ISSN 1648-4142 / eISSN 1648-3480

VILNIUS TECH Vilnius Gediminas Technical University

TRANSPORT

2023
Volume 38
Issue 1
Pages 52–66

https://doi.org/10.3846/transport.2023.18291

Review Article

AN OVERVIEW ON OPEN SCIENCE IN THE EUROPEAN RAIL SECTOR

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Highlights:

- comprehensive analysis of the Open Science (OS) landscape in the European rail sector;
- identification of stakeholders' groups impacted by and interested in OS;
- analysis of the main issues preventing the uptake of OS in the European rail sector;
- a set of policy recommendations to promote OS within the European rail sector has been issued.

Article History:

- submitted 8 June 2021;
- resubmitted 13 May 2022;
- accepted 24 May 2022.

Abstract. Despite the increasing relevance of Open Science (OS) in the European research landscape, very few publications have addressed the analysis of its role within the European rail context. To this effect, the present paper aims at contributing to shed light on the topic by setting the cornerstone for a differentiated analysis of OS in this sector. In order to do so, the analysis is divided into 2 main sections. The 1st provides an overview of initiatives and experiences regarding OS, which have been recently carried out in the sector. The analysis of initiatives and scientific publications has shown that Open Data (OD) is the area attracting more attention and with more potential for expansion mainly due to the commercial interest of the data. As expected, the use of Open Tools (OT) is common but, interestingly, a growing interest in the development of OT in the sector has been detected. The creation of Open Standards (OSt), developed by specific rail stakeholders' groups or by coalitions of different stakeholders is increasing in the last years. Amongst the OS areas analysed, Open Access (OA) and Citizen Science (CS) have shown less progress. However, tendencies toward an increasing interest in these areas within the sector has been also detected. The 2nd section aims to uncover the issues or barriers preventing a wider spread of OS specifically in the rail sector and suggest regulatory avenues and actions to overcome them. The identified issues revolve around 3 topics: the lack of initiative on behalf of the European Union (EU) to a) engage other stakeholders beyond the field of research, and b) leverage untapped OS potential in sector-specific situations, which could contribute to its development; and finally, the absence of a sector-specific OS framework. The establishment of such a framework could have a significant positive impact in OD, which is the most appealing area and thus contributing to the uptake of OS as a whole in the sector. In view of such issues, the present paper suggests the establishment of: (1) a *European Rail Open Science Policy Platform* in order to create a forum-like space in which to align the stakeholder's positions, and (2) a *Joint Rail Data Action Plan* to design an OS governance framework, with the aim to ensure the usability, quality, and reliability of data. After identifying the state of OS in the rail sector and the uncovering of several issues that are hindering its development, this paper concludes that the constant further monitoring with regards to needs, challenges and interests (or lack of such) of the different rail stakeholders is key to ensure the continuous development of OS.

Keywords: open science, railways, open access, open data, citizen science, open standards, open tools, semi-systematic review.

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Notations

API – application programming interface;
BIM – building information modelling;
CCS – command, control and signalling;
CEN – *European Committee for Standardization* (in French: *Comité Européen de Normalisation*);
CENELEC – European Committee for Electrotechnical Standardization (in French: *Comité Européen de Normalisation Électrotechnique*);
CIP – customer information system;
CS – citizen science;
CSV – comma-separated values;
DB – *National Railway Company of Germany* (in German: *Deutsche Bahn AG*);
DOAJ – directory of open access journals;
EC – *European Commission*;
EOSC – European open science cloud;
ERRAC – *European Rail Research Advisory Council*;
ERTMS – *European Rail Traffic Management System*;

ETSI – *European Telecommunications Standards Institute*;
EU – *European Union*;
GIS – geographical information system;
GTFS – general transit feed specification;
IM – infrastructure managers;
IoT – internet of things;
ITEA – *International Test and Evaluation Association*;
MaaS – mobility as a service;
OA – open access;
OCORA – open CCS on-board reference architecture;
OD – open data;
OER – open educational resources;
ORE – open research Europe;
OS – open science;
OSc – open source;
OSf – open software;
OSt – open standard;
OT – open tools;
RFC – rail freight corridors;
RNE – *Rail Net Europe*;
SNCF – *National Railway Company of France* (in French: *Société Nationale des Chemins de Fer Français*);
TAF – telematics application for freight;
TRC – transport research cloud;
TSI – technical specifications of interoperability;
UBL – universal business language;
UIC – *International Union of Railways*;
WoS – *Clarivate Analytics Web of Science*;
XML – extensible markup language.

Introduction

OS has been receiving growing attention since the last few years by a wide range of stakeholders. Originally promoted as a programmatic concept by academics (Heimstädt, Friesike 2021), interest in OS has expanded to other stakeholders, such as industry and policy makers. As the exponential growth of the use of the term OS in printed media since 2010 shows (Google Books 2021), this interest does not seem to be limited to small and highly specialized circles.

Fecher & Friesike (2013) offered a summary of the expected advantages of OS depending on the discourse different stakeholders are closer to. This analysis has been complemented by a number of authors. For instance, according to Allen & Mehler (2019), OS should improve the quality of research and boost early career researchers. Fell (2019) highlights that OS can lead to savings in access, labour and transaction costs and to promote the creation of new products and services. Institutions such as the OECD (2015) also stresses the promotion of public engagement by OS and the contribution to the international coordination for global issues such as climate change mitigation.

The widespread enthusiasm for OS has been also accompanied by a number of studies analysing the different, and sometimes conflicting, interests and points of view of stakeholders involved in OS as well as criticism of the new OS paradigm. A good overview of the different points of view and potential conflicts is offered by Fecher & Friesike (2013) who analyse the main discourses around OS, proposing 5 different schools of thought, as well as their targets and argumentations. Mirowski (2018) highlights the pursuit of monetization as the primary driving force of OS, facilitating the value capture freely donated by researchers or other stakeholders. Heimstädt & Friesike (2021) argue that a close connection of OS and Open Innovation may have negative consequences for the science domain, pointing out that this may lead to a greater science dependence on profit-oriented platforms.

