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New and Emerging Transport Technologies and Trends in European Research and Innovation Projects 2024

An assessment based on the Transport Research and Innovation Monitoring and Information System (TRIMIS)

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Abstract

Technological innovation is a key enabler for reaching the strategic EU objectives in the transport field, such as decarbonisation and digitalization. This report identifies and presents a selection of new and emerging technologies in transport, based primarily on the Transport Research and Innovation Monitoring and Information System (TRIMIS) database. The presented technologies are divided into cross-cutting digital technologies, such as AI, and transport-specific ones, with a narrower and more specific transport scope. The overview of the technologies includes technology background, state of the art, European R&I activities, and the relevance for the EU policy.

Acknowledgements

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Executive summary

The study presents an overview of new and emerging technologies in the field of transport. The report includes 7 cross-cutting digital technologies with a variety of transport applications, and 10 transport-specific technologies with a narrow and clearly delineated scope. The selection of technologies was based primarily on the Transport Research and Innovation Monitoring and Information System (TRIMIS) database. In addition to TRIMIS-based indicators regarding R&I activity, such as number of research projects per technology and total funding, the study also took into account additional information from external sources, including scientific trends, policy and industry interest, and general sentiment associated with the particular technology. The report provides an overview of each of the selected technologies, including rationale and technology background, state of the art, European R&I activities, and alignment with the EU policy goals.

Policy context

The strategic EU objectives for transport were outlined in key policy documents, most importantly the European Green Deal, and the Sustainable and Smart Mobility Strategy (SSMS). While the first defines the principal goal of a 90% cut in transport emissions by 2050, the latter draws a strategic roadmap for the sector to achieve this reduction in the coming decades. This plan builds on three main pillars: making all the transport modes more sustainable, promoting a massive shift of passengers to more sustainable modes, and introducing regulatory measures and incentives for more sustainable transport choices. Innovation in the sector will be of key importance, in particular for deployment of the first two pillars. This fact is highlighted by the SSMS, which further lays out specific objectives for zero-emission cars, aircrafts and vessels, connected and automated mobility, low-carbon fuels, and big data and artificial intelligence applications in transport.

In this context, it is important and necessary to monitor the new and emerging technologies that have the potential to contribute to the above objectives. All the technologies presented in this report bear relevance not only to the mentioned high-level strategic goals, but are often strongly connected to other EU policies, such as the European Chips Act, the European Critical Raw Materials Act, or the EU Batteries Regulation. For each transport-specific technology, its relevance to the EU policy goals was briefly discussed in the dedicated section within the chapter. In case of cross-cutting digital technologies such exercise was impractical due to the breadth and variety of their applications. However, it should be stressed that all the presented digital technologies play a vital role for the European Commission priority of making Europe fit for the digital age and achieving the goals of the European digital agenda.

Key conclusions

- **Two types of new and emerging transport technologies can be distinguished**: cross-cutting digital technologies and transport-specific technologies. The digital technologies are involved in a large share of projects, and represent a great variety of applications all across the transport sector, oftentimes being essential for development of transport-specific solutions, e.g. as a support for engineering design. Therefore, digitalization of the transport sector, including R&I activities, should be treated as an utmost priority.

- Among **cross-cutting digital technologies**, artificial intelligence is the most represented one with 182 projects. Most of AI-related research activity takes place in the aviation sector, followed by electromobility and connected and automated mobility. Most common applications are traffic management, support for engineering design, and navigation. The number and variety of projects suggests that AI will be the key digital technology for transport in the coming years, followed by additive manufacturing and digital twins.

- Within the category of **transport-specific technologies**, comparison and classification of technologies, e.g. in terms of impact or market readiness, is challenging. Some of them, like software-defined vehicles or EV lightweighting, represent a trend rather than a concrete technology. In other cases, there might be different advancement levels within a technology, with varying TRL levels (e.g. U-space), discrepancies between scientific literature representation and actual implementation (e.g. virtual coupling and digital automatic coupling), or a single value cannot be assigned due to various options involved (e.g. alternative shipping fuel) or many building blocks (e.g. automatic train operations).

- Based on the **scientific literature trends**, it can be concluded that alternative fuels for shipping (in particular hydrogen and ammonia), cobalt-free batteries, and virtual coupling are the most researched technologies, while digital automatic coupling, EV lightweighting, and hydrogen-powered airplane have attracted the least attention.

- Based on the own judgement of the authors of the report, considering all the factors taken into account for technologies selection, **the three transport-specific technologies that particularly stand out are**: software-defined vehicle, due to the scale of transformation and challenge that it brings to the automotive sector; digital automatic coupling, due to its closeness to the market and very high potential impact on the competitiveness of the European railway sector; and hydrogen-powered airplane, due to scarce alternatives, the required level of research activity and investment, and high industry commitment.

- Two technologies seem especially critical from the point of view of the **European resilience and competitiveness**. Software-defined vehicle poses a risk for the European automotive industry, considering pressure from the Chinese and American competitors, and increasing dependence on advanced electronics, chips in particular. Cobalt reduction in batteries, on the other hand, is relevant for decreasing dependence on raw materials and vulnerable supply chains for the critical transport sectors, in this case batteries and electromobility.

Main findings

The current developments in the transport technologies were found to be driven by five principal megatrends:

- **Decarbonization**: High dependence of the transport sector on oil products, reflected in its large contribution to the total global GHG emissions, makes decarbonisation the most urgent driver for innovation in the sector. Stimulated by the EU decarbonisation strategy, transport R&I is largely concentrated on sustainable technologies, e.g. electrification of road transport, and alternative fuels for aviation and maritime.

- **Digitalization**: Rapid advancement of information and communication technology gave grounds for deep digitalization and concepts like Industry 4.0. It is also altering the transport sector, with advent of navigation and route planning services, intelligent transport systems, or Mobility as a Service. This trend will continue in the future with the rise of new generation of digital technologies, most notably artificial intelligence.

- **Automation**: Traditionally one of the main objectives guiding industry innovation, automation has been already widely implemented in more isolated transport circumstances, such as metro operations and cruise phase in aviation. The progress in digital technologies is extending this trend to other applications, such as automated cars, infrastructure maintenance, or mainline railway operations. In the long run, automation could help to mitigate the increasing worker shortages in the European transport sector.

- **Circularity**: Replacing the traditional linear model of economy with a more circular one is essential for reduction of raw materials use, pollution and waste. This trend affects also the transport industry, for example the automotive sector in the context of electromobility transition, e.g. in the use of materials used for weight reduction of electric vehicles, and battery design.

- **Resilience**: Transport is becoming increasingly vulnerable to external factors, such as severe weather events caused by climate change. As a consequence, resilient design, monitoring and maintenance of transport infrastructure is becoming of paramount importance. In addition, the unstable global political situation is affecting the resilience of critical supply chains, such as chips and raw materials for battery production.

The selection of the most relevant new and emerging technologies was based primarily on research projects coming from the TRIMIS database. Filtering the database for the study period covering years 2018-2024 resulted in nearly 1300 projects, that were further analysed and integrated with findings coming from external sources. The outcome is 17 technologies, grouped into two main categories: cross-cutting digital technologies, and transport-specific technologies. The first group includes transversal technologies with a wide array of transport applications, while the latter covers technologies with a narrower and clearly defined scope.

The following 7 cross-cutting digital technologies were identified:

- **Artificial intelligence**: AI is an umbrella term for several branches of technology, with the common characteristic of mimicking human intelligence. The most prominent areas of AI include machine learning, machine perception and natural language processing. Transport problems are often complex, ambiguous, and data-intensive, providing an ideal testing ground for the AI capabilities. So far, the focus in European transport research is put on AI application in aviation, electromobility and connected and automated mobility, in particular for traffic management and assistance in engineering design process.

- **Digital twins**: Digital twins are detailed computer models of real-world objects, that are practically indistinguishable from their physical counterparts. Thanks to their ability to exchange data with the modelled

object, they find a wide array of applications in prototyping, maintenance and monitoring. Some of the transport-related use cases include automotive and aviation design and manufacturing, aircraft monitoring, and predictive maintenance of railway infrastructure.

- **Additive manufacturing**: Additive manufacturing, also called 3D printing, is a method of producing objects by layer-by-layer material deposition. Its advantage over traditional subtractive processing lies in the ability to produce very complex shapes with minimal waste of material. This characteristic makes it particularly applicable in aviation and automotive, for manufacturing of intricately shaped elements, rapid prototyping, and production of spare parts.

- **Blockchain**: Blockchain is a distributed database, offering some specific features due to its particular design. These include secure transactions that do not require mutual trust or a centralized supervising authority, and smart contracts – triggered automatically when certain conditions are met. Blockchain is mostly applied in logistics, where it helps to track the goods flow and automatize operations, but many other applications are investigated, e.g. in air traffic management.

- **Internet of things**: IoT is a network of physical objects (e.g. machines or vehicles) embedded with electronics and connectivity that enable collection and exchange of data, and as a consequence, automation. Most common applications include cargo tracking and process optimization in logistics, smart ports and manufacturing lines, e.g. in shipyards, and data collection for remote monitoring of infrastructure, vehicles, or even truck drivers or railway workers.

- **Extended reality**: Extended reality (XR) is an umbrella term for several technologies expanding the physical world by incorporating 3D graphic elements and sensory experiences. Virtual reality places the user in a completely artificial environment, while mixed and augmented reality enhance the real world with virtual elements. XR can facilitate design and manufacturing process, e.g. in aviation or shipbuilding, help in inspection and maintenance, or be a tool for CCAM safety simulations.

- **Edge and cloud computing**: Edge and cloud computing represent a computing paradigm which shifts the data storage and processing from local to network-centric computing. Cloud computing relies on centralized data centers with high computing power, but offer poor latency as the data travels over long distances. This problem is addressed by edge computing. Edge computing is essential for CCAM applications, which require very fast processing of vast amounts of data.

In addition, 10 transport-specific technologies were identified.

In road transport:

- **Software-defined vehicle**: The automotive industry is going through a transformative departure from its traditional hardware-oriented paradigm towards cars with dominant role of electronics and software. This transition is a challenge for the European industry, due to strong global competition and other issues: obsolete car architecture, inflexible supply chains, and shortage of talents with the suitable profile.

- **Cobalt-free batteries**: Cobalt is a critical component of lithium-ion batteries, which currently constitute the majority of batteries available on the market. At the same time cobalt is a critical earth material, which extraction raises concerns regarding ethics, environment, and supply chain vulnerability. Cobalt reduction is heavily investigated, by testing new materials and battery chemistries, e.g. solid-state batteries.

- **Lightweighting of electric vehicles**: The weight of an electric car affects driving range and battery size, therefore impacting the EV prices and adoption of the technology. Making EV lighter poses different challenges compared to internal combustion engine vehicles. In addition to investigating new, lighter materials, circularity and emissions throughout the whole life cycle become the key objectives.

In rail:

- **Digital automatic coupling**: Railway coupling is a procedure of connecting the locomotive and consecutive wagons to form a train. If done manually, it can be a dangerous and time-consuming process. Europe is one of the few remaining world regions where manual coupling is still the norm. DAC is seen as a game changer for the European rail industry, able to eliminate huge inefficiencies caused by the current approach.

- **Automatic train operation**: Although isolated train operations, such as metro, are already largely automated, the automation of mainline operations practically does not exist. At the same time, a substantial research activity is being carried out on this topic. The transition is challenging due to high cost, and the need for communication-based control systems, and automation of track monitoring and maintenance.

- **Virtual coupling**: Rail capacity can be increased either through costly and complex infrastructure investments, or through improvements in operations. Virtual coupling belongs to the latter category: by merging trains into digitally connected convoys it is possible to coordinate their speed and braking behaviour, allowing thereby for shorter headways and more efficient utilization of the existing rail capacity.

In aviation:

- **U-space**: The number of drones in the air is rapidly increasing, requiring their coordination and safe inclusion in the existing airspace. U-space is an airspace dedicated specifically for drones, consisting of a variety of dedicated procedures and services. The technology has several layers, from the simplest, like e-registration and tracking, up to collision avoidance, integration with manned aviation, and eventually full automation.

- **Hydrogen-powered airplane**: Hydrogen is intensely revisited by the aviation sector, as the most viable pathway for the long-term industry decarbonisation. In comparison to other options, like sustainable aviation fuels or electric planes, it raises less environmental and technological concerns. Current research focuses on challenges like hydrogen storage on board, new propulsion systems, and refuelling infrastructure.

In maritime:

- **Wind-assisted propulsion**: Wind is the most ancient energy source for shipping. While it was abandoned in favour of oil-based fuels, it is currently being revisited. Various types of wind-assisted propulsion are being investigated, e.g. cylindrical rotors, modern versions of traditional sails, suction wings and kites. Although their performance relies heavily on weather, in certain circumstances they could theoretically act even as the only propulsion source.

- **Alternative fuel for shipping**: The maritime industry is looking for alternatives that could replace the omnipresent oil-based fuels. Although there are several main candidates, the future fuel mix is under heavy debate, as each of the options comes with their own advantages and challenges. Currently, hydrogen, ammonia, methanol, and biofuels are among the most promising fuel alternatives.

Related and future JRC work

Several of the transport technologies presented in the report have been recently investigated by the JRC. On the topic of alternative maritime fuels, the JRC is supporting DG INTPA with a proposal to establish a Global Gateway Green Shipping Corridor (GGGSC) under the EU's Global gateway initiative The GGGSC proposal will support the definition of a network of point-to-point green shipping routes on which commercially operating ships use exclusively renewable and low-carbon fuels, with focus on the RLCFs bio-methanol, bio-methane, ammonia, and hydrogen. With regard to electric cars lightweighting, the JRC is monitoring the growing market for zero emission vehicles in the EU, and assessing market penetration and characteristics of these vehicles, such as energy efficiency and weight. Technologies for potential further improvement of electric vehicle energy efficiency are represented in the energy consumption reduction cost curves produced with the JRC's DIONE model, which are periodically updated to reflect latest knowledge. The JRC is also involved in assessment of the future regulatory needs in order to accommodate software-defined vehicles, revising the suitability of traditional approaches to car development, validation and type-approval.

Moreover, since 2017 TRIMIS reports cover a wide range of the transport-related analyses on research and innovation initiatives in Europe. The recent TRIMIS reports concentrated on specific, transport-related topics: urban mobility and logistics, transport safety and resilience, and drones. The forthcoming TRIMIS reports will focus on heavy duty vehicles, waterborne transport and smart mobility.

Quick guide

Section 1 provides the context and rationale for the report, highlighting the increasing role of new transport technologies. Section 2 introduced the TRIMIS project and database, and describes the methodology used for the selection of technologies addressed later in the report. Section 3 includes an overview of megatrends guiding the innovation in transport, providing a background for the rest of the analysis, and drawing the connection between the megatrends, EU strategy, and the selected technologies. Section 4 provides an in-depth assessment of the identified new and emerging technologies. The chapter is divided into two main subsections, addressing transversal digital technologies and transport-specific ones. Section 5 concludes the findings presented in preceding chapters.

1 Introduction

A well-functioning transport system is an essential enabler of all the human activity in the modern world. Not only does it facilitate freedom of movement to individuals, but it is also a pillar of all economic activity, international trade, and essential public services such as health and education. Better access to otherwise isolated areas stimulates the economic activity, creates new jobs, and contributes to a better quality of living for everyone. Free movement of people and goods is essential for the European Single Market, and plays a key role in strengthening cohesion of the EU and consolidating European identity. In 2022, the transport sector contributed around 5% to the EU's GDP and gave employment to more than 10 million people (Eurostat, 2023).

At the same time, transportation faces two key challenges: the accommodation of rapidly growing demand, and the urgent reduction of environmental impact. The pre-pandemic period was an era of exuberant growth. In the first two decades of this century, the total kilometres travelled by European passengers increased by more than 20% (European Commission: Directorate-General for Mobility and Transport, 2022). After the sudden dip caused by the COVID-19 crisis the demand is quickly rebounding to the previous levels (European Environment Agency, 2022). Transport is also the only major sector of the EU economy for which emissions have increased in the same period. It is also the one with the slowest rate of decarbonisation – transitioning three times slower than the rest of the economy. This makes for dire predictions – whereas today transport is responsible for one-quarter of all European emissions, by 2030 it is likely to contribute to almost half of them (Transport & Environment, 2024).

Research and innovation plays a central role in addressing these challenges. Recent advancements in digital technologies have opened avenues for a number of disruptive concepts and technologies, such as connected and automated driving, Mobility as a Service, and various drone applications. Transport electrification and new kinds of sustainable fuels have become mainstream instruments for tackling the adverse environmental impact. Technological progress continues to bring to light new solutions that can play a role in making the European transport greener, more efficient, and safer for all. Keeping track of these latest developments is therefore a prerequisite for designing a well-informed and evidence-based transport policy that will set the right investment priorities and optimally accommodate the emerging technologies within the transport system.

The purpose of this report is to provide the reader with an overview of the new and emerging technologies and trends in the transport field. The analysis was based primarily on an assessment of the EU-funded research activity in recent years, supported, where possible, by a literature and internet analysis of the emerging technologies and trends. This work was carried out within the activities of the Transport Research and Innovation Monitoring and Information System TRIMIS, taking advantage of its vast database of transport-related European research projects. The report presents an overview of the main megatrends driving transport research and innovation, and provides a closer look at a selection of identified emerging technologies.

2 Methodology

The work presented in this report was performed within the activities of the European Commission's Transport Research and Innovation Monitoring and Information System (TRIMIS), and was primarily based on the information available in its transport research projects database. The following two sections provide an overview of the TRIMIS activities and database, and explain in detail the method applied for selection of technologies and trends included in the report.

2.1 TRIMIS project and database

TRIMIS was established in September 2017 at the Joint Research Centre (JRC) of the European Commission, with the overall goal of making use of past & ongoing research to help steer future transport research and innovation (R&I) policy. The system serves as a one-stop-shop for information about transport R&I at the EU and Member State level. This objective is realized by collection, curation, and dissemination of data on R&I activity in Europe and beyond, and by analysis of technology trends and innovation in the transport sector.

TRIMIS database provides the backbone for all of the project activities. It gathers information about research and innovation projects funded from various programmes, including Horizon 2020, Horizon Europe, or Framework Programme 7, as well as the national initiatives of the Member States. Currently it contains detailed information on nearly 9000 projects. This includes over 2000 projects funded within the H2020 Framework Programme and a growing number of projects under Horizon Europe. The database ensures the availability of reliable and up-to-date information on R&I projects in the transport field.

It also serves as the essential input for all the analytical work of TRIMIS, notably the Science for Policy reports providing an in-depth assessment of specific transport areas, including an overview of R&I achievements, main challenges, gaps, and possible avenues for future research activities. Examples of some of the most recent topics include drones, and transport safety and resilience. In addition to those standard TRIMIS elaborations, the New and Emerging Technologies and Trends (NETT) analysis provides a more forward-looking perspective complementing the Science for Policy reports. The concept guiding the NETT analysis is to identify and analyse emerging technologies and trends in transport R&I at a low to medium maturity level, that have not yet reached the stage of wide market implementation. In addition, the exercise does not cover only one specific topic, but instead looks across the entire transport sector. For that reason, the typical method applied to the Science for Policy reports is not fit for purpose (TRIMIS, 2024). The NETT-specific approach is addressed in detail in the following section.

2.2 NETTs selection

The selection of relevant technologies and trends was based primarily on the EU-funded research projects available in the TRIMIS database, accessed in April 2024. The period of analysis was set for the years 2018-2024. A two-year overlap was foreseen with regard to the previous NETT report (covering period 2007-2020) in order to capture the technologies that could have been missed due to insufficient clarity of some of the trends emerging at the time, e.g. due to relatively low number of relevant projects. Initial selection from the period consisted of nearly 1300 projects that were further divided by transport mode, and the main technology addressed by each project was identified. Due to the large number of results this work was supported by AI (ChatGPT), prompted to extract the primary technology based on project information derived from the TRIMIS database.

The output was further analysed in order to select technologies and trends that could be considered as new and emerging. This task was performed based on indicators stemming both from the TRIMIS database and external sources. The factors taken into account are summarized in the table below.

Table 1. Factors taken into account for NETTs selection.

Indicator	Type	Source	Description
Number of projects	Quantitative	TRIMIS database	Number of projects investigating the technology
Amount of funding	Quantitative	TRIMIS database	Total amount of funding for the projects investigating the technology
Number of participating entities	Quantitative	TRIMIS database	Total amount of entities participating in projects addressing the technology
Potential impact	Qualitative	External source	The magnitude of possible technology impacts. Level of disruption.
Technology 'hype'	Qualitative	External source	General interest and enthusiasm around the technology. Based mainly on industry-oriented resources, e.g. websites, reviews
Policy interest	Qualitative	External source	Presence of any significant policy initiatives to promote the technology
Industry interest	Qualitative	External source	Presence of any significant industry statements or initiatives regarding the technology
Expert judgement	Qualitative	External source	Input gathered from JRC experts working on diverse transport topics
Scientific trends	Quantitative	External source	The number of scientific publications regarding the technology.
TRL level	Quantitative	External source/TRIMIS database	Technology Readiness Level. Level of technology maturity and readiness for the market, on a 9-grade scale.

Source: JRC

Although many of the above indicators are quantitative, there is a certain level of ambiguity involved and therefore the results could not be taken at face value. For example, amount of funding and number of projects are mode-specific, meaning that there is a tendency for some modes (e.g. road transport) to have high number of projects per technology with relatively low funding, whereas for others (e.g. railway) it is more common to have a single project with a broad technological scope and plentiful financing. Number of participating entities might be higher for projects with a 'softer' objective, such as building a research network or setting a common research agenda, therefore not necessarily being an indication of above-average interest in a particular technology. Technology Readiness Level (TRL) level might be difficult to assess in case of complex technologies, as they consist of many technological blocks of different maturity level. For some technologies multiple TRL levels could be assigned. For example, U-space, an emerging airspace for drones, includes a variety of digital services and procedures. Those are categorized into different U-space levels with increasing complexity, each

level exhibiting different stage of technological maturity. Lastly, a TRL is a less suitable measure for describing trends, as opposed to technologies.

Considering the above, the final selection of NETT included in the report was not based on a straightforward quantitative assessment, but rather on an educated judgement on all the above factors combined, taking note of the specific context of each analysed technology. For example, a software-defined vehicle is an emerging paradigm-changing trend driving the automotive industry, with profound technological and economic implications. Despite very high interest from the industry, academia and policymakers, during the initial analysis only a single low-funded project was identified. However, the goal of this particular initiative was to gather main industry stakeholders in order to harmonise the vision of the software-defined vehicle and set a common R&I roadmap, which in fact only emphasises the novelty of the trend. Another example is Digital Automatic Coupling – a technology commonly seen as a game-changer for the European rail freight, yet greatly underrepresented in scientific literature, and with relatively low, although highly funded, number of projects. At the same time, the technology is characterized by a high TRL – however, despite its maturity it has not yet been implemented anywhere in the world.

Eventually, both the above examples were included in the report, as we believe that an overview of new and emerging technologies and trends in transport would be otherwise incomplete. It should be emphasised that the NETT report is based primarily on the analysis of the recent EU-funded research projects, notably Horizon 2020 and Horizon Europe, which investigate technologies that are already somewhat established. In this sense it is different from a horizon scanning type of exercise, which looks further into the future trying to predict technological trends to come, barely outlined at the moment of analysis. Therefore, in terms of TRL, the NETT report does not consider very low levels (up to TRL 3), which do not cover much more than early technological concepts, but looks at low to medium maturity (up to TRL 7). Nevertheless, such scope still covers only the technologies that clearly have not yet reached the implementation phase.

Once the initial list of technologies was established, other sources were investigated to identify any missing projects that were possibly not yet present in TRIMIS database at the moment of its exportation. This mainly included CORDIS project database and websites of relevant EU Joint Undertakings, such as Clean Aviation, Europe's Rail, or Zero-Emission Waterborne Transport. A separate chapter is devoted to each selected technology, enriched by deepened literature review of relevant scientific, industry, and policy resources. In addition, scientific trends extracted from Scopus database are also presented (Scopus, 2024).

The results section makes a distinction between transport-specific and digital technology. The cross-cutting nature of the second category prompted this separation, as well as some minor methodological adjustments, which are addressed more in detail in the introduction to the corresponding section.

The report is intended primarily for policymakers; therefore, it should be understandable also for audience without a technology-oriented background. With this consideration, the NETT analysis was kept at a higher level of abstraction. For example, a hydrogen-powered airplane is enabled by a number of intricate technologies, such as hydrogen storage, propulsion system, refuelling infrastructure etc. While each of them constitutes a prominent research trend of its own, they have been only outlined in accordance with the overall scope of the report, which is to provide a high-level overview of NETT in the European R&I. Lastly, in accordance with this scope, an effort was made to provide a representative NETT selection, with similar number of results for each transport mode.

3   Megatrends

The technological advancements presented in this report do not exist in isolation but rather represent broader trends that go beyond the transport field and determine the general direction of technological progress in decades to come. These high-level trends, also defined as megatrends, have some distinguishing characteristics. First, their scope of impact is global, affecting whole states, regions, industries, and often the entire world. Second, their timespan is much longer, often counted in many decades.

This section explores a selection of megatrends particularly impactful for transport R&I. Thereby, it sets the scene for the following part of the report and provides context for the presented technologies by drawing a connection between them and the megatrends. Each megatrend is presented from both global and transport-specific point of view, followed by a summary of related high-level EU policies and legislation, and a brief overview of the specific technologies included in the main part of the report.

3.1   Decarbonisation

Human-induced global warming has already caused a temperature rise of 1.1 degrees C, spurring changes to Earth's climate unprecedented in the recent human history. The effects are already here to be seen: the last decade was the warmest on record, with 2023 being the hottest year on record, by a large margin (NASA, 2024). Current global greenhouse gases (GHG) concentration has already gone beyond the level required for staying below 1.5 degrees of warming. According to a 2023 report of the Intergovernmental Panel on Climate Change, there is now more than 50% chance of surpassing that threshold somewhere between 2021 and 2040, if no immediate, rapid, and large-scale reductions in GHG are taken (Calvin et al., 2023). In 2015, the Paris Agreement was signed by 197 countries pledging to pursue efforts of limiting temperature rise to 1.5 degrees C, and well below 2 degrees C. The already observed warming and failure to adhere to necessary emissions reduction goals makes this objective increasingly unrealistic.

Transport sector relies on oil products for 91% of its final energy and is a major contributor to climate change, being responsible for 25% of global GHG emissions (International Energy Agency, 2023). In Europe, transport is the only major economic sector for which emissions have increased in the past several decades. The total transport-related GHG emissions in 2019 were 33.5% higher than in 1990, and after a recent drop in 2020 caused by COVID-19 pandemic quickly rebounded close to the previous levels. Today, transport is responsible for around one-quarter of all EU GHG emissions. The major contributor is road transport, responsible in 2021 for 76% of all the sector emissions (European Environment Agency, 2022; European Environment Agency, 2023). At the same time other modes are quickly catching up, such as aviation which doubled its emissions between 2000 and 2019 (Transport & Environment, 2024).

Given these circumstances, decarbonisation has become the main driving force for the transport sector. The trend can be exemplified by the rapid electrification of the main culprit – road transport. In recent years, passenger electric cars have surged in popularity, accounting for 18% of all cars sold worldwide in 2023. The growth dynamics are exceptional, considering just 1% five years prior (International Energy Agency, 2024). In Europe, the number of new electric vehicles registrations increased 51 times in the period 2013-2022, constituting 14.1% of all new passenger cars registrations in year 2022 (Eurostat, 2023).

EU strategy

The severity of the climate predicament has led the EU to place decarbonisation at the centre of its long-term strategy. The European Green Deal (EGD) provided a policy initiative package effectively aiming at transitioning Europe into the first climate-neutral continent by 2050, and achieving at least 55% GHG reduction by 2030. The EGD states that a 90% reduction in GHG emissions from transport will be required by 2050, with respect to the 1990 baseline (European Environment Agency, 2022). Transport decarbonisation strategy was elaborated in the 2020 Sustainable and Smart Mobility Strategy (SSMS), which draws a roadmap for the European transport sector in the coming decades.

SSMS recognizes GHG reduction as the most critical element within its vision. Transport decarbonisation measures can be generally divided into three categories: avoiding the need for travel, shifting to more environmentally friendly modes, or improving the existing transport options, e.g. by optimising energy efficiency and advancing vehicle technology. Building upon these assumptions, the SSMS action plan is comprised of three pillars. The first of them aims at making all the transport modes more sustainable, by deploying zero-emission vehicles, low-carbon fuels with related infrastructure, and by greening airports and marine ports. By 2050, nearly all vehicles on the European roads should be zero-emissions, with a midterm goal of 30 million zero-

emission cars and 80 000 lorries by year 2030. In addition, the plan sets a date by which zero-emission ocean-going vessels and large zero-emission aircraft should be ready for the market, to 2030 and 2035 respectively. The second pillar advocates for a massive shift to more sustainable transport modes, in particular rail, walking and cycling. For moving freight transport away from roads, both rail and waterborne alternatives must become more competitive. The mobility patterns can be optimized and some trips can be avoided thanks to digital solutions, e.g. teleworking or electronic commerce. Concrete objectives to be achieved by year 2050 include carbon-neutral collective travel under 500 km, tripling the passenger high-speed rail traffic, doubling rail freight traffic, and increasing waterborne transport by 50%. The third pillar addresses regulatory measures and incentives to be put in place for promoting sustainable transport choices. This includes shifting the external costs to the polluters, and ending fossil fuel subsidies. In this way, rail and waterborne-based intermodal transport should be able to compete on equal footing with road-only transport by 2030, and by 2050 all the external transport costs should be covered by the actual users (European Commission, 2020).

In this report

Most of the covered technologies bear at least some relevance for transport decarbonisation, with **hydrogen-powered airplane**, **alternative maritime fuels**, and **wind-assisted propulsion** having the most direct impact. Many technologies demonstrate an indirect connection. For example, railway innovations such as **digital automatic coupling** and **virtual coupling** will make rail more efficient and competitive, contributing to a modal shift away from less sustainable modes. **Lightweighting of electric vehicles** and the development of **cobalt-free batteries** enable a higher driving range and can drive down battery costs, and are therefore important drivers for road transport electrification and decarbonization.

