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Technologies to Address the Future Rail Challenges

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Abstract

The digital revolution is happening, transforming the way we move and produce. Over the last two decades, the European rail sector has undergone major changes. In view of this situation, the railway sector is of great importance for the Europeans economy due to its relations with other sectors (industrial and services) and its intense international activity. The aim of this study is to analyze the existing technologies to address the technological challenges identified in the railway sector, in order to understand their role in the sector's innovation processes. The analysis will identify the different solutions offered by the railway industry in terms of Infrastructure, Rolling Stock and Digital Systems. The study has been carried out under the RIN-Rail Innovation Network project, funded by the Basque Government in the Elkartek 2022 programme (KK-2022/00027).

Keywords

Railway, Innovation, Technology

1. Introduction

Over the last two decades, the European rail sector has undergone major changes. Rail transport plays a key role for the European economy and society, but it has the potential to contribute much more. The number of kilometres travelled by the passengers has grown by more than 10% in the last eight years, and rail has been gaining share of passengers over air travel on the main inter-city routes. Around 7% of passenger traffic in Europe is carried by rail (Lotz et al., 2020). Despite the strength of European rail, the industry relies, in part, on outdated legacy systems that are becoming more difficult, and in some cases, almost impossible to maintain. To overcome these difficulties and remain competitive, the industry must recognize that digital technologies are changing the rules com-

pletely. The development of digital technologies will be key to achieve the ambitions of the European Green Deal and the Sustainable Development Goals. Furthermore, the digitisation of rail will increase its capacity, safety and comfort, maintaining the EU's leadership in rail equipment and services. New technologies such as artificial intelligence, big data, cloud computing, etc. will have a major impact on the sector. Innovation will play a vital role as it will serve as a catalyst for the development of the necessary advances for the sector.

In 2021, the European Commission adopted the Communication "*The 2030 Digital Compass*: *the European way for the Digital Decade*", which mentions the importance of digital solutions to promote a more connected and automated mobility that reduces accidents, improves the quality of life and increases the efficiency of transport, as well as reducing its environmental impact. These growing mobility needs and demands of society, as well as the technological progress achieved by other modes of transport and new technologies from other sectors, represent both a challenge and an opportunity for the sector, which makes it necessary to continue to focus on innovation as a bridge to excellence.

In view of this situation, the railway sector is of great importance for the Europeans economy due to its relations with other sectors (industrial and services) and its intense international activity. The railway sector is considered a key player, and the European Commission has invested more than €1 billion in railway research and innovation projects since 2007 (Lotz et al., 2020).

In the case of the Basque Country, the railway sector is an innovative sector with a strong international presence (Lotz et al., 2020). The Basque Country is among the most advanced European regions in terms of innovation. According to the data of the Basque Innovation Agency—Innobasque (Innobasque, 2023), the annual investment in R&D as a percentage of GDP in the Basque Country is 2.11%, placing it in 10th place in the EU-27, with an average value of 2.27%. In Spain, the Basque Country is in first position, above the average, with the national average for R&D investment being 1.43%.

In the Basque Country, the railway sector employs around 7200 people and represents approximately 40% of the entire sector in Spain, which means that the railway industry in the Basque Country is undoubtedly a point of reference. 51% of the people working in this sector work in SMEs and the rest in tractor companies. Basque companies linked to the railway sector export a global value of approximately 1700 million euros. The Basque railway sector invests 4% of its turnover in innovation, which makes it a lever for the internationalisation of small and medium-sized enterprises (Lotz et al., 2020). It is also important to highlight the strategic location of the Basque Country in the European context, as it is situated in the neuralgic centre and critical point of the Atlantic Axis. The Basque Country is a key link in the European Atlantic Corridor, which covers more than 2000 kilometres in length and is home to around 60 million inhabitants, 12% of the European population, as well as 30% of the GDP of the Eurozone.

At the European level, companies in the rail sector are focusing on R&D projects to take advantage of the EU funds' drive for cleaner and more efficient transport. Railway companies in Spain are an example of the robustness of R&D&I.

It is important for the railway sector to be aware of the global challenges facing the sector, which present great opportunities:

1) Demographic growth, which demands more and better infrastructure for the transport of people and goods.

2) An ageing population, which demands safer, more reliable, more comfortable and more practical means of transport in the event of reduced mobility.

3) Integration with other forms of transport: from transport to mobility.

4) The development of new technologies: rail is well positioned in the race to offer an "autonomous" means of transport.

This paper presents first the theoretical background on the key technological and digital challenges for the sector. Then, data analysis and results are examined. Finally, the research findings are discussed, including the limitations and concluding remarks.

2. Objective

The aim of this study is to analyze the existing technologies to address the technological challenges identified in the railway sector, in order to understand their role in the sector's innovation processes.

The analysis will identify the different solutions offered by the railway industry in terms of Infrastructure, Rolling Stock and Digital Systems. In addition, special attention will be paid to the contributions they make to innovation in the rail sector and to the strategies they follow in the field of collaboration and innovation.

The study has been carried out under the RIN-Rail Innovation Network project, funded by the Basque Government in the Elkartek 2022 programme (KK-2022/00027).

3. Background

The rail sector is of great importance in Europe, as a global leader in rail transport that easily adapts to technological opportunities. In addition, rail passenger transport is essential to ensure the mobility of people and territorial structuring.. The European Union has promoted the gradual opening to competition in the railway sector, which has led to the liberalization of rail freight, the international transport of passengers and, as of December 14, 2020, domestic passenger transport throughout the European Union (del Estado, 2022). The need to place the rail sector as the backbone of European mobility and to remain competitive has posed different challenges for the sector in the areas of sustainability, efficiency, user experience and freight.