The interest in OS has also extended to the transport sector. *Horizon 2020* project BE OPEN (*https://beopen-project.eu*) has analysed OS within the sector in a systematic manner and has developed an action list to promote OS in transport. The list includes the formulation of a framework to enable a common understanding, the generation of an inventory of OS resources, the creation of a transport forum and observatory (*https://www.topos-observatory.eu*), and the stimulation of a suitable regulatory framework for the OS development in the transport sector (Anagnostopoulou, Boile 2018). In addition to this project, the EC has promoted the creation of a thematic pillar for transport research to be federated in the EOSC called TRC (Böhm *et al*. 2018). However, the rail sector requires an individual analysis due to its technical, organisational and operational specificities in comparison to other transportation modes.

This work aims to contribute to 3 objectives mentioned as good practices on relevant literature on transport reviews; a compilation of the state of knowledge on OS in the rail sector (Van Wee, Banister 2016), the provision of recommendations for policy makers at European Level, and the provision of suggestions on future research needs (De Vos, El-Geneidy 2022). The paper starts with a discussion about the concept of OS as well as the areas comprising it and assesses the relevance of each area for the rail sector. Next, the main areas of OS in rail have been identified and mapped employing a semi-systematic approach. The following section includes a brief analysis of the rail stakeholders and a discussion on the issues identified in the sector related to the low expansion of the OS in the sector. This section concludes with some policy recommendations to promote the uptake of OS in rail. Finally, the conclusions capture the main findings of the work and future research needs.

1. The nature of open science

One of the 1st obstacles when talking about OS lies in defining the concept in a precise manner. Although the origin of the concept of OS as a system of shared knowledge can be traced back to the beginning of modern science (David 2008), there is no common understanding of the term. The most robust attempt to provide a definition based on a systematic methodology has been made by Vicente-Saez & Martinez-Fuentes (2018). This work has analysed numerous publications on OS, which have been clustered around 5 key terms: accessible, shared, collaborative-developed, transparent and knowledge. These 5 concepts have been integrated in an OS definition ("OS is transparent and accessible knowledge that is shared and developed through collaborative networks"). Despite these efforts to systematize OS, the term still remains what Fecher & Friesike (2013) refer to as an "umbrella term" under which a wide range of elements and principles can be accommodated. This lack of common understanding along with the use of OS as an umbrella term led to the expansion of different areas linked to OS to which are attributed different degrees of importance in function of the scientific field and stakeholders' points of view. Often, these areas show blurry boundaries and similar OS elements are designated in different ways.

Within all OS areas, those which draw more attention regardless of the scientific field or stakeholders' points of view are OA and OD. OA promotes unrestricted access, typically via internet, to scientific literature and other materials. OD is an extension of the OA principle to data. The relevance of these 2 areas has been stressed, for instance, by the EU (EC 2016) and by the OECD (2015).

Apart from OA and OD, a large group of OS areas are promoted by different publications and initiatives. Pontika *et al*. (2015) mention several other fields other than OA and OD such as Open Reproducible Research, OSc, CS and Open Science Evaluation. Open Reproducible Research consists in offering free access to experimental elements for research reproduction (FOSTER 2021). This, along with opening the whole research process from early stages as defend Open Peer Review supporters, has been frequently mentioned as a possible solution to the so-called reproducibility crisis in some fields of science and to avoid questionable research practices distortions such as p-hacking (Chiang *et al.* 2015). OSc is rooted in the beginning of software development and encourages providing free access to source code written for the creation of computer software. CS emphasizes the importance of actively involving citizenship in the research process. Open Science Evaluation focuses on improving the existing system to evaluate the relevance of research. This includes, among other aspects, the development of alternative metrics to those used nowadays in order to assess the impact of research. Fecher & Friesike (2013) also highlighted a subset of OS areas of those mentioned by Pontika *et al*. (2015). Apart from the previously mentioned areas, another OS area with growing importance is the OER. This area has a more defined focus on educational purposes and has been gaining growing attention under the current pandemic situation (Tang 2021; Van Allen, Katz 2020).

Focussing on the transportation field, OD seems to be the OS area which is drawing more attention. This area is at the centre of documents analysing transport research needs in the framework of the European OS policies (Böhm *et al*. 2018). This interest has been mainly driven by the opportunities arising from road transport traffic data for the development of intelligent transport system for private (Gellerman *et al*. 2016; Rohunen *et al*. 2014) and public mobility services (UITP 2019). In addition to the OD, the analysis performed in the BE OPEN project (Palts *et al*. 2019) also underlines the importance of OSf and OA.

Despite the growing interest in the transport sector as a whole, OS seems to attract rather little attention from the rail sector. Apart from BE OPEN no other similar initiatives with emphasis on the peculiarities of the rail sector have been organized. This contrasts, for example, with the air transport sector, which launched the *Horizon 2020* project OSCAR in 2019 to explore the perception and implementation of OS in the sector (*https://oscar-h2020.eu*).

2. Open science in rail

No comprehensive analysis of the OS landscape in the rail sector has been carried out so far. The present paper aims to explore the situation of the OS in the rail sector in this chapter. To do this, an overview of the experiences and initiatives carried out in relation to OS within the sector in the last years is provided. This also includes a literature review of scientific publications relevant for OS in the rail sector, which has been also used to assess the relevance of the different OS areas for the sector.

