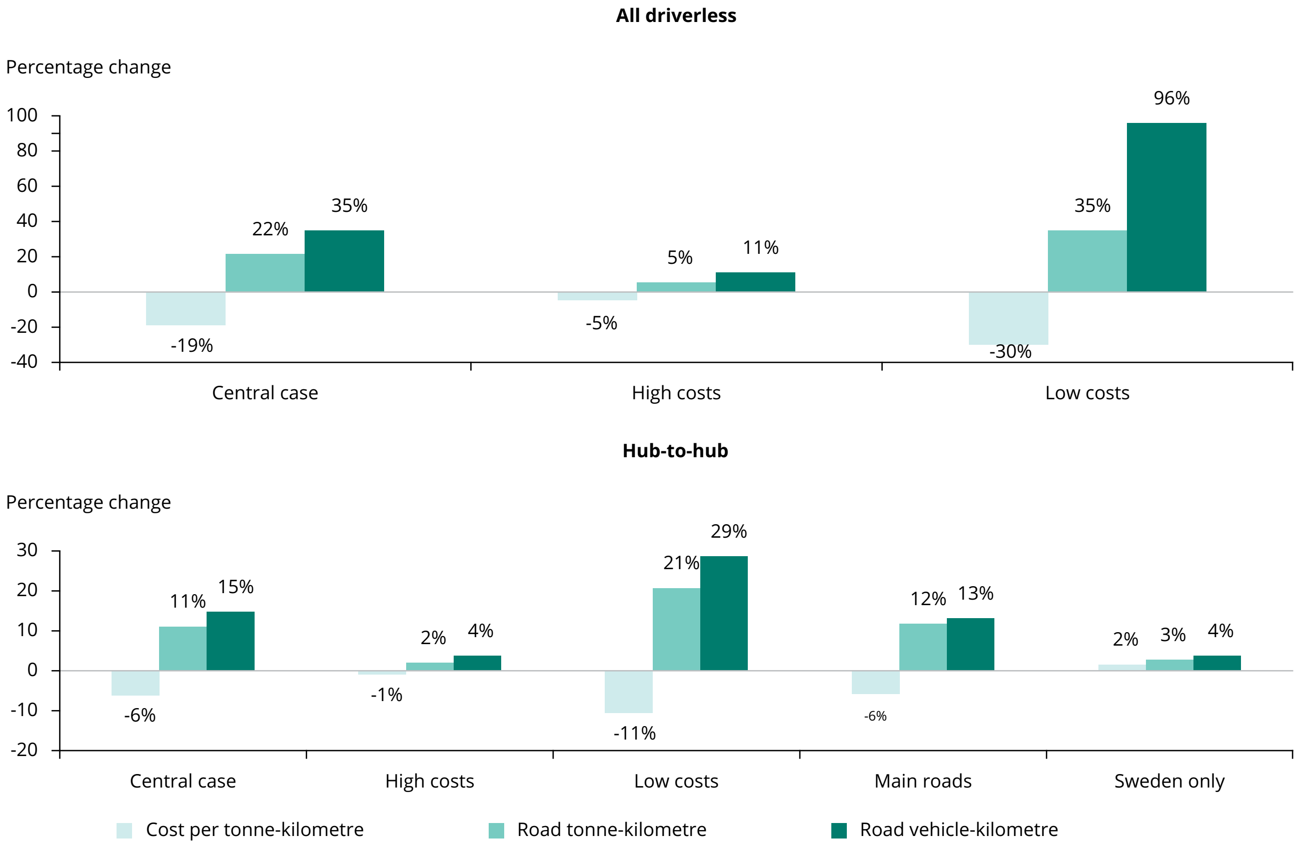
Note: The percentages represent the relative changes in tonne-km transported by the three modes in comparison with the baseline scenario.

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).