There is concern about the environmental and social problems caused by the

generalization of a transport model based on fossil fuels. Transport accounts for a quarter of the European Union's greenhouse gas emissions and is on the rise. To achieve climate neutrality, a 90% reduction in transport emissions is needed by 2050 (Lotz et al., 2020).

The disadvantages of the current mobility model, including air pollution, excessive energy consumption, health effects, etc., have led to a desire to find alternatives that help to alleviate these negative effects, among which electric traction means of transport should be highlighted.

Rail transport is the most sustainable mode of transport and is a key element in achieving Europe's environmental sustainability objectives. Rail transport accounts for only 0.4% of greenhouse gas emissions in Europe, which means that it is capable of moving a greater load while emitting up to 9 times less CO_2 than other means of transport. A key aspect to take into account when creating a more sustainable railway system is traction consumption. In this sense, three key lines of analysis have been identified: defining self-consumption plans, defining technological developments for energy use and resource use.

In the area of efficiency, there is a main challenge for companies in the sector in the short term: to align supply with demand. A reduction in demand would involve a reduction in costs and investments and would require supply chains to have greater planning and efficiency capacity. This challenge can be addressed by further digitalization of the sector increasing its flexibility, planning capacity and receiving market information more quickly.

Innovation is also a key factor in improving users' experience in the sector, increasing safety, comfort and reliability of rail transport. Innovation in supply and demand management, through digitization and automation, can improve the user experience by enabling greater flexibility and planning capacity as well as increased user convenience. In this area, the main objective is focused on the search for innovative solutions to improve services and user experience through the use of technologies. Some of the solutions developed focus on improving comfort in the passenger environment (lighting and presence sensors), as well as customization and flexibility inside the trains. Another area of work is integrated mobility, offering solutions that enable door-to-door mobility and the integration of all modes of transport in the city on a single platform.

Digitalization provides travellers with more attractive and integrated mobility, enhancing the passenger experience. It also enables rail operators to make their infrastructures smart, ensuring availability and increasing sustainability throughout the product lifecycle.

Another important aspect is rail freight. Europe has nine market-oriented international rail freight corridors (European Commission, 2019). When transporting goods, it is considered that for the same quantity transported, rail emits 70% less CO_2 than trucks, which is why current research is based on improving the conditions of supply via rail so that companies decide to opt for this means of transport. In the field of freight, work is being done on standardizing and au-

tomating the loading and unloading of freight, as well as on the autonomous/virtual coupling of the fleet to optimize the operation. Work is also being done on the integration of the different types of transport-goods-passengers in search of optimal transport, taking into account the criteria of energy efficiency, cost and time.

4. Methodology

In 2022-2023, a consultation was made with MAFEX aiming to align the sector's offer to the challenges from the technological point of view, considering the current technologies and the development and adoption of emerging technologies. During the consultation and validation process 118 members of MAFEX participated. MAFEX members account for 83.45% of exports, representing more than 8% of the industrial GDP at state level.

A survey has been carried out to analyze the capabilities of the Technology Centres and R&D Units of the RVCTI (Basque Science, Technology and Innovation Network) and the Universities based in the Basque Country in relation to the innovation challenges identified.

The methodology and the survey have been developed in collaboration with the University of the Basque Country/Universidad del País Vasco (UPV/EHU), based on the analysis of existing technologies to address each challenge. This methodology allows an effective replication of the analysis.

The survey has been elaborated with the EUSURVEY program. A tool offered by the European Commission for the management of online surveys, available to all citizens of the European Union. The questionnaire has been designed in web format and with a high degree of structuring (quasi-intelligent) offering a limited number of options to the respondent based on their previous answers and considering the conclusions reached in previous sectorial analyses among professionals of the sector, fostering the consistency of the answers collected and partially compensating the dispersion effects typical of such a qualitative object of study and subject to interpretation.

Once the survey was developed, 3 validation meetings were held with different entities. These validation meetings were carried out in order to know the sensation of the target audience about the survey and to make the necessary improvements before launching it to the agents from RVCTI.

After validation, different RVCTI agents have been invited to answer the survey through a meeting. This meeting has served to explain the project, to present the technological challenges of the sector, as well as the methodology.

In spite of this effort, and given that the comprehension of the Driving Factors and Milestones described in the questionnaire could have a different interpretation depending on the specific knowledge that the interviewee may have, a series of guidelines have been defined for the selection of the interviewees so that all of them can satisfy a minimum profile of specialization in some of the subjects on which they can answer. In this way, the results obtained will reduce the bias of a

misinterpretation of the meaning of the Driving Factors and Milestones to which to link the competencies about which he/she is asked.

When selecting the profiles of the interviewees for each of the entities, a series of criteria were established to be applied to the candidates in order to obtain the most complete results of the entities' capabilities. Among the criteria established were the degree of experience of the candidate in the technological field, the years of experience in the entity in order to contribute to the identification of other possible interviewees in other technological areas of interest for the analysis and the profile of the candidate, preferably with positions of department director, principal investigator, R&D director or equivalent that might exist in different organizations.

In addition, the interviewee has been asked to report possible limitations that he/she may state about his/her detailed knowledge in certain technological areas and that could bias his/her ability to identify competencies residing in that agent. It has been considered convenient that the interviewee is familiar with the methodology used in the study.