Literature reviews typically relies on the analysis of scientific publications to assess the state of the art of a scientific field or to check the validity of a theory (Baumeister, Leary 1997). However, the lack of a significative number of scientific publications focussed on OS in rail; the abundant information available in other formats, such as grey literature, webpages or wikis; as well as the homogeneous nature of the research field; complicates conducting a systematic review, which requires a very strict search strategy (Liberati *et al*. 2009). Due to its flexibility, it has been decided to apply an adapted version of the semi-systematic approach for the review. This approach provides the fundament of a solid methodological fundament together with the needed flexibility to include other inputs beyond scientific publications and has been already applied to the field of transport (Zunder 2021). The analysis has been carried out taking as basis the results from the WoS database and complemented with additional inputs from search engines, such as *DuckDuckGo* as well as results from the database of German-speaking technical journals belonging to the group *Eurailpress*. The results from WoS have been refined manually to eliminate duplicates and to select those relevant for this work. The relevance has been assessed by analysing the abstracts and the keywords used by the authors. This approach has been adapted to match the needs of the different OS as explained in each section.

The selection of the OS areas, which are relevant for the rail sector has been guided by the information found during the research. The preselection of OS areas carried out in Section 1 has been also confirmed by an analysis of OS publications linked to railways in the database WoS, showing that the OS areas analysed in this paper are those returning more results in the database. The analysis has consisted in searching the term "railways" plus the OS areas discussed in Section 1. Search queries of the term "railways" in combination with "open reproducible research", "open peer review", "open science evaluation", "alternative metrics", "open educational resources" and "open metrics" have yielded no results. This selection does not imply that these OS areas have no significance at all for the rail sector, but rather that the interest has been considered reduced, only relevant for very specific groups or that very little information on the area is available.

2.1. Open data

The 1st step of the research on OD has consisted on an analysis of the scientific publications found in the WoS database using the search terms "railways" + "open data". This yielded 32 results, which were later reduced to 24 after being scrutinise to check its importance for the rail sector. This search has been complemented with a mapping via search engine of OD initiatives from European operators and IM as well as other key players.

On the operational side, the intensive use of data both in passenger and freight is expanding rapidly. In passenger transport, the importance of the data exchange has increased with the irruption of the new paradigm of MaaS and the smart use of resources to increase operational efficiency and better service planning (UITP 2019). These 2 elements are typically linked to public transport and also include the rail sector. MaaS has facilitated the development of 3rd parties' businesses and start-ups whose business model strongly relies on the access to OD from operators and IM. Developers can use the data free of charge by using the API to feed apps for different purposes. A number of different sites and apps such as *Real Time Train* (*https://www.realtimetrains.co.uk*), *CityMapper* (*https://citymapper.com*) or *Moovit* (*https://moovitapp.com*) have emerged in the last years. The examples of online platforms currently under planning or already providing rail and mobility OD are numerous. Multitude of rail operators such as *Renfe* (*https://data.renfe.com/dataset*), SNCB (*https://www.belgiantrain.be/en/3rd-party-services/mobility-service-providers/public-data*), NS (*https://www.ns.nl/en/travel-information/ns-api*) or DSB (*https://www.dsb.dk/dsb-labs*) offer APIs and datasets in different formats such as GTFS or CSV. In addition to these experiences, the research on delays (Gadd *et al*. 2022; Okuda, Takahashi 2021) and vehicle positioning (Delva *et al*. 2021) have been the fields where OD have had a more central role.

One of the main reasons for the intensive use of data in rail freight sector is the integration of the rail in the multimodal supply chain and the implementation of the TAF services TSI. Demands linked to just in-time logistics together with the growing pressure to ensure the quality of multimodal transport in the rail leg have fostered this development. Some European initiatives have been launched in the last years to facilitate data exchange, such as the UIC group *RailData* (*https://www.raildata.coop*), which comprises several major rail freight companies. Some components of the portal RNE, created by the European IMs to facilitate the access to the European rail network, also aim to facilitate data exchange between freight operators, IMs and terminal operators (RNE TIS 2018). However, despite the growing relevance of data in the rail freight sector, most initiatives launched so far are not releasing OD beyond terminal and other infrastructure related data.

Regarding infrastructure data, research using BIM tools related to infrastructure monitoring (Costa *et al*. 2018) or track design (Amann, Borrmann 2016) as well as research linked to GIS (Jeansoulin 2021) make an intensive use of infrastructure OD and are dependent of its quantity and quality. Additionally, station accessibility (Sun *et al*. 2021) and studies on network capacity are also resorting to OD (Francesco *et al*. 2016). The pressure on IMs and transport authorities from the EC and 3rd party companies to share data openly has contributed to the publication of OD beyond stations and the data provided in their network statements. For example, SNCF publishes large volumes of data related to timetables, information on station-based equipment and services, lines and connections, accessibility as well as operational aspects (*https://data.sncf.com/pages/accueil*). DB also provides similar data in openly licensed form in various formats and free of charge (*https://data.deutschebahn.com*). Similar services are provided also in Netherlands, UK, Belgium, Sweden or Finland (Wiki 2021). Much of these data and additional ones can be also found in the *European Data Portal* (*https://data.europa.eu/en*). It is important to highlight that OD published by IMs include very often operational data such as those from Finland (*https://rata.digitraffic.fi/swagger*) and Sweden (*https://api.trafikinfo.trafikverket.se*). At European level, RNE CIP offers interactive information about the 11 RFC (*https://rne.eu/it/rne-applications/cip*). In addition to infrastructure data published by IM or other authorities, rail enthusiasts have been gathering infrastructure data in database (*https://www.openrailwaymap.org*). The contribution of rail enthusiasts will be later discussed in-depth in the section dedicated to CS.