3.2 Digitalization

Information and communication technology (ICT) is the source of the most revolutionary technological breakthroughs of our times, such as personal computers, the internet, smartphones, and most recently artificial intelligence (AI). ICT has been the fastest growing sector in the last 20 years, growing twice as fast as the rest of the world economy, and being currently responsible for around 6% of the global GDP. The majority of R&I funding is now spent on ICT-related technologies, with the world's seven biggest spenders being all ICT companies. The ICT industry generates massive positive impact on the broader economy in terms of growth and job creation, driving digital transformation of many other sectors (World Bank, 2023).

Digitalization can be defined as applying ICT technologies for converting physically collected information and knowledge into a computer-readable language, together with the resulting automation of processes. Digital transformation, on the other hand, refers to strategic changes in activity of businesses and whole industries in search of new, digital ways of value creation. This trend is commonly referred to as Industry 4.0, or the fourth industrial revolution. This concept represents a deeply digitalized future, in which intelligent and highly interconnected machines will be able to communicate with one another, interact with the environment, and make decisions with minimal human involvement (Ghobakhloo, 2020).

The progress of digitalization can be divided into several stages, marked by emergence of the key ICT innovations. The first stage covers the well-established and mature technologies, already commercialized and well-integrated into the modern world, such as the internet, satellite imagery and geographic information systems (GIS), databases, mobile phones and remote sensing. These technologies provide a backbone of digital transformation. Stage II technologies build on the stage I, and despite their high maturity, the wide commercialization occurred relatively recently. This wave is represented by mobile apps, social media, and cloud computing. Stage III represents the emerging digital technologies of the future – it includes artificial intelligence, Internet of Things, blockchain, big data, extended reality, digital twins, and advanced robotics. These technologies will be key enablers for transformation towards the Industry 4.0 (Asian Development Bank, 2021).

Transport is no exception on the digital transformation map, undergoing major changes driven by ICT technologies. On the demand side, teleworking and online shopping can have a major impact on mobility patterns, as demonstrated during the Covid-19 crisis. In 2021, almost half of EU-citizens worked regularly from home, compared to only 5% in the pre-pandemic period (European Environment Agency, 2023). Digitalization on the supply side makes mobility more accessible and efficient for the users, e.g. by providing real-time traffic information, online ticketing or route planning services. The Mobility as a service (MaaS) concept, aiming at combining multiple mobility services accessible through a single digital platform, has attracted great interest in recent years. In logistics, trapped value can be unlocked by leveraging vast amounts of data generated by the industry, e.g. for better planning and control of goods flow. The burdensome paper-based documentation is being continuously replaced with more convenient digital alternatives. Intelligent transportation systems (ITS)

help to use the existing physical capacity more efficiently, with solutions such as dynamic parking management, variable speed limits or smart traffic lights. ICT technologies will be key enablers for smart charging and vehicle-grid integration for EVs – key technologies for balancing the power grid in the light of mass deployment of electric cars and growing share of renewables in the energy mix (European Environment Agency, 2022).

EU strategy

Digital transformation plays a central role in the EU strategy as making Europe fit for the digital age is one of the six priorities of the European Commission for the years 2019-2024. Specific strategic goals were outlined in two digital agendas for Europe. The first digital agenda for years 2010-2020 achieved several key objectives such as elimination of roaming charges, enhancing internet connectivity by ensuring comprehensive basic broadband, and strengthening consumer protection in telecommunications through privacy and general data protection measures. The digital compass published in 2021 outlined the objectives of the second digital agenda for years 2020-2030. The document sets specific goals regarding digital skills and number of ICT specialists, digitalization of businesses, access to digital infrastructure, and digitalization of public services (European Parliament, 2024).

Some aspects of the digital transformation were addressed with dedicated strategies and specific legislation. The EU data strategy aims at making more data available for use in the economy in the society, while keeping the companies and individuals that generate the data in control. The regulatory framework includes the General Data Protection Regulation, the European Data Governance Act on data availability and trust, and the European Data Act on fair access and user rights. The AI Act adopted in 2024 safeguards general-purpose artificial intelligence, classifying AI-related risks and providing AI developers and users with clear requirements and obligations. The European Chips Act aims at bolstering Europe's competitiveness and resilience in semiconductor technologies. Digital Services Act and Digital Markets Act aim at facilitation of single European digital market, while Interoperable Europe Act addresses e-government and cross-border public sector cooperation. Other examples include cybersecurity legislation such as EU cyber defence policy and Cyber Solidarity Act, and digital education plan aiming at adaptation of the educational system to the digital era (European Parliament, 2024).

Also digitalization of transport is high on the EU strategic agenda. Smart mobility constitutes one of the pillars of the SSMS plan, in particular transition to connected and automated multimodal mobility, and leveraging data and AI. The strategy mentions wide deployment of ITS, CCAM, digital ticket services, drones, and digital solutions for efficient capacity allocation and traffic management. By 2030, the SSMS assumes paperless freight transport and seamless multimodal passenger transport enhanced by electronic ticketing, as well as large-scale deployment of automated mobility (European Commission, 2020). New rules for ITS deployment were adopted in 2023, increasing the availability of digital traffic data, facilitating data sharing in the transport context, and ensuring interoperability of various ITS services. The recently revised regulation for the Trans-European Transport Network (TEN-T) was updated to emphasize the digitalisation aspect, e.g. by advancing 5G infrastructure (Official Journal of the European Union, 2024).

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The analysis of the European R&I revealed a number of digital technologies that are being developed all across the transport field, in a diverse spectrum of contexts and applications. Being different from the transport-specific technologies addressing one specific transport area, they are treated separately in the section on transversal digital technologies. The following digital technologies have been included, based on their prominence among the analysed research projects: **artificial intelligence**, **digital twins**, **internet of things**, **blockchain**, **additive manufacturing**, **extended reality**, and **edge and cloud computing**. In addition, two transport-specific technologies are especially relevant: the **software-defined vehicle**, representing the great shift of traditionally hardware-oriented automotive industry towards digitalization, and the **U-space**, a digital air traffic ecosystem dedicated for drones.

3.3   Automation

The rise of digital technologies has greatly contributed to acceleration of another megatrend – automation. Delegation of tedious and tiresome working tasks has been a long-standing human desire, increasingly enabled by the technological progress. Transport has always been at the forefront of this transformation. Inventions such as steam and internal combustion engines led to development of railways and cars, overcoming the limitations of human and animal power. Currently, the world is entering the next stage of this process. The recent advancement of AI and robotics, able to deal with less structured problems and to perform ever more

accurate and human-like movements, holds a promise of replacing humans also in the tasks requiring mental effort.

In transport, automation can be applied either on operational or management level. The first category refers to automation of the driving task, while the latter covers areas like traffic control or infrastructure maintenance. Some transport modes have already reached advanced automation levels in certain areas, in particular in more isolated conditions, like automated metro systems or autopilots for cruise phase in aviation. Currently, the technological progress is allowing to extend these capabilities to more complex circumstances, like road traffic or mainline railway operations. The rise of this trend can be illustrated by the quick advancement of automated driving. The last two decades have seen the popularization of driver assistance features such as adaptive cruise control, lane-keeping systems, emergency braking or self-parking. As of 2024, first cars with level 3 automation according to SAE classification have entered the market, allowing the driver to completely delegate the driving task to the vehicle in certain operational domains (International Transport Forum, 2023).

Increased safety, reduced congestion, more optimized transport operations, and more accessible mobility for excluded groups are among most often discussed rationales for transport automation. One of the contentious issues is the impact of automation on the future of work. The question is of particular interest to the transport sector, which is the third-largest world's job provider, representing roughly 7% of the total global employment. Automation might provide a solution for the ageing working population. In 2019, 52% of European transport workers were older than 45 years. At the same time, the influx of young employees is not sufficient, contributing to work shortages. For example, almost 10% of heavy-goods driver positions were unfilled in Europe in 2021. In addition to filling these vacancies, automation could also create new jobs, e.g. self-driving vehicles technicians, safety drivers, and specialised AI or automated driving engineers. Although these new occupations could make up for the jobs replaced by AI, they would require a different skillset, and most likely a specialised education or staff retraining (International Transport Forum, 2023).

EU strategy

Connected and automated multimodal mobility is one of the flagship objectives of the SSMS. The document advocates for deployment of automated mobility at large scale by 2030, recognizing its potential for reducing pollution and congestion. The strategy envisions Europe to become a leader in CCAM technologies, calling for development of a common R&I agenda and harmonization of traffic rules and regulations. Digital automatic coupling and train automation are recommended as tools for improving the competitiveness of rail freight transport. For automation of cross-border rail mainlines, the strategy plans an update of the existing interoperability specifications.

The EU has been especially active in its support of CCAM, laying out its implementation strategy in the 2018 document "On the road to automated mobility: An EU strategy for mobility of the future". The communication led to creation of the CCAM Partnership, fostering CCAM-oriented research and deployment activities. The EU General Safety Regulation and vehicle type-approval framework for CCAM, adopted in 2022, are the first world's regulation setting rules for deployment of level 4 automated vehicles. Several pieces of legislation are particularly relevant: the Data Act, facilitating data management and exchange for automated vehicles, the Chips Act aimed at boosting the European semiconductors industry, and the AI act which defines a balance between development of the AI-based automation and ethical and security precautions (European Commission, 2024).

In this report

Given the relative maturity and good coverage of the road automation in literature, the report focuses rather on examples of other transport modes, in particular railway with **automatic train operation**, **digital automatic coupling**, and **virtual coupling**. Higher level **U-space** services represent automation trend in aviation. The rising share of car software components responsible for the advanced automated functions is represented by the **software-defined vehicle**. Several digital technologies bear particular relevance for automation, e.g. **edge and cloud computing** for vehicle-to-vehicle and vehicle-to-infrastructure communication, **blockchain** with the smart contract concept for automatic transactions in logistics, and **digital twins** in combination with **Internet of things**, enabling constant monitoring and automatic notifications in case of a required intervention, e.g. replacement of a component in an airplane.

3.4 Circularity

Throughout the 20th century the world has seen a tremendous expansion of human activity, with the global population doubled, and economic activity quadrupled between 1970 and now. This growth was enabled by an unprecedented increase in the use of natural resources. In the same period, the global extraction of materials more than tripled, growing from 27 to more than 90 billion tonnes per year. The underlying economic model that enabled this development is based on a linear approach, which is focused on producing increasing amounts of goods from virgin raw materials. In this model, at the end of their lifetime the items are typically discarded or processed in a way that compromises the value and functionality of the product and its constituent materials. In consequence, such system creates a constant demand for new virgin raw materials, generated pollution, and produces large volumes of waste requiring treatment (European Environment Agency, 2024).

An alternative is the circular approach. In contrast to the linear model, the circular economy is a model of production and consumption involving sharing, leasing, reusing, refurbishing, and recycling existing materials as long as possible, thereby extending the life cycle of products. In the circular paradigm, when a product reaches the end of its life, the materials are kept in the economy and are used again for production of new products, resulting in less waste and less demand for virgin raw materials (European Parliament, 2023).

In transport, the transition to a circular model is particularly evident in the automotive sector, where the strategic shift from internal combustion towards electric vehicles provides an impulse for the industry to reinvent itself more deeply, including the traditional paradigms for manufacturing and product lifecycle management. In 2021, the Renault Group launched the Refactory, a factory dedicated entirely to circular economy. The facility is working on circular initiatives and technology development, e.g. extending life time of vehicles, and optimized resource management (Renault Group, 2024). Another noteworthy example is the Circular Economy Hub established in 2023 by Stellantis, developing solutions for waste sorting, vehicle reconditioning and dismantling, and remanufacturing of batteries and other car parts (Stellantis, 2024). The transition to circular economy gains momentum also in other transport sectors, although to a various extent. Especially the aviation industry made significant improvements in the last decades, currently able to recycle nearly 80% of aircraft components. Typically, up to 50% of an aircraft goes back to the parts distribution pipeline and is reused again in aircraft maintenance (KPMG, 2024).

EU strategy

The current European sustainable growth strategy is outlined in the European Green Deal, with circularity being its central element. The current circular economy strategy of the EU was further addressed in detail in the new Circular Economy Action Plan (CEAP), launched in 2020. Prior to publishing these key policy documents, the circular approach was reflected in many fragmented EU policies, such as the Waste Framework Directive, the Directive on Packaging and Packaging Waste, the Raw Materials Initiative, and Communication on Raw Materials — Tackling the challenges in commodity markets and on raw materials. The common European circular economy policy was first explicitly launched in 2015 with the first CEAP. The document established 54 concrete actions, with measures covering the whole life cycle: from production and consumption to waste management and the market for secondary raw materials and a revised legislative proposal on waste. After successful delivery of the objectives, the package was followed up by the new, updated CEAP (European Environment Agency, 2024).

The current CEAP introduces both legislative and non-legislative measures, translated into 35 concrete actions covering several key areas, e.g. sustainable product design, empowering consumers and public buyers, introducing circularity in production processes, enhanced waste policy, creating a well-functioning market for secondary raw materials, progress monitoring, and leading the global efforts towards circular economy. CEAP also outlines specific goals for value chains of seven selected industries, including batteries and vehicles. The plan calls for a new regulatory framework for batteries, including rules on recycled content, collection and recycling rates, and guidance to consumers. For the automotive industry, the plan assumes revision of the rules on end-of-life of vehicles, with more stress on circular business models, mandatory recycled content for certain materials, and recycling efficiency improvement. The proposed circular approach for batteries was included in the new 2023 Battery Regulation, while a new, updated End-of-life vehicles Regulation was also proposed by the Commission in the same year (European Commission, 2023).

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Circular approach is present especially in the **lightweighting of EVs**, and battery research represented by the **cobalt reduction** trend. Among digital technologies, **additive manufacturing** is investigated in several projects particularly in the circular economy context.

3.5 Resilience

According to a widely accepted general definition from the United Nations, resilience can be defined as "the ability of a system, community or society exposed to hazards to resist, absorb, accommodate to, and recover from the effects of a hazard in a timely and efficient manner, including through the preservation and restoration of its essential basic structures and functions" (United Nations, 2009). In the transport sector, it can be further specified as "the ability of a transport system to absorb disturbances, maintain its basic structure and function, and recover to a required level of service within an acceptable time and costs after being affected by disruptions" (Wan et al., 2017).

In recent years, events like the COVID pandemic and the conflict in Ukraine emphasize the critical role and vulnerability of transportation networks when confronted with major disruptions (European Parliament, 2022). In particular, the COVID-19 pandemic has demonstrated how increased multimodality is also crucial to improving the resilience of our transport system (European Commission, 2020). Moreover, the incidence and severity of climate-related hazards such as flooding have escalated in recent times, with forecasts indicating a substantial increase in these events as a consequence of ongoing climate change. At the same time, inland waterborne transport is also subject to the effects of floods, but also droughts and low water levels.

EU strategy

In response to the challenges that natural or human-induced disruptions may pose to the EU transport system, a series of policy interventions has been established. These interventions are designed to reinforce the resilience of the transport infrastructure, secure the ongoing operation of its services, safeguard passengers and goods, and improve the cybersecurity defences of transport networks.

In particular, transport resilience is a prominent aspect in the SSMS, acknowledging expected disruptions caused by climate change and extreme weather events, as well as the need for cyber security with the increasing automation and connectivity.

To safeguard transport continuity, policy measures include the upgrade of physical and digital transport infrastructure, to ensure multimodality and interoperability between different modes and the completion of the Single European Transport Area (European Commission, 2011), with an emphasis on the TEN-T network to ensure multimodal transport options and system compatibility (Official Journal of the European Union, 2024).

Other strategic and policy documents that address transport resilience encompass the EC Contingency Plan for Transport (European Commission, 2022). The plan outlines recommended actions to direct the EU and its Member States in the implementation of crisis-response measures.

Furthermore, various on-going initiatives tackle cyber security. The EU established a dedicated agency – the European Union Agency for Cybersecurity – for this purpose. The Directives on Security of Network and Information Systems establish a common baseline for improving cyber-resilience, including in transport.

On the other hand, EU investments in connectivity, digitalisation and digital connectivity infrastructures and multimodality are vital for enhancing the resilience of the single market, as well as reducing its dependence on fossil fuels (European Commission, 2022).

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An example of technology that supports resilience of infrastructure is predictive maintenance, allowing for timely inspection and repairs before the actual failure of an infrastructure element. It is enabled by several digital technologies, such as **digital twins**, **Internet of Things**, and **artificial intelligence**. **Additive manufacturing** can be used to produce spare parts needed for maintenance, providing flexibility and independence in case of supply issues. Two technologies are relevant for the topic of resilience from the supply chain and resource availability point of view. **Reduction of cobalt in batteries** is on one hand motivated by ethical concerns, but it also addresses the issue of supply chain fragility, with this critical material being imported from politically and economically unstable regions. In the case of **software-defined vehicles**, the question of chip supply becomes critical, as the key component of the future cars. Europe is currently strongly investing in developing its own chip industry to make its supply chains more resilient and become less dependent on external suppliers.

4 NETTs analysis

The identified technological trends are presented one by one in two separate sections. A distinction was made between cross-cutting digital technologies (e.g. AI), and transport-specific ones (e.g. hydrogen-powered airplane). The first category comprises transversal technologies that find a variety of applications across the entire transport field, whereas in the other case the technology scope is much narrower and clearly delineated. Due to this difference, the way of presenting the results was adjusted accordingly, and the two categories were split into separate sections.

4.1 Cross-cutting digital technologies

The following section provides a closer look at the key technologies that will drive the digitalisation megatrend in the future. The selection includes artificial intelligence, digital twins, additive manufacturing, blockchain, internet of things, extended reality, and cloud and edge computing. Unlike the transport-specific technologies addressed later in the report, the digital technologies are transversal, meaning that they find a variety of diverse applications across the whole transport sector. The intention is to present an overview of each digital technology, including a general description, a literature review on the typical transport applications, and a review of relevant R&I projects, supported by a quantitative analysis breaking down the research activities by transport area and type of application.

The selection of relevant technologies was based both on TRIMIS database and external indicators, as outlined in the methodology. The projects for the review were selected based on key word search of TRIMIS database. Large number of results and various level of importance of a given technology led us to introduce an additional metric – role of the technology in the project. Depending on the project description it is classified as either central, important, or supplementary. 'Central' includes the projects in which the considered digital technology is clearly the key object of investigation, while 'Important' means that the main focus is elsewhere, but the digital technology is mentioned explicitly as one of the important project achievements. The category 'supplementary' covers the projects where the digital technology is merely mentioned, the level of detail is low, or its role is ambiguous. The in-detail project review was performed mainly on the projects belonging to the first two categories. On one hand, it is due to practical reasons, to limit the number of revised projects, as the focus of the report is not directly linked to digital technologies. Many of the omitted projects will be revised in detail in the upcoming report on Innovation, Data and AI for smart mobility, focusing directly on this topic. On the other hand, it is to provide additional context on the statistics on the amount of projects and funding per technology. These numbers are provided for all the three categories combined, which might produce artificially inflated values.

4.1.1 Artificial Intelligence

Transport mode	Key megatrend	No. of identified projects	Total funding [€]
Various	Digitalization	182	943 mln

Technology introduction

Artificial Intelligence (AI) is certainly the most discussed digital technology in the recent years, in particular after the exposure of the general public to generative AI and large language models such as ChatGPT. As of 2023, AI is already surpassing human performance on a number of benchmarks, e.g. image classification, visual reasoning or language understanding. At the same time, humans are still superior at complex cognitive tasks, such as visual common-sense reasoning and planning, and competition-level mathematics (World Economic Forum, 2024). The AI industry is rapidly expanding. The global AI market is currently valued at over €130 billion, and expected to grow up to nearly €1.9 trillion by 2030 (European Parliament, 2024). It is estimated that 40% of the jobs worldwide will be affected by AI (Cazzaniga et al., 2024).

Despite the great popularity of the term AI, it cannot be assigned a simple definition. In a broad sense, it can be described as machines able to mimic human intelligence. AI algorithms are able to interpret and analyse data, and draw conclusions without explicit programming. Many subfields can be distinguished within the AI field, with distinct characteristics and applications. Some of the most well-known branches are natural language processing (NLP), machine perception, and machine learning (ML). NLP allows the AI model to communicate in human languages such as English, and covers problems such as speech synthesis and recognition, machine translation, information extraction and question answering. Large language models (LLM), such as ChatGPT, are

a subset of the NLP field. Machine perception refers to the ability of using the input from sensors (e.g. microphones or cameras) to deduce information about the real world. This category includes image classification, facial recognition, object recognition and tracking. ML is a field of knowledge present in the world of AI from the very beginning. It covers algorithms able to learn from large amounts of data and automatically improve their performance. It is typically classified into supervised and unsupervised learning, the first requiring a labelled training dataset with the expected answers, and the latter learning from unstructured and unlabelled data. Supervised learning is typically used for prediction and classification, while unsupervised learning aims at clustering data, and revealing hidden structures and patterns. Reinforcement learning, considered as another large subset of ML, is based on the principle of maximising the reward by the AI agent. At the beginning of its interaction with the environment, the agent is devoid of any prior knowledge or experience, therefore it must embark on an exploratory phase to understand the situation and determine the optimal actions. Deep learning (DL) is a subset of ML, using an artificial neural network, mimicking the functioning of a human brain. In addition to the usual input and output layers, DL uses multiple hidden layers in between (Sadou and Njoya, 2023).

AI is considered as a potentially revolutionary technology for many fields, with a wide array of potential applications. Examples include agriculture (early crop disease detection, precision farming, soil management), education (chatbots for student support, automated essay scoring, virtual classrooms, personalized learning), manufacturing (design and process optimization), healthcare (medical image analysis, hospital management optimization) and others. At the same time, AI deployment is associated with potential risks, in particular in terms of data privacy and security, ethics, job loss, lack of transparency in decision-making and potential malicious use (Rashid and Kausik, 2024).

Applications in transport

Transport is a complex socio-technical system, combining human behaviour with technology, underlying infrastructure, and policy. The intricate relationship of all these factors is often difficult to understand. As a result, transport modelling and predicting travelling patterns is particularly challenging. AI is a technology that has the potential to deal with such high level of complexity and ambiguity, and its use being heavily investigated for various transport applications, both at strategic transport planning and decision-making level, e.g traffic management, as well as at the level of vehicles and their components, such as environment recognition and navigation of autonomous cars (Abduljabbar et al., 2019).

In the road transport realm, AI is often combined with big data gathered by various sensors and applied in the context of intelligent transportation systems (ITS). The ability of AI to identify patterns and correlations in complex datasets can be applied to key ITS domains, such as prediction (forecasting of traffic flow and speed, travel time, and accidents), recognition (number plate and vehicle identification), optimization (traffic signal control, route planning, traffic and parking management), and vehicle automation (obstacle identification, environmental awareness, autonomous navigation) (Abirami et al., 2024). In case of electric vehicles, AI is increasingly used in optimization of the energy management systems, for improving range and energy efficiency (Arévalo, Ochoa-Correa, and Villa-Ávila, 2024).

For the aviation industry, the majority of scientific literature focuses on AI-assisted methods for forecasting and optimization. On the aircraft level, AI algorithms are investigated for trajectory tuning in navigation systems, regulating fuel consumption, and as diagnostic tools for health monitoring. Another topic is prediction of delays and the impact of natural phenomena such as wind, fog or icing on the aircraft operation. On the level of air traffic management AI offers the possibility of intelligent scheduling and automation of some processes for better handling of high traffic volumes. Airlines apply AI for their own fleet management and seat pricing optimisation. In case of airports, AI is often used in security applications, such as detection of suspicious behaviour, luggage classification, and x-ray scanners. Other, less frequently addressed domains include AI-assisted analysis of human experience, e.g. airline customer satisfaction, and environmental impact analysis, for example estimation of aircraft emissions and airport air quality (Sadou and Njoya, 2023). In case of drones, AI will play a key role in environmental recognition, autonomous navigation, and dynamic path optimization. It is also applied for specific drone use cases, e.g. in agriculture for crops monitoring based on AI-powered image recognition (Caballero-Martin et al., 2024).

In the railway sector, the majority of scientific literature investigates AI applications for maintenance and inspection, followed by traffic management and planning. In the first case, image processing techniques are often applied for detection of physical defects like cracks or missing items within railway components. Other sensor data can also be used, e.g. sound or vibration measurements. AI is also investigated for predicting possible failures before their occurrence and dynamic scheduling of inspections. In case of traffic management and planning, AI is typically used for the problems of rescheduling in case of disruptions, delays prediction, and

timetabling. Other applications include conflict prediction, railway capacity management, shunting and train routing. Less addressed domains include safety and security, autonomous trains, and passenger flow prediction (Tang et al., 2022).

Maritime applications include aid in ship design and shipbuilding (e.g. as an aid for welding processes), as well as assistance in ship operations. AI is able to optimize navigation and detect potential risks by integrating vast amounts of data coming from various sources, including real-time weather patterns, ocean currents, vessel traffic and historical navigation routes. Other uses include predictive maintenance of the ship machinery, assistance in handling of dangerous materials, and crew training (for creating dynamic and realistic practice scenarios). In ports AI has been applied for reducing the uncertainty regarding the arrival of ships, workday scheduling and optimization of the terminal operations (Durlik et al., 2024).

AI in European R&I transport projects

The largest share of projects, with almost 40% of all AI-related projects, belongs to the aviation field, followed by CCAM, electromobility, and road transport initiatives, each corresponding to roughly 10% of the total. Inland waterways, public transport, and urban mobility were the least represented areas. AI was most commonly applied for traffic management, engineering design process, monitoring and maintenance, and navigation algorithms.

Figure 1. Artificial intelligence in European R&I transport projects

The topic of traffic management is strongly dominated by aviation projects. Several of them address high-level decision making, harnessing AI for understanding the optimal path of air traffic management (ATM) evolution. SIMBAD applied air traffic microsimulation and ML techniques on vast historical air traffic data, to develop new ATM performance modelling approaches for reliable evaluation of new ATM concepts and technologies. This effort was complementary with NOSTROMO, a parallel project developing new ATM system-wide simulation methods, taking advantage of active learning for better computational efficiency of the models. A related topic is the optimal integration of AI in the future ATM systems. TAPAS investigated the principles and criteria that would ensure AI deployment for ATM in a safe and trustworthy manner. MAHALO, on the other hand, focused

on the explainability of AI-assisted ATM, especially how good the AI is able to explain its decisions and how well aligned they are with those of a human operator. The resulting framework will serve as a model for future AI system. On the operational level, several projects explored ATM enhancements with AI-based speech recognition. HAWAII developed tools that automatically transcribe voice commands issued by air controllers and pilots, addressing the issues related with distinguishing various accents, deviations from standard phraseology and limited real-time recognition performance. Other projects in this domain include ATCO2 (platform for collection, storage, processing and sharing of voice communication from real-world air traffic control data), PJ05-W2 DTT (automatic speech recognition technologies for air control tower), and VOICI (voice recognition system for the cockpit crew). ARTIMATION developed algorithms based on explainable AI to support two common ATM tasks: air traffic conflict resolution and delay propagation (understanding the reasons for delays). The ISLAND project is developing AI-based air traffic services that can flexibly adapt to meet traffic demand. DISPATCHER3 produced ML techniques for improving pre-departure processes, by estimating the variability between planned and executed flight plans. ISOBAR integrated weather forecasts for predicting imbalances between capacity and demand and applied AI for selection of optimal mitigation measures. PJ18-W2 4D SKYWAYS and START used AI for managing trajectories of aircrafts. Two other projects used AI for optimizing flight allocation. To this end, AICHAIN applied machine learning to data (including sensitive data) coming from airlines in a decentralised, protected way, while SLOTMACHINE developed a semi-automated flight allocation swap platform, based on the cost structure priorities of different airlines. Finally, in the realm of drones, TINDAIR, USEPE, and BUBBLES projects applied AI for automatic management of drone separation.

The other traffic management applications belong mostly to various areas related to road transport. In CCAM, 5GMED carried out cross-border autonomous driving demonstrations, including AI-powered traffic management enabled by sensors deployed along the road, while CONDUCTOR is working on advanced fleet and traffic management solutions and simulations empowered by ML and data fusion. URBANDYNAMICS developed a model for management of urban mobility, in particular applying AI for video content analysis to understand the behaviour of vulnerable road users (VRU). ACUMEN and TANGENT stress the multimodal aspect of traffic management. In the maritime sector, PROMENADE applied AI to improve vessel tracking, behaviour analysis and automatic anomaly detection.

A large cluster of initiatives used AI as an assisting tool in the engineering design process. Also in this case it was employed in a variety of aviation projects. ADMITTED developed an advanced platform for analysis of massive data gathered from test flights, for the purpose of design and testing of rotorcrafts. MYTHOS is applying ML to innovative engine modelling methods, with the ultimate goal of developing engines able to make flexible use of various sustainable fuels. INVIGO used a predictive AI model trained on data coming from aerodynamic tunnel testing for early design of new engine architectures. NABUCCO is working on application of advanced composite structures for design of new generation of aircrafts, assisted by AI for large multi-objective optimizations, high-fidelity simulation methodologies and advanced testing techniques. DIAS used AI for exploring new methods for aircraft weld assembly, and ADENEAS applied it in design tools for design of power and data distribution networks for electric and connected aircrafts. NEXTAIR is combining advanced physical modelling with AI for exploring possible configurations of next generation digital aircraft. In automotive sector, AI is widely used for design of electric vehicles. UPSCALE project incorporated AI into computer-aided engineering tools for EVs design, in particular focusing on aero/thermal and crash modelling. PANDA applied ML for developing a method to organise and interconnect models for all EV components, while REVOLUTION used AI to optimise the input of recycled materials and injection moulding process to deliver high-quality vehicle parts. AI is widely applied for assistance in design of battery system, especially for modelling thermal behaviour of batteries (e.g. ALBATROSS, I-HECOBATT, HELIOS) and battery management systems (DEEPBMS, ENERGETIC, EFFEREST).