The questionnaire has been developed in 3 parts:

1) Context

Introduction and context of the project and survey.

2) Identification of competencies

"*Competence is defined as the aptitude* (*ability*, *capacity or knowledge*) *of an agent to reach a Milestone within one of the defined Driving Factors. In this project*, *and to respect the defined methodology*, *competencies will be defined linked to a Driving Factor and in a technological context*".

2.1. Inventory the competencies available in the sector.

2.2. Classify the competencies in terms of the technological theme to which they are attached.

2.3. Classify the competencies according to their contribution capacity.

- Innovation and/or development (ability to create a new solution)
- Adaptation and/or application (ability to adapt or apply an existing solution)
- Testing (ability to design and carry out a test)

3) Characterization of the agents

"*An agent is defined as a set of resources consisting of knowledge*, *relational capital and facilities*, *whether or not integrated into a stable structure or within a larger organization*, *with the capacity to transfer competencies to third parties in any form*".

5. Results

The railway sector is undergoing a period of change and transformation, in which innovation and technology play a fundamental role in facing current and future challenges. In this sense, four key blocks for competitiveness have been identified, such as sustainability, efficiency, user experience and freight transport, which encompass the challenges that the sector is currently facing and will

face in the future.

To address these challenges, six technology areas have been identified that offer solutions to the aforementioned challenges: 1) Models (Industry 4.0), 2) Data, 3) Electronics and Connectivity, 4) Energy and Energy Management, 5) Materials and 6) Applications and Services. Each of these technological areas has a number of key technologies that enable these challenges to be met.

In this context, it is relevant to analyze the capabilities of Technology Centres and R&D Units of the RVCTI and Universities based in the Basque Country with activity in the railway sector in each of these technological areas. In particular, the technologies in which the Basque Country has a greater and lesser capacity will be explored, with the aim of identifying opportunities for improvement and potential for development in the railway sector.

1) Models (Industry 4.0)

The technology area of Models (Industry 4.0) is presented as a key area to improve the efficiency and competitiveness of the railway sector, through the application of technologies such as additive manufacturing (3D printing), machine learning, digital twin, robotics, hydrodynamic pressure, infrared heating, embedded electronics, printed electronics and BIM.

This technology area offers a wide variety of technologies to address the challenges faced by the railway sector. Rolling stock and infrastructure monitoring, intelligent optimization of traffic planning and adjustment to demand, and new manufacturing processes are just a few examples of how these technologies can be of great help.

Intelligent optimization of planning and matching traffic to demand are key areas for improving efficiency in the rail sector. Machine learning-based production planning systems can help reduce costs and improve efficiency in resource planning and scheduling.

The development and production of smart and sensorised materials for the intelligent construction of rolling stock and infrastructure is another major challenge. Additive manufacturing, embedded electronics and nanotechnology materials can enable the creation of innovative and efficient materials. In addition, the use of BIM (Building Information Modelling) can help in the intelligent design and construction of rail infrastructure.

Standardization and automation of freight loading and unloading, monitoring of infrastructure, safety and rolling stock, and optimization of networked energy management are other important challenges that can be addressed with technologies in this area.

Technologies applied to provide real-time information, for smart stations and smart information windows, are becoming increasingly important for the industry. The inclusion of new solutions for inclusive mobility and infrastructure, the evolution towards Automated Train Operations (ATO), noise reduction in night freight trains and optimization and cost reduction in operation and maintenance are other important challenges that can be addressed with technologies in this

area.

The result of the analysis of the capabilities in the technological area of Models (Industry 4.0) shows that most of the existing capabilities respond to the *Optimization and reduction of operations and maintenance costs* Milestone. 9.73% of the capabilities respond to this Milestone, ahead of the capabilities that respond to the *Infrastructure Monitoring* Milestone with 9.3% or to the challenge of *Rolling Stock Monitoring* with 8.67%.

On the contrary, the analysis shows that the agents interviewed do not have technological capabilities to respond to the following milestones: *Smart windows* (0%), *Night freight train* (*including noise reduction*) (0.42%), *Real-time travel information to the passenger* (0.63%) and *Inclusive mobility and infrastructure* (0.63%) (see Figure 1).

2) Data

The railway sector generates huge amounts of data, which are collected in different areas such as operation, safety and maintenance, among others. The management and analysis of this data has become increasingly important in the industry, and this is where the Data technology area comes into play, encompassing technologies such as artificial intelligence, big data, data analytics, cybersecurity, predictive algorithms and control, blockchain, perception technologies (lidar, artificial vision), HPC supercomputing and data spaces.

In the context of the rail sector, these technologies can be applied in a variety of ways. For example, artificial intelligence and big data can be used to predict potential infrastructure or vehicle failures, allowing preventive measures to be taken before they occur. Predictive and control algorithms can be applied to optimize the operation and maintenance of the rail network, thereby reducing costs and improving efficiency.