Other areas of transversal importance for the sector are also using OD for research and development of products, such as cybersecurity of communications (Pawlik 2019) or asset management (Metso, Kans 2017). In a similar manner to the automated car, automated train driving systems also require very intensive data processing for obstacle recognition and data exchange with other vehicles, infrastructure and other rail subsystems (Eschmann *et al*. 2020). These applications will use OD (Roth, Winter 2020) but due to the expected commercial importance of the data produced, it is probable that these areas will not make significant amounts of available OD. The use of OD is also gaining importance for ticketing applications (Stavinova *et al*. 2021) and for detecting customer satisfaction in internet (Rahman *et al*. 2015). The relevance of the OD in the sector has even driven the research on the exploitation of OD within sector as research topic (Buyle *et al*. 2021; Wandelt *et al*. 2017).

2.2. Open access

The methodology applied to the other OS areas, consisting on searching "railways" and "open access" in WoS database comes across with a problem. Within the European rail sector, the term "open access" refers to those rail services operated under full risk by the operator. After an analysis of the 290 results obtained, no publication with focus on OA as OS areas has been found. As an alternative strategy, it has been decided to look at the railways related OA journals. In addition to traditional scientific publications, due to the importance in the sector, other types of publications have been included in the analysis, such as trade journals as well as recent alternatives to publish research in OA.

OA, identified as peer reviewed research literature, is the OS area with greater historical importance in science as OS driver. The percentage of scientific publications under any of the (legal) OA modalities has increased from around 25% in the 1990s to almost 50% of the total production in 2018 (Piwowar *et al*. 2018). However, despite the importance of research and innovation within the rail sector, discussions about OA publications have never become a major topic. This may have several explanations. The traditional dominance of state-owned large companies, oriented towards national markets and integrating operation and infrastructure, may have led to a concentration of research activities within the companies' boundaries. In addition, rail innovations have been linked to new technical developments whose dissemination is typically limited by the protection of intellectual property.

OA publications are commonly offered in several routes. Gold OA are articles published in OA journals, which are freely available in the publisher's website. Under this model, authors bear the publication costs. Platinum OA is similar to the gold OA but in this model publication costs are typically bore by sponsoring organisations. Green OA are articles published in a subscription journal but also made available by the authors in open repositories. Hybrid OA are articles published in subscription journals but free to read if authors bear the publication costs. Delayed OA are articles published in subscription journals, which are free after an embargo time. Bronze OA are articles free to read on the publisher's website but without a clearly identifiable license, such as creative commons or similar (Laakso *et al*. 2011). In addition to these routes, the so-called Black OA enables free access to paywalled literature by unlicensed online platforms, such as *Sci-Hub* (*https://sci-hub.se*). This last modality has been described as a technical implementation of pre-existing practices consisting in the sharing of publications in an informal way among researchers (Swab, Romme 2016).

Rail research has been often published in journals with a transport or engineering wide thematic. This overlapping with other disciplines hinders the performance of a precise quantitative assessment of OA publication's relevance in the rail sector. To have a 1st idea of the relevance of OA in the sector, an analysis of the publications, which contained the term "railways" in their titles, abstracts and/or keywords, which can be found in the databases Scopus and WoS (*Core Collection*) has been carried out. Figure 1 below shows the percentage of OA publications in Gold, Platinum, Green and Bronze modalities over the total of publications found in a search conducted on 1 April 2021.

Data confirms a clear increase in the percentage of OA publications since 2010. The percentage increased from approximately 10% in 2010 for both databases to 40% in WoS and over 30% in Scopus by 2020.

For a 1st assessment of OA journals in the rail sector the database DOAJ has been analysed. This database contains over 15000 peer-reviewed gold and platinum OA journals (DOAJ 2020). The 88 journals, which yielded the search of the term "transportation" have been assessed

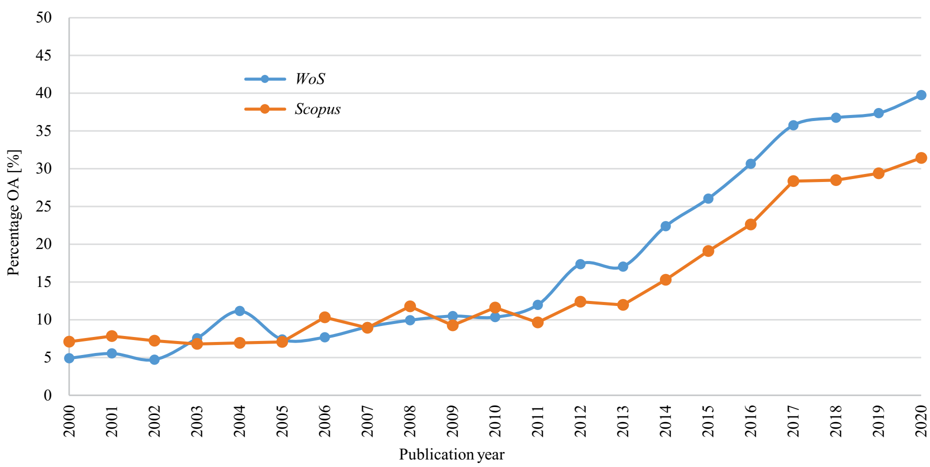

Figure 1. Percentage of OA publications from 2000 to 2020 obtained using the search word "railways" (source: *WoS*, *Scopus*)