In case of monitoring and maintenance, the AI applications can be divided into detection of existing faults (e.g. by image recognition), and prediction of possible failures. For example, in aviation, DCADE used neural networks to detect and locate an arc fault in an aircraft power distribution network, while GENEX and AVATAR are combining AI with digital twins for health monitoring and predictive maintenance. For railway, DAYDREAMS, ASSETS4RAIL, and FP3 – IAM4RAIL applied AI for prescriptive asset management and maintenance. FR8RAIL III developed an Intelligent Video Gate. The gate is able to take pictures of the trains going through, and check for defects and wear with assistance of AI-based image recognition. In road transport, PAVE-SCAN is combining machine vision with satellite images for detection, classification, and georeferencing of roadway pavement surface anomalies. The PANOPTIS project explored similar topic, enriching the data also by drone recordings and terrestrial sensors. HERON used AI for optimal coordination of road maintenance workflows and intelligent processing of data coming from the vehicle and infrastructure sensors. In automotive field, SCAPE is applying AI in combination with digital twin for predictive maintenance of power conversion systems for EVs.

Among navigation applications, AI is present in aviation, CCAM, and maritime domains. FIVER advanced the flight management systems, through massive testing methods based on simulation and artificial intelligence. The ultimate goal is to reduce environmental impact by optimizing flight path and fuel consumption. To similar end, REFMAP is optimizing aircraft trajectories with deep learning methods. PERF-AI employed machine learning on flight data, to measure performance over its life time and optimise flight trajectories. In case of drones, AGILEFLIGHT is developing vision-based, agile navigation in unknown, GPS-denied, and cluttered environments, similarly to the AUTOFLY project. For CCAM, DYNAI is applying deep learning for dynamic scene understanding, similar to PRYSTINE and ALBORA projects. ROADVIEW proposed a solution for AI-based snow removal model, which filters out falling snowflakes in 3D LiDAR data. In the maritime sector, ECOSAIL integrated weather forecasts with route optimization, while PREPARE SHIPS combined data from various sources (satellite, sensors, and historical data) into a navigation solution taking advantage of ML hybrid models. MARINA and SMAUG address the problem of underwater threats detection, by harnessing AI for detection and classification of objects based on sonar and laser data.

Several projects applied AI for high-level transport system planning. MAIA project is exploring the future airport scenarios, in which CCAM and drone-based services will be integrated into airport operations. AI tools in combination with digital twins were used to anticipate the impact of different service configurations. ECON-ML, MOMENTUM and URGENT developed ML models for analysis of travel behaviour, for better informed transport policymaking. SOTERIA is working on AI simulation models for supporting policy decisions on inclusion of vulnerable road users into transport system. DELPHI, on the other hand, is focusing on the strategic dimension of integrating passenger and freight transport in a single transport system. A number of projects applied AI for EV charging planning, serving partially also as an engineering design tool. Examples of projects include Energy ECS (development of smart energy solutions for future mobility), AHEAD (AI-informed charging station locations and grid balancing) and DriVe2X (smart charging and integration with power grid).

A number of projects explored AI interaction with humans. In aviation, this problem was explored for both the air traffic controllers and pilots in the cockpit. AISA developed the concept of an intelligent traffic control system, which instead of automatizing isolated individual tasks would share situational awareness with the human operators. CO2TEAM, on the other hand, introduced a system involving an AI partner to collaborate with the pilot and ultimately assist during flight operations. The project analysed all the tasks and know-how needed by pilots to establish which of them should be kept by the human, and which delegated to the system. HAIKU and SAFETEAM are contributing to the development of digital assistants for various aviation segments and users, focusing on the optimal AI-human interaction, AI explainability, system performance assessment, and approval and certification issues. The CCAM projects stress the importance of AI trustworthiness. AI4CCAM is carrying out simulations scenarios of road users interacting with automated vehicles. The project will develop an open environment for integrating trustworthy-by-design AI models of VRUs behaviour anticipation in urban traffic conditions. AITHENA is working to establish the basis of trustworthy AI, by building explainable AI, researching data, models, and testing. One of the outcomes will be a human-centric methodology and propose a set of key performance indicators on explainable AI. CONVEY is developing adaptive and interactive methods for conveying the behaviour of AI agents, and SUAAVE integrated ethical principles and emotional experience of passengers into the AI controlling automated vehicles. AI was also applied for understanding VRU safety in the overall traffic context. VEVUSAFETY project harnessed AI methodologies to create a privacy-aware deep learning framework learning road users' behaviour in various mixed traffic situations.

In addition to exploring the interaction of AI with humans, several projects applied AI for monitoring and analysis of human behaviour. HIPNOSIS, PEGGASUS, and E-PILOTS developed methods for monitoring of cognitive states of pilots in the cockpit. Image processing allows to detect drowsiness and assess the level of mental workload. Similar work is being performed for car drivers by FITDRIVE, which is developing an AI-based tool for monitoring driving performance, cognitive load, physical fatigue, and reaction time. Some projects used AI for analysis and clustering of driving behaviour patterns, e.g. ROAD LIFEGUARD or MINDED. In CCAM context, the MEDIATOR project developed a mediating system to provide safe switching between the driver and the system based on the driving fitness. AI was used to evaluate driver state, automation status and driving context in real time.

AI use for planning of operations and scheduling is the prevalent application in the logistics domain. Typical problems include real-time asset localisation, cargo management and accurate forecasting and planning. Examples of relevant projects include LOGISTAR, LOGISTICSBRAIN, BX PLATFORM, PREDICTS, and TRANSMETRICS. In case of public transport, AI was applied for finding the most efficient routing for on-demand services (INNOAIR) and optimal use of passenger capacity in a hybrid system combining carpooling and public transport services (UNITE). In aviation, PILOT3 developed a tool for multi-criteria decision support in flight management, able to generate alternative trajectories for the crew, integrating airlines' flight policies and

consider the overall flight performance. ML was applied to estimation of the expected cost of delay and operational uncertainties (such as holding, sequencing and merging distance, taxi time).

In manufacturing, AI is often applied for quality control of the produced elements. Some examples include inspection of aircraft fuselage (ASSASSINN) and engine (CAELESTIS), flange wheels (INN-PAEK), aircraft structures based on composite materials (SONICSCAN), welding quality for maritime (RESURGAM), or train car body elements (CARBODIN). In some cases, AI was used for supporting other manufacturing stages. MASTERLY applied AI-driven control and perception capabilities for manufacturing robots, MARI4_YARD developed AI-assisted exoskeletons for reducing fatigue and physical stress of workers in shipbuilding industry, and SEUS is working on a roadmap for transformation towards smart shipbuilding, including AI implementation at various stages of manufacturing process.

A number of projects applied AI for other purposes, that do not fall easily into any of the above categories. Some projects evaluated the potential and broader impacts of AI: PLANET focused on logistics industry, RAILS on railway, and WE-TRANSFORM investigated the effects on workforce in the whole transport sector. SINAPSE and VACCINE developed AI-based tools for aviation cybersecurity. SMACS developed a ML algorithm for cabin luggage recognition for airports, while FARO applied ML for recognizing patterns that might indicate airport safety risks. HS4U and HEALTHY SAILING provided computational methods for early health risk detection on large passenger and cruise ships. Several projects had more environmental-oriented focus: BECOM is using AI algorithms for detection, classification, and prediction of contrails in aviation, SUPREME focused on ship performance monitoring for reducing emissions and fuel consumption, and AEROSOLS for categorization and prioritising road emissions based on their health impact. A number of projects indicate use of AI, but do not provide sufficient details on the actual application.

4.1.2 Digital twins

Transport mode	Key megatrend	No. of identified projects	Total funding [€]
Various	Digitalization	59	667 mln

Technology introduction

A digital twin (DT) is understood as a digital model of a real-world object, system or process, which is effectively indistinguishable from its physical counterpart. The concept first appeared in the beginning of 21st century, as a tool supporting product life cycle management. The first DT model consisted of three components: real space, virtual space, and a linking mechanism enabling data flow between the two. Due to technological limitations, e.g. low computing power or poor internet connectivity, the idea did not have practical application at the time, but that initial concept remains the core premise of DTs. The term "Digital Twin" itself was coined in 2010 by NASA, as one of the elements of its technological roadmap. In the recent years DTs found multiple applications, initially mainly in aerospace industry, followed by manufacturing, urban planning, healthcare and many other fields.

As the array of DT applications grows, its exact definition became somewhat ambiguous. Although currently there is no general consensus on what constitutes a DT, the common element is the bidirectional exchange of data between the modelled object and its DT, in particular real-time data. It is also the key difference distinguishing DTs from classic simulations and computer models, which are typically static in their nature and while enabling generalized analysis and observations, they do not allow for accurate real-time object representation and production of fresh insights, unless new data is deliberately fed to them. This feature makes the use DTs advantageous for a variety of tasks, for example tracking the status of the physical twin throughout its lifetime, real-time control and optimization, performance and health prediction, and design and validation of new or existing products and processes.

One of the main advantages of DT lies in the cost reduction. Traditional prototyping or redesigning a product requires use of physical materials and labour, and might require destructive tests. DTs allow for testing prototypes in purely virtual manner, exploring multiple scenarios and designs at zero additional cost and in a much shorter time. DTs are particularly useful for maintenance and monitoring. Thanks to real-time data connection it is possible to constantly monitor the state of the physical twin and detect potential problems at different stages of its life cycle. This feature can be used, for example, in predictive maintenance or system optimization. Some other advantages include the potential of using DTs for remote control of the physical counterpart, increased safety, especially in hazardous industries like oil and gas or mining, or the possible use for training purposes before accessing the actual physical machinery.

DTs can be classified in several ways, one of them being the scale of the model. In case of a single element design DTs at a unit level are used, whereas broader use cases such as optimization of the whole manufacturing process require models at a system level. DTs can be also categorized by their application, into general categories of predictive and interrogative models. While the first type is focused on the future behaviour of the physical twin, the second is used for interrogation of the past and current states. Further differentiation can be made by the level of sophistication of the model or extent of data integration with the physical counterpart.

Applications in transport

DTs find their applications across the whole transport value chain, in particular in the automotive and aviation sectors. In the car industry they assist in the design process, contributing to cost reduction by reducing the number of physical tests. Given the increasing complexity of modern cars, especially the vehicle electronics, DTs allow for easier design and monitoring at system level. At manufacturing stage DTs facilitate integration of new car models production into existing production lines. At later stages of the vehicle life cycle, the data collected by the vehicles can be fed back to a DT and used for health monitoring and optimization of the vehicles, possibly by over-the-air software updates. On a transport system level the possible applications include road traffic management, and verification of intelligent driving (Deng et al., 2023; Piromalis and Kantaros, 2022).

In aviation, DTs are mostly applied at manufacturing and maintenance stages. Due to high complexity of aircrafts and high level of coupling of variables DTs facilitate tracking interdependent characteristics of a plane during the design process. The assembly process in aviation is characterized by high complexity, uncertainty and strong dynamics – DTs facilitates manufacturing management by real-time update and processing of data that would otherwise be scattered in multiple businesses and management systems. Other important applications include aircraft health monitoring and maintenance planning (Xiong and Wang, 2022).

In rail transport DTs are mainly used for predictive maintenance, inspection, and health monitoring of railway infrastructure (Zhang and Zhang, 2023). In maritime sector DTs are still considered to be at an infant stage. In addition to the typical DT applications, some maritime-specific use cases include testing and design of autonomous vessels (DNV, 2024), monitoring of port infrastructure, or remote ship maintenance by an expert operating from a distant location (Madusanka et al., 2023). DTs are also a promising enabler for a more resilient transport infrastructure, thanks to remote monitoring capabilities and condition-based maintenance (Vieira et al., 2022).

Digital Twins in European R&I transport projects

The majority of projects that incorporated DTs belongs to aviation, followed by a roughly equal share of automotive, maritime and railway applications. In the majority of cases DTs were used at the development stage, as engineering tools for virtual prototyping. In several cases, the scope of such model went beyond the design phase, e.g. including the possibility of full life cycle monitoring. Among the other applications, the most popular were life cycle assessment, predictive maintenance and decision support systems. The last category covers those DTs that represent systems at high level, aiming to facilitate strategic policy decisions.

Figure 2. Digital twins in European R&I transport projects

Digital Twins in European R&I transport projects
Number of projects by transport area, type of application and role in the project
Total number of projects: **59**

TSM – Transport System Management
PT – Public transport
UM – Urban mobility

Number of projects by the role of technology

Central	Important	Supportive
12	30	17

Source: JRC

In aviation domain, several projects work on engineering tools where DTs play a central role. CAELESTIS is developing a platform for virtual prototyping of aircrafts, covering the whole aviation value chain. The platform will use high-detail DTs to leverage on multidirectional data flows linking product design and distributed engineering teams. The ultimate goal is to accelerate and optimize the engineering and manufacturing of disruptive aircraft and engine configurations. NEXTAIR is working on new digital tools for aircraft performance optimization, e.g. novel design methodologies, data-fusion procedures and smart health assessment tools. DTs developed within the project will serve for smart prototyping and maintenance. Two projects address the incorporation of composite materials in the aircraft design. GENEX is developing an end-to-end digital twin-driven framework based on enhanced computational models, to support manufacturing optimization and health monitoring of composite structures. INFINITE is working on a similar solution, harnessing data for the DT with

a system of sensors embedded in the composite structural parts of the aircraft. Lastly, AVATAR is dedicated to creating a digital twin platform enabling continuous monitoring and predictive maintenance of an air vehicle throughout its service life. Several projects used DTs as an engineering aid tool while developing some specific aviation technologies, mainly for virtual prototyping. Examples include HECATE and HYPOTRADE (hybrid-electric aircraft power system), FLHYING TANK (hydrogen storage for aviation), and THEMA4HERA (thermal management for hybrid-electric aircrafts).

The last type of application was also most common in automotive projects, typically for optimization of various EV-related technologies. DTs facilitated the development process in projects such as EM-TECH and MAXIMA (electric machine technologies for automotive traction), VISION-xEV (hybrid powertrain layout for an urban bus application, and battery management system), and HELIOS (battery packs). ESCALATE developed several DTs accompanying five test cases covering various zero-emission powertrain technologies for heavy-duty vehicles. SCAPE project equipped its EV power conversion system with a DT for health monitoring and predictive maintenance purposes.

In waterborne transport, similar to aviation, some projects built comprehensive, scalable tools based primarily on DTs. DT4GS is developing an Open Digital Twin Framework, with the general objective of boosting DT use in the sector. Among others, the project analysed the potential of DT, and developed DT-based tools for ship and fleet performance optimization. FLEXSHIP is working on a DT tool for vessel electrification, allowing for electrical grid architectures optimization, integration of a high-efficiency battery system, and creation of a safe integration guide for system interoperability. RETROFIT55 is building a decision support system for finding the optimal configuration of energy-saving solutions in ship retrofitting. The tool fuses DTs of different ship systems into an integrated digital ship model. VESSELAI developed a DT-based tool for highly accurate modelling, estimation and optimization of design and operation of ships and fleets under various dynamic conditions in near real time. In the RAPID project, DT of the Port of Hamburg was used to simulate airborne hazards, in order to understand how drones can be applied for automatic port inspection. FIBRE4YARDS applied DTs at the stage of manufacturing: its DT model of shipyard allows for monitoring and control of different production and maintenance processes.

In railway, the leading topic is asset management and predictive maintenance. Several projects developed DT-based solutions for improving the reliability, availability, and maintainability of the railway system, e.g. FP3 – IAM4RAIL, IN2SMART2, and LOCATE. The FUNDRES project developed a DT assisting in railway electrification. The tool offers the possibility to predict the behaviour and the impacts of the proposed unified electrical system based on 9 kV-DC.

In addition to railway maintenance, some projects worked on similar solutions for road infrastructure. BRIDGESCAN developed a method of bridge health assessment, using laser scanning to acquire 3D topographic data points of bridges. The data can be integrated into a digital twin platform, for more accurate bridge response prediction. INFRAROB is working on a range of solution for automation of road construction and maintenance. The project is developing a DT-based tool for predictive maintenance planning based on real-time data on pavement conditions. CIRCUIT is developing technologies supporting circularity and resilience for transport infrastructures. Among others, it is working on tools for managing highway infrastructure, e.g. bridges and tunnels, combining DTs with drones for scanning the monitored structures.

Other noteworthy examples of projects include LEAD (DT of urban logistics network for experimentation and decision making with on-demand logistics operations in a public-private urban setting), SPINE (DT tools for building and testing scenarios combining different smart mobility interventions in cities), and ACUMEN (DT to support traffic management and decision-making in complex urban mutimodal networks).

4.1.3 Additive manufacturing

Transport mode	Key megatrend	No. of identified projects	Total funding [€]
Various	Digitalization	62	196 mln

Technology introduction

Additive manufacturing (AM), also known as 3D printing, is defined as a manufacturing process where objects are produced through deposition of material in a layer-by-layer fashion. It can be seen as the opposite method to the traditional and more commonly used subtractive manufacturing, in which layers of material are removed to achieve the desired geometry (Abdulhameed et al., 2019). The first concepts of AM date back to 1980s, intended mainly for rapid manufacturing of small-scale prototypes. The technology development remained

relatively stagnant up to mid-2010s, when advancements in materials and computer science caused exponential growth of AM-related research and enabled significant improvements of precision, speed and scale of 3D printing (Kanishka, 2023).

AM offers certain unique characteristics compared to other manufacturing methods. Contrary to subtractive processing, with layer-by-layer fabrication it is possible to produce objects of intricate shapes relatively easily and with minimal amount of material waste. The design process is highly simplified by software tools – typically a digital 3D model is prepared first with CAD software, which is then automatically translated into machine-readable code used as an input for the 3D printer. Due to these features AM is often associated with the idea of "complexity for free", meaning that complex geometries can be easily fabricated without an increase in production cost. In addition, AM can be applied to a variety of materials, ranging from plastics, ceramics, and metals to sand and biochemicals.

Thanks to these features AM has the potential to bring disruptive transformation to manufacturing and entire supply chains. Rapid prototyping reduces cost and time needed for the testing phase of innovation, thereby reducing the time needed for products to reach the market. By enabling easy production of customized objects AM opens the avenue for mass manufacturing of personalized items. One of the promising fields of application is healthcare, for example for production of customized implants. In case of advanced machinery, even the most complex spare parts can be easily printed on-demand, which means reduction of repair times and required storage space. Another novel possibility is remote manufacturing, where the parts are printed in distant locations based on digital models created elsewhere. A remarkable example is remote printing on the International Space Station, where AM allows for necessary maintenance without waiting for spare parts to be transported from the Earth (Airbus, 2024). 3D printing is also seen as one of the key components of the Industry 4.0 concept, which is built on the assumption of more versatility, flexibility and individualization of the manufacturing process (Horst, Duvoisin, and de Almeida Vieira, 2018).

The AM technology is still characterized by quite some limitations. The range of materials it can work with, however broad, is still limited compared to more conventional methods. The choice can be limited by the required printing temperature or a need for specialized machinery. AM is sensitive to the manufacturing conditions, which might affect product strength and mechanical properties. Possible inconsistencies among fabricated elements require rigorous testing and validation, especially for safety-critical applications. 3D-printed objects often require additional post-processing to obtain the desired finish and functionality. In many cases hybrid manufacturing methods have to be applied, contributing to the higher cost of the overall process (Kanishka, 2023).

Applications in transport

So far, AM has been most widely applied in aerospace and automotive sectors, and for these applications the technology has reached the highest maturity. In case of aerospace industry, the key consideration is to minimize the weight of the aircraft, often by reduction of the material used. Since this process often entails an increase in components complexity, AM with its ability of layer-by-layer freeform fabrication is especially beneficial. Traditionally AM was merely a prototyping tool for fabricating simulation models of aircraft parts, e.g. for testing streamlines around the airfoils and fuselage. For such use cases it is usually not required to use the target material – 3D printing of polymer-based elements instead of metal-based ones provides quick and cost-effective measures to validate new designs. Nowadays, AM is also widely applied to direct manufacturing of actual aircraft components, both critical (e.g. nozzles, engines, and combustion chambers) and non-critical ones. For example, Boeing incorporated more than 70 000 3D-printed parts in their airplanes to date (Aviation International News, 2022). Airbus managed to reduce the time needed for development and manufacturing of a cable routing mount for the A350 XWB model to less than two weeks, corresponding to time savings of 90%. The component consisting previously of 30 separate parts can now be manufactured as a single element (EOS, 2024). AM is seen as a great candidate for production of heat exchangers, since the heat transfer is directly proportional to the complexity of their geometry (Alami et al., 2023). Further aerospace applications include rapid tooling, meaning production of tools and moulds needed to fabricate other components, and manufacturing parts for repair and restoration.

In automotive industry, AM is traditionally linked mainly to tooling and prototyping. A developing trend is AM application for spare parts manufacturing. For example, Porsche Classic cars are highly sought-after by collectors, while production of relevant vehicle components either has been discontinued completely or is not financially viable due to small batches. As a solution, Porsche offers on-demand manufacturing of rare spare parts for its older inventory (Haria, 2018). Car personalization is yet another emerging trend. Daihatsu, a Japan car manufacturer, allows the customers to design and order customized 3D-printed panels for front and rear

bumpers (Hipolite, 2015). Ford installed in their Maverick model a series of slots that can be used by the user to attach their self-designed and printed 3D customized parts, according to their individual needs (Ford, n.d.). Porsche offers the possibility to customize the driver's seat, adjusting the rigidity and shape with the help of AM (Porsche, 2021).

3D-printing is also being explored in other transport fields, although the maturity of solutions is at considerably lower level. Maritime industry is characterized by operations in remote areas and random, often harsh and corrosive environmental conditions, which affects the criticality of ship maintenance. AM is investigated for on-board or next port spare parts production, to increase the flexibility and reliability of the necessary repairs (Kostidi and Nikitakos, 2017). In railway, the use of 3D-printing for rolling stock design and repair were investigated (Gomes and De Jesus, 2024), as well as for manufacturing of railway infrastructure elements (Fu and Kaewunruen, 2021). These applications are however still at an exploratory stage.

Additive manufacturing in European R&I transport projects

Out of 62 identified AM-related research projects almost three-quarters belong to aviation sector. Second most populated transport area is railway with 5 projects, same amount as for projects addressing various transport modes. Some examples in this latter group include MAST3RBOOST, which 3D-printed hydrogen containers with dedicated on-board optimized shapes for various transport applications, or GLAMOUR, utilizing AM for manufacturing catalysts prototypes for biofuel production in aviation and marine applications. Automotive is represented with an unexpectedly low number of 3 projects, followed by 2 maritime initiatives. The least populated research areas are logistics and road infrastructure, with a single project per each.

Figure 3. Additive manufacturing in European R&I transport projects

Additive manufacturing in European R&I transport projects
Number of projects by transport area, type of application and role in the project
Total number of projects: **62**

Source: JRC

A number of research avenues can be distinguished. Several projects are focused on advancing the AM technology itself, including novel AM methods for manufacturing hydrogen tanks (MAST3RBOOST), non-destructive methods for testing 3D-printed aircraft alloy parts (3TANIUM), simulation models and numerical methods for defect prediction in AM-produced objects (SUPERMODEL, ASSALA), or new AM methods for manufacturing of large aviation components, e.g. engine parts (MONACO) and elements with high curvature (RIB-AM). SUSTAINAIR applied AM for manufacturing of pins for joining metal parts of the aircraft. STREAM and AMANECO advanced AM technology for aircraft heat exchangers manufacturing, by addressing certain technological barriers to apply metal AM for this kind of elements, and providing simulation tools for modelling turbulence and roughness in such parts.

The most common application is employing AM for manufacturing the principal product developed in a project. AM was often used to fabricate particularly complex shapes, e.g. high-precision antennas (3DGUIDE), electrical raceways (ICEPASS) or heat exchangers (C-ALM AOHE, NATHENA). In certain cases, AM was used for creating moulds used later for the manufacturing of the final product., e.g. flange wheels for aircrafts (INN-PAEK) or various train body elements (CARBODIN). Some other aviation applications include flap track system (ADDIFLAP), seals (ADDAPTTA SEALS), door locking mechanisms (TOD), engine combustion chamber (START) or fuel level sensor (STRONGRCRAFT). In railway projects AM was applied for manufacturing of traction systems (RECET4RAIL) and aerial brackets for metro trains (NEXTGEAR).

In some cases, AM was not used to produce the final product, but served for creating small-scale prototypes during the design process. Project examples include SACOC (heat exchanger design for aviation), ANTIFOD (debris protection in electric aircrafts), LOOPS (testing different designs of spinning combustion for helicopters), or DOLPHIN (various architectures for fuel cells in automotive).

Several projects explored the potential of AM in the broader context of novel manufacturing concepts and value chain innovation. For example, FLEXCRASH employed 3D-printing for hybrid manufacturing methods aimed at production of crash-tolerant structures for automotive sector, while MAYA developed new approaches for aircraft fuselage production. Another common theme is AM application to circular manufacturing (e.g. EURECOMP, ECO-CLIP). FIBRE4YARDS investigated how 3-D printing could be applied to shipbuilding, expanding on the Industry 4.0 concept.

Lastly, few projects applied 3D-printing specifically for repair and maintenance purposes. RETPAIR developed AM-based repair technologies for aviation, FP3 – IAM4RAIL addressed management of railway assets, and INFRAROB focused on road maintenance, employing AM for repairing cracks and potholes in asphalt.

4.1.4 Blockchain

Transport mode	Key megatrend	No. of identified projects	Total funding [€]
Various	Digitalization	18	82 mln

Technology introduction

Blockchain (BC) can be described in simple terms as a decentralized database with some special characteristics. The first BC was launched in 2009 as a technological enabler for implementation of Bitcoin, the first ever digital cryptocurrency. Although finance remains the main area of application, the underlying technology is considered promising for a large number of other sectors, such as transport, healthcare, e-commerce or insurance (Bugawa, 2024).

Essentially, BC is a chain of time-stamped blocks containing information, linked together in a particular architecture. The main working principle can be explained by breaking it down to several layers. The bottom-most one is the data layer, referring to the blocks themselves. Each block has the same structure, consisting of a header and a body. Header of each block contains a reference (hash) to the previous block in the chain, timestamp with the block creation time, and a Merkle root – essential part of a binary tree mechanism for ensuring integrity of the blockchain. The body contains a transaction recorded in the block. Depending on the context, it can be monetary data, medical record, industrial information, etc. Linked together, the blocks constitute a virtual, chronological ledger of all the registered transactions.

Such ledger is not stored in a single centralized location, but instead exists in the form of many identical copies in the network layer. These duplicates are stored on multiple computers, called nodes, that can be scattered in various locations around the world. The purpose of this layer is to distribute and authenticate the transactions. When a new transaction is made, it is sent to the network and validated based on a consensus principle, before being added to the BC. The consensus layer is the core element of the technology, ensuring that all the nodes in the network agree on the same state of the BC. Many consensus mechanisms exist, proof-of-work (PoW) and proof-of-stake (PoS) being the most common ones. Participation in the validation process is encouraged based on a layer of incentives. According to this mechanism it is in the nodes' self-interest to add new blocks to the chain and to replicate other blocks added to it. For example, in case of PoW, the nodes carrying out the validation must solve a complex mathematical problem, which requires considerable computational work, but of which the answer can be easily verified by the other nodes once found. The node which found the solution is rewarded for the work performed. The prize depends on the BC itself, in case of the Bitcoin BC (based on PoW) the winner will be awarded with the corresponding cryptocurrency – bitcoin. The incentives motivate users to participate in the network, and the more nodes and copies of the BC exist, the higher the overall security of the system.

As a consequence of its design, BC offers some specific features in comparison to traditional databases. Since a copy of the ledger is held by all the participants of the network, there is no need of supervision of a centralized authority to validate the transactions. At the same time, mutual trust between the parties becomes irrelevant in terms of ensuring a safe transaction. Moreover, once the data is added to the BC, it practically cannot be changed or lost - the historical record of transactions is immutable and stored permanently in the system. From security point of view, BC is easier to manage in terms of risks such as network disruption or single point of failure. BC also facilitates execution of smart contracts. In essence, they represent a set of rules which automatically trigger a BC transaction once the predefined conditions are met.

There are several limitations and challenges surrounding the technology. One concern is the high energy consumption. Certain consensus mechanisms, most notably PoW, require high computational power. Less energy-expensive methods exist, but they usually come at the price of reduced security (BelMannoubi et al., 2023). Even though theoretically BC is a secure system, concerns regarding data safety and privacy nevertheless exist (Bhutta et al., 2021). Another issue is scalability – as the networks becomes larger, its throughput and latency might affect the time required for transactions. In systems involving many different software platforms and data structures interoperability might be challenging (BelMannoubi et al., 2023).

Applications in transport

The most widely discussed transport-related BC application area is logistics. Modern supply chains are characterized by large size and complexity, in terms of flow of information, physical goods, and financial transactions. At the same time, fragmentation of the industry, lack of process standardization and reliance on paper-based documentation cause significant inefficiencies. BC might be able to unlock the value trapped by these reasons. If all the actors have unrestricted access to a digital ledger storing all relevant transactions, real-time cargo location, documents and shipping data the information asymmetry can be greatly reduced. Smart contracts have the potential to digitalize payments, which would be carried out automatically once the goods

are delivered. Currently, lengthy administrative procedures lead to excessive waiting times, for example in maritime logistics it takes on average 42 days for the money to reach the invoicing organization (Farah et al., 2024). BC offers an improved traceability of products – if the life cycle of an item is registered it can be easily verified by the logistics actors, but also by the final customer. Food quality and safety control or tracking product sustainability and authenticity are some of the possible applications. BC can also be used for keeping track of warehouse inventory. For many of such applications it is important that the data is reliably registered and stored on the BC, therefore Internet of Things sensors are often mentioned as a necessary component for BC implementation.

In maritime, BC was also proposed for keeping tamper-proof documentation of ship operations, including vessel movements, maintenance records and fuel consumption, as well as streamlining the claims processing in marine insurance. Similarly, BC was proposed for keeping track of drones for purpose of air traffic management, as well as some other applications, e.g. safe data exchange for coordinated drone services. In case of road transport, the concept of cooperative transport systems assumes interaction between vehicles and infrastructure and continuous data collection. Reliability of these data is essential as it is used for traffic management, directly affecting road safety. BC is proposed to maintain the required integrity, privacy and homogeneity of the collected information. Other examples are matching of supply and demand for electric vehicles charging, tracking vehicles life cycle or collection of data for forensic services in case of road accidents (BelMannoubi et al., 2023). In railway, BC can help to securely store data pertinent to infrastructure maintenance and train operations (Sharma and Sharma, 2022).