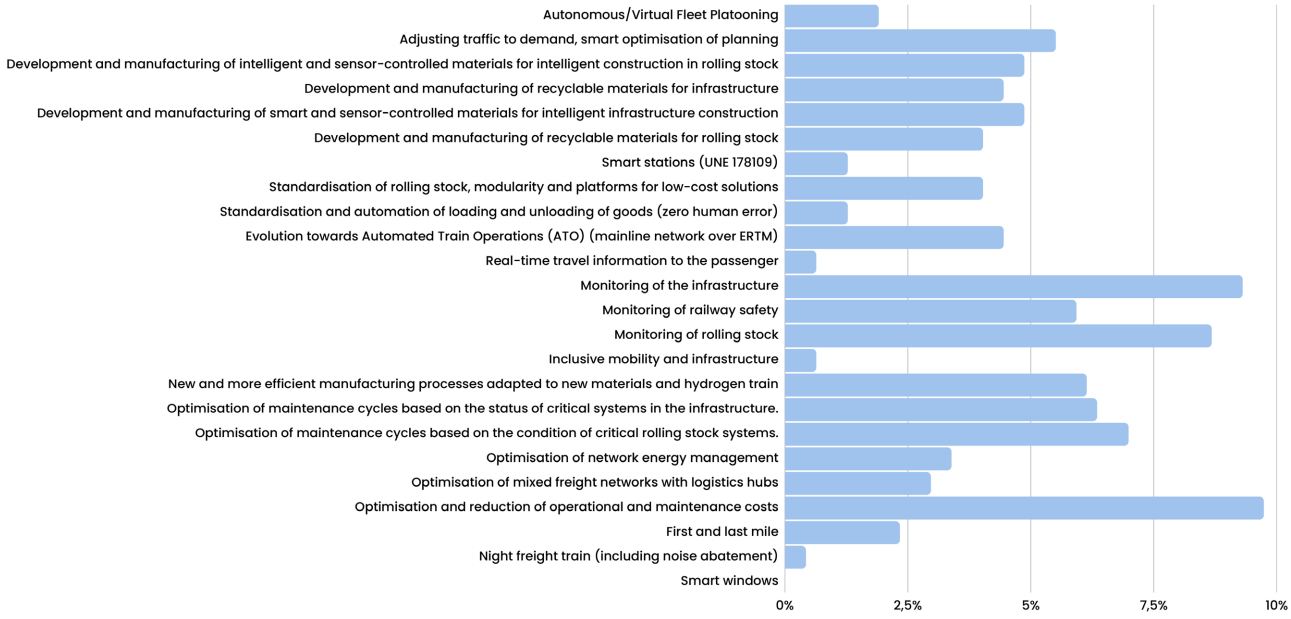

Figure 1. Milestones in the technology area of models (Industry 4.0). Own elaboration.

Developments in cybersecurity and blockchain can be used to protect information and prevent potential attacks. Sensing technologies can also be applied to improve the safety and efficiency of railway operation by detecting potential obstacles and adjusting train speed accordingly.

Finally, HPC supercomputing and data space can be used to handle and process large volumes of information efficiently, enabling more effective management of collected data and better decision making.

In the case of the Data technology area, the three Milestones in which the entities have shown more capabilities are: *Optimization of maintenance cycles based on the condition of critical infrastructure systems* and *Optimization of maintenance cycles based on the condition of critical rolling stock systems*, both with 7.85% of the capabilities, followed closely by *Infrastructure monitoring* with 7.62% of them.

When analyzing the minimums again we see that the Information *Intelligent Windows* Milestone has no capabilities in this area. Followed by *Adequacy of Access Methods* (0.11%) and *Night freight Train* (0.23%) (see Figure 2).