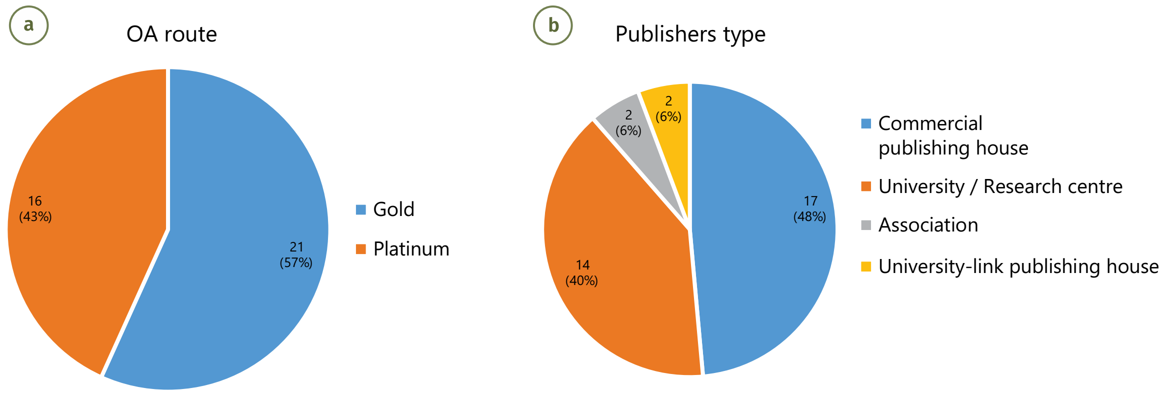

Figure 2. OA (source: DOAJ): (a) – number and type of OA journals; (b) – type of publishers for OA journals

with the aim to identify if the journals publish rail-related articles. Those journals with at least one article containing the keyword 'rail' or 'train' in the last 3 issues have been considered. This has yielded a total of 35 OA journals. The main results are shown in Figure 2.

As can be seen in Figure 2, 16 journals have been classified as platinum OA and 21 have been classified as gold OA, with fees from 100 € to around 1700 €. Regarding the type of publishers, approximately half of the journals (17) are published by commercial publishing houses, 14 are published by universities or research centres, 2 journals are published by associations, and 2 journals are published by publishing houses linked to universities. It is important to highlight that all Platinum journals are directly published by universities, research centres or associations, or sponsored by one of them.

In addition to gold and platinum OA journals, there are a number of journals which offer other OA modalities. For example, the well-known *International Journal of Rail Transportation*, published by *Taylor & Francis* is a hybrid OA journal and enables green OA under certain conditions (Taylor & Francis Group 2021). Another popular rail journal, *Elsevier*'s *Journal of Rail Transport Planning & Management* is also a hybrid OA journal and offers a delayed OA after a 24-month embargo (Elsevier 2021).

Apart from the typical publication of scientific results in journals, some other European initiatives with different approaches have emerged in the last years. One of these initiatives is the ORE, promoted by the EC. ORE represents a free, open-access, peer-review publishing platform for the publication of results from EU-funded research (EC 2020). This platform is a complement to other existent platforms such as CORDIS (*https://cordis.europa.eu*), which provided access to publicly available research output from *Horizon 2020* and previous European research programmes, which includes also the public-private programme *Shift2Rail* with focus on railways research. Due to its recent creation, by the end of 2020, the success of the new ORE approach cannot be yet determined.

Another different group of relevant publications within the sector are the so-called trade journals. These non-peer reviewed journals have a more commercial oriented audience and have a strong focus on intrasectorial news, dissemination of technical developments, and use cases. Often, rail enthusiasts are also part of the target audience of some of these journals. The importance of this type of publications can be rapidly understood after visiting the German Wikipedia page dedicated to them (Wikipedia 2021). These journals have usually a national scope and are published or sponsored by professional associations (e.g., *Der Eisenbahningenieur*), publishing houses (e.g. *La vie du Rail*, *Eisenbahntechnische Rundschau*, *Railway Gazette International*) or have links to rail operators or IM (e.g. *Vía Libre*, *Deine Bahn*). They have been generally accessible only under paid subscription but there is a growing number of trade journals freely available online. For example, *Global Railway Review*, managed by a publishing house, offers an overview of European rail news.

2.3. Open standards

As with OD, the 1st step of the research on OSt has consisted of an analysis of the scientific publications found in the WoS database using the search terms "railways" + "open standards". This yielded 5 results, which were later reduced to 4 after being scrutinise to check its importance for the rail sector. This search has been complemented with a mapping via search engine of OSt initiatives from European key players and emerging tendencies of OSt in the rail sector.

Unlike closed standards, OSt are those which are publicly available (or accessible against limited costs) and are usually developed (or approved) and maintained via a collaborative and consensus driven process. OSt facilitate interoperability and data exchange among different products or services and are intended for widespread adoption (ITU 2021).

Despite not been typically considered as a part of OS, this area plays a central role in the sector to integrate and coordinate the actions of rail stakeholders (Golightly *et al.* 2013). The development of the rail sector after the *World War II*, tailored towards a national operational framework, contributed to the segmentation of the European rail landscape. Accordingly, legislation, standards and technical subsystems such as interlocking, signalling or electrification followed a national logic. This changed in the 90s with the adoption of Europe-wide policies for enabling interoperability and promoting sector liberalisation. This process included the development of the TSI, drafted by the *European Railway Agency*. These standards strive to facilitate the transition from the old integrated national railway system governed by national rules to a European rail area governed by common EU rules (ERA 2012). This new approach, along with the rise of the digitalisation-driven new paradigms such as *Industry 4.0* and IoT, has accelerated the need for common standards.

Apart from the TSI, which comprises a wide variety of rail subsystems, the developments of OSt for communications and data exchange are not new (Renz 2004; Mingozzi *et al*. 2002) and have further developed in the last years to promote integration and interoperability of electronic components, such as those employed in signalling and interlocking subsystems. Another example is the UBL v2.1 to support data interoperability in transport, developed by OASIS *Open Standards Consortium* and which has become the standard ISO/IEC 19845:2015 (OASIS Open 2021).

Unlike previous standards, which were usually promoted by official standardisation bodies such as CENELEC, ETSI, CEN or standard-setting organisations such as UIC (2016), new OSt are often developed by wide coalitions of different stakeholders and created ad-hoc.

One of these examples is the ITEA project OpenETCS (*http://openetcs.org*), whose purpose consists of developing a framework to model, develop, validate and test the implementation of ETCS. The initiative will provide a tool chain across the whole development of the ETCS software. This project involved rail operators, IMs, universities and research centres as well as other active industrial partners in the rail sector.