Blockchain in European R&I transport projects

In line with the expectations, the majority of BC projects focused on logistics applications, followed by aviation and railway. One project was identified for each of the remaining categories: ride sharing, CCAM and inland waterways. Although each project provides a specific context for BC implementation, usually the emphasis was put on either the need for secure data management or on smart contracts. Initiatives not classified in these two categories were usually of a larger scope and a more exploratory character, for example aiming at understanding the broader BC implications.

Figure 5. Blockchain in European R&I transport projects

The logistics-focused projects investigated a number of various industry dimensions, applying BC mainly for smart contracts implementation. TRACE is developing a universal web platform for improving integration and harmonization of operations across the logistics sector, applying BC for real-time conclusion of transport contracts and financial operations. Similar work is done in ESEP4FREIGHT, which is developing a web platform with tools for rail freight, aiming at increasing the sector competitiveness. COG-LO implemented BC-based smart transactions for developing its concept of "cargo hitchhiking" – a dynamic form of optimal cargo merging based on collaborative approach. URBANE, on the other hand, developed novel collaborative solutions for last-mile logistics, among others utilizing the smart contract functionality. FOR-FREIGHT aims at integration of innovative technologies into multimodal logistics, stressing BC application specifically for secure data storage.

Data security is the main motivation for BC implementation in case of aviation-oriented projects. Several projects developed new concepts for air traffic management (ATM). AICHAIN developed a solution for exploitation of private datasets coming from various aviation stakeholders to train machine learning models for ATM optimization. BC was employed to ensure data privacy and trustworthiness. In case of CERTIFLIGHT, BC is used for secure storage of drone position and flight information, for managing drone traffic. In addition, the solution enables the use of smart contracts, which can be activated based on a particular flight path or performance. SLOTMACHINE developed a system for swapping ATM slots between airlines. So far, the airline is allowed to only swap their own slots, while the new solution allows secure swapping between different companies, without disclosure of sensitive information. Lastly, SHOGANAI developed a tool for controlling the airplane operational costs, where BC is used for safe storage of data registered during the flight.

Other relevant project examples include B4CM (evaluation of BC potential and applications in rail sector), DAYDREAMS (BC for secure data tracking for predictive rail maintenance), COSAFE (BC for cooperative sensing and computing in CCAM), IW-NET (innovative solutions for inland waterways digitalization, smart contracts used

for synchromodal booking), and RIDE2RAIL (smart contracts for enhancing trust between the driver and the passenger in case of ride-sharing).

4.1.5 Internet of Things

Transport mode	Key megatrend	No. of identified projects	Total funding [€]
Various	Digitalization	30	278 mln

Technology introduction

The Internet of Things (IoT) represents a network of physical objects, such as machines, buildings, and vehicles, embedded with electronics and connectivity that enable data collection and exchange, and performance of actions without the active involvement of a human operator. IoT in its current form started to emerge in early 21st century, and in the recent decade it has seen a rapid growth, facilitated by major improvements in wireless networking technologies, internet connectivity, and declining sensors cost. It is estimated that in 2020 for the first time ever there were more machine-to-machine type connections than non-IoT connections, such as smartphones or personal computers (OECD, 2023).

IoT relies on three layers of technological building blocks. The bottom-most tier refers to data acquisition. Depending on the purpose it can be realized either through radio-frequency identification (RFID), QR-codes, or bar codes for product identification, various types of sensors for more precise measurements (e.g. temperature, humidity, etc.), or services like GPS or General Packet Radio Service (GPRS) for geolocalization and tracking. Connectivity between IoT devices is guaranteed by the communication layer, covering several technologies depending on the required range, spanning from satellite or cellular connectivity (5G) for global applications, to Wi-Fi or Bluetooth for short-range coverage. Lastly, the large amount of collected data is processed in the data layer, with help of cloud computing and big data analytics (Tran-Dang et al., 2020). The challenges surrounding IoT are related to the underlying technologies, among the most discussed ones are security and privacy of the communication layer, as well as bandwidth and network coverage. Another concern is the large amount of energy consumed by massive sensor networks (Singh et al., 2022).

Since pretty much any object can be equipped with IoT devices, there are endless possible applications of the technology. In healthcare, IoT is used for remote health monitoring, allowing the patients to stay at home. In agriculture it can help to reduce water waste by monitoring the state of soil and automatically turning on irrigation system when necessary. IoT is an enabler for the smart home concept, e.g. for measuring home conditions, managing household appliances or controlling access to the house. It also plays a central role in smart cities, allowing for collection of massive amounts of data, that can be used for improvement of city services. For example, in case of smart waste management it can be used for measuring the amount of waste in the containers garbage collection optimization. IoT is also central to the Industry 4.0 manufacturing concept, enabling constant monitoring of factory operations and predictive maintenance of the production line (Chataut, Phoummalayvane, and Akl, 2023).

Applications in transport

In logistics, IoT allows for a data-driven management and optimization of goods flow. On the transport side of the business, it helps to track cargo and trace vehicle parameters such as temperature, humidity, or lighting conditions. The gathered information can be applied for optimizing vehicles routes, fuel consumption reduction, or maintaining the right quality of products. Apart from moving goods, IoT also helps to keep track of the inventory in warehousing (Crnjac Milić, Dujmenović, and Peko, 2023). IoT is the fundamental technology for physical internet – a new logistics paradigm where the goods flow is similar to the flow of data over the Internet. In maritime logistics, IoT is a key technology for the smart port concept, which relies strongly on interconnectivity and process automation. Some of the elements are automatic cranes, predictive maintenance, and the use of automatic guided vehicles (AGVs) for transporting containers between the berthing area and a storage yard. IoT sensing capabilities are applicable for tasks like structural health monitoring of cranes, tracking container position, and localization and navigation of AGVs (Yang et al., 2018).

As mentioned, IoT is essential for smart cities, which also includes urban transport. Data from IoT sensors, combined with citizen participation data, can be employed for better understanding of traffic flows and improving the efficiency of a transport system. In case of parking management, IoT is used for parking demand management and space optimization, enabling features like personalized parking guidance, booking systems, dynamic parking price or illegal parking detection. In public transport, information coming from IoT sensors can

be combined with crowd sensing for better crowd management and service information systems (Zeng, Pang, and Tang, 2024).

In case of drones, IoT enables a variety of use cases in areas like agriculture, surveillance or medical services. In addition, it can work as an extension of terrestrial communication infrastructure contributing to the overall performance of drone traffic management (Labib et al., 2021). In railway, IoT can collect real-time data on trains and the infrastructure. So far, it was applied to problems like rolling stock monitoring, condition-based maintenance of railway tunnels, train localization, dispatch systems, or weather monitoring (Laiton-Bonadiez et al., 2022).

IoT in European R&I transport projects

The majority of research projects applied IoT to logistics and maritime, followed by road transport and aviation. In total, 30 relevant projects were identified. As mentioned, essentially IoT devices can be attached to any object for data collection, which is reflected by the large variety of identified applications.

Figure 6. Internet of things in European R&I transport projects

Internet of Things (IoT) in European R&I transport projects
Number of projects by transport area, type of application and role in the project
Total number of projects: **30**

Three projects dealt with
Cargo tracking and optimisation in *logistics*.
In two projects **IoT** technology is *central*,
in another two is important and in one – *supplementary*.

One square – one project.
The shade refers to
role of the technology in the project

IoT – Internet of things
PT – Public transport

Number of projects by the role of technology
Central | Important | Supplementary
8 | 13 | 9

Source: JRC

The logistics projects applied IoT mainly for cargo tracking and process optimization. ICONET advanced the concept of physical internet (PI) by developing new architecture for interconnected logistics hubs. The outcomes included new PI-based business models and an experimental platform for simulation and testing of PI concepts. COG-LO introduced its own PI-related idea of Cognitive Logistics Objects, which can represent any physical object in a supply chain (cargo, vehicle, warehouse, etc.). By connecting such objects with IoT they are able to communicate and negotiate potential collaborations for cargo consolidation. DECARBOMILE applied collaboration concepts for decarbonisation of last-mile logistics. IoT is used by the project to keep track of the content and location of smart boxes used for deliveries. NEXTETRUCK developed a variety of new concepts for electric medium-duty vehicles, among others a fleet management system based on IoT.

Maritime projects focused mostly on developing various IoT solutions for smart ports, e.g. port asset management, predictive analytics, or real-time dynamic KPIs reporting (ITERMINALS 4.0, COREALIS, PIXEL, PORTFORWARD). FIBRE4YARDS used IoT for implementation of a Shipyard 4.0 concept. The IoT devices provide a real-time input for a digital twin for controlling and maintaining the shipbuilding process. For inland waterways, IW-NET used IoT to enable real-time monitoring, tracking, and control of vessels, cargo, and infrastructure. The insights from the data were used to optimize operations. The project also applied IoT for development of a new shore power concept.

In road transport, EBRT2030 is working on innovative solutions for bus rapid transport, notably an IoT-based fleet management system for such vehicles. FITDRIVE is developing a system for monitoring performance of drivers, including cognitive load, physical fatigue and reaction time. The data is collected from IoT devices and fed to neurophysiological models able to detect anomalous behaviour. Safety improvement is also the goal of STREAM, which developed smart technologies for improvement of workers' safety in railway industry. The project proposed two robotic tools – a mobile manipulator and an exoskeleton. The data registered by these devices is constantly monitored via IoT devices, allowing supervisors to quickly react in case any danger is detected. Among aviation-oriented projects, two of them apply IoT in combination with digital twins: AVATAR develops a platform for continuous monitoring of an airplane for predictive maintenance based on digital twin combined with IoT sensing skin, while GENEX implements the two technologies in a tool for monitoring the state of aircraft components throughout their life cycle. CERTIFLIGHT builds a drone tracking system combining IoT with satellite system (EGNSS).

Several projects were related to some of the technological challenges surrounding IoT itself. REACT addressed security issues, more precisely developed simulation models for measuring and modelling of the impact of cyberattacks on 6G-enabled massive IoT networks. SWAN-ON-CHIP investigated the problem of high power consumption, developing IoT chips based on spintronics technology. AB4RAIL explored the possible communication bearers that could accommodate the increasing number of IoT devices present in trains.

4.1.6 Extended reality

Transport mode	Key megatrend	No. of identified projects	Total funding [€]
Various	Digitalization	20	68 mln

Technology introduction

Extended reality (XR) refers to a combination of technologies that enable users to explore a world beyond reality, using three-dimensional (3D) graphic elements and sensory experiences (e.g. touch, motion) to create a sense of spatial presence (Postelnicu and Boboc, 2024). XR is an umbrella term used to cover Virtual Reality (VR), Augmented Reality (AR) and Mixed Reality (MR). VR creates a completely artificial, digital environment that is immersive and interactive, essentially simulating a different reality (Chhabhaiya, Bhumeshwar, and Praveen, 2024), while AR is a technology that expands and enriches the perception of the real world (Mikušová et al., 2024). Mixed reality (MR) is a collective term encompassing all the environments where both physical and virtual element coexist (Chhabhaiya, Bhumeshwar, and Praveen, 2024).

More specifically, VR can be defined as a collection of technologies for generating a human–computer interface allowing the user to be immersed and interact with computerized 3D environments while using their natural senses and motor skills in real time (Hardiess, Meilinger, and Mallot, 2015; Wong and Lee, 2024). VR essentially replaces the natural environment with a virtual one. On the other hand, AR's basic functionality consists of creating links, direct or triggered by user interaction with the device, between the real world and the additional layer of digital information (Arena et al., 2022). It is typically done by using head-up devices, AR glasses, or common electronic tools like smartphones or tablets. The goal is to increase the comfort of perception, support the user's convenience, and provide the availability of information in real-time (Mikušová et al., 2024).

Although first concepts of the technology existed as early as the 1960s, XR only began to emerge in the 2010s as a result of advancements in other fields such as electronics and computer graphics (Anastasiou, Balafoutis, and Fountas, 2023). XR has evolved significantly in the last decade and today it is used in various domains including manufacturing, entertainment, education, medicine and agriculture. Some examples include assistance on an automotive assembly line, safety training for construction workers, interactive museum guidance, teaching human anatomy to medicine students, and many more (Adriana Cárdenas-Robledo et al., 2022). During the last decade, the hardware and software used in XR applications have matured, while portable and wearable device manufacturers have been continuously investing in research and development. As a

consequence, XR capabilities and the number of its (especially industrial) applications have grown exponentially (Molina Vargas, Vijayan, and Mork, 2020). At the same time, the technology cost is rapidly decreasing (Mikušová et al., 2024; Wong and Lee, 2024).

Applications in transport

XR is being used in a variety of applications in the transport sector and the number of XR-related studies has been continuously growing in the last years (Wong and Lee, 2024). Different studies are dealing with the possible connection or implementation of XR in transport control, management, and realisation (Mikušová et al., 2024), facilitating the verification and testing of design solutions in realistic environments (Wong and Lee, 2024; Schaffernak et al., 2021).

In road transport, XR has been adopted for a variety of different applications, including vehicle design, testing and simulation, training, education and marketing and sales experiencing a significant research growth over the last decade (Postelnicu and Boboc, 2024). Initial research with XR was predominantly conducted for safety and driving assistance features (Riegler, Riener, and Holzmann, 2021). More recent research explores the support of immersive (non-)driving related activities, and finally enhances driving and passenger experiences, as well as assists other road users through external human-machine interfaces (HMIs) (Riegler, Riener, and Holzmann, 2021). XR may also be the enabling technology to increase trust and acceptance in automated vehicles through explainable artificial intelligence (AI), and therefore help on the shift from manual to automated driving (Postelnicu and Boboc, 2024; Riegler, Riener, and Holzmann, 2021). Other recent applications include virtual aid for vehicle maintenance and for training and education purposes (Postelnicu and Boboc, 2024; Prathibha et al., 2024).

In the aviation sector there has been an emphasis on utilising XR to support engineering, strategic navigation, and training and simulation (Wong and Lee, 2024; Schaffernak et al., 2021; Blundell and Harris, 2023). XR technologies have also been applied to aircraft assembly, maintenance and inspection (Wu, Liv, and Shuhong, 2021). As an example, AR technology has been used to guide operators to optimize the maintenance path automatically through various aircraft areas (Wong and Lee, 2024; Wu, Liv, and Shuhong, 2021).

XR in railway transport represents a supportive and complementary technology. XR can support the operation of railway transport in specific areas, such as the digitalisation of processes to the current technological level, which is associated with benefits such as time and costs saving, increasing efficiency and reducing the error rate (Mikušová et al., 2024). Other applications include education and training, operation, maintenance, supporting activities, service and safety and crisis-management (Mikušová et al., 2024; Wong and Lee, 2024).

Concerning waterborne transport, XR is one of the technologies that is intended to provide powerful tools to support site manufacturing and engineering tasks. Such tools include context-aware assistance, manufacturing data visualisation and interaction, maintenance applications, quality control, and material management (Molina Vargas, Vijayan, and Mork, 2020; Burova et al., 2023). In addition, studies have been focusing on preventing users from taking actual risks in real environment. As an example, the use of VR to simulate firefighting scenarios on ships' decks and elsewhere (Wong and Lee, 2024).

Extended reality in European R&I transport projects

The majority of the identified research projects applied XR to aviation (9 projects), followed by waterborne and railway, each represented by 4 projects. In total, 20 relevant projects were identified. Since XR covers many different fields, a large variety of type of applications were identified.

Figure 7. Extended reality in European R&I transport projects

Extended reality in European R&I transport projects
Number of projects by transport area, type of application and role in the project
Total number of projects: **20**

One square – one project.
The shade refers to
role of the technology in the project

Two projects dealt with
virtual experiments in **CCAM**.
In one project *extended reality* technology
is *central* and in one – *important*.

CCAM – Cooperative, connected and automated mobility

Number of projects by the role of technology

Central	Important	Supplementary
2	14	4

Source: JRC

Among the aviation projects very diverse applications are found. The majority of projects deal with manufacturing: ASSASSIN developed an XR system (with AR and MR) to assist the operator during aircraft construction, HLFC 4.0 used AR methods to enable a real-time manufacturing feedback to the operators working on Hybrid Laminar Flow Control systems improving the aerodynamic efficiency of aircrafts, and the ongoing GENEX project is applying XR as a manufacturing and repairing virtual aid for aircraft components.

Two aviation projects deal with design enhancement. SMAR-TER developed VR based and 3D-printed methods to define the best inceptor ergonomic architecture and functionality for improving the pilot and co-pilot comfort and reducing the workload. In the SAIS project, on the other hand, AR supported the design phase of next-generation civil tilt-rotor aircrafts. In VISTA AR was applied as an interface for data transmission, visualization and documentation in post-assembly testing of aircraft interior installations. Within this project, AR allowed to over-impose important information on the part of the aircraft panels being inspected allowing for a more informed decision.

XR in aviation can also help in environmental and noise assessment. This topic is investigated by the GREENPORT2050 project, focused on realistic simulations of aircraft traffic and the quantification of environmental impacts using enhanced models and data collection methods. The project assessed Clean Sky 2 technologies for fixed-wing aircraft, particularly those aimed at increasing fuel efficiency to reduce CO_2 emissions and lowering NOx and noise emissions.

Other relevant aviation projects are the ARTIMATION project, which used VR and Brain-Computer Interface (BCI) systems as part of the technical objective to design human-AI-interaction (hAIi) and provide a data-driven

storytelling for transparent and interpretable AI models that aid in predicting air traffic flow and optimizing traffic management, and the RATIOS project, focused on improving the design and layout of aircraft cabins through virtual, augmented and immersive reality.

In railway transport, two projects focused on enhancing railway travel experience, e.g. by providing intelligent assistance to travelers (EXTENSIVE) or by simplifying the process of journey planning and travel (MAASIVE).

Two of the identified projects deal with road transport and CCAM. In particular, the ongoing I4DRIVING project aims at developing a simulation library for human driving behavior for virtual assessment of CCAM. In this project AR is used to create critical driving simulations that cover the full performance spectrum of human drivers, comparing the safety performance of automated vehicles and human-driven vehicles. In addition, in the ongoing MOVE2CCAM project, the role of XR would be to create more immersive simulations or demonstrations, allowing stakeholders to better visualize and understand the potential impacts and implications of CCAM solutions.

Concerning waterborne transport, the ongoing MARI4_YARD project uses XR as a virtual aid in ship construction and maintenance processes, while the RAPID project developed a MR digital twin of the Port of Hamburg for the simulation of potential hazards that can then be detected and avoided by drones. In addition, the PORTFORWARD project developed an AR application using smart glasses for container inspection, with the possibility of remote support. Two waterborne projects were focused on inspection: in particular, in the BUGWRIGHT2 project AR facilitated autonomous robotics for ship hull inspection and cleaning. Similarly, the ROBINS project developed AR applications for ship inspection tasks in confined and hazardous spaces.

Another relevant project on XR is the HYRESPONDER project, which applied VR for training purposes on the state of the art in hydrogen safety for responders. In case of projects where XR role was deemed as supplementary, it was mainly used as virtual aid for design and automation of operations.

4.1.7 Edge and cloud computing

Transport mode	Key megatrend	No. of identified projects	Total funding [€]
Various	Digitalization	21	192 mln

Technology introduction

Nowadays the amount of data generated by fast-growing technologies accelerating digital transformation, including Internet of Things (IoT) devices, artificial intelligence (AI) and machine learning (ML) applications requires unprecedented computational capabilities for data management and analysis. In this context, cloud and edge computing have become crucial for data handling. **Cloud computing** relies on centralized data centers to process and store data, offering high scalability and resource availability but potentially higher latency due to the data traveling over long distances. On the other hand, in **edge computing**, data are processed closer to where they are generated, thereby balancing the computing load and saving network resources (Zhou et al., 2021). The edge device serves as a bridge between the physical and virtual layers (Dogea, Yan, and Millar, 2023), reducing network latency and bandwidth use (Moura, Aquino, and Loureiro, 2024). **Fog computing** is an additional computing layer between the edge and cloud layers that pre-processes data before sending it to the cloud (Dogea, Yan, and Millar, 2023). Thus, the fog layer allows the cloud to receive only the relevant data useful for the specific purpose (Dogea, Yan, and Millar, 2023).

Cloud and edge computing represent a paradigm shift from local to network-centric computing, motivated by more powerful computing and storage resources provided by large data centers and server farms. The cloud computing age started in 2006 when Elastic Cloud Computing (EC2) and Simple Storage Service (S3) were offered by Amazon Web Services (AWS). In 2012, EC2 was already used by businesses in 200 countries (Marinescu, 2023). Edge computing gained traction in the late 2010s, driven by the proliferation of IoT devices, the need for real-time analytics, and the advancements in networking technologies, such as 5G (George, George, and T.Baskar, 2023).

Data analytics, data mining, computational financing, scientific and engineering applications, gaming, and social networking, as well as other computational and data-intensive activities benefit from cloud and edge computing (Marinescu, 2023). Content previously confined to personal devices, such as workstations, laptops, tablets, and smartphones, no longer need to be stored locally (Marinescu, 2023). Data stored on computer clouds can be shared among all these devices, and it is accessible whenever a device is connected to the Internet.

As a result of the extraordinary development in the number of connected devices, mobile data traffic, and the limits of 4G technologies, there is an increasing focus on defining the standards for 5G (Oladimeji et al., 2023). 5G brings several advancements that can benefit cloud and edge computing. This new generation of mobile network technology will enable high-speed connectivity, low latency, longer battery life, and the ability to handle a massive number of connections (Gohar and Nencioni, 2021).

Applications in transport

Intelligent Transportation System (ITS) is defined as a combination of cutting-edge information and communication technologies for the advancement of traffic management (e.g. traffic signal control, smart parking management, electronic toll collection, variable speed limit, route optimization, and, more recently, connected and automated vehicles) (Zhou et al., 2021). An ITS combines various advanced communication, control, monitoring, and management technologies, (Moura, Aquino, and Loureiro, 2024) generating massive amount of data that requires instant processing, thus being highly sensitive to communication latency (Moura, Aquino, and Loureiro, 2024).
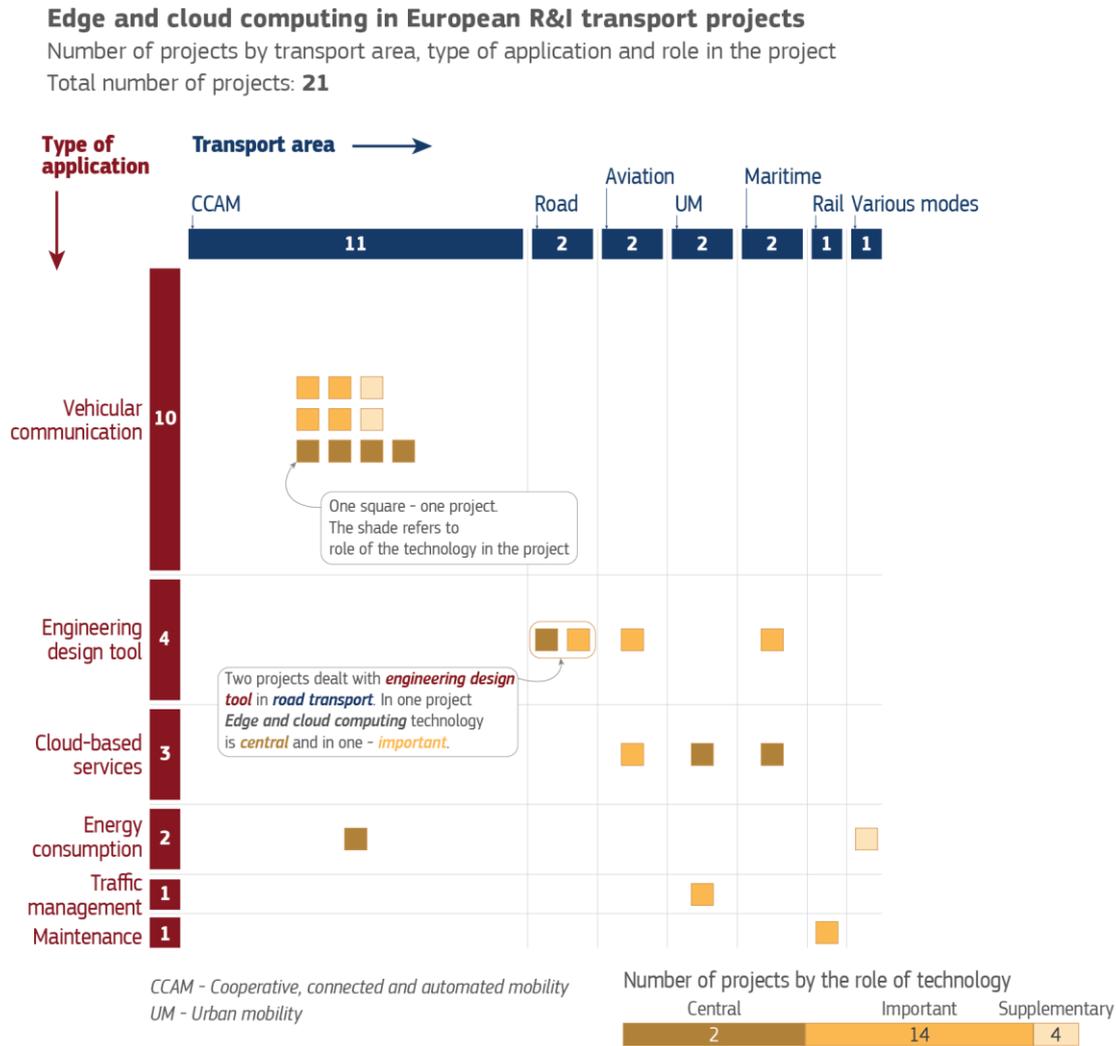
In this context, edge and cloud computing have several applications that can enhance ITS performance and safety, including autonomous driving, real-time traffic updates, fleet management and predictive maintenance (Hernandez, Hassan, and Shukla, 2023). In the framework of autonomous driving, edge computing has been extensively studied to handle the large latency, unstable connection, and network congestion of conventional cloud computing-based approaches (Du et al., 2020). Edge and cloud computing can enable vehicular communication, providing drivers with real-time information that can help them avoid accidents and make better decisions while on the road (Hernandez, Hassan, and Shukla, 2023). Vehicular communication use cases (collectively referred to as V2X – Vehicle-to-everything) can be classified into four categories: V2X refers to Vehicle-to-Vehicle (V2V), Vehicle-to-Infrastructure (V2I), Vehicle-to-Pedestrian (V2P), and Vehicle-to-Network (V2N) communications (Oladimeji et al., 2023).

Edge and cloud computing are also being explored in other transport areas, including rail, aviation and waterborne. For rail, these technologies, together with 5G communication, AI and virtualisation empower railways with new levels of connectivity, safety, reliability and sustainability (Atanasov et al., 2024). Applications include railway traffic management, analysis of real time data to identify anomalies, potential damages or hazardous conditions (Atanasov et al., 2024). In aviation, cloud computing was investigated in the context of the development of collaborative manufacturing of complex products (Yin et al., 2023). In the waterborne sector, edge and cloud computing are being used as enabler of fleet management tools, predictive maintenance, logistics and routing.

Edge and cloud computing in European R&I transport projects

The vast majority of research projects applied edge and cloud computing to cooperative, connected and automated mobility (CCAM), followed by urban mobility, road and waterborne transport. In total, 21 relevant projects were identified. As mentioned, edge and cloud computing have several applications in intelligent vehicles which makes CCAM the main involved transport area.

Figure 8. Edge and cloud computing in European R&I transport projects

Edge and cloud computing in European R&I transport projects
Number of projects by transport area, type of application and role in the project
Total number of projects: **21**

One square – one project.
The shade refers to
role of the technology in the project

Two projects dealt with *engineering design tool* in *road transport*. In one project *Edge and cloud computing* technology is *central* and in one – *important*.

CCAM - Cooperative, connected and automated mobility
UM - Urban mobility

Number of projects by the role of technology
Central: 2 — Important: 14 — Supplementary: 4

Source: JRC

The R&I projects on CCAM applied edge and cloud computing mainly for enhancing vehicular communication, e.g. for safety-oriented applications. Examples from the COSAFE and CLASS projects include sharing information such as driving paths or moving objects within drivable areas. NEXTPERCEPTION enhanced the features of perception sensing technologies like Radar, LiDAR and Time of Flight cameras to the next level for more accurate detection of human behaviour using edge and cloud computing for autonomous driving solutions and for vulnerable road users protection. The ongoing ASCENT project aims at creating a novel AI-powered autonomous vehicular edge computing and networking system for reliable and efficient ITS for enhancing road safety, alleviating traffic congestion, and saving energy in transport. Autonomous vehicles were also in the focus of HAILO-8, which designed a new edge computing processor with high computational efficiency.

Many of the CCAM projects exploited the potential of the new generation of cellular networks (5G) in combination with edge and cloud computational capabilities. For example, 5G-DRIVE developed enhanced mobile broadband and vehicle-to-everything, while within the 5G-CARMEN project a distributed mobile edge cloud allowed to provide a CCAM platform leveraging the most recent 5G advances. Similarly, the 5GCroCo project demonstrated the technical feasibility of providing cross-border CCAM services, guaranteeing uninterrupted connectivity using multi-access edge computing, and the C-AVOID project predicted vehicle collisions and improved safety thanks to low end-to-end latency and edge computational capabilities of the Multi-Access Edge Computing (MEC) platform. The ongoing CONNECT project will use edge computing to establish a trust relationship between different entities in the CCAM ecosystem, to verify the trustworthiness of transmitting stations and infrastructure, and to establish a verifiable chain of trust throughout the entire application stack of the host vehicle.

Still in the road transport field, the PANDA project developed digital models to integrate virtual and real testing of EVs and their components to support the development and testing of electrified vehicles. Cloud facilities were set up to enable cloud-based simulations. AI4CSM aims at developing advanced electronic components and systems and architectures for future mass-market Electronically Controlled Air Suspension (ECAS) vehicles, where Vehicle/edge/cloud computing integration concepts will be applied.