3) Electronics and Connectivity

The Electronics and Connectivity technology area is key to the development

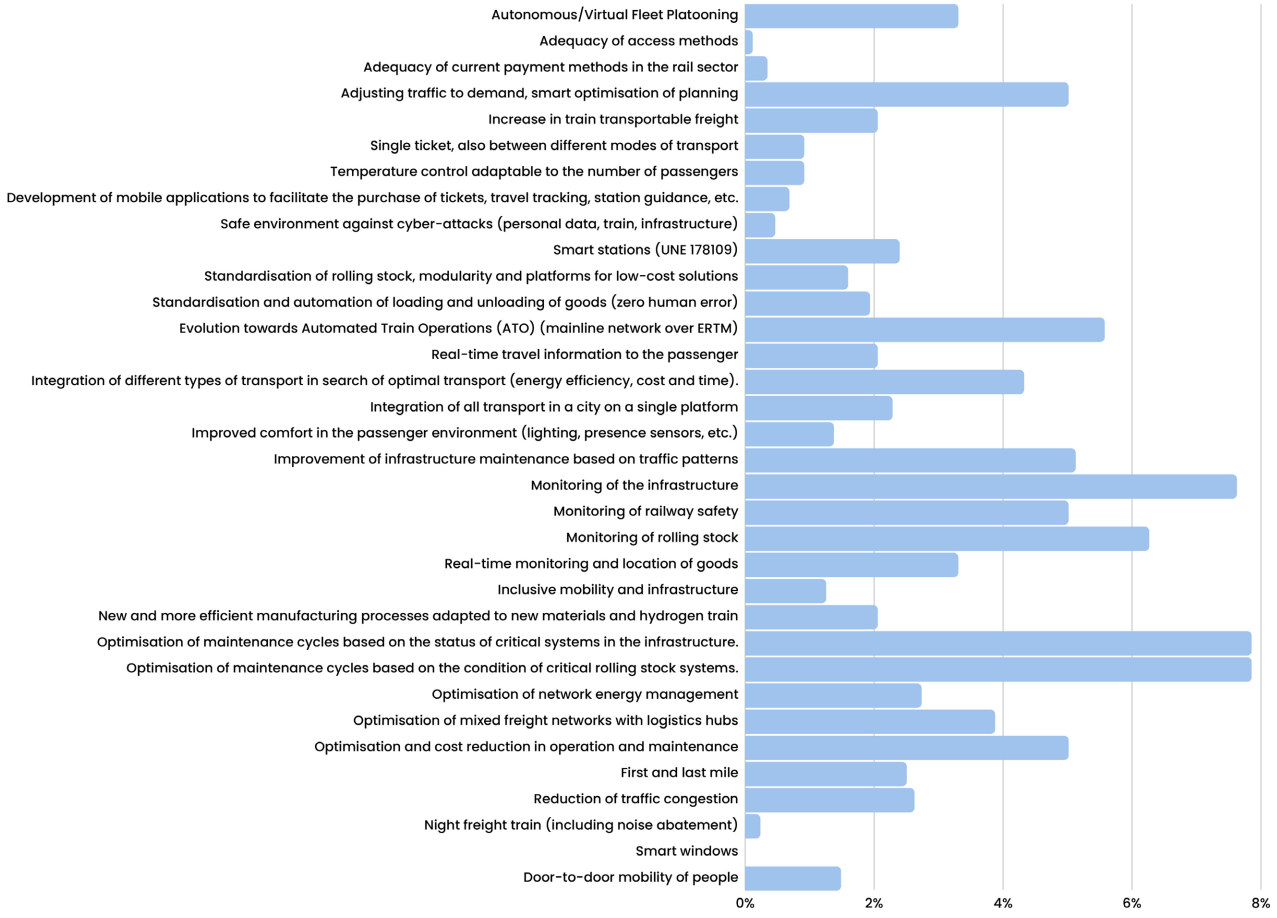

Figure 2. Milestones in the technology area of data. Own elaboration.

of the railway sector, as it encompasses technologies that enable communication, connectivity and automation of railway systems. Among the technologies included are advanced communications (5G, WIFI, Bluetooth), plug&play, positioning systems, cloud computing, edge computing, biometric reading, magnetic levitation, flexible electronics, sensorics, actuators and the Internet of Things (IoT).

Electronics and Connectivity technology plays a key role in the rail sector by addressing the various challenges faced by this sector. For example, access and payment methods can be improved through biometric reading technology and mobile applications that enable real-time ticket purchasing and trip tracking. In addition, advanced communications technology, such as 5G, WIFI and Bluetooth, enable greater speed and capacity for real-time data transmission between the various systems involved in traffic planning, allowing planning to be optimized and traffic to be matched to demand.

Positioning and sensor technologies also contribute to this, as they allow real-time tracking of vehicle position, which can be used to optimize operation and reduce waiting times. These technologies can also be applied to temperature control to adapt to the number of passengers and improve passenger comfort.

Technologies such as Edge Computing and Cloud Computing can be used for real-time monitoring of the status of infrastructure, rolling stock and transported goods, enabling more efficient maintenance management and early detection of potential problems.

The technologies in this area respond to many other important challenges (see Figure 3). With the exception of the *Smart Windows* Milestone, Technology Centres and R&D Units of the RVCTI and the Universities based in the Basque Country have the capabilities to respond to all the challenges. Most of the capacities are concentrated in the Milestones of *Infrastructure Monitoring* (7.36%), *Optimization of maintenance cycles based on the condition of critical systems of the infrastructure* (6.75%), *Real-time travel information to the passenger* (6.45%) and *Optimization of maintenance cycles based on the condition of critical systems of the rolling stock* and *Evolution towards Automated Train Operations* (*ATO*) (*mainline network over ERTM*), both with 6.35% of the capacities.

4) Energy and Energy Management

The rail sector is one of the most energy-efficient modes of transport, as it has significant advantages over other modes of transport. Responsible for 9% of passenger transport and 7% of freight transport (Lotz et al., 2020), it accounts for less than 0.4% of the GHG emissions of the entire transport sector and less than 2% of global transport energy consumption, which is about 0.5% of total global energy consumption, with rail's modal share of about 7%. For all these reasons, rail is set to be a key driver in the decarbonization of the transportation industry.

In this area, the adoption of technologies in the area of energy and energy management can reduce energy consumption and improve efficiency in railway