Another relevant initiative is RailML.org (*https://www.railml.org/en*). This coalition has promoted the development of a specific OSc railway markup language to simplify data exchange between railway applications. RailML.org set a common XML-based railway data format suitable for timetable, infrastructure, rolling stock and interlocking data to enable its use in a large range of railway applications. As in OpenETCS project, RailML.org members comprise a wide range of stakeholders: rail operators, IMs, universities and research centres, software developers and consulting firms, and public institutions.

Other OSt of relevance for specific subsystems are fostered by coalitions of specific stakeholders. One of the oldest cooperation of this type is the ERTMS users group, created in 1995 by the German, French and Italian state-owned rail companies for the development of the ERTMS system (Albert, Hundt 2020). Several additional IMs have joined this initiative in the last years (ERTMS 2021).

In the area of railway signalling, the initiative EULYNX (*https://www.eulynx.eu*) has developed a system architecture for interlocking systems. The idea behind the creation of a common system architecture is to allow the use of signalling and interlocking components from different suppliers, enabling in this way the development of a modular system. This initiative is being supported by 13 European IMs. In a similar way to EULYNX but with focus on on-board components, OCORA has been launched as a joint initiative founded by 5 European IMs to define the architecture and interface for on-board ETCS systems (Mühlemann 2020).

Apart from the OSt previously mentioned, the topic is also relevant for the development of geospatial applications, such as those for risk assessment (Sadler *et al*. 2016) or for the assessment of the impact of the rail infrastructures (Brovelli *et al*. 2010). The tendency towards integrated ticketing systems, including several means of transport and the rail market liberalisation with several operators offering their services, has made that OSt have become also important in ticketing, promoting the expansion of OSt in this area (Burroughs 2020). In addition to this, the growing needs for software control for more subsystems of trains are making that some companies make appeals to the adoption of OSt for embedded computing (Wiersch 2019).

2.4. Open tools

The area OT comprises OSc, open code software as well as other software related tools developed under the same philosophy. OSc software represents a radical model-oriented technology, which enables the organisation to develop customized, flexible and interoperable solutions under affordable cost. The importance of OSc software and cheaper applications in the transport and logistics area is expected to increase in the near future (Adesiyun *et al.* 2019). The research of this area has followed the general methodology. It has started with the analysis of the scientific publications found in WoS database using the terms "railways" and "open source" or "open tools" or "open code". 85 results have been found under these terms. After an analysis of the abstracts, 49 of them have been considered relevant for this work. The information obtained from this material has been complemented with a mapping via search engine of these search terms

From the analysis of the results 3 groups can be distinguished. Those analysing the use of OT in the sector, those using OT and those creating OT. As expected, some overlapping between groups has been also detected. Within the 1st and smaller group, Sahal *et al*. (2020) has explored the use of OT for big data in railways, focussing on the area of predictive maintenance. Hase (2011) proposed an approach for the analysis of critical rail components based on applying OSc concepts to the entire life cycle of the components.

As in other disciplines, the use of general OSc software in the rail sector is widespread. Software such as GIS based tools, *Linux*, *Python* are generalized. For big data applied to rail sector, *Apache Stark* (Contreras *et al*. 2018; Sadler *et al*. 2016) is very present. *Modelica* language (*https://modelica.org/modelicalanguage.html*) for modelling of electrical systems (Ceraolo *et al*. 2018; Li *et al*. 2019a) and OpenFOAM (*https://www.openfoam.com*) as numerical solver for continuum mechanics problems appear in several publications examined (Herzog, Egbers 2013; Weiss *et al*. 2018). The use of OSc libraries for specific purposes are also common, for example for extracting image data (Tseng *et al*. 2019) or for the analysis of noise (Klöckner *et al*. 2017). Apart from the OSc software, other OT such as *Arduino* (*https://www.arduino.cc*) is commonly used for the construction of prototypes (Ozdagli *et al*. 2018). Focussing on OT specifically designed for rail, RailML.org has a prominent place within the publications examined (Luteberget, Johansen 2021; Phienthrakul *et al*. 2018).

Regarding the creation of OT for rail, the number of publicly accessible OT is limited. Software SUMO (*https://www.kcsoftwares.com/?sumo*) is one of such OT. Originally developed by the German DLR Institute for road traffic simulation, it has also been used for rail traffic simulation (Shankar *et al*. 2020). Further examples of OSc tools used for commercial purposes can also be found, such as – *https://www.openrailwaymap.org*. Looking at the examined publications, there is a wide range of topics for which OT have been developed. OT for the simulation of electrical supply for rail (Almagro, Marano 2016), for improving maintenance of point-machines (Li *et al*. 2019b), for the analysis of cybersecurity in the rail sector (Teo *et al*. 2016) as well as specific smartphone apps for wagon maintenance (Cowan *et al*. 2018) or for improving the safety of workers working in track maintenance (Ferrier *et al*. 2021) are only a few examples of them. The commercial interest of many OT applications is often unclear due to the existence of alternative commercial solutions. In addition, they are commonly developed for research purposes or as initial prototypes for validation and it is difficult to have access to the OT themselves. Often, OT with more commercial success have a strong link with the development of OSt, such as RailML.org, and have often been promoted by coalitions of different stakeholders. In the field of infrastructure, the OpenETCS project provides an OSc software for trackside ETCS modelling divided in several components (*http://openetcs.org/about*). Regarding rolling stock, the TCNOpen initiative aims to develop several OSc modules for train communication applications and their initiators are several rail vehicle manufacturers and other suppliers (*www.tcnopen.org*).