Vulnerable road users like cyclists and pedestrians are the focus of the URBANDYNAMICS project. This project developed an advanced traffic management system which uses video content analysis enhanced with machine learning with edge- computing and deep learning algorithms for real-time monitoring and managing of urban traffic. Similarly, the IDEAL-CITIES project developed a platform integrating big data analytics and cloud services to manage smart cities applications and information exchange between citizens and public authorities.

In waterborne transport, the VESSELAI project developed modelling, estimation and optimization of design and operation of ships and fleets under various dynamic conditions in near real time, where AI, cloud computing and advanced high performance computing encouraged the digitalization. In addition, the PORTFORWARD project developed a cloud-based platform that provides central components of a middleware, cloud infrastructure for service orchestration and the PortForward dashboard, which enables customised dashboards to integrate different port services.

Cloud and edge computing are less commonly used for other transport modes, nevertheless still several relevant projects exist. In railway, the IN2ZONE project developed a transition zone system for railway tracks. Edge computing and artificial intelligence were used to develop an advanced resilience-based monitoring specification for transition zones for just-in-time maintenance.

In the aviation sector, the ongoing CAELESTIS project aims at developing an end-to-end Interoperable Simulation Ecosystem (ISE), to accelerate the design and engineering optimization of disruptive aircraft and engine configurations. Online monitoring edge computing devices will be used to support product performance prediction and produce informed corrective actions. In the drone field, the COMP4DRONES project delivered a framework of key enabling technologies for safe and autonomous drone use, including in transport applications. Cloud computing was used in conjunction with edge computing to enable IoT to cloud continuum in the deployment of drone-based services and solutions. The project offered an embedded platform featuring reusable, qualified components, as well as an agile engineering environment to support the development of drone industry.

4.2 Transport-specific technologies

This section provides a closer look at the ten selected transport-specific technologies. Unlike the digital technologies described in the previous chapter, they address a single transport mode and a specific transport-related topic. Each section first provides a background explaining the technology origin and its rationale, followed by the state of the art based on literature, a graph presenting the scientific trends, and an overview of the European R&I activities. Finally, the relevance of the technology for the specific EU policy goals is briefly discussed. The technologies have been ordered by mode for the reader's convenience.

4.2.1 Software-defined vehicle

Transport mode	Key megatrend	No. of identified projects	Total funding [€]
Road	Digitalisation	2	66 mln

Background

The automotive sector is currently driven by several disruptive trends which are strongly reshaping the traditional hardware-oriented character of the industry. The rise of connected, cooperative, and automated mobility makes software the central component of future cars. Higher levels of vehicle automation require constant monitoring of the environment through collection and analysis of data from multiple sensors, advanced human-machine interaction, and real-time route optimization and decision making. These tasks are performed by computationally intensive machine learning and deep neural learning models. Software components become indispensable also for EVs – for example for battery management systems.

In parallel to the technological change there is also a shift in customer preferences, which evolve towards a more user-centric approach. The future car owner experience is more likely to be similar to that of a smartphone user, with the possibility of custom personalization of various features, as well as updating and modifying

vehicle performance. This concept is already strongly embedded in Tesla business model, which offers over-the-air software updates, optional upgrades (e.g. Acceleration Boost) or subscription schemes (Full Self-Driving capability). The customers are also increasingly interested in in-vehicle infotainment with its global market size expected to grow more than twofold in the current decade and reach 50.8 billion $ by 2030 (Aktas, 2023).

Lastly, the current automotive value chain is increasingly characterized by the so-called hardware commercialization, meaning ever growing homogeneity of car parts. The decreasing differentiation of car hardware drives down profits of the manufacturers, who turn to software as the alternative way of standing out and maintaining their competitive market position. In this way, autonomous driving full-stack software companies, high-precision map manufacturers, chip and semiconductor enterprises become some of the driving forces of the automotive industry (Deloitte, 2021). This tendency can be exemplified by the share of electronic systems in the total car cost, expected to reach 50% by 2030 (Deloitte, 2019).

In line with the above trends, the traditionally hardware-centric automotive industry is rapidly becoming predominantly software-oriented. Already today, software of an average car contains 100 million lines of code – a number expected to triple by 2030 (Aktas, 2023). This paradigm shift makes the old way of thinking about automotive industry outdated and gives rise to a brand new car concept: the software-defined vehicle (SDV).
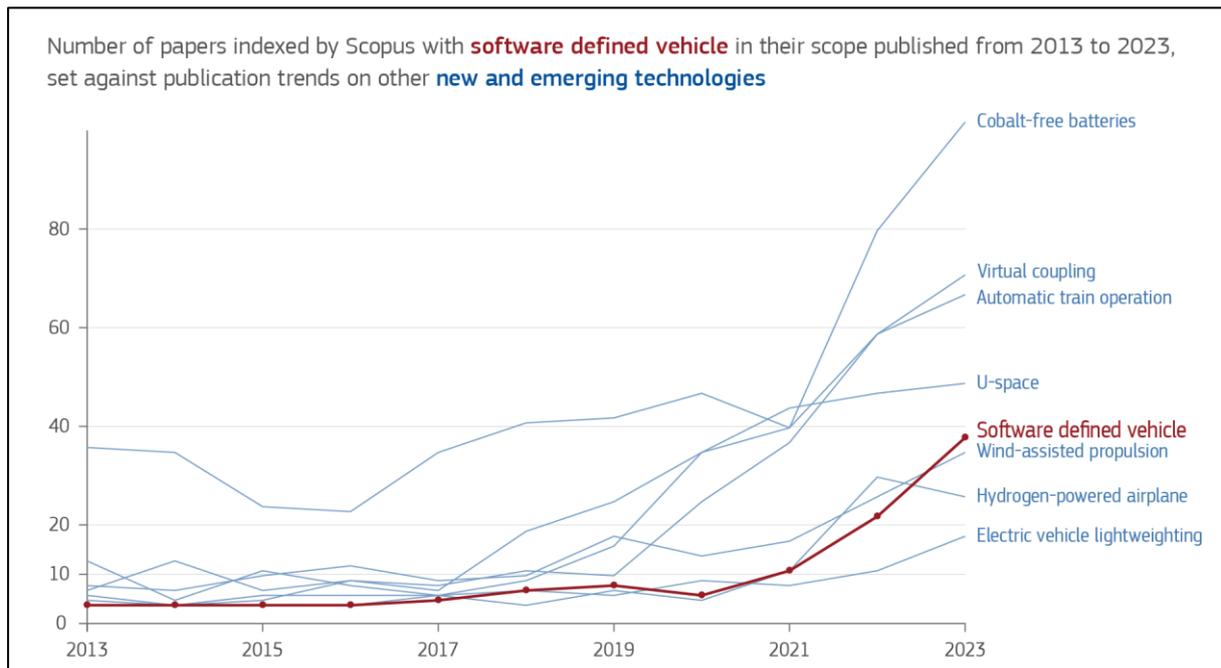
State of the art and relevant projects

So far, the transition of the European automotive sector towards SDVs is not proceeding at a satisfactory rate, hampered by a number of barriers. Most importantly, the traditional electronic and electrical architecture (EEA) of cars cannot properly facilitate the software-centric design. Currently, the EEA is typically highly distributed, with many separate Electronic Control Units (ECU) responsible for each particular car function, such as engine monitoring, braking, fuel-saving, etc. An average high-end car with advanced driver-assistance systems (ADAS) is likely to contain over 100 ECUs. Such fragmentation of EEA is a drawback for development of more intelligent vehicles, being characterized by low computing power, insufficient bandwidth, high latency, and excessive wiring. It also involves high level of software/hardware integration, which constraints car manufacturers in terms of software development and updates. For example, if a modification of one ECU affects functioning of others, it is necessary to upgrade all of them separately. Given the fact that ECUs are typically provided by various suppliers, often using different programming languages and interface standards, such process is slow and labour-intensive (Deloitte, 2021).

The industry is responding to this problem, evolving towards more centralised architectures. This process is likely to proceed in stages: first phase should be domain centralization, meaning reduction of ECUs by dividing EEA into respective functional domains, such as power domain, chassis domain, body domain, infotainment domain, or ADAS domain. Each domain should then be controlled by a specific Domain Control Unit (DCU), and run by multi-core processors with high computing power. In next steps, the domains are expected to be further integrated and centralized in the process of zone centralization, eventually leading to central vehicle computing.

The traditional automotive software engineering is not yet well prepared to tackle this transition, not being able to maintain high productivity and to keep up with the growing complexity. As mentioned before, currently ECUs are developed independently and use embedded software developed individually by diverse suppliers. As the software becomes increasingly decoupled from the underlying hardware, lack of common implementation standards, middleware, and hardware abstraction concepts prevents reuse of tested and proven software, requiring a lot of redundant effort to adjust towards different technologies. Moreover, the traditional waterfall model used for automotive software development is no longer suitable. The approach is too rigid, assuming a linear workflow and clear delineation of work based on the developed functions. As the vehicle architecture becomes more centralized and interconnected, the development process will require more flexibility and iteration, therefore the industry will have to rely on more agile workflows. Lastly, the industry suffers from talent shortage. As the importance of software grows, there is more demand for IT specialists with specific automotive domain knowledge, a scarce resource in a field historically dominated by mechanical engineers.

These challenges are likely to affect the whole automotive supply chain, especially to redefine the traditional relationships between vehicle manufacturers and their suppliers. On one hand, the need for more standardization and flexibility prompted some original car equipment manufacturers (OEM) to invest heavily in their own software departments and development of proprietary technology platforms. On the other hand, the industry recognizes the need for closer vertical collaboration, as neither OEMs or the traditional suppliers are able to define the new technological requirements on their own.

Figure 9. Scientific research trends for "software-defined vehicle"

Number of papers indexed by Scopus with **software defined vehicle** in their scope published from 2013 to 2023, set against publication trends on other **new and emerging technologies**

- Cobalt-free batteries
- Virtual coupling
- Automatic train operation
- U-space
- Software defined vehicle
- Wind-assisted propulsion
- Hydrogen-powered airplane
- Electric vehicle lightweighting

Source: Scopus

European research initiatives on SDVs are still at an early stage, and the current activities focus indeed on strengthening the collaboration and setting a common agenda for the industry. FEDERATE project brings together stakeholders from the mobility sector, the open-source software community, the semiconductor industry, and public authorities to accelerate the development of an SDV Ecosystem and to orchestrate the relevant R&I activities. More specific goals include prediction and evaluation of future SDV-related trends, deriving high-level requirements for stakeholders and definition of common non-differentiating building blocks that would be reusable and scalable across departments and companies. The HAL4SDV project focuses on specifying the hardware abstraction layer, its standardisation, the development of appropriate tool chains and methodological aspects to achieve or regain technological leadership in core areas. More projects are in preparation, and the output of the two initial activities is expected to provide feedback for setting future research objectives.

Relevance for the EU policy goals

The global transition to SDVs poses a significant threat to the European automotive industry, which is currently lagging behind its competitors. Non-EU manufacturers have gained competitive advantage thanks to adopting a software-driven approach from the outset and not relying on legacy solutions. Large tech companies with enormous budgets, such as Tesla, are already dominating some areas of the market. At the same time, generous state aid allows Asian enterprises to enter the competition and achieve aggressive growth, like in case of BYD.

SDVs are relevant for a number of EU policy objectives. Future cars will be highly dependent on microchips. The semiconductor industry is controlled overwhelmingly by non-EU companies, with the EU holding only 10% of global market share. The response to the growing dependency on outside suppliers is the European Chips Act, aimed at bolstering Europe's competitiveness and resilience in semiconductor technologies, with over 43 billion € investment in the sector. Other relevant aspects include handling and protection of vast amount of SDV-related data, as outlined by the European data strategy and the Data Act, as well as cybersecurity issues covered by the Cyber Resilience Act. From safety point of view, SDVs will need to comply with the new Vehicle General Safety Regulation, setting requirements for obligatory ADAS in future vehicles.

4.2.2 Cobalt-free batteries

Transport mode	Key megatrend	No. of identified projects	Total funding [€]
Road	Resilience	16	113 mln

Background

Electric vehicles are viewed as the key component in road transport decarbonisation. The EV market has seen an exponential growth in the recent years, reaching 13.6 million electric cars (BEV or PHEV) sold around the world in 2023 (Reuters, 2024). In Europe, in 2023 48.1% of all newly registered vehicles were electrified (including HEV), a significant spike compared to the mere 5.9 % five years earlier (ACEA, 2023; ACEA, 2024).

While such dynamic adoption reaffirms the potential of electric cars for combating CO_2 emissions, it also raises some concerns. One of the issues is the growing demand for rare earth materials used for the production of batteries. The majority of the EVs today are powered by lithium-ion batteries, which are charged by lithium ions flowing between a positively charged electrode (cathode) and a negatively charged electrode (anode). Cobalt is an indispensable component of most of the lithium-ion batteries currently available on the market.

At the same time, the use of this particular material raises significant ethical, environmental and cost-related considerations. The largest deposits of cobalt are located in the Democratic Republic of Congo (DRC) – roughly 70% of the world's annual demand comes from this Central African country. The DRC is one of the most unstable countries in the region, troubled by poverty and corruption. Cobalt extraction often involves child labour and is carried out with poor safety standards, bad working conditions, and extremely low salaries. There are also environmental risks, such as dust and sulphur dioxide emissions leading to pollution of air, soil and drinking water. Fragility of the supply chain and relative scarcity of the material contribute to high volatility of prices (Lee and Manthiram, 2022).

While cobalt is used for a variety of applications, most notably portable electronic devices, the predicted dynamic growth of demand is mostly driven by the advent of electric vehicles. In 2021, for the first time EV-related cobalt demand exceeded other battery applications and became the largest end use sector at 34% of total demand (Cobalt Institute, 2021). At the same time, lithium-ion batteries are expected to continue dominating the market in the following years, with the whole value chain growing annually by over 30% (McKinsey, 2023). As a result, in the recent years the EV batteries industry started to heavily investigate reduction of cobalt content in lithium-ion batteries, with the ultimate goal of achieving cobalt-free energy storage without compromising energy and power performance.
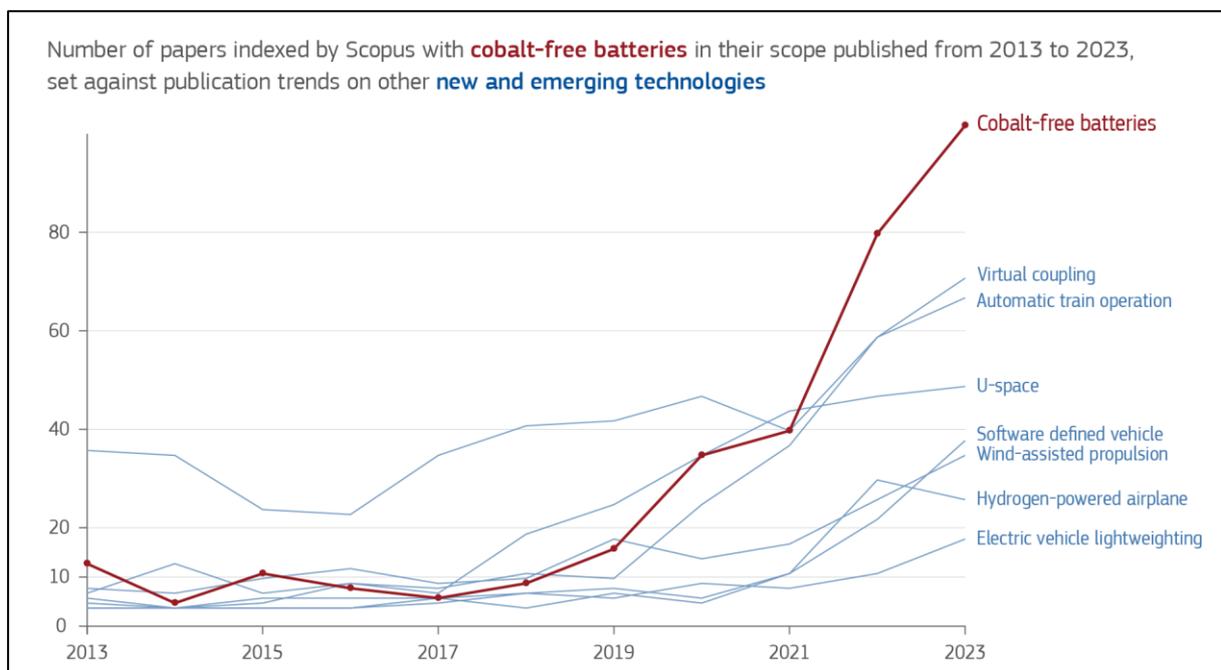
State of the art and relevant projects

Performance of a cathode can be assessed on an array of indicators, such as energy density, cycle life, rate capability, thermal stability, ease of synthesis, availability of materials and cost of production. Cobalt owes its wide application to scoring particularly well on a number of key characteristics, in particular high energy density, stability and extended cycle life. Reducing cobalt content in batteries poses the challenge of finding novel cathode materials that despite the cobalt reduction still exhibit overall good performance across all the indicators.

In 2022, the market was dominated by three battery chemistries: lithium nickel manganese cobalt oxide (NMC) with a 60% market share, followed by lithium iron phosphate (LFP) with a share of 30%, and nickel cobalt aluminium oxide (NCA) having 8% of the market (International Energy Agency, 2023). LFP is the only one that does not contain cobalt, however it is also characterized by lower energy density and more sensitivity to cold temperatures. NMC and NCA are both nickel-based chemistries. For these types of cathodes, the main direction in the recent years was to increase the nickel content in order to reduce cobalt reliance. However, increasing nickel content also tends to increase surface, structural and thermal instabilities adversely affecting battery lifetime and safety (Lee and Manthiram, 2022). In addition to the dominant battery chemistries, also many novel cobalt-free designs are under investigation. Some of the promising cathode materials for lithium-ion batteries are lithium-rich oxides, nickel-rich layered oxides and spinel lithium nickel manganese oxide (LNMO) (Zhao et al., 2022). Technologies that might replace the conventional lithium-ion technologies in the longer term include sodium-ion batteries and, in particular, solid-state batteries (Itani and De Bernardinis, 2023).

Solid-state batteries (SSB) represent a radical departure from the conventional battery architecture based on liquid electrolytes. This transformation is driven mainly by the limitations of traditional approach, such as higher flammability, thermal runaway risks, dendrite formation during charging, and the extraction of rare materials such as cobalt. The core element of SSB are solid electrolytes made of ceramic, polymer, glass, or sulphide

materials. Compared to liquid electrolytes, they present several advantages. Most importantly, thanks to the absence of flammable liquid electrolytes, they have improved safety profile. Thanks to the possibility of using lithium-metal anodes, as opposed to graphite ones typically employed in liquid-based architectures, they offer increased energy densities. Solid electrolytes are also less prone to degradation, which contributes to longer lifespan. SSB also offer superior performance stability across a wide range of temperatures, remove the risk of leakage or drying out, and offer more flexibility in design. SSBs can be developed in previously unfeasible sizes and shapes, offering better integration of the battery in the final product. However, commercialisation of SBB is hindered by several bottlenecks. The critical problem is related to interface stability: unlike in conventional batteries in which the liquid electrolyte conforms easily to the electrode surface, in SBB the rigid character of the solid electrolyte may cause poor contact, contributing to high interfacial resistance. This issue is also relevant for manufacturing complexity and scalability: fabricating thin, defect-free layers of solid electrolyte and ensuring perfect contact with the electrodes requires high-precision engineering and control. Other challenges include the high cost of synthesis of solid electrolyte materials, as well as their brittleness. Lastly, the understanding of solid electrolytes functioning under various conditions is still not complete and requires further research (Machín, Morant, and Márquez, 2024).

Figure 10. Scientific research trends for "cobalt-free batteries"

Source: Scopus

A number of European projects investigated the problem of cobalt reduction in batteries. Several of them focused on the use of LNMO. COBRA developed a cobalt-free li-ion battery by enhancement of each component in the battery system in a holistic manner. The developed solution uses battery chemistry consisting of an LNMO cathode in combination with a composite anode based on nanometre silicon and graphite as active particles. The battery pack achieves high recycling rate of 90% of components coming from circular sources, such as recycled silicon extracted from photovoltaic panels. 3BELIEVE project, in addition to LNMO-based battery, also developed sensors for monitoring of the battery cell, and analysed the whole life cycle of the product, developing strategies and tools for circular manufacturing, second life and recycling. Both projects delivered solutions at TRL6 maturity stage. HYDRA focused on reduction of critical raw materials by 85%. The developed solution achieves this by blending high-capacity silicon together with graphite in the anode and applying cobalt-free LNMO and LFP in the cathode.

SENSE project investigated NMC batteries, reaching improvement of cycling stability and energy density by applying silicon-graphite composite anode and a nickel-rich cathode. The solution also provides a battery management system coupled to dynamic in-cell sensors to enable faster charging, improved sustainability and recyclability. SI-DRIVE on the other hand, focused on investigating lithium-rich cathode materials.

ASTRABAT addressed the design of an all-solid-state battery for the next generation of lithium-ion batteries, focusing on the critical issues of electrolyte/electrode interface. Surface coatings are specially developed on each inorganic component (anode, cathode and electrolyte) to improve interface chemical stability and reduce capacity fading. The technology was brought up to TRL6, and was accompanied by a concept for future battery cell manufacturing lines. LISA, SAFELIMOVE, and SILIS explored SSB cell technologies to enhance safety, energy density, and performance. The projects reported the development of advanced materials, hybrid ceramic-polymer electrolytes, and scalable processing for all-solid-state batteries, aiming to double the energy density of conventional lithium-ion batteries. The currently ongoing EXTENDED project is working on a multifunctional, modular, and scalable solid state batteries system, based on a SSB technology with almost double energy density compared to conventional lithium-ion batteries. It is the first time when a large solid state battery cell (30Ah) is being implemented in a EU research project.

To accurately understand the performance of various battery designs and chemistries it is necessary to use computational tools allowing to model the battery at various levels of granularity – stochastic, mechanistic, or machine learning (Itani and De Bernardinis, 2023). This potential bottleneck was addressed by two complementary projects (DEFACTO and MODALIS2), which developed open-source modelling source for future battery research.

Relevance for the EU policy goals

The new EU Batteries Regulation was put in place in 2023 to ensure that batteries on the EU market are sustainable and circular throughout their whole life cycle, from the sourcing of materials to their collection, recycling and repurposing. Some of the relevant goals include targets for collection of waste batteries for light means of transport (61% by the end of 2031), recovery of lithium from waste batteries (80% by 2031), and mandatory minimum levels of recycled content (16% for cobalt, 85% for lead, 6% for lithium, and 6% for nickel). The regulations also introduce tight due diligence rules for verification of the source of raw materials used for batteries (European Commission, 2023).

The EU is overall highly dependent on critical raw materials coming from external sources. This dependency combined with the growing demand due to the global shift towards digital and green economy makes supply chains vulnerable. The 2023 European Critical Raw Materials Act establishes the EU strategy for securing the resilience of critical raw materials value chains. The regulation sets priorities by distinguishing between critical and raw materials and codifying them in law, and establishes benchmarks for domestic capacities along the supply chain to diversify EU supply: extract at least 10% of the EU's annual consumption; process at least 40% of the EU's annual consumption; and recycle at least 15% of the EU's annual consumption. Moreover, not more than 65% of the Union's annual consumption of each strategic raw material at any relevant stage of processing should come from a single third country (European Commission, 2023).

4.2.3 Lightweighting of electric vehicles

Transport mode	Key megatrend	No. of identified projects	Total funding [€]
Road	Circularity	11	80 mln

Background

User's acceptance is a key factor for a successful rollout of electric vehicles. Some of the barriers mentioned by the potential EV users most frequently are limited driving range and high purchase price. While range depends on the battery chemistry, driving style or environmental factors, purchase price is mostly driven by technological advancements, maturity of the market and governmental subsidies. There is however one EV characteristic that affects both – the vehicle weight.

EVs are typically 25% heavier than their conventional ICE counterparts, which they owe mainly to the weight of the battery, typically constituting 20-30% of the EV's total weight (Anderson, 2024). This has a significant impact on the driving range – a 10% weight reduction typically leads to roughly 14% increase in driving range (Czerwinski, 2021). Larger batteries mean extended range, but with batteries being the most expensive component of the car (up to 40% of total vehicle value (Reuters, 2023)) it comes at a cost of increased EV price. Overall weight reduction of a vehicle allows to maintain the same range and simultaneously downsize the battery and drivetrain components, leading to substantial reduction in the price of the car. Moreover, some negative effects of increased weight are associated with any type of vehicle, e.g. reduced safety (due to extended braking distance and maximised crash impact), higher environmental impact (due to excessive tyres wear) or infrastructure damage (negative impact on road surface). For example, concerns have been raised

about suitability of existing bridge (Hope and Simpson, 2023) and parking (Mata, 2023) infrastructure in the wake of accelerating EVs adoption.

All these considerations prompt the car manufacturers to intensify their efforts on EVs weight reduction. Lightweighting is not a new concept and in some industries plays central role since the very beginning (e.g. aerospace). In case of EVs it becomes increasingly important, on one hand due to its impact on cost and performance explained above, but also because of additional challenges in comparison to conventional ICE vehicles. EVs have a fundamentally different architecture than ICE cars, with large battery packs located typically beneath the floor, rather than inside a large engine bay. The need for securing large and heavy battery pack at the bottom of the vehicle while using a single platform for multiple vehicles is seen as a driving force for development of new lightweight frame arrangements for EVs.

State of the art and relevant projects

Traditionally, lightweighting in automotive was achieved through substitution of heavy materials with lighter alternatives, e.g. replacement of steel with aluminium. The current approach is more oriented towards multi-material design, meaning application of multiple materials with diverse properties in the right position, depending on the design requirements. The multi-material design is applied to the entire vehicle and to single vehicle components (smart/hybrid components). The choice of materials depends on characteristics like strength, ductility or crashworthiness. This strategy leads to an abundance of possible design options, with varying results in terms of functionality, cost, aesthetics and manufacturability. The necessary trade-offs between these conflicting objectives make the multi-material design a particularly complex process.
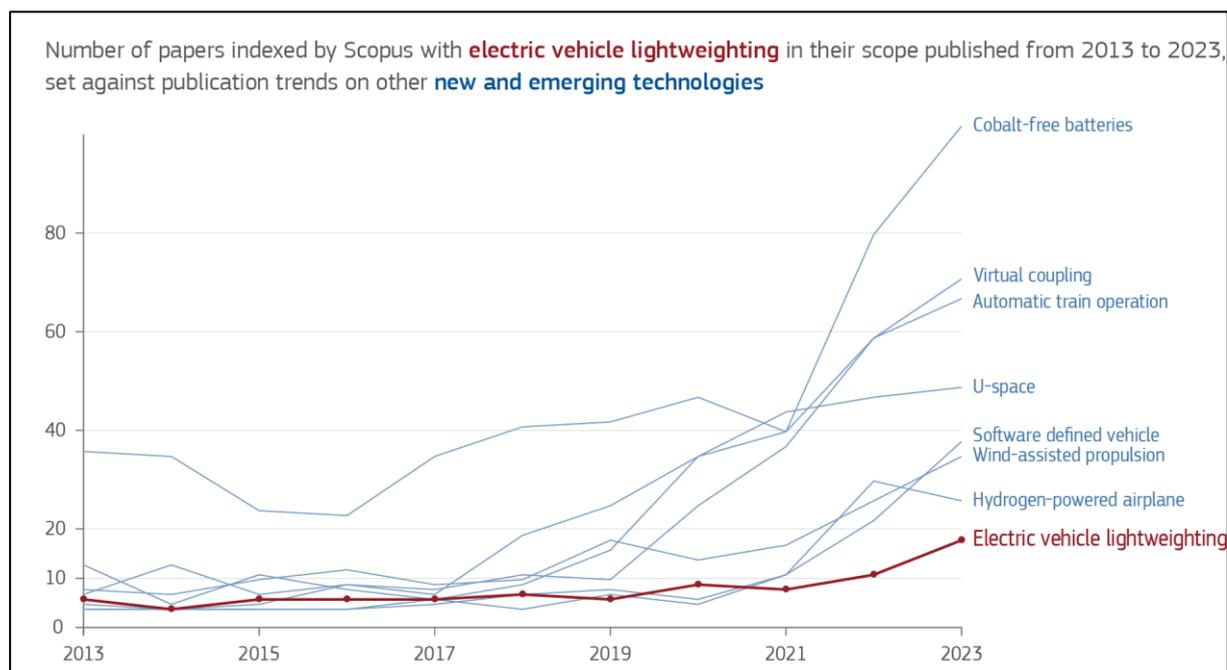
Currently, ferrous materials are still dominant in automotive design, with steel and iron contributing to about 70% of the car weight. Ferrous alloys are not typically considered light materials due to their high density. At the same time, they are advantageous in terms of strength, durability, easy manufacturing and cost. For this reason, a lot of attention is paid to reduction of steel weight, either by lowering steel density with lighter alloying materials, or by increasing the steel strength, thereby reducing its amount required for manufacturing. For steel density reduction aluminium is typically used as the alloying element, but it poses a challenge by causing detrimental changes to steel microstructure. Other limitations are the aluminium cost, thermal stability in higher temperatures, and the energy required for the extraction and refining processes. Apart from aluminium, only magnesium is seen as a realistic commercial alloying alternative, but it faces many problems related to manufacturing, cost and poor in-service performance. In case of steel strengthening, the technology is constantly advancing, leading to arrival of three generations of advanced high-strength steel (AHSS). The AHSS steels achieve superior mechanic characteristics due to addition of martensite, bainite, or austenite. AHSS sheets can be therefore thinner than those made with conventional steel without any loss of performance.

Another alternative are composite materials, extensively applied in aerospace industry. Carbon-fiber-reinforced plastics (CFRP) are the most prominent candidate for lightweight designs in this category. The material is ten times stronger than steel but only one-fourth as heavy, demonstrating in addition outstanding vibration, fatigue, and corrosion resistance. The use of CFRP in automotive is limited mainly by the high cost of carbon fiber components (at least 20 times as much as steel) (Czerwinski, 2021) (Zhang and Xu, 2022). An example of successful CFRP application for mass car production is the electric BMW i3 model, in which the composite material allowed for 50% weight reduction compared to traditional steel body (BMW, 2013). Metal-matrix composites (MMC) is another family of composite materials consisting of hard reinforcing particles embedded within a metal matrix phase, usually aluminium. MMC is mostly applied to the engine, brake system and driveshaft due to its high strength and ductility, and good resistance to corrosion and high temperature. Natural fibers such as kenaf, hemp or flax are an alternative for synthetic reinforcement of composites. Although they offer good strength and cost, their implementation into existing manufacturing processes is challenging, next to increased flammability and moisture absorption.