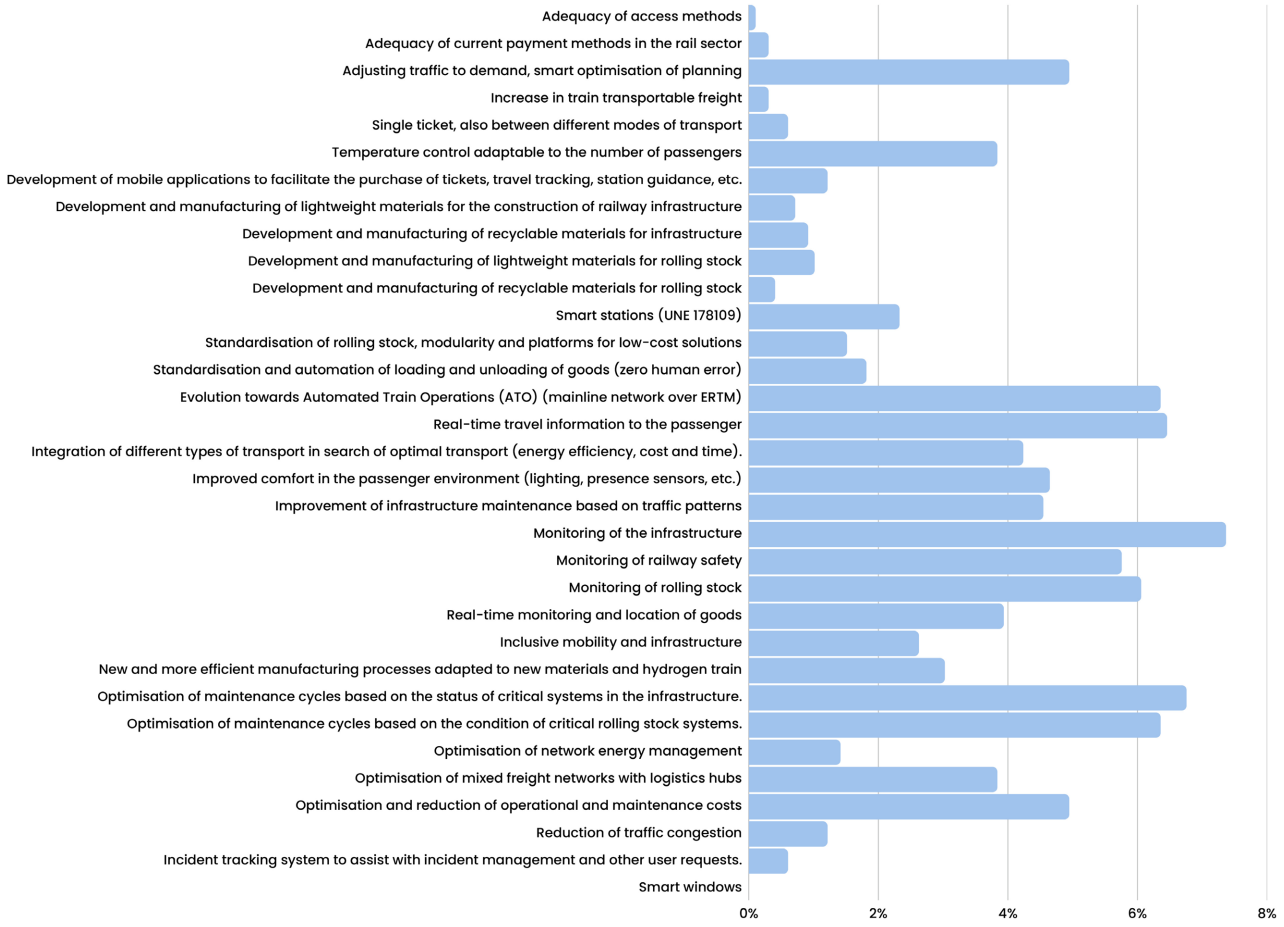

Figure 3. Milestones in the technology area of electronics and connectivity. Own elaboration.

operation. This technology area offers a wide variety of technologies to address the challenges faced by the railway sector. In particular, electronics and power technologies, catenary, platooning, battery technologies and hydrogen technologies.

The challenges related to these technologies are oriented both to the development of technologies and methodologies that maximize energy efficiency, and therefore fuel consumption per kilometre, and to the use of technologies that allow the supply of the required energy with minimum CO_2 emissions.

This is why, in the case of this technological area, most of the capacities are focused on the *Optimisation of network energy management* (48.15%). The growing demand for energy, on the one hand, and the decrease in resources from non-renewable sources, make it necessary to acquire energy from alternative sources and increase the efficiency of energy consumption (see Figure 4).

5) Materials

The railway sector has evolved significantly in recent decades and has demonstrated a strong commitment to environmental sustainability, energy efficiency and improving the user experience. In this regard, the Materials technology area plays a key role in the development and innovation of new materials and solutions to improve the sustainability and efficiency of railway systems.