The interest in OT in the rail sector is confirmed by an initiative launched in 2019 by UIC to promote OSc project in rail. Among its objectives are to enable the consolidation of OSc projects and to foster the use of proofs of concepts (UIC 2019). The next step in this direction has been the recent launching of the *Open Rail Foundation* website (*https://openrailfoundation.gitlab.io*).

2.5. Citizen science

The research of CS status in rail has also followed the general methodology. It has started with the analysis of the scientific publications found in the WoS database using the search terms "railways" + "citizen science". This yielded 8 results, which were later reduced to only one after being scrutinise to check its importance for the rail sector. This search has been complemented with a mapping via search engine of CS initiatives linked to railways.

CS has been commonly defined as the participation of citizenship in the scientific process but some definitions have also included the involvement of citizenship in more technical or engineering related tasks (Vohland *et al*. 2021). In the rail sector, with less importance of fundamental science and a more commercial and technical affinity, the participation of citizenship in the scientific process has not been as high as in other fields such as the natural sciences. However, railways have attracted a relatively large number of interested people, which are not necessarily bound professionally to the rail sector. Activities such as trainspotting, rail photography or railway modelling have been hobbies with tradition in Europe. This group has been already involved in CS activities such as the identification of hazardous materials shipments in US (Ziolkowski 2020).

The expansion of internet facilitated the networking of rail enthusiasts and the development of online communities of rail enthusiasts. This enabled the creation of online forums where rail professionals and enthusiasts exchanged information about a wide range of rail topics such as new infrastructure plans, building developments, new schedules and services, traffic incidents, rolling stock features or policies discussions. In addition to internet forums, the collaborative initiative *https://www.openrailwaymap.org* is producing an online map of the world's railway infrastructure and includes information about maximum speeds, signalling, electrification and track type. This tool is based on other open initiative, *OpenStreetMap* and has been available since 2013 (Wiki 2021). This information is used for the development of routing applications, train position tracking or network simulations.

A more recent approach related to CS in rail has been the organisation of so-called hackathons. They originally consisted in mass events to improve or develop software in a reduced period of time (Cambridge Dictionary 2023), but they have also extended to other areas such as graphic design topics or as a tool for developing innovative ideas about non-computer related issues (GOV.UK 2014). These events are commonly open to everyone and enable the active participation of rail enthusiast in solving specific rail related problems. Hackathons started getting popular in rail sector several years ago promoted by IM, rail operators, associations or policy makers. One of the 1st rail-focused hackathon was boosted in 2015 by the British Department of Transport to improve Britain's train (Topham 2015). An Internet search for hackathons in the European rail sector in 2021 yields several events organised by different stakeholders. UIC will organise a hackathon together ASTONRail project (*http://astonrail.eu*) to explore rail resilience in pandemics (UIC 2021), DB organised another one to improve rail operation and develop new ideas by analysing data from DB Regio (GoBeta 2021). *Shift2Rail* also plans to organise a hackathon event with the focus on young and start-ups (Shift2Rail 2021).

3. Further rail open science expansion: current issues and policy recommendations

As stated in Section 1, the European rail sector is in the midst of an ever-increasing technological transformation with numerous research and innovation actions aiming at improving the sector's competitiveness and, consequently, reverse the previous modal shift trend favouring road and air transport.

It is clear in the context of this transformation that among all of its elements, OS is bound to play a pivotal role as a practice with the potential to untap economic benefits by cutting costs associated with knowledge retrieval in industry or avoiding data duplication in academic circles. Being aware of its benefits, and as mentioned in the introduction of this paper, the EU has been slowly but steadily promoting OS in its agenda reaching out to several sectors, including transportation.

However, the integration of OS principles in the rail sector seems to lag behind in comparison to its modal counterparts. It is thus crucial that the sector establishes a tailored OS policy framework containing best practice guidelines for its application and achievement of fundamental goals, in alignment with national and EU level related initiatives.

Nevertheless, the success of such a framework cannot be guaranteed unless stakeholders manage to align -or at the very least, make compatible- their different understanding, approaches and envisaged goals in OS, as introduced in Section 1, which if left unchecked can result in conflict.

In this context, the aim of this section is to suggest a series of policy actions in order to encourage the uptake of OS in the rail sector. In order to achieve this, the section 1st identifies the main stakeholders likely to be affected by or influence OS in the rail context. It then analyses the main issues preventing a widespread implementation of OS resulting from an examination of each of the stakeholder's concerns. Finally, it offers policy actions based on the alignment of the stakeholders' positions.

3.1. Stakeholder identification

The identification of stakeholders has been performed based on the clustering performed by BE OPEN (Fioretto, Anagnostopoulou 2019), which identified a set of 8 key stakeholder groups applicable to the transport sector. By exploring each of the identified stakeholder groups and applying it to the rail and publishing sectors, this paper has identified a set of 9 stakeholders, which are affected by OS in the rail sector. These are:

- *EU (represented in the majority of cases by the EC)*: refers to the EC and other depending EU bodies with direct competence on rail transport, with special reference to the EU Agency for Railways and the Shift2Rail Joint Undertaking, as the main bodies focused on rail research and innovation. Due to its relevance in the promotion of OS, it has been decided not to integrate it in the same category as other policy makers and authorities but to classify it as a specific stakeholder.
- *research and universities*: refers to all public and private universities, which together with research centres, conduct research activities in the railway sector
- *authorities and policymakers*: local, regional, or national enforcement body or authorised representative with jurisdiction over the transportation sector.
- *publishing houses*: refers to all companies and public entities, which acquire, produce, and distribute scientific knowledge within the railway sector.
- *rail operators*: refers to any licensed public or private undertaking, the principal business of which is to provide services for the transport of goods and/or passengers by rail with a requirement that the undertaking ensure traction.
- *rail IM*: refers to any body or firm responsible in particular for establishing, managing, and maintaining railway infrastructure, including traffic management, control-command and signalling.
- *industry*: refers to all companies whose primary business activity is related to the rail sector (e.g., infrastructure construction and maintenance; rolling stock manufacture; suppliers; etc.) with the exclusion of IM and rail operators.
- *users*: refer to all natural persons, which are users of the passenger transport services offered by railway operators and to all legal persons, which are users of freight transport services offered by rail operators.
- *rail enthusiasts*: refer to all natural and legal persons, which have an interest in the rail sector beyond meeting a specific transport demand as user.