Next to the more conventional lightweighting methods, a variety of innovative materials is being developed under the umbrella term of advanced materials, often inspired by natural structures present in biological systems. Another unorthodox approach for EVs are 'massless' batteries, which in addition to energy storage have also a load-bearing function (Bellini, 2021).

The future direction of lightweighting in case of EVs is under debate. It is possible that with a decrease of battery cost and more efficient powertrains the attention will shift from making vehicles lighter to reducing the carbon footprint across the whole vehicle lifecycle. With zero tailpipe emissions, the relative carbon footprint of materials applied for EVs will increase, especially for energy- and carbon-intensive materials such as CFRP (Lampinen, 2022). For this reason, there is an increasing interest in the circular aspect of lightweighting, e.g. use of secondary materials and the potential for recycling after vehicle scrapping (Lewis et al., 2019).

Figure 11. Scientific research trends for "electric vehicles lightweighting"

Source: Scopus

Circularity trend is clearly emphasized in many projects in the European research agenda. ALMA applied AHSS, advanced sheet moulding and steel hybrid materials for designing a multi-material modular platform for BEV. The platform is made with the "made to be recycled" approach, to enable the separation of components at the end-of-life for repair and reuse. LEVIS focused on designing lightweight EV parts with CFRP and metal hybrid materials, integrating them with a structural health monitoring system. Circular design was considered to enable easy dismantling and reuse of the components. REVOLUTION looked at the problem of reusing materials for automotive parts manufacturing, more precisely it developed a platform for optimising the use of recycled materials and injection moulding for delivering lightweight EV components. FOREST investigated CFRP waste recovery methods and biocomposites recycling uses for transport applications. FLAMINGO focused on advancing aluminium MMC materials for BEV lightweighting, while FATIGUE4LIGHT applied AHSS, aluminium alloys and hybrid fibre-reinforced composites in the same context. Several battery-oriented projects emphasized the lightweight design in their work, e.g. ALBATROSS, MARBEL, and LIBERTY.

Relevance for the EU policy goals

Having impact on both the range and cost of EVs, lightweighting is relevant for the success of one of the key EU policies on transport decarbonisation – the ban on new petrol car sales from 2035 onwards. Moreover, an effort is being made for enhancing circularity of the automotive sector. Currently proposed measures include easy dismantling of vehicles at the end of their life cycle, use of 25% of recycle plastic for manufacturing new cars (out of which 25% must be recycled from scrapped vehicles), or recycling of at least 30% of plastics from end-of-life vehicles (European Commission, 2023). The emphasis of the recent research activities on the circularity of lightweighting is highly relevant for achieving these goals.

4.2.4 Digital automatic coupling

Transport mode	Key megatrend	No. of identified projects	Total funding [€]
Rail	Automation	6	149 mln

Background

Railroad coupling is a mechanism connecting the locomotive to the following rail wagon and by which successive cars in a train are linked. The easiness of use and efficiency of such device are of key importance, since they affect the time required for shunting operations, impacting the efficiency of the whole rail transport system.

For that reason, from the very beginning of railway there was a push for coupling automation, with first automatic solutions developed over 100 years ago. Today, the vast majority of the world uses some form of automatic coupling as a standard, with only few countries utilizing semi-automatic mechanisms or other methods, e.g. hook coupling (Hecht, Leiste, and Discher, 2020).

Europe is one of the few remaining areas of the world still using manual screw coupling. Despite a long ongoing debate on coupling automation the old-fashioned solution remains the standard, due to a combination of political disagreement, high cost of systemic transition, technical challenges and resistance within the sector (de Kemmeter, 2021). Connecting wagons is done manually by a worker who has to climb between them to hook and unhook the cars – a physically exhausting and hazardous manual labour that can lead to severe injuries. It is largely inefficient, taking around 60 minutes to connect a 25-car train (Belov and Litvintsova, 2022). DB Cargo, the Europe's largest rail freight operator, estimated that its staff carries out the coupling process 54 000 times every day and walks roughly 700 000 km a year just for train formation (EDDP, 2021). The screw link strength is relatively low due to the need for a lightweight solution enabling manual operations. This in turn puts a limit on the possible length and load of trains.

At the same time, railway is considered to be the key component in greening freight transport in Europe. The EU policies assume shifting a large portion of freight from road to more sustainable modes, such as railway and inland waterways. However, despite the political pressure, rail freight is not able to successfully compete with road transport. In 2021, rail accounted for only 5.4% of European freight (measured in tonne-kilometres), a decrease by 0.6 pp compared to 2011. In the same period, road freight grew by 1.7 pp reaching 24.6% (Eurostat, 2023). One of the key reasons for this decline is lack of efficiency and time-consuming organization of rail transport (Djordjević et al., 2024).

Given these circumstances, the European rail freight industry has a strong incentive for efficiency improvement, and coupling automation is a key challenge in reaching this ambition. The approach is not to merely copy the solutions already existing elsewhere but to take them a step further by adding a digital layer to the coupling mechanism. This new technology, known as digital automatic coupling (DAC) is advertised not only as a game-changer for rail freight industry, but will also be a crucial enabler for railway digitalization in general, e.g. for implementation of automatic train operations.

State of the art and relevant projects

Overall, train coupling can be divided into 6 categories with increasing level of automation. The lowest is screw coupling (SC) with no automation, followed by two levels of automatic coupling (AC) and three levels of digital automatic coupling (DAC). As the level increases, more train subsystems are connected automatically, e.g. air lines for braking system, power supply and data connection. Continuous power and data connection throughout the whole train are prerequisites for more advanced rail digital services. Couplers above AC2 level also enable electronically controlled pneumatic brake (ECP). Such system makes it possible to activate air-powered brakes on all the train cars simultaneously, improving train control and reducing braking distances.
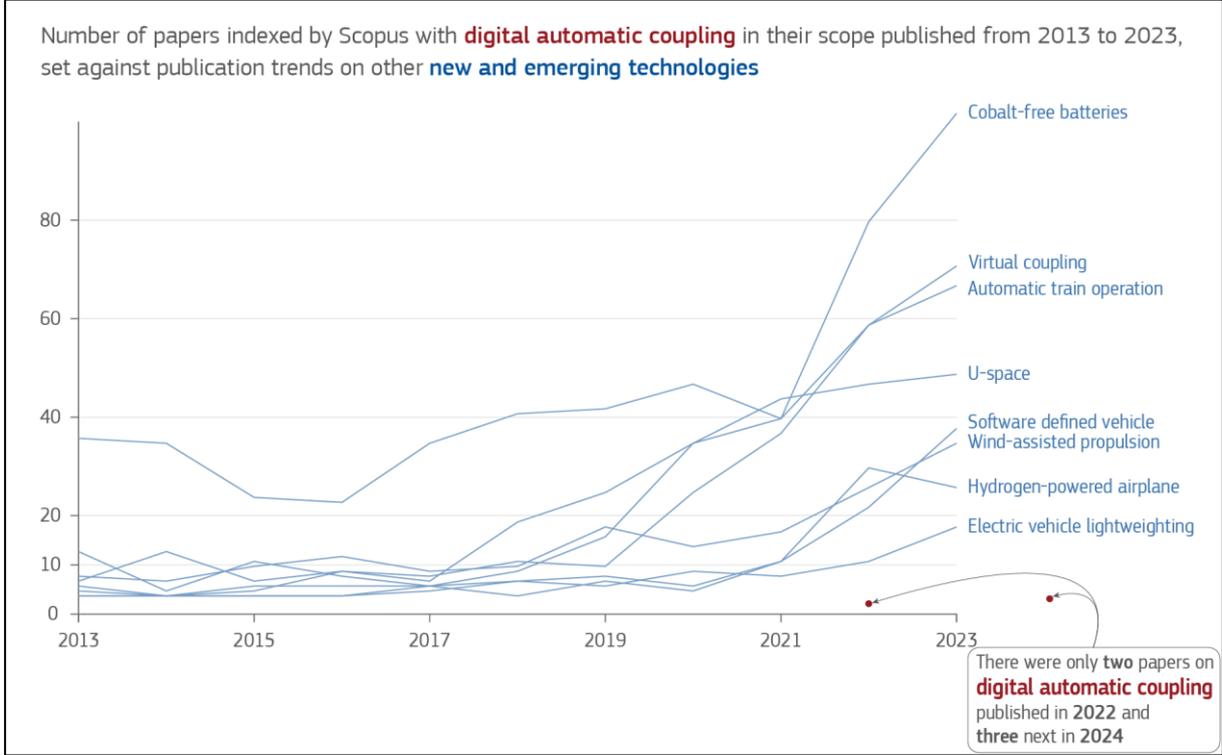
Table 2. Train coupling systems

	SC	AC1	AC2	DAC3	DAC4	DAC5
Mechanical coupling	manual	automatic	automatic	automatic	automatic	automatic
Coupling of air lines	manual	manual	automatic	automatic	automatic	automatic
Coupling of power lines	manual	manual	manual	automatic	automatic	automatic
Coupling of data lines	manual	manual	manual	manual	automatic	automatic
Decoupling	manual	manual	partially automated	partially automated	partially automated	remote + automatic
ECP brakes	no	no	no	yes	yes	yes

Source: Cantone et al., 2022

Currently, Europe is on its way to direct transition from SC to DAC4. The ultimate goal is to reach DAC5 for which also decoupling is fully automated and can be done remotely, however this technology is still at early stages of development and presents some safety challenges, e.g. related to cybersecurity (Rail Cargo Group, 2021).

DAC is scarcely mentioned in the scientific literature of the last ten years, with only a handful of relevant publications. The available work addresses mainly the system-wide impact on freight efficiency, relevance for smart trains, and impact on train control and dynamics. This might be due to the fact that the technology itself is already fairly mature, and the main remaining challenges involve large-scale testing of the prototypes, harmonization and the Europe-wide rollout of DAC.

Figure 12. Scientific research trends for "digital automatic coupling".

Number of papers indexed by Scopus with **digital automatic coupling** in their scope published from 2013 to 2023, set against publication trends on other **new and emerging technologies**

Cobalt-free batteries
Virtual coupling
Automatic train operation
U-space
Software defined vehicle
Wind-assisted propulsion
Hydrogen-powered airplane
Electric vehicle lightweighting

There were only **two** papers on **digital automatic coupling** published in **2022** and **three** next in **2024**

Source: Scopus

These efforts are coordinated by the European DAC Delivery Programme (EDDP), under auspices of EU-Rail Joint Undertaking. The deployment of DAC is largely a political challenge, requiring a common agreement among numerous actors within the highly fragmented railway sector. EDDP provides a platform for close collaboration of all the involved stakeholders, including railway undertakings, infrastructure managers, wagon keepers, rail supply industry, concerned sector organisations, rail research centres and national and political institutions.

From a technical point of view, the current DAC implementation in Europe is focused around large-scale testing of different types of DAC prototypes, to achieve readiness for serial production and step-wise implementation. DACCELERATE aimed to directly support EDDP by creating strategies and guidelines needed to bring the technology to the market, and developing technical specifications for DAC and the energy and data system. The initiative is currently followed up by the DACCORD project, which is working on a detailed migration map towards DAC for the European railway industry. DAC4EU carried out a testing campaign of four different DAC4 prototypes, performing detailed tests of each individual coupling, both in isolated conditions and in real operating processes with freight wagons. During the first phase some new challenges were identified, e.g. with regard to robustness of the communication systems, which are now under evaluation in the second phase of the project, scheduled for completion in 2024. The work is expected to continue in the coming years – DAC development is an essential part of the TRANS4M-R flagship project managed by EDDP, aiming at the transition to fully digital and seamless rail freight operations in Europe. The initiative is strongly supported by the EU, having received over 40 million euro in funding for research activities.

Relevance for the EU policy goals

DAC implementation is a key enabler for improved competitiveness and growth of rail freight which is essential for fulfilling European green freight ambitions. The European Green Deal calls for 75% reduction of inland freight currently carried by road and shift to rail and inland waterways. The specific objective for rail set in the

2021 Sustainable and Smart Mobility Strategy assumes an increase of rail freight traffic by 50% by 2030 and double by 2050 (European Parliament, 2024).

There is a strong push for DAC within the rail sector itself, expressed in the common sector statement in 2023. The statement emphasizes the broad commitment for intensive testing and deployment of DAC, and calls the European Commission and member states for more work on shaping the political, budgetary and legal framework conditions for coordinated European DAC deployment (EIM, 2023).

4.2.5 Automatic train operation

Transport mode	Key megatrend	No. of identified projects	Total funding [€]
Rail	Automation	6	253 mln

Background

Automation is entering virtually all transport areas, to a varying extent and with a different maturity level. Autonomous road transport is most likely the mode that has received the most publicity in recent years. Driverless car technologies have recently reached the point where commercially available vehicles are able to drive completely by themselves in certain operational domains (level 3 according to SAE taxonomy) (SAE, 2021; Edward, 2023). In parallel, large-scale testing campaigns are carried out for vehicles of even higher automation levels (SHOW, n.d.). Aviation is the transport field where automation is most mature and widespread, with the cruising phase largely controlled by autopilot. Pushing automation further might be technically feasible, but given the safety-sensitive nature of civil aviation it encounters regulatory difficulties. Some operations, like take-off or taxiing are more challenging to automatize. Certain rare and critical situations, like wrong sensor readings, might require a human operator to be detected and acted upon (Kelvey, 2023). Moreover, passengers acceptance of ubiquitous aviation automation was negatively affected in recent years by disasters of Boeing 737 MAX caused by its autonomous MCAS system (Cai, 2019). In maritime, some specialized units are already in operation, e.g. for monitoring of water quality or infrastructure in open sea. Initial tests of larger vessels are being conducted, but the technology is still at an early stage. One of the challenges is the amount and diversity of work required for ship operations beyond just navigation, e.g. maintenance and cargo handling (Nature, 2023). At the same time, the European research in this field is quite active, with several noteworthy ongoing initiatives (CORDIS, 2024).

Compared with other transport modes, railway can be placed somewhere in the middle of the automation spectrum. On one hand, it seems like a perfect candidate for full automation, with its fixed tracks and predictable routes. Moreover, train automation is already present in subway applications for years, with more than 60 autonomous metro systems over the world as of 2024 (Fraunhofer, 2024). On the other hand, automated train operation for mainline is still practically non-existent. Still, some important breakthroughs for advanced train automation were achieved in recent years: in 2018 in Australia, the Rio Tinto mining company launched the first ever fully autonomous heavy haul railway system for its iron ore operations. In Europe, mainline automation is high on the research agenda, receiving funding comparable only with autonomous road transport. Several European states are involved in pilot programmes, e.g. Germany (International Railway Journal, 2023), France (International Railway Journal, 2020) or the Netherlands (RailTech, 2021). A closer look into automatic train operation (ATO) is presented in this chapter, as a representative example showcasing the overall automation trend in transport.

State of the art and relevant projects

ATO, similarly to autonomous cars, can be classified into several categories presented in the table below. The following taxonomy was initially created for urban railway systems, but it can be applied also to mainline operations. The full potential of ATO is realized at GoA4 level, corresponding to fully unattended train operations.

Table 3. Automation levels for trains

Grade of Automation (GoA)	Type of train operation	Staff presence required	Starting train motion	Driving and stopping the train	Door opening and closure	Emergency situations
GoA1	ATP* with driver	Yes	Driver	Driver	Driver	Driver
GoA2	ATP and ATO with driver	Yes	Automatic	Automatic	Driver	Driver
GoA3	DTO	Yes	Automatic	Automatic	Attendant	Attendant
GoA4	UTO	No	Automatic	Automatic	Automatic	Automatic

(*ATP – Automatic Train Protection, DTO – Driverless Train Operation, UTO – Unattended Train Operation)
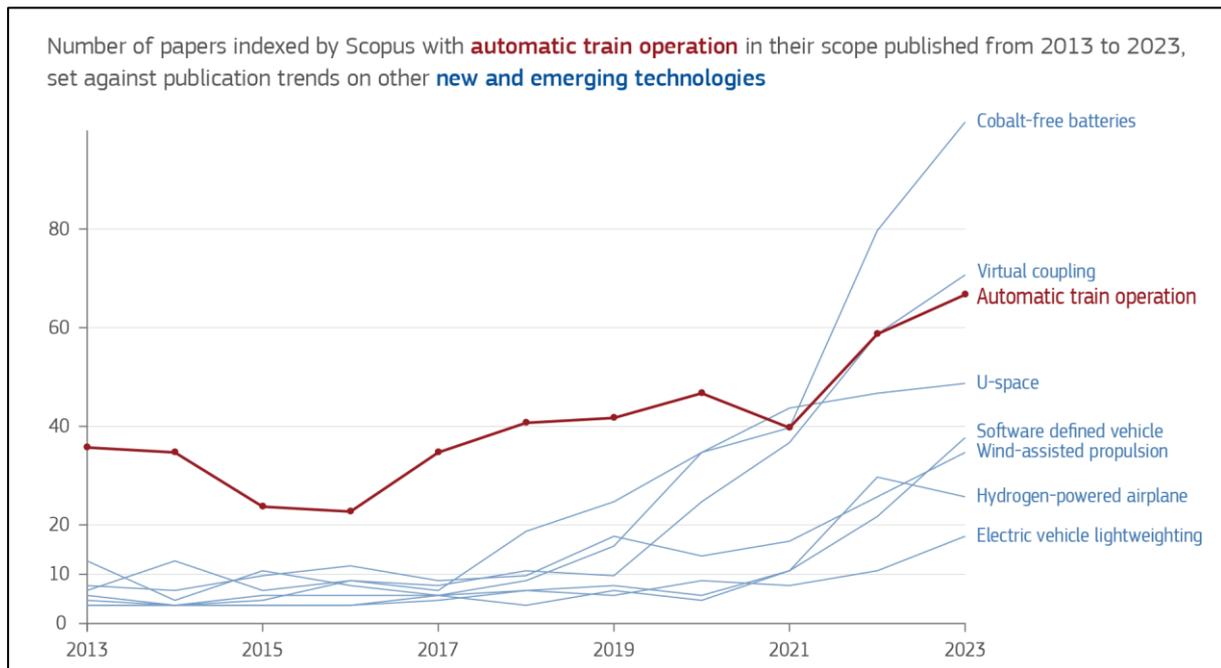
Source: Singh et al., 2021

As indicated earlier, higher automation levels (up to GoA4) have been reached so far only in metro systems, characterized by relatively low operational complexity and limited variety of unplanned or emergency events. Mainline automation is a much more demanding task due to the open environment, shared tracks and presence of multiple train operators. So far, there is only a handful of examples of mainline operations reaching GoA2 level (International Railway Journal, 2020; International Railway Journal, 2018).

One of the major advantages of ATO, given the growing rail demand, is the improvement of capacity without the need to build new infrastructure. From GoA2 level onwards braking and acceleration is taken over by autonomous systems. Train movements are not prone to variability of the human driver behaviour anymore, allowing for more optimal braking curves and shorter headways between trains. In addition, ATO brings more flexibility and resilience at a system level in case of disruptions or unexpected peaks of demand. Highly automated trains should be able to detect potential disruptions and adjust running speed and dwelling times at the stations. From fleet management point of view, more advanced ATO should facilitate ad-hoc rescheduling as no staff shifting is required. Moreover, eliminating the human factor takes away the need for frequent stops for breaks or crew changes that can lead to significant time gains (Jansson, Olsson, and Fröidh, 2023). In addition, railway is one of several transport modes that will suffer from staff shortages in the future, in particular regarding train drivers (RailTech, 2023). Other benefits include improved safety by elimination of human errors and improved energy efficiency, coming from the optimisation of acceleration, traction and braking procedures (Singh et al., 2021).

From technological point of view, ATO requires a transition of rail signalling from track-based approach to communications-based control systems, for more accurate train positioning. For wide deployment of ATO, interoperability of various systems must be ensured. In Europe, the European Train Control System (ETCS) is a foundation for ATO implementation, providing common signalling and control standards at the transnational level. It is important to understand well the current role of train drivers and how those can be executed in an automated system. Apart from operating the train, the driver has also other technical and safety responsibilities. Therefore, higher GoA levels will require also more automated rail tracks monitoring and maintenance. An important barrier to ATO implementation is substantial initial costs. However, in the long term, they might be compensated by savings coming from the train crew reduction, and the associated management, training and labour costs. In this sense, automation might be more beneficial on regional lines with fewer passengers, rather than on more crowded connections where the ratio of train staff to the carried passengers can already be quite efficient (International Railway Journal, 2022; Singh et al., 2021).

Figure 13. Scientific research trends for "automatic train operations"

Source: Scopus

In the European rail research, much effort is spent on advancing mainline automation to higher GoA levels. FP2-R2DATO is the largest currently ongoing project, with the goal of delivering scalable GoA4 automation by 2030. The initiative, concentrated around rail automation and digitalisation, is developing several ATO-related technologies, such as absolute safe train positioning, autonomous route setting, or self-driving freight wagons. Some key digital enablers will be addressed, e.g. train-to-ground and on board communications. FP2-R2DATO builds on a number of preceding projects. TAURO developed solutions for several automation areas: environment perception and automation, remote driving and command, automatic status monitoring and diagnostics, and technologies supporting migration to ATO over ETCS. X2RAIL-3 and X2RAIL-4 contributed to advancing communications system for ATO, cyber security, and testing freight use cases of ATO over ETCS. CLUG and CLUG 2.0 address the accurate train positioning with satellite systems, as one of key enablers for higher automation levels.

Relevance for the EU policy goals

By enabling more optimal use of the current rail capacity ATO can contribute to achieving several strategic goals for the sector set out by the European Commission in the SSMS, such as the shift of 75% of inland freight carried by road to more sustainable modes, doubling rail freight traffic by 2050, or tripling the traffic on high-speed rail by 2050.

4.2.6 Virtual coupling

Transport mode	Key megatrend	No. of identified projects	Total funding [€]
Rail	Digitalisation	3	42 mln

Background

Railway is typically seen as the most environmentally friendly mode of transport, generating up to 15 times less CO_2 emissions per passenger than airplanes, up to 6 times less than internal combustion vehicles, and almost 2 times less than electric cars (McKinsey, 2021). It is therefore not surprising that in the ongoing European green mobility transition it is heavily promoted and expected to accommodate a large portion of the current and future passenger transport. The number of rail passenger-kilometres in Europe is steadily growing. In the 2015-2019 period it increased by over 10%, reaching 413 billion passenger-kilometres, and after post-COVID dip it currently shows signs of quick recovery and further growth (Eurostat, 2023). For example, the demand for long-distance trips already starts to exceed the available supply (McClanahan, 2024).

The demand growth puts a strain on the existing rail capacity. Typically, construction of new infrastructure is the first proposed solution, however its high cost, complexity and time requirements are significant drawbacks. The alternative option is improving the capacity of existing railway lines. One of the possible pathways is reduction of distance between consecutive trains. The traditional and still the most common way of ensuring safe train separation is the fixed block system (FBS). In this approach the track is divided into separate segments called blocks, that can be occupied only by one train at a time. The succeeding train can only move up to the beginning of the next occupied block, where it is obliged to stop in case the block is busy, irrespectively of the exact position of the preceding train. The length of a block can vary from a few hundred meters to several kilometres, depending on factors like maximum allowed speed or geographical conditions. Although FBS is reliable and has been used successfully, it leads to large inefficiencies and is not sufficient for high-capacity rail lines.

The quest for a more optimal track utilization accompanied by progress in enabling technologies like telecommunications led to arrival of a new train signalling concept – the moving block system (MBS). In this case the blocks are no longer fixed, but instead are calculated in real time and move together with the train. In practice, the MBS is realized by constant communication of the current speed and position between the trains and track equipment along the line, allowing for continuous calculation of safe zones around the trains and speed adjustment.

Both above concepts are based on the idea of absolute breaking distance (ABD). The ABD assumes that two consecutive trains must at all times be separated by a distance allowing the following train to come to a full stop before reaching the last known position of the end of the preceding train. This conservative approach causes trains to run far apart. The alternative idea, relative braking distance (RBD), takes into account the fact that both trains are in motion, and depending on their speed and deceleration the headway can be further reduced. RBD can be compared to how cars operate on a highway: a vehicle is driving at a safe distance from the vehicle in front, and the driver reacts to the brake lights of the preceding car. This distance is far shorter than the distance required for a full stop. A similar concept can be applied to railway by merging trains into digitally connected convoys, a technology known as virtual coupling (VC).

State of the art and relevant projects

The central idea behind VC is that two or more trains are able to continuously communicate their position, speed, and braking capabilities in real time, in order to enable coordinated movement. Currently, with mechanical coupling of trains, the forces are transferred via a physical link, which ensures train integrity and enables data transfer and brake pipes connection for synchronised braking. In case of VC, all these functionalities would be realized through a digital, wireless link. As the physical link is missing, trains in the convoy are likely to have different dynamic states at any time, which poses a challenge of ensuring sufficient safety while keeping the trains possibly close to one another. There are several critical elements for achieving this goal that are still under development.
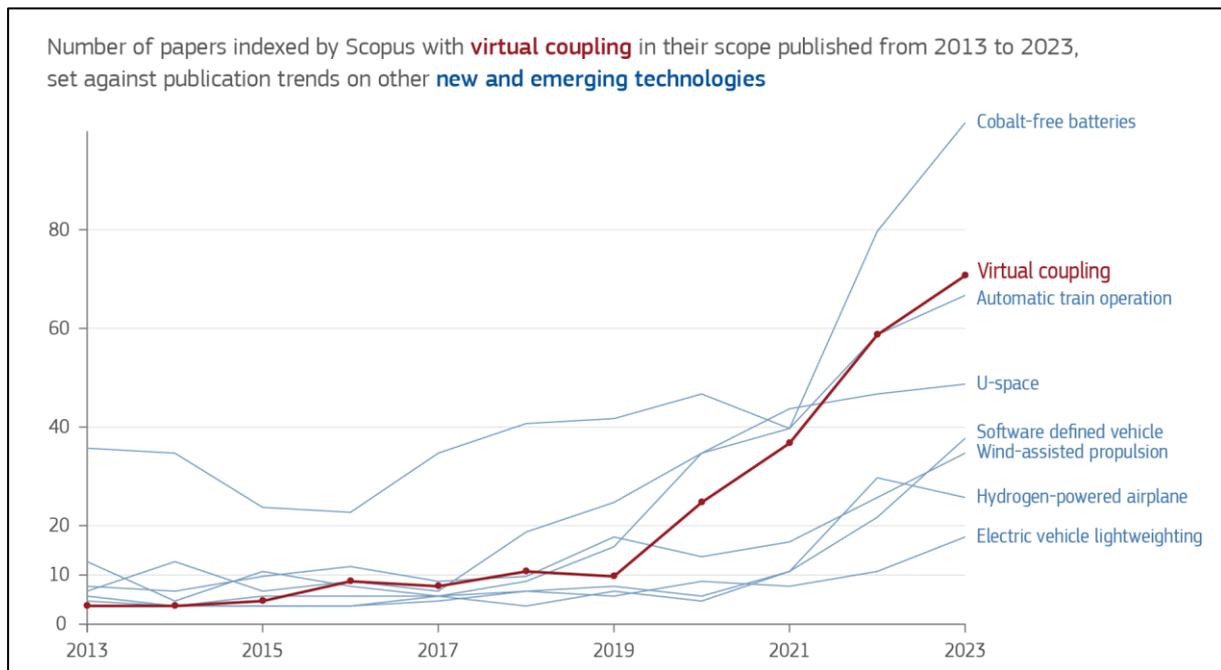
One of the difficulties is establishing a continuous, reliable and safe train-to-train (T2T) communication. The required communication range and latency are different depending on the market segment, with high speed trains requiring the fastest and most distant communication. Introduction of adaptable communication systems supported by a range of technologies such as LTE, 5G, Wi-Fi or satcom is seen as a potential solution. A related problem is the availability of frequency bands for railway applications. In addition to the direct communication between trains, the T2T layer should also be integrated into the existing train-to-ground (T2G) communication structure, including interfaces with the existing interlocking and traffic management system (Stickel et al., 2022).

Braking characteristics of different trains in a convoy are heterogeneous, which might lead to a collision, for example if the train in front has higher braking rates than the following one. In case of main lines, on which many types of trains run on the same network, it might be necessary to adjust the braking rate of the convoy to the train with the worst braking performance (Aoun, Quaglietta, and Goverde, 2020). Current pneumatic braking systems do not fulfil this requirement, an obstacle possibly to be overcome with the next generation of more stable and accurate electronic brakes and closed-loop controls (Stickel et al., 2022).

Another issue is ensuring safety of convoys at diverging junctions. Field equipment needs to be adjusted, in particular the switches should be able to change positions very quickly and reliably to accommodate coupling and decoupling of trains without the risk of derailment. Some other challenges include interoperability, development of sensors for accurate positioning and securing on-board train integrity. VC is also challenging from the rail operations planning perspective, by adding an extra layer of complexity. A new approach to rolling

stock management and scheduling is needed, centred no longer around single trains, but convoys instead (Aoun, Quaglietta, and Goverde, 2020).

Figure 14. Scientific research trends for "virtual coupling"

Among the EU-funded VC research initiatives two are of particular interest. X2RAIL-3 focused on definition of the overall functional, performance and safety requirements of VC, identifying the possible technological architecture of the solution and characterizing functionality and its business case. One of the project outcomes is a technical feasibility study and a proposal for VC implementation strategy. X2RAIL-3 also addressed some related topics, like adaptive communications or cybersecurity. In MOVINGRAIL, VC was studied from technological, operational, and economic perspectives. Formal methodologies and simulation tools were used to benchmark and propose radio-based architectures for T2T communication. Some existing architectures were evaluated, for example those used for automated vehicles platooning. The project evaluated market potential of VC by applying SWOT analysis for various railway market segments. A multi-criteria cost-effectiveness analysis was conducted, based on railway simulation models and expert opinions. One of the project results is an application roadmap and business risk analysis for the VC implementation. In the most recent Europe's Rail JU research agenda VC is mentioned as one of the priority research areas, with the goal of reaching TRL 4/5 by 2026 (EU-Rail, 2024).