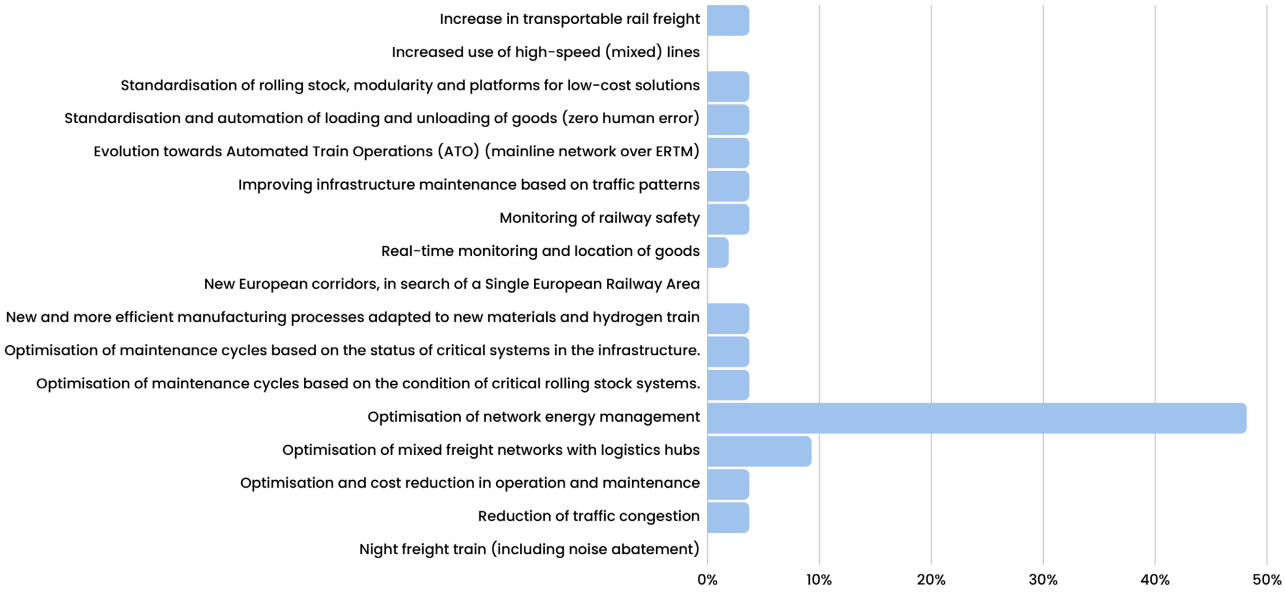

Figure 4. Milestones in the technology area of energy and energy management. Own elaboration.

The Materials technology area is essential to address the challenges posed by the railway sector. With technologies such as smart fabrics, nanomaterials, materials from natural sources, renewable materials and new inductive materials, for example, for the development of smart and sensorised materials that adapt to the needs of smart construction in rolling stock. This will improve passenger comfort and safety, as well as energy efficiency and maintenance management.

In addition, the development and production of lightweight materials for train and rail infrastructure construction will reduce weight and thus energy consumption and CO_2 emissions. Recyclable materials are also important, as they reduce the waste generated and favour the circular economy.

Another key aspect is temperature control adaptable to the number of passengers, which can be achieved through the use of intelligent, sensor-controlled materials. This will save energy and improve the efficiency of the air conditioning system.

In terms of improving the user experience, materials can play an important role in the construction of smart stations, with real-time information systems and smart window technology.

Among the main Milestones in which the entities have the highest capacities are *Development and manufacturing of recyclable materials for infrastructure* and *Development and manufacturing of recyclable materials for rolling stock*, both with 16.92% of the capacities, followed by *Development and manufacturing of lightweight materials for the construction of railway infrastructure* (15.41%) and *Development and manufacturing of lightweight materials for the construction of rolling stock* (14.66%) (see **Figure 5**).

6) Applications and Services

The rail sector not only focuses on hardware and software technology to improve

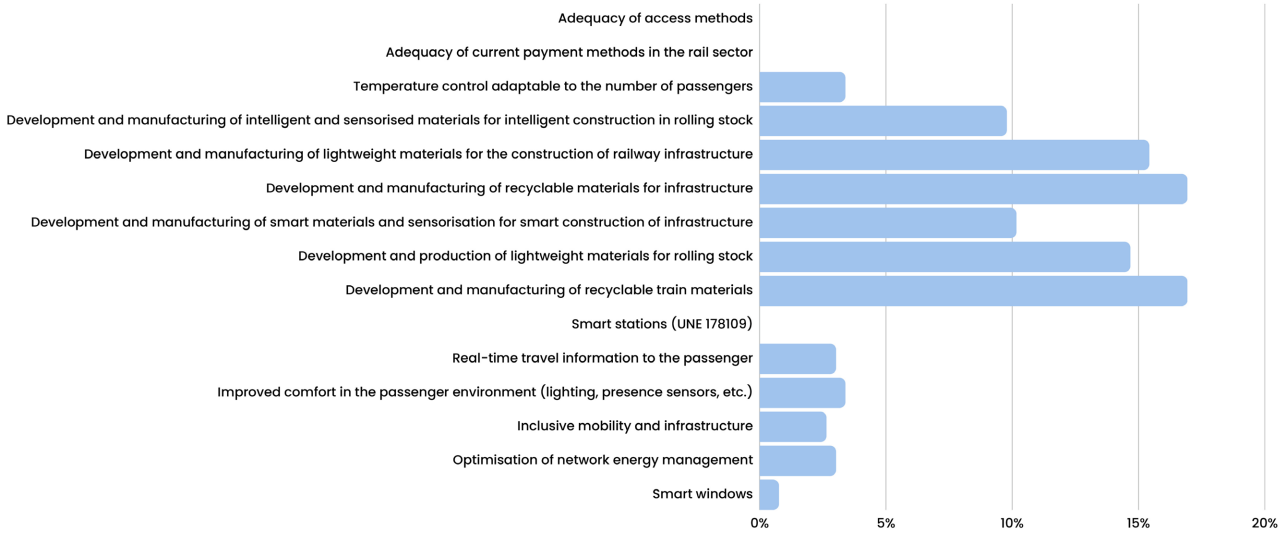

Figure 5. Milestones in the technology area of materials. Own elaboration.

its processes and products, but also on the user experience and services that can be provided through technology. This is where the Applications and Services technology area plays a crucial role in the development of the railway sector.

To respond to the different challenges in this area, technologies such as the metaverse, augmented and virtual reality, simulators and mobile apps are proposed.

For example, applications and services related to the railway sector can be very diverse, from e-commerce platforms for the sale of tickets and travel-related products, to mobile applications to improve the user experience on the train or tools for calculating the carbon footprint of a train journey.

The technological area of applications and services has a major impact on the optimisation of rail services and user satisfaction. Technologies such as mobile applications or VR/AR can improve the user experience by enabling faster and more convenient ticket purchase and journey management. Web platforms and e-learning can help rail workers to be more skilled and updated on the latest innovations and techniques.

Simulators for example can be useful tools for employee training, allowing workers to learn more effectively and safely without having to be exposed to real-life dangerous situations.