3.2. Identified issues preventing the uptake of open science in the rail sector

This section presents the most significant issues which are currently preventing the development and uptake of OS in the rail sector. In order to correctly identify them, each of the previous stakeholders has been analysed in terms of motivations, concerns, and approach to OS.

- *inaction towards the engagement of industrial actors*: the EU, the most active stakeholder with regards to OS implementation, has been pushing for its widespread use for the last years in an attempt to increase science quality, impact, and response to society's needs. Proof of this is the generous amount of legislation produced in this line addressed to researchers, universities, and policymakers: (e.g., the inclusion of OS in the ERA, the Commission's "eight ambitions of OS" (EC 2021), the EOSC, etc.). However, it has failed to involve key industrial actors, with the exception of certain initiatives addressed to the transport sector as a whole. While the implementation of OS beyond the research and universities area is considered by the Commission and the EU (EC 2019), it is still relegated to a background position;

- *lack of initiatives to untap OS potential*: the EU has also been missing opportunities related to OS elements due to its inaction beyond the research area. For instance, the general public, users and rail communities generate vast amounts of data, which is freely available and exempt of any legal restraints, or in other words, OD. If solved the issue concerning the reliability of these data, part of them may be of interest for other stakeholders: IM could benefit from incident reporting or infrastructure monitoring, rail operators could use timetable follow-up and real-time travelling conditions updates, rolling stock manufacturers could utilise opinions and evaluations on specific units to improve their product and authorities and policy makers could benefit from information exchange to better support investment decisions, among other examples. The lack of collaboration channels to and from other rail stakeholders, which could have been established by means of EU initiatives is preventing the leverage of such opportunities. Furthermore, the expected increase of digitisation in the rail sector will contribute to increase both useful data generation and potentially create new ways for further OS implementation;
- *lack of a sector-specific OS framework*: a sector-specific OS framework refers to a system, which guarantees the reliability, quality, structure and format of research, data, standards, and tools. The lack of a specific OS framework for the sector may discourage the sharing of otherwise relevant data by key actors, for instance, network capacity or operation information by rail operators and IM (beyond the legal disclosure provisions set by the 4 railway packages within the railway liberalisation process). It also discourages researchers from sharing their work and results by creating uncertainty as to how it will affect their careers. In addition to the lack of incentives for sharing OD, it is not uncommon to believe that OA journals may have poor or non-existent peer review, which leads some researchers to believe that such journals present low quality and consequently that publishing in these venues could be esteemed as less prestigious within academic evaluations (Krawczyk, Kulczycki 2021);
- *key stakeholders demand for fair OD obligations*: OD obligations may in various occasions be uneven. For instance, network industries public actors have raised concerns about the obligation imposed by the recent directive on OD and the reuse of public-sector information (EC 2013), which obliges them to make documents available in any pre-existing format or language and, where appropriate, by electronic means in formats that are open, machine readable, accessible, findable, and reusable, complete with their metadata. Specifically in the rail sector, public rail operators have emphasised the lack of a level-playing since the published data may have commercial interest for competing operators.

3.3. Policy recommendations

- *establishment of a European Rail Open Science Policy Platform*: the 1st 3 of the above identified issues stem from the same problem: a lack of a sector-specific forum in which to discuss needs and concerns with regards to OS, with the aim to align interests and promote it in such a way that it may benefit all stakeholders. To this aim, the establishment of a rail sector Platform made up of expert representatives for each of the stakeholder groups identified as well as stakeholder-wide bodies (such as ERRAC) could prove to be a very effective tool to address the significant challenges in coming to an agreed position on how to address OS in the sector. Building upon the findings from previous work for setting up a TRC (Böhm *et al*. 2018), the platform could develop implementation plans based on the agreed approach to further engage specific stakeholder groups, such as industry, identify collaboration opportunities between different OS areas, and introduce initiatives to leverage unidentified possibilities. This Platform could also include existent initiatives such as those identified in Section 2 related to OD (e.g., OD portals from IMs), OA (e.g., ORE platform), OSt (e.g., RailML.org, EULYNX or OCORA), and OT (e.g. *Open Rail Foundation*). The integration of the new platform in the EOSC and the liaison with other transport sectors for intersectoral topics (e.g., MaaS) should also be considered.
- *establishment of a Joint Rail Data Action Plan*: as pointed out in Section 2, OD is the most attractive element of OS for the rail sector's stakeholders. The use of data could become a very important catalyst of industry collaboration and better planning by administrations and policymakers. Yet the degree of its leverage in the sector today still remains low. This is partly explained by the commercially sensitive nature of data generated especially in the industry, which it refuses to share in order to avoid losing its competitive advantage. However, there is already large amounts of data available that aren't being used. This is due to a lack of a well-defined OS framework for rail that ensures its quality and usability by interested stakeholders and actors. In order to address this problem, one of the 1st initiatives of the proposed *European Rail Open Science Policy Platform* should be the creation of a *Joint Rail Data Action Plan* to contribute to regulate this issue by designing an industry-wide OS governance framework. The generated framework would then include the necessary provisions to regulate the issues of data transparency, usage and access, standards, value, and principle. If well designed and implemented, the Plan could encourage the industry to publish more data by, for instance, developing an industry-agreed definition of commercially sensitive data. In addition, the Plan should ensure that

the workforce can keep up with the innovative changes introduced above, funding authorities should liaise with universities to provide the required skills to work