Relevance for the EU policy goals

Enhancing Europe's rail network capacity plays a key role in delivering some of the long-term strategic objectives of the EU. The Sustainable and Smart Mobility Strategy assumes a massive shift to rail from less sustainable transport modes. Some of the specific goals include carbon-neutral scheduled collective travel under 500 km by 2030, increase of rail freight traffic by 50% by 2030 and by 100% by 2050, and doubling of high-speed rail traffic by 2030 and tripling by 2050 (European Commission, 2020). The capacity boosting potential of VC relies on multiple factors. For example, depending on the underlying signalling system the capacity gains can be anywhere in the 10%-50% range compared to MBS. On the other hand, for some regional and high-speed scenarios implementation of VC is expected to even double the capacity. Overall, the high potential impact makes VC a highly relevant technology for meeting the increased railway demand in the future (Schenker, Parise, and Goikoetxea, 2021).

4.2.7 U-space

Transport mode	Key megatrend	No. of identified projects	Total funding [€]
Aviation	Digitalisation	26	153 mln

Background

In recent years, drones established their position as an important component of the future green transport ecosystem. The potential logistics applications hold a promise of reducing car traffic congestion and emissions, in particular in urban context. Versatility of drones makes them potentially applicable in a variety of fields, some of them investigated in large-scale EU research projects, e.g. transport infrastructure maintenance and construction, agriculture monitoring, border surveillance, medical aid distribution, environmental monitoring or landmine detection (TRIMIS, 2024).

Drones are already rapidly entering the commercial market, having attracted attention of some large players in logistics industry. In the US Walmart established 36 of its stores as drone delivery hubs. In Ireland, Tesco launched drone services that delivered nearly 10 000 items to the customers in the first year of operation. Meituan, a food delivery company in China, offers food deliveries with drones, managing to successfully complete over 100 000 deliveries in a single year (MIT Technology Review, 2023). Globally, the number of drone deliveries is growing by roughly 135% every year since 2018, reaching more than one million deliveries in 2023 (McKinsey, 2023).

Consequently, the rapidly growing number of drones in the sky must be safely accommodated into existing airspace, in particular ensuring seamless operations in presence of manned aerial vehicles. Lack of a drone traffic management ecosystem poses a technological, legislative and regulatory bottleneck for a large-scale deployment. This challenge was recognized by many aviation regulatory authorities which began to develop concepts of operations for incorporating drones into existing air traffic management (ATM) and supporting research to investigate relevant technological challenges. Among several such concepts developed in parallel around the globe, also Europe committed in 2016 to developing its own operational framework for drones, known under the name of U-space (Aposporis, 2024).

State of the art and relevant projects

U-space is defined as a set of services and specific procedures designed for supporting safe, efficient and secure access to airspace for a large number of drones. The enabling infrastructure and technologies (e.g. wireless communication) are an essential part of the system, since U-space services rely on a high digitalisation level and automation of functions, both on board of the drone, as well as on the ground-based environment side. The U-space services are divided into four levels with increasing level of complexity:

U1: Foundation services – e-registration and e-identification of drones, geofencing

U2: Initial services – flight planning and authorization, flight tracking, air traffic information

U3: Enhanced services – airspace capacity management, tactical conflict resolution

U4: Full services – full integration with manned aviation, high level of automation and digitalisation

Since implementation of various levels depends strongly on the presence on enabling technologies, U-space is being deployed progressively, according to the availability of the necessary building blocks, and goes in parallel with research and development activities aimed at bringing the technology to higher TRL levels.
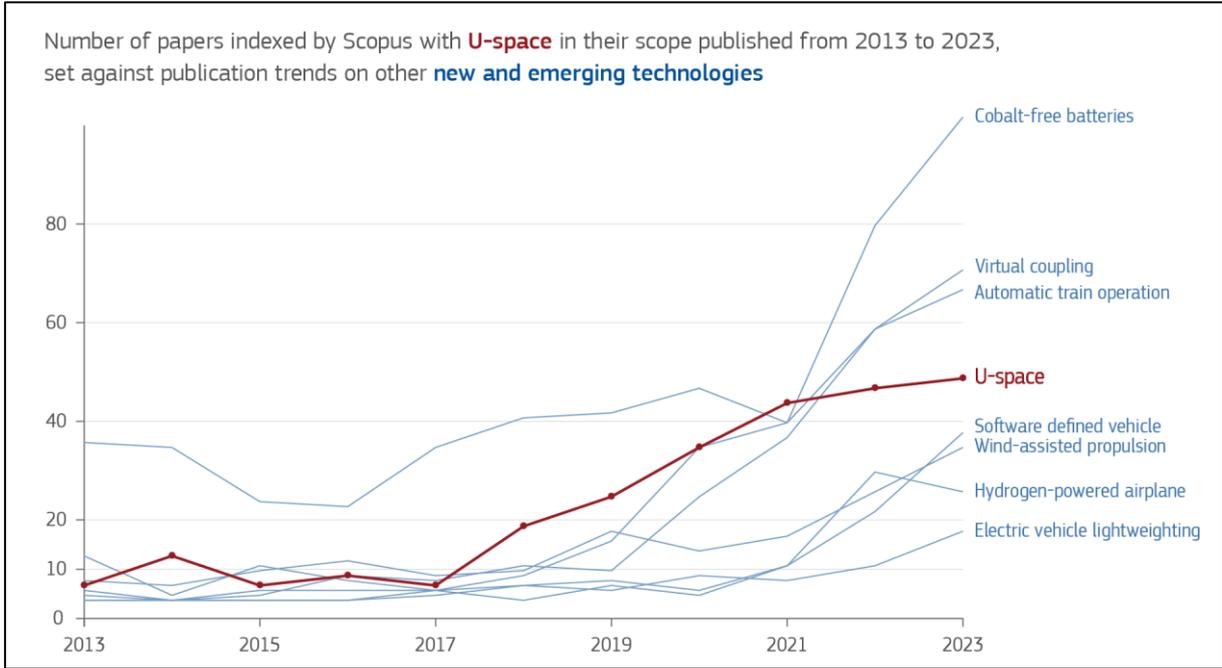
The research efforts focus on several fronts (TRIMIS, 2024). One of the topics is the development of a concept of operations (CONOPS) – a comprehensive specification of how a system should work which provides common ground for further definition of details. For drones it means setting definitions and operating principles for the operating environment (such as phases of flight, rules for airspace management, ground infrastructure, system architecture, etc.) and for specific services corresponding to different U-space levels. One part of this task is CONOPS development for very low-level urban airspace (METROPOLIS 2, CORUS, CORUS-XUAM, USEPE). On the other hand, also operational concepts for integration of drones into existing traffic air control are being investigated (INVIRCAT, TERRA, DREAMS). Some attention was also devoted to operational concepts for ensuring security, for example in case of unlawful interference with geofencing (SECOPS).

Some of the research effort is dedicated to the development of specific U-space-related tools and services, such as algorithms and methods for ensuring drone separation and deconfliction (BUBBLES, LABYRINTH,

TINDAIR), or demand and capacity balancing for air traffic management (DACUS). Another topic is harnessing the existing enabler technologies for U-space, both on infrastructure side, e.g. mobile networks (MONIFLY), and on the vehicle side (AIRPASS). The VUTURA project investigated the challenge of sharing the same airspace by multiple U-space service providers.

A large share of U-space research projects concentrates on large-scale demonstrations. The goal of such campaigns is advancing the initial concepts and bridging the gap between development and deployment of U-space services. Large portion of these efforts investigates various urban applications of drones, such as air taxis, emergency services, goods delivery, surveying and transport of medical supplies (AMU-LED, USPACE4UAM, SAFIR-MED). At the same time, a lot of attention is also paid to demonstrating integration between U-space and existing air traffic management system (SAFEDRONE, EALU-AER, U-ELCOME).

Figure 15. Scientific research trends for "U-space"

Source: Scopus

As already mentioned, research activities go hand in hand with the actual U-space deployment. As of 2022, the majority of European states (Single European Sky members) were still at the stage of U1 services implementation. 52% of the states had registration service in place, with only 10% rate for e-identification and 21% for geofencing readiness. It is expected that by 2025 drone registration will reach 76% rate, while e-identification and geofencing will be implemented at 41% and 55% respectively. The majority of U2 and U3 level services did not exceed implementation rate of 20% with the majority of services not being yet in the planning stage, although the overall share of services in the implementation phase increased in comparison to the previous assessment of 2018. For the more advanced levels (beyond U1), the services closest to implementation include weather information, procedural interface with air traffic control, and accident/incident reporting, while advanced geofencing, conformance monitoring and navigation infrastructure monitoring are among the least advanced ones. (Eurocontrol, 2022)

Relevance for the EU policy goals

The EU considers drones as one of the vital elements of its future transport ecosystem which was emphasized by the adoption of the European Drone Strategy 2.0 in 2022. The strategy envisions drones to be an important part of European daily life already by 2030, assuming availability of both unmanned services (emergency flights, mapping, urgent deliveries of small consignments etc.), as well as manned operations (e.g. air taxis) by that date. The strategy underlines the importance of societal support for the drones uptake, and the crucial role of enabling technologies, such as AI, robotics, semi-conductors and telecommunications services. The

implementation of U-space is also seen as a key enabler, which "will lay the ground for increased operations". (European Commission, 2022)

The paramount role of U-space is further emphasized by special regulatory framework that was put in place. In 2021 the EU adopted and published a policy package for U-space regulation, consisting of three implementation regulations entering in force in January 2023. The package consists of regulations 2021/664 (technical and operational requirements of U-space system), 2021/665 (common procedures and communication facilities for air traffic management and air navigation service providers for integration with U-space), and 2021/666 (common rules for effectively making the presence of manned aircraft operating in U-space airspace electronically conspicuous). (ECAC, 2021)

4.2.8 Hydrogen-powered airplane

Transport mode	Key megatrend	No. of identified projects	Total funding [€]
Aviation	Decarbonisation	17	430 mln

Background

Aviation is among the most carbon-intense ways of travelling, in particular in case of short-distance flights (Ritchie and Roser, 2024). Combined with the booming demand for flying it makes it particularly difficult to decarbonize. Rapid increase in passenger numbers corresponds to a heavy emissions growth: in 2019 the sector was responsible for 4.7% of all European emissions, compared to only 1.5% in 1990. If the current growth trajectory is maintained, the emission share can further double by 2050 (Transport & Environment, 2024). Carbon emissions is not the only problem: CO_2 is responsible for only one-third of adverse climate impacts of aviation, the rest being caused by nitrogen oxides, soot, and water vapour (Transport & Environment, 2024).

Prompted by increasingly stringent regulations, a large effort has been made to mitigate these negative impacts. In recent decades the aviation sector has been very successful at fuel efficiency improvements. Increase of seat density and utilization, optimization of flight routing and airport operations, and more efficient engines and airframes cut down fuel burned per passenger by approximately 50% (Fuel Cells and Hydrogen 2 Joint Undertaking, 2020). However, the increase in passengers compromises these achievements. Shifting the extra demand to greener transport modes, e.g. high-speed rail, is limited to relatively short trips – at the same time short-distance flights are responsible for less than 5% aviation emissions (Fuel Cells and Hydrogen 2 Joint Undertaking, 2020). Consequently, next to efficiency improvements, more radical and preferably zero-emission alternatives are needed, such as sustainable substitutes for kerosene-based fuel and unconventional propulsion technologies.

In terms of fuel, the so-called sustainable aviation fuel (SAF) has drawn major attention. SAF is produced from a bio-based feedstock, including food waste, biomass, fats, etc. Since its properties are close to kerosene, it can be used without any significant modifications in the current airplane or infrastructure design. SAF is not entirely carbon-free: when burned, it produces emissions similar to conventional fuels. However, unlike the kerosene-powered airplanes, it does not exploit fossil fuels stored underground, but instead utilizes carbon already present in the carbon cycle in various feedstock. Therefore, the exact emissions reduction depends on the whole SAF life cycle. Moreover, the dependency of SAF production on water- and land-use patterns (crop monocultures) presents an environmental risk, and raises concerns about volatility and sufficiency of supply. Alternative option is synthetic (power-to-liquid) SAF, obtained by synthetizing CO_2 captured from the air and hydrogen with the use of renewable energy. However, unlike bio-based SAF, this technology is still in its nascent stage and is not expected to reach required maturity in the foreseeable future (McKinsey, 2022).

On the propulsion side, one of the popular ideas is electrification. Despite significant advancements in battery technology, the currently available batteries still have way too low energy density for typical aviation applications, which limits battery-electric airplanes only to very short-range flights. At the same time, it is currently the only viable option allowing for complete elimination of any environmental impact in flight. Another potential option are hybrid-electric aircrafts, which combine various energy sources (e.g. jet fuel, battery- or fuel-cell-based electricity) in different flight stages. This is however usually not carbon-free and, just as any kind of electrification, requires significant changes to airport infrastructure and operations.

An option that responds to a number of the above downsides is powering airplanes with hydrogen. Although the idea of using hydrogen in aviation was explored in the past, due to technical obstacles it never went beyond early prototypes phase. Currently, in the face of increasing regulatory and environmental pressure it has attracted substantial attention and is being intensely revisited by the industry. For example, Airbus has

announced its ambition to bring to the market the world's first hydrogen-powered commercial aircraft by 2035, and is currently developing four different concept airplanes as a part of its ZEROe program (Airbus, 2021)

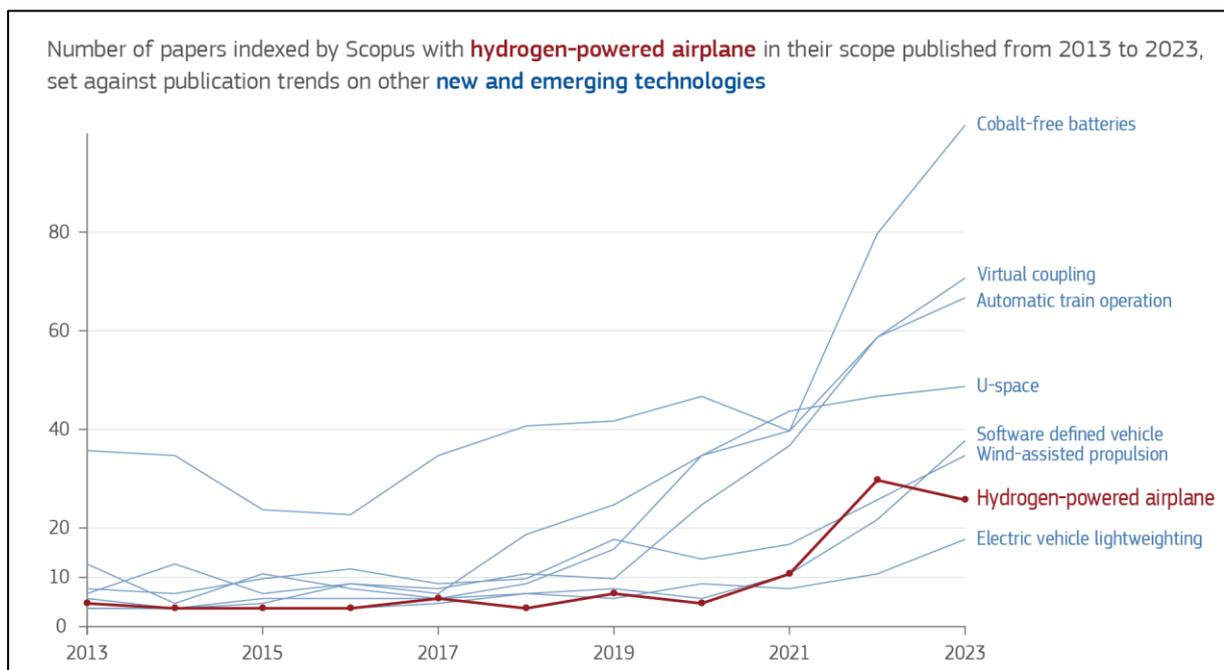### *State of the art and relevant projects*

Hydrogen can be applied as an energy source in airplanes in two ways: either burned in a combustion engine or used in a fuel cell for electricity generation. Hydrogen has 2.8 times higher energy content than kerosene, which makes it particularly efficient in case of combustion. In fuel cells, hydrogen is used to generate electric power through a series of chemical reactions involving oxygen, with water being the by-product. Although the fuel cells do not offer enough power density to allow long-range flights, they can serve as a carbon-free component of hybrid-electric propulsion systems. Overall, the hydrogen aircraft technology is still at a very early stage with TRL estimated at level 3-4. Several key challenges stand in the way of reaching higher maturity level.

One of them is hydrogen storage. Although less hydrogen is needed for the same flight than kerosene thanks to its higher gravimetric energy density, at the same time hydrogen is four times less dense, even when stored cryogenically in liquid form. As a consequence, hydrogen requires four times larger storage volume than kerosene (Tiwari, Pekris, and Doherty, 2024). Typically, in most commercial airplanes the fuel is stored in the wings. However, in case of hydrogen a larger storage volume is required, as well as a spherical or cylindrical tank shape to minimize losses through vaporization. It means that hydrogen tanks must be located in the fuselage, possibly at the expense of passenger space. To maintain liquid state, the hydrogen must be stored at very high pressures and low temperatures. A new fuel distribution system is needed, with pipes, valves and compressors able to safely and reliably transfer the fuel.

Another challenge is the propulsion system. In case of combustion-based engines, more research on the design of hydrogen gas turbine is required, including simulation and testing of various combustor technologies and thermal management options. Manufacturing processes and application of advanced materials are under investigation. In case of fuel cells, increasing the energy density is the key challenge for enabling flights beyond short distances. In case of high power fuel cells the resulting rise in heat is problematic, and requires development of better cooling systems.

Other issues include rollout of refuelling infrastructure, safety and regulatory framework development, and scale-up of hydrogen production. Currently the high cost of green hydrogen is problematic, but it is expected to go down with increased supply of renewable electricity. Finally, the environmental impacts of hydrogen combustion need to be better understood. Although there are no CO_2 emissions involved, hydrogen gas turbines generate NOx and water vapour contributing to contrails formation (Boyles, 2023).

Figure 16. Scientific research trends for "hydrogen-powered airplane"

Source: Scopus

Those challenges are reflected in the focus of recent and ongoing research projects. ENABLEH2 examined the potential of hydrogen in aviation, focusing on safety, energy efficiency, fuel storage and systems integration into new aircraft designs. Laboratory experiments were conducted on hydrogen combustion and fuel system heat transfer. HYDEA aims at exploring feasibility of hydrogen propulsion in a demonstration study. CAVENDISH and HESTIA projects investigate hydrogen combustion engines, whereas NEWBORN, HYPOTRADE, and HEAVEN focus on hydrogen fuel cells. Several projects explore hydrogen storage systems for airplanes, e.g. H2ELIOS, FLHYING TANK, COCOLIH2T, OVERLEAF, and ECOHYDRO.

Relevance for the EU policy goals

For achieving the goal of climate neutrality the European Green Deal sets the goal of 90% reduction of transport emissions by 2050. In case of aviation, some specific legislation has been introduced. Within the scope of the EU Emissions Trading System all airlines operating in Europe are required to monitor, report and verify their emissions, and to surrender corresponding allowances. Under the recent ReFuelEU aviation initiative, fuel suppliers are obliged to include a minimum share of SAF in the jet fuel, reaching 70% by 2050 (European Parliament, 2022).

The potential positive impact of hydrogen is high: H2 combustion could reduce climate impact in flight by 50 to 75 percent, and fuel-cell propulsion by 75 to 90 percent (Fuel Cells and Hydrogen 2 Joint Undertaking, 2020). It is therefore likely to play an important role in addition to the already existing measures.

4.2.9 Wind-assisted propulsion

Transport mode	Key megatrend	No. of identified projects	Total funding [€]
Maritime	Decarbonisation	8	46 mln

Background

In case of maritime decarbonisation, while a lot of effort is being devoted to development of low- and zero-carbon fuels such as hydrogen, ammonia or methanol (see 4.2.10 for detailed background), shipping industry is also investigating alternative pathways in order to meet these targets. One of the promising options is wind-assisted propulsion (WASP). Wind is a renewable, abundant and inexhaustible source of energy that can be converted into ship thrust and supplement or even replace the main engine of a ship. This traditional way of powering ships is being increasingly revisited in the recent years.
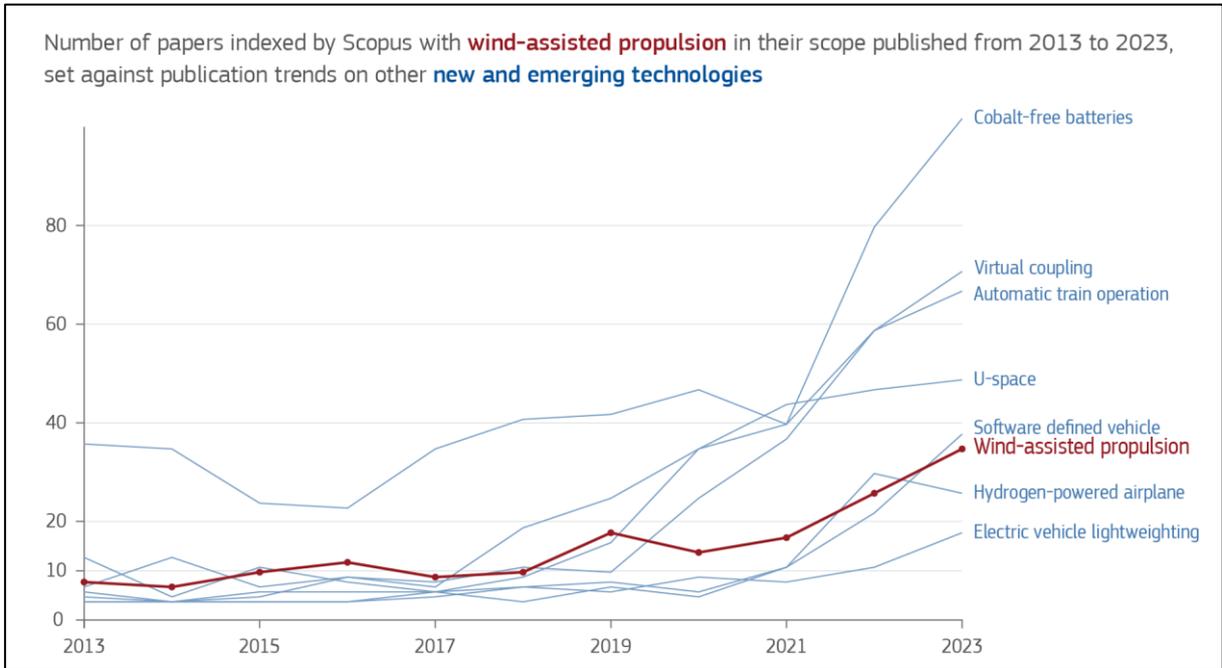
State of the art and relevant projects

There are several types of WASP systems that can be differentiated by the maturity of the technology, but also by the cost, potential fuel savings and suitability for various types of ships. Rotor sails are vertical spinning cylinders mounted vertically on the deck of the ship, that are driven by small electric engines. This active rotation together with the wind creates a pressure difference on the rotor that provides propulsive force. Soft sails are flexible sails like traditional ship sails. Modern sails of this kind can also be shaped in a particular manner to maximise the thrust force. Hard sails are similar to soft sails but they have a rigid geometry and are manufactured with strong and light materials such as carbon fibre. They are usually automatically rotated to optimise their orientation relative to wind direction and maximise propulsion. Hard sails are often referred to as wing sails due to their wing-shape geometry. Suction wings are vertical structures somewhat similar to rotor wings, however they generate thrust not by rotation but instead make use of boundary-layer suction and internal ventilators. Kites can be attached to the ship to generate thrust. The advantage of kites is that compared to other technologies they can take advantage of higher wind speeds found at higher altitudes. Finally, also the hull of a vessel can be shaped in a way that generates lift and pull in the ship's direction. In this case retrofitting existing ships is difficult and it can be applied only to newly constructed ships (European Maritime Safety Agency, 2023).

Some ships currently in operation are already equipped with WASP systems. Although this number is not very high (56 completed/planned implementations as of 2023), it keeps rapidly increasing, with a fivefold growth in the 2018–2023 period. Currently, the most mature WASP technology are rotor sails, representing roughly 40% of all deployments, followed by suction wings and hard sails with 23% each. Both kites and soft sails are at lower maturity level, although they have both undergone successful sea trials. Ships equipped with kites constitute 10% of all ships equipped with WASP, whereas soft sails have been installed only on a single ship up to date. Special hull shape design is the least mature technology, with no successful deployment in real operational conditions so far (European Maritime Safety Agency, 2023).

The potential emissions savings are subject to type, number, size and positioning of the WASP system on the ship. Wind speed and angle play a crucial role, and different wind conditions might be considered favourable depending on the type of the system. Stronger winds are often correlated with larger waves which in turn place additional burden on the ship's performance. Considering the importance of wind, choice of the route with the optimal environmental conditions become critical for the WASP performance. Lastly, the size and type of ship determines the possible number and size of WASP devices on board. Most of the solutions require sufficient structural strength, stability and available space. This makes some ship types more suitable for this technology, e.g. bulk carriers, flat-decked general cargo ships, tankers and gas carriers. WASP could be also applied to ro-ro and passenger ships, but the relatively low deck space in passenger ships poses a challenge. Container ships are the most problematic ones due to very little deck space. In this case less common solutions like kites might find their application (European Maritime Safety Agency, 2023).

Due to the multitude of relevant factors and the emission savings value range reported in the literature is rather broad. Various studies state savings of up to 30% for rotor sails, up to 50% for hard sails, and up to 40% for suction wings and kites. In addition to cutting air pollution, WASP could also contribute to reduction of underwater noise by lowering the load on the ship engine and the propeller (European Maritime Safety Agency, 2023).

Figure 17. Scientific research trends for "wind-assisted propulsion"

Source: Scopus

Among the EU-funded research initiatives several avenues can be distinguished. One of the topics under investigation is retrofitting existing ships with WASP technologies. WHISPER project is developing a modular retrofit solution comprising a wind-solar hybrid power system and a tilting wing sail system. RETROFIT55 aims at combining more mature technologies (ship electrification and hydrodynamic design optimisation, operational optimisation) with more innovative, such as WASP and new ways of air lubrication. The end product will be a digital ship model, serving as Decision Support System for exploring optimal retrofitting configurations for different ships and operational contexts. Some projects explore the optimal combination of WASP with other technologies for maximising emissions reduction and energy savings. OPTIWISE project aims at combining wind propulsion with a rigorous, holistic optimised ship design, control and operation, including a change in conventional propeller propulsion. The newly developed solution will be tested in different use cases for a bulk carrier, tanker, and a passenger vessel. CHEK project developed and demonstrated two vessel designs – a wind energy optimised bulk carrier and a hydrogen powered cruise ship – equipped with an interdisciplinary combination of innovative technologies working in symbiosis to reduce GHG emissions by 99% and achieve at least 50% energy savings. Several initiatives focused on a single specific WASP technology. Both BOUND4BLUE and WINNEW projects developed innovative wing sails, while ASPIRING WINGSAILS designed a new type of wing

sail adapted specifically for fishing vessels. Finally, ORCELLE is developing a technology that would enable wind as main propulsion, meaning an average energy efficiency gain of at least 50% in one full year of operation, and instantaneous gain close to 100% under ideal sailing conditions. The project will carry out tests on two physical demonstrators: A ship with 1-wing retrofit solution and a multi-wing vessel designed and built from scratch.

Relevance for the EU policy goals

WASP technologies are relevant for several EU policies. As a part of 'Fit for 55' package, the FuelEU Initiative introduced a harmonized regulatory framework to increase the share of renewable and low-carbon fuels in the fuel mix used for international maritime transport. The regulation sets a gradually increasing GHG-intensity limit for ships of 5000+ GT (gross tonnage), together with a binding compliance mechanism. Wind power is recognized by the framework as a sustainable energy source and is considered in calculations of the GHG-intensity indicator.

EU Emissions Trading System (EU ETS) is based on trading EU emissions allowances and puts a limit on the yearly maximum amount of GHG emissions. From 2025, shipping companies have to surrender sufficient emission allowances based on EU Monitoring, Reporting and Verification data of the previous year. Since the shipping companies will have to pay for the GHG they emit, it provides them with an incentive for emissions reduction. The method of achieving this reduction is up to them to decide, and WASP is one of the potential pathways to achieving the required compliance.

4.2.10 Alternative fuel for shipping

Transport mode	Key megatrend	No. of identified projects	Total funding [€]
Maritime	Decarbonisation	34	322 mln

Background

Sea shipping is responsible for moving an overwhelming share of world's goods, estimated at around 90% of all trade. At the same time, the global shipping is projected to grow by more than 2% each year in the 2024-2028 period. The maritime sector GHG emissions have increased by 20% over the last decade and are currently responsible for 3% of global GHG emissions (United Nations, 2023). At the same time, the increasingly stringent regulations put the industry under heavy pressure to reduce its environmental impact.

In 2023, the International Maritime Organization adopted a Strategy on Reduction of GHG Emissions from Ships, advocating for near zero-emission international shipping by 2050, with at least 40% CO_2 reduction by 2030. Essential role in this transition will belong to the adoption of sustainable fuels and energy sources that by 2030 should represent at least 5% (with the aim of 10%) of the energy used by international shipping (International Maritime Organization, 2023). As a stimulus for achieving these goals, IMO established two ratings: attained Energy Efficiency Existing Ship Index (EEXI) to determine ships energy efficiency, and their annual operational Carbon Intensity Indicator (CII) and associated CII rating. From the beginning of 2023 it became mandatory for all ships to calculate their attained EEXI and to collect data for the reporting of their CII and CII rating. The calculated attained EEXI value for each individual ship must be below the required EEXI, obtained with an applicable reduction factor expressed as a percentage relative to the Energy Efficiency Design Index (EEDI) baseline.