The integration of different types of transport on a single platform, as well as the implementation of a single ticket, can improve the user experience and make transport more accessible and simpler. Real-time monitoring of infrastructure, rolling stock and freight can enable more efficient management and faster response to incidents.

Finally, implementing an incident tracking system and improving the door-to-door customer journey can improve customer satisfaction and ensure that problems are resolved quickly and effectively.

Looking at the graph in **Figure 6**, we can see that a large part of the capacities

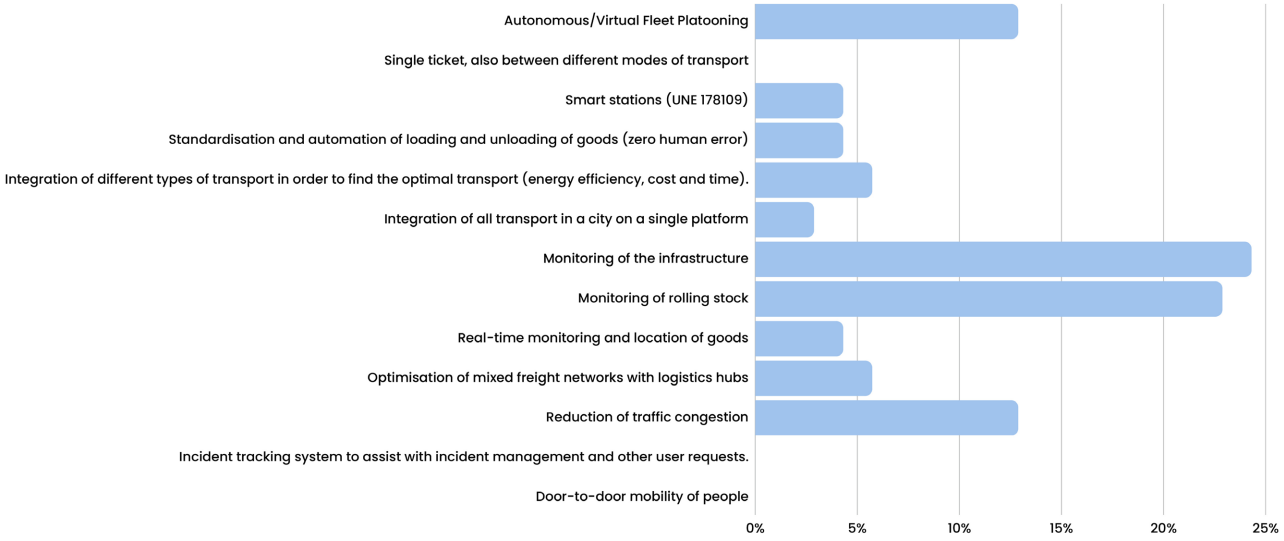

Figure 6. Milestones in the technology area of applications and services. Own elaboration.

are focused on responding to the Milestones of *Infrastructure Monitoring* (24.29%) and *Rolling Stock Monitoring* (22.86%). It is also worth mentioning that, although the sector's interest in the development of a single ticket between different types of transport has been mentioned, there is no capacity in this area, as there is for the last mile milestone.

6. Conclusions & Future Research

Innovation has a positive impact on people's mobility. Without a properly developed and innovative railway system, thousands of people would not be able to get to their jobs on time, would not be able to travel and would not be able to transport large loads of freight. Railway technological challenges would be unattainable without technological developments in applications and services, materials, energy and energy management, models (Industry 4.0), data, electronics and connectivity. Innovative technology has achieved a competitive European railway system, so innovation and knowledge are the main sources of economic growth for the sector (de Loizaga et al., 2022).

This analysis shows the great potential that the railway sector has in the field of innovation. In terms of applications and services, the analysis confirms significant progress in the integration of mobile technologies and intelligent systems, which has improved passenger experience and operational efficiency. In terms of materials, the introduction of new, lighter and stronger materials has enabled the construction of lighter rolling stock, thereby improving efficiency and sustainability.

In the field of energy and energy management, work has been carried out on the development of more efficient propulsion systems and the implementation of smart energy management solutions, which has led to a significant reduction in energy consumption and greater sustainability in railway operations.

In addition, the adoption of Industry 4.0-based models has enabled greater automation and digitisation of production and maintenance processes in the rail sector, which has improved efficiency and responsiveness to potential problems.

On the data side, data collection and analysis has played a key role in decision-making and optimisation of railway operations. However, there is ample scope to explore and make more effective use of data generated by trains and associated systems.

In addition, electronics and connectivity have enabled the incorporation of technologies such as the Internet of Things (IoT) and wireless communication, which has improved safety, monitoring and predictive maintenance in the rail sector.

In terms of future research, it is essential to continue to explore and develop new applications and services to meet the changing needs of passengers and transport companies. Continued research into new materials that are more sustainable and efficient is also required. In the field of energy and energy management, even more innovative solutions are needed to reduce the sector's environmental footprint. Industry 4.0-based models can be further optimised and adapted to the specific needs of the railway sector. In addition, data collection and analysis should be fully exploited to improve decision-making and operational efficiency. Finally, electronics and connectivity can continue to evolve to improve safety and maintenance of railway systems. Overall, innovation in these six areas offers ample scope for research and development that can further drive the transformation of the rail sector in the coming years.

Declarations

Availability of Data and Material

The datasets generated during and/or analyzed during the current study are available from the corresponding author on reasonable request.

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Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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