At the moment, the transition to sustainable fuels is still at its infancy, with 98.8% of the global fleet still running on fossil fuels (United Nations, 2023). Many alternative maritime fuels are under investigation, but there are several options deemed as the most promising. Based on the number of EU-funded research projects the most trending candidates are hydrogen, its derivatives such as green ammonia and methanol, and biofuels. If renewable resources are used for the fuel production, the first three alternatives have the potential to achieve near-zero emissions throughout the whole life cycle. Each option is characterized by specific pros and cons, in terms of supply-demand dynamics, technological readiness, sustainability, safety, and other considerations.

State of the art and relevant projects

For hydrogen one of the key challenges is its production, both in terms of sustainability and sufficiency of supply. Hydrogen can be produced in several ways, leading to general categorization in grey, blue and green hydrogen. Grey hydrogen is produced from fossil fuels, most commonly natural gas. If the CO_2 emissions from the production are captured and stored the hydrogen is categorized as blue. However, the efficiency of CO_2

capture is low and blue hydrogen production leads to other GHG emissions, e.g. methane. Green hydrogen is made from water in the electrolysis process, utilizing energy from renewable resources. Since it is the only truly sustainable type of hydrogen, it is an essential enabler for a hydrogen-based decarbonisation. Currently, the majority of hydrogen produced worldwide is grey, with only 1% being green hydrogen (International Energy Agency, 2023). Global capacity of green hydrogen production needs to be heavily increased to meet the future maritime demand, given the competition with other sectors looking at hydrogen-driven decarbonisation, e.g. steel or cement industries, or other transportation modes, most notably aviation. In numeric terms, current global green hydrogen production amounts to 0.1 million tonnes per year, far below the global energy demand of international shipping, estimated as equivalent of 95 million tonnes of hydrogen per year (European Maritime Safety Agency, 2023).

At the same time, once the supply of green hydrogen is secured it generates no further emissions during ship operation. In shipping, hydrogen can be used either in fuel cells (FC) or internal combustion engines (ICE). Whereas FCs are practically emissions-free, in case of ICEs some GHG might come from burning of pilot fuel used for initial engine ignition. Both propulsion systems are still in development, with FCs being somewhat more mature, but so far tested mainly for smaller vessels like ferries or passenger ships. Hydrogen storage poses a challenge – it can be stored either as a compressed gas or a cryogenic liquid under very low temperatures, and is characterized by high flammability. Hydrogen fuel tanks need to be stronger and heavier, which requires additional cargo space. The necessary infrastructure for hydrogen storage and bunkering is not yet in place. As a result of the above issues, cost becomes the main problem regarding hydrogen-powered shipping. Significant investments are needed for retrofitting of ship propulsion systems, and deployment of storage and refuelling facilities (International Renewable Energy Agency, 2021).
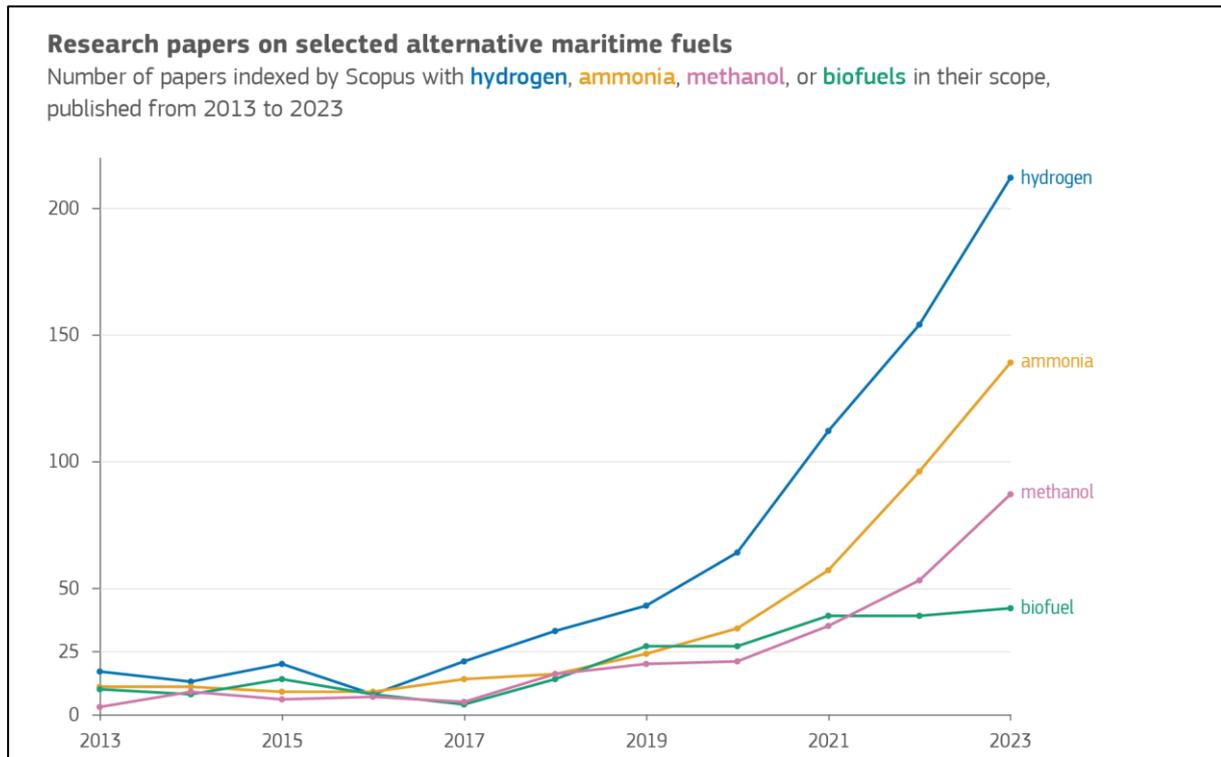
Hydrogen can be applied for powering a ship directly, but it can also be used for producing other fuels: notably methanol and ammonia. Compared to conventional fuels, methanol can reduce SOx and NOx by up to 60%, and particular matter by up to 95% (International Renewable Energy Agency, 2021). Depending on the production method, it is a low-carbon fuel on a life-cycle basis, being therefore considered as one of the options for shipping decarbonisation. Currently, the majority of methanol is produced using natural gas and coal as feedstock, both being carbon-intensive and unsustainable methods. Green methanol can be obtained either by biomass gasification and reformation (bio-methanol), or by combining green hydrogen and captured CO_2 (e-methanol). From point of view of technological feasibility for shipping methanol appears particularly advantageous. It would not require and major modifications to the existing infrastructure. Methanol is liquid at ambient temperature and pressure, thus easier to store and transport than gaseous or cryogenic fuels, like hydrogen. Currently, more than 100 ports worldwide have loading/unloading infrastructure for methanol in place. Moreover, methanol would not require any major engine retrofitting, with many commercial ships already being able to work with this fuel. Major obstacles stem from the supply and cost point of view. To satisfy 50% of current bunkering demand would require about triple of the current methanol production. For e-methanol, supply and high cost of renewable electricity and sustainable carbon capture is problematic, whereas in case of bio-methanol it is the availability of biomass resources and the related land use issues (International Renewable Energy Agency, 2021).

Ammonia is another attractive fuel option for the maritime sector. Its gravimetric energy density is comparable to some carbon-containing fuels like methanol, but lower than diesel or hydrogen. Similar to other fuels, sustainability of ammonia depends on the production method. Currently, almost 100% of global ammonia production relies on coal gasification and steam methane reforming to make hydrogen, subsequently used for ammonia synthesis (World Economic Forum, 2022). On the other hand, production of green ammonia with green hydrogen from water electrolysis with renewable resources is effectively carbon-free. The ammonia supply chain is already well established, providing a crucial input for agriculture (fertilisers) and chemical industries. Nevertheless, just as in case of other fuels it would require a major scale-up to meet shipping requirements. According to the current forecasts, by 2040 there will be enough renewable energy to meet maritime demand for green ammonia, however without considering the competition for both the energy and ammonia with other sectors. Ammonia, similar to hydrogen, can be used in ICEs and FCs, both propulsion systems being still in the phase of development. Ammonia use comes with safety challenges due to its toxicity, but relevant measures and regulations for handling and storing of ammonia have already been widely applied and tested in other sectors (European Maritime Safety Agency, 2023).

Contrary to the above options, biofuels production does not rely on green hydrogen. Thanks to the possibility of replacing conventional fuels with biofuels without any substantial modifications to engines, fuel tanks, pumps or supply systems they are seen as an option that can enter the market relatively quickly. There are many types of biofuels, the most promising being fatty acid methyl ester (FAME) biodiesel, hydrotreated vegetable oils (HVOs), Fischer-Tropsch (FT) diesel, dimethyl ether (DME) and bio-methanol. Availability of biomass, related

strongly to environmental concerns, is the main challenge. Most forecasts predict biomass shortages in the future, and the cost of biofuels is expected to keep rising (European Maritime Safety Agency, 2023).

Figure 18. Scientific research trends for selected alternative maritime fuels.

Research papers on selected alternative maritime fuels
Number of papers indexed by Scopus with **hydrogen**, **ammonia**, **methanol**, or **biofuels** in their scope, published from 2013 to 2023

Source: Scopus

Due to a large number of projects on alternative maritime fuels, a comprehensive project review is not suitable for the current report. For a more in-depth analysis the reader is invited to refer to the upcoming TRIMIS report on decarbonisation of waterborne transport, where all the recent R&I activities on in this specific area will be treated in much more detail.

The distribution of EU-funded projects reflects the trends in scientific literature, with hydrogen being the main area of research. HYMETHSHIP developed a hydrogen-methanol ship propulsion system using on-board pre-combustion carbon capture. HYSEAS III demonstrated a successful integration of fuel cells with a proven marine hybrid electric drive system along with the associated hydrogen storage and bunkering arrangements. The project developed one of the first ever green hydrogen-fuelled sea-going vehicle and passenger ferry vessels. FLAGSHIPS is working on development and demonstration of two commercially operated hydrogen fuel cell vessels, including design of the hydrogen systems on board. HYSHIP is advancing towards the construction and operation of a commercial cargo vessel running on liquid hydrogen, equipped with a 1 MWh battery pack and 3 MW fuel cells. HYEKOTANK project aims to develop a 2.4 MW hydrogen proton-exchange membrane (PEM) fuel cell system to retrofit the 18,600 DWT product tanker for emission-free operations. RH2IWER intends to demonstrate the practical use of hydrogen fuel cell technology on six commercially operated inland vessels of different types—container, bulk, and tanker, operating on the Rhine and Danube rivers. The recently started BLUEBARGE project aims to design, develop and demonstrate a fully integrated and more sustainable power barge solution primarily for offshore power to moored and anchored vessels. The project will consider the use of hydrogen fuel cells and hydrogen generators. ZEAS, another recently started project, is developing a hydrogen-powered ferry demonstrator for the Adriatic Sea. Some projects are investigating hydrogen storage more heavily. SHYPS is developing a specialized 40' ISO C-type hydrogen storage container and a modular powertrain system based on optimized PEM fuel cells, complemented by a novel logistics strategy for hydrogen container exchange. LH2CRAFT develops an innovative membrane-type containment system for large-scale storage and transportation of liquid hydrogen for commercial vessels.

Among ammonia-oriented projects, several aim at testing, validating, and implementing ammonia in single and dual-fuel engine systems. SHIPFC is developing an offshore vessel, equipped with a large 2MW ammonia fuel

cell, allowing it to sail solely on the clean fuel for up to 3,000 hours annually. The project will also look at three other vessel types and operational profiles, to illustrate the transferability to other segments of the shipping industry. ENGIMMONIA is developing an ammonia dual-fuel engine concept on a standard marine engine platform. The project will test the dual-fuel configuration at a laboratory scale with the target of 50% GHG reduction compared to the reference vessel. Two projects address the challenge of retrofitting existing ships. AMMONIA2-4 will demonstrate two types of dual-fuel marine engines running on ammonia as main fuel: a 4-stroke engine, demonstrated in laboratories conditions closely mimicking real-life operations in ambient conditions and a 2-stroke medium-pressure ammonia fuel injection platform, for retrofitting on existing 2-stroke marine engines. The recently started APOLLO project is dedicated to retrofitting existing offshore vessels with engines capable of running on ammonia. The project will conduct a large-scale demonstration of tri-fuel engines (ammonia, liquefied natural gas, and marine gas oil) aiming for a 70% reduction in GHG emissions. Several projects worked on methods for converting ammonia into hydrogen (ammonia cracking). AMON seeks to enable the use of ammonia as a clean energy carrier by developing a system to convert ammonia into electric power using solid oxide fuel cells. The GAMMA project will demonstrate safe integration of bio methanol and ammonia and fuel systems, bioethanol reformer, NH3 cracker and 1MW low-temperature PEM fuel cell, on board the ship by performing steam reforming and ammonia cracking. APOLO is developing an efficient ammonia cracking technology for power conversion. The project will demonstrate this technology in a 125kW power conversion system paired with both a PEM fuel cell and a 4-stroke engine. Finally, NH3CRAFT is developing an innovative ammonia storage technology to decarbonize shipping. It aims to design and demonstrate a commercially attractive and safe on-board storage system for 1,000 m3 of ammonia as marine fuel.

In case of methanol, the FASTWATER is investigating its application in maritime through four demo-cases: a harbour tug boat, a pilot boat, a coast guard vessel and a river cruise vessel. A methanol fuel injector and a high speed compression ignition methanol engine were developed for the retrofit of medium-speed engines. The recently started GAMMA is looking at retrofitting a bulk carrier ship to operate on alternative fuels such as green ammonia and bio-methanol. The project will demonstrate the operational safety of these systems and the practicality of a sustainable fuel value chain for maritime vessels. Some projects investigate the supply side. POSEIDON looks at the use of e-methanol as e-fuel in shipping by building and testing an innovative TRL7 e-methanol pilot plant based on a novel concept using two complementary CO_2 valorisation routes: a biogenic CO_2 from a biogas plant and an industrial plant from a lime plant. Finally, the UP-TO-ME project focuses on converting decentralized CO_2 sources, like biogas, into methanol using a hybrid process in fully autonomous, unmanned plants. The project will also establish quality standards for renewable methanol, assessing its suitability for marine engines and setting limits for water content and impurities.

For biofuels, the BIOSFERA project developed a combined thermochemical-biochemical Biomass-to-Liquid pathway for the production of maritime liquid fuels. Non-food bio-based feedstock was investigated for drop-in biofuels production. IDEALFUEL developed a low-cost chemical pathway to convert woody residual and waste materials such as sawdust and wood chips into a Biogenic Heavy Fuel Oil with ultra-low sulphur levels. BL2F developed a commercially viable HydroThermal Liquefaction conversion technology to produce sustainable drop-in biofuel for aviation and marine transport using a by-product of the pulp industry, the black liquor. The two more recent HE projects CARBIOW and E-TANDEM are looking at new conversion technologies: CARBIOW aims at establishing novel techniques such as torrefaction to convert the Organic Fraction of Municipal Solid Waste and other hard-to-utilize solid organic wastes to biofuels, while E-TANDEM will demonstrate a new hybrid-catalysis route for the production of a higher oxygenated diesel-like e-fuel based on higher alcohols and ethers from CO_2, water and renewable power only.

Relevance for the EU policy goals

Maritime transport decarbonisation is one of the elements of the broader EU strategy for sustainable transport, outlined in the Smart and Sustainable Mobility Strategy. The SSMS points out the waterborne sector as one of those which should have a priority access to renewable and low-carbon fuels, due to lack of alternative suitable powertrains in the short term. The importance of carbon pricing for maritime is highlighted. The strategy foresees the development of a market-ready zero-emission vessel by year 2030. Several specific EU maritime regulations and policy initiatives are in place, concretizing these high-level objectives.

Since January 2024, the EU's Emissions Trading System (EU ETS) has been extended to cover CO_2 emissions from all large ships (of 5 000 gross tonnage and above) entering EU ports. The ETS is a market-based measure that sets a limit (cap) on allowed emissions (allowances) and creates financial incentives to reduce a sector's emissions. The system covers 50% of emissions from voyages starting or ending outside of the EU, and 100% of emissions that occur between two EU ports and when ships are within EU ports. The emissions covered

include CO2 (carbon dioxide), CH4 (methane) and N2O (nitrous oxide), the last two only as from 2026 onwards. The ETS is supported by the EU Monitoring, Reporting and Verification Regulation for maritime transport, requiring shipping companies to monitor and report their CO2 emissions from voyages to, from, and within EU ports.

FuelEU Maritime Regulation sets maximum limits on the yearly greenhouse gas intensity of the energy used by a ship. Those targets will become more ambitious over time to stimulate and reflect the expected developments in technology and the increased production of renewable and low-carbon fuels. The targets cover CO2, CH4, and N2O emissions over the full fuels lifecycle. FuelEU takes a goal-based and technology-neutral approach, allowing for innovation and the development of new fuel technologies to meet future needs, and offering operators the freedom to decide which to use based on ship-specific or operation-specific profiles.

Regulation 2023/1804 on the deployment of alternative fuels infrastructure sets targets for shore-side electricity supply and bunkering infrastructure in TEN-T maritime ports. An appropriate number of refuelling points for liquefied methane should be available by 2025. Refuelling points for liquefied methane include liquefied methane terminals, tanks, tank truck trailers, truck tankers, mobile containers, bunker vessels and barges.

5 Conclusions

Based on the information on the European R&I activity in transport extracted from TRIMIS database, an analysis of the new and emerging trends and technologies in transport was carried out. The outcome is a selection of 7 cross-cutting digital technologies with a variety of applications across the transport sector, and 10 transport-specific technologies, which are strongly linked to a particular mode or transport issue.

In addition to these technologies, 5 megatrends were identified as the underlying drivers for the development of the presented technologies: decarbonisation, digitalization, automation, circularity and resilience.

The following digital technologies were identified:

Artificial intelligence	In general terms, AI means machines mimicking human intelligence. The most prominent AI branches include machine learning, machine perception and natural language processing. So far, the European transport R&I is mostly focused on AI applications in aviation, electromobility and connected and automated mobility, in particular for traffic management, assistance in engineering design process, monitoring and maintenance, and navigation.
Digital twins	DT is a digital model of a real-world object, effectively indistinguishable from its physical counterpart. A characteristic feature of DTs is their ability to exchange data with the modelled object. Typical uses include low-cost prototyping, maintenance, and monitoring. In transport, the common applications include automotive and aviation manufacturing, aircraft health monitoring, and predictive maintenance for railway.
Additive manufacturing	AM, also known as 3D printing, is a manufacturing method which produces objects by layer-by-layer material deposition. Contrary to the more traditional approach of subtractive processing, AM allows for easy production of very intricate shapes with minimal material waste. AM finds its applications mostly in aerospace and automotive industries, mainly for manufacturing complex components, rapid prototyping, and spare parts production.
Blockchain	BC is a distributed database, offering some specific features due to its particular design. BC enables secure transactions that do not require mutual trust, nor a centralized supervising authority. BC also supports smart contracts – triggered automatically when certain conditions are met. It is mostly used in logistics, where it helps to track the goods flow and automatize operations, but many other applications are investigated, e.g. in air traffic management.
Internet of Things	IoT refers to a network of physical objects (e.g. machines or vehicles) embedded with electronics and connectivity that enable collection and exchange of data, and as a consequence, automation. Most common applications include cargo tracking and process optimization in logistics, smart ports and manufacturing lines, e.g. in shipyards, and data collection for remote monitoring of infrastructure, vehicles, or even truck drivers or railway workers.
Extended reality	XR is an umbrella term for several technologies expanding the physical world by incorporating 3D graphic elements and sensory experiences. Virtual reality places the user in a completely artificial environment, while mixed and augmented reality enhance the real world with virtual elements. XR can facilitate design and manufacturing process, e.g. in aviation or shipbuilding, help in inspection and maintenance, or be a tool for CCAM safety simulations.

Edge and cloud computing	Edge and cloud computing represent a computing paradigm which shifts the data storage and processing from local to network-centric computing. Cloud computing relies on centralized data centers with high computing power, but offer poor latency as the data travels over long distances. This problem is addressed by edge computing. Edge computing is essential for CCAM applications, which require very fast processing of vast amounts of data.

Among the above digital technologies, artificial intelligence is by far the most represented one in terms of the amount of projects, with the total of 182 initiatives and total funding of 943 mln €. AI is followed by additive manufacturing (62 projects, 196 mln €), and digital twins (59 projects, 667 mln €). The most common AI applications belong to traffic management, support for engineering design, and navigation, with aviation, electromobility, and CCAM being the most frequent transport areas addressed.

The digital technologies cover a very broad range of use cases, often acting as facilitators for the development of specific transport technologies, e.g. serving as engineering design tools for modelling and quick prototyping. It can be therefore expected that digitalization will be a key trend for advancing R&I in transport, calling for high-priority treatment in the future research agenda.

In addition to the cross-cutting digital technologies, the following transport-specific technologies were identified:

Software-defined vehicle	Traditionally hardware-oriented automotive industry is undergoing a digital transformation towards software-defined cars, offering advanced infotainment, over-the-air updates and personalized modifications. SDVs are characterized by rapidly growing number of lines of code and share of software in the total value of the vehicle. Transition to SDVs poses a challenge to the EU automotive sector, which faces strong pressure from its global competitors.
Cobalt-free batteries	Reduction of cobalt content is among the main challenges of the current battery research. This critical earth material is an indispensable component of the majority of the lithium-ion batteries currently available on the market. At the same time, its use raises ethical and environmental concerns. New materials and battery chemistries are under investigation that could reduce the amount of cobalt in batteries or possibly eliminate it completely.
Lightweighting of electric vehicles	Vehicle weight is a key consideration for electric cars, having impact on driving range and battery size, thereby affecting the EV prices. Lightweighting of EVs is increasingly investigated, posing different challenges compared to conventional ICE vehicles. In case of EVs carbon footprint throughout the whole life cycle becomes the predominant concern, placing circularity and use of recycled materials at the forefront of lightweighting efforts.
Digital automatic coupling	Railway coupling refers to connecting the locomotive and consecutive wagons to form a train. Europe is one of the few remaining world regions where it is still done manually, causing huge inefficiencies. DAC is seen as a game changer for rail industry, representing a direct upgrade to an automated system, able to quickly couple and uncouple wagons. Next to mechanical connection DAC also provides digital connectivity - a key enabler of smart trains.
Automatic train operation	Compared to other modes, railway automation status is quite particular. Despite being widely automated in isolated circumstances, e.g. metro, automation of mainline is virtually non-existent. ATO can bring the much needed capacity gains, e.g. by better fleet coordination and optimized braking and acceleration. Key challenges include transition to communication-based control systems and automated track monitoring and maintenance.

Virtual coupling	Reduction of distance between consecutive trains is one of the ways of extending the available rail capacity without costly and time-consuming development of new infrastructure. VC applies the concept of relative braking distance, similar to behaviour of cars on a highway – by merging trains into digitally connected convoys their speed and braking can be coordinated, thereby allowing for shorter headways between virtually coupled trains.
U-space	The ever increasing number of drones in the skies requires their coordination and safe accommodation into the existing airspace. U-space can be defined as an airspace dedicated specifically for drones, comprising a set of services and procedures for their safe, efficient, and secure large-scale operations. The features include e-registration and tracking, flight planning and authorization, automatic collision avoidance, up to full integration with manned aviation.
Hydrogen-powered airplane	Hydrogen is being intensely revisited by aviation industry, with some of the major players looking at development of a hydrogen-powered commercial airplane by the end of the next decade. Hydrogen offers an attractive alternative to other options that either raise sustainability concerns (SAF), or are limited by low energy density (electric planes). Hydrogen storage on board and hydrogen-based propulsion are currently main unresolved challenges.
Wind-assisted propulsion	Apart from the alternative maritime fuels for the future, other shipping decarbonisation measures are under investigation. WASP aims to harness the most ancient shipping 'fuel' – wind. The options range from cylindrical rotors, modern versions of traditional sails, to suction wings and kites. WASP performance highly depends on its design, wind conditions and ship type – in favourable conditions it could theoretically act as the only source of propulsion.
Alternative fuel for shipping	Maritime industry is under heavy pressure to reduce its emissions, and alternative fuels will play a central part in this transition. However, the future fuel mix is under heavy debate. There are several potential fuels on the table, each coming with advantages and shortcomings of its own. This report focuses on the four most promising options, with the highest representation in the European R&I projects: hydrogen, ammonia, methanol, and biofuels.

Direct comparison of the above transport-specific technologies is challenging, due to a variety of reasons. Some of them represent a trend rather than a concrete technology, e.g. software-defined vehicles and EV lightweighting. In other cases, there might be different advancement levels within a technology, with varying TRL levels (e.g. U-space), discrepancies between scientific literature representation and actual implementation (e.g. virtual coupling and digital automatic coupling), or a single value cannot be assigned due to various options involved (e.g. alternative shipping fuel) or many building blocks (e.g. automatic train operations).

As a result, classification of the technologies, e.g. by their potential impact, is difficult. Looking at the scientific literature trends, the most researched technologies are alternative fuels for shipping (in particular hydrogen and ammonia), cobalt-free batteries, and virtual coupling, while digital automatic coupling, EV lightweighting, and hydrogen-powered airplanes are among the least addressed ones. However, the scientific trends are only one of multiple indicators considered, as indicated in the methodology. Considering all the factors together, the authors would like to bring attention to three technologies in particular, which based on their own judgement are likely to be most impactful. First is the software-defined vehicle trend, which due to the scale of transformation and challenge for the automotive sector represents a major disruption with significant ramifications for the industry as a whole. Secondly, the digital automatic coupling is a potential game changer for the railway industry. It owes its relevance to the high market readiness, and a high potential impact on the European rail, thanks to a radical departure from the inefficient manual coupling. Lastly, the hydrogen-powered airplane is expected to be the key R&I direction in aviation, due to a scarcity of long-term alternatives, the required level of research activity and investment, and the high industry commitment to development of this technology.

Two technologies seem especially critical from the point of view of the European resilience and competitiveness. Software-defined vehicle poses a risk for the European automotive industry, considering the pressure from the Chinese and American competitors, and the increasing dependence on advanced electronics, especially microchips. Cobalt reduction in batteries, on the other hand, is relevant for decreasing dependence on raw materials and vulnerable supply chains for the critical transport sectors, in this case batteries and electromobility.

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List of abbreviations and definitions

TRIMIS	Transport Research and Innovation Monitoring and Information System
ABD	Absolute breaking distance
AHSS	Advanced high-strength steel
AI	Artificial intelligence
AM	Additive manufacturing
AR	Augmented reality
ATM	Air traffic management
ATO	Automatic train operation
BC	Blockchain
BEV	Battery-electric vehicle
CCAM	Cooperative, connected and automated mobility
CEAP	Circular Economy Action Plan
CFRP	Carbon-fiber-reinforced plastics
CONOPS	Concept of operations
DAC	Digital automatic coupling
DL	Deep learning
DRC	Democratic Republic of Congo
DT	Digital twin
ECU	Electronic Control Unit
EDDP	European DAC Delivery Programme
EEA	Electronic and electrical architecture
EEDI	Energy Efficiency Design Index
EEXI	Energy Efficiency Existing Ship Index
EGD	European Green Deal
ETCS	European Train Control System
EV	Electric vehicle
FBS	Fixed block system
FC	Fuel cell
GHG	Greenhouse gases
GIS	Geographic Information System
GoA	Grade of Automation
ICE	Internal combustion engine
ICT	Information and communication technology
IoT	Internet of Things
ITS	Intelligent transportation system
JRC	Joint Research Centre
LFP	Lithium iron phosphate
LLM	Large language model
LNMO	Lithium nickel manganese oxide
MaaS	Mobility as a service
MBS	Moving block system
ML	Machine learning
MMC	Metal-matrix composites
MR	Mixed reality
NCA	Nickel cobalt aluminium oxide
NETT	New and Emerging Technologies and Trends
NLP	Natural language processing

NMC	Lithium nickel manganese cobalt oxide
OEM	Original equipment manufacturer
PEM	Proton-exchange membrane
PI	Physical internet
PoS	Proof-of-stake
PoW	Proof-of-work
R&I	Research and Innovation
RBD	Relative braking distance
SAF	Sustainable aviation fuel
SDV	Software-defined vehicle
SSB	Solid-state battery
SSMS	Sustainable and Smart Mobility Strategy
T2G	Train-to-ground
T2T	Train-to-train
TEN-T	Trans-European Transport Network
TRL	Technology Readiness Level
VC	Virtual coupling
VR	Virtual reality
VRU	Vulnerable road user
WASP	Wind-assisted propulsion
XR	Extended reality

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Annexes

Annex 1. List of Scopus prompts for extracting scientific literature trends

Software-defined vehicle	TITLE-ABS-KEY("software_defined_vehicle")
Cobalt-free batteries	TITLE-ABS-KEY("cobalt_free" AND ("battery" or "batteries"))
Lightweighting of electric vehicles	TITLE-ABS-KEY(("lightweight" OR "lightweighting" OR "weight_reduction") AND ("electric_vehicle" OR "electric_vehicles" OR "electric_car" OR "electric_cars" OR "EVs")
Digital automatic coupling	TITLE-ABS-KEY("digital automatic coupling" OR "digital automatic coupler")
Automatic train operation	TITLE-ABS-KEY("automatic train operation")
Virtual coupling	TITLE-ABS-KEY("virtual_coupling" AND ("rail" or "train"))
U-space	TITLE-ABS-KEY("u-space")
Hydrogen-powered airplane	TITLE-ABS-KEY("hydrogen_aircraft" OR "hydrogen_airplane" OR "hydrogen_powered_aircraft" OR "hydrogen_powered_airplane")
Wind-assisted propulsion	TITLE-ABS-KEY(("wind_assisted_propulsion" OR "Wind_propulsion_system" OR "Wind_assisted_ship_propulsion" OR "Wing_sails") AND ("ship" OR "maritime" OR "vessel"))
Alternative fuel for shipping	TITLE-ABS-KEY('methanol' AND ('maritime' or 'shipping'))
	TITLE-ABS-KEY('biofuel' AND ('maritime' or 'shipping'))
	TITLE-ABS-KEY('ammonia' AND ('maritime' or 'shipping'))
	TITLE-ABS-KEY('hydrogen' AND ('maritime' or 'shipping'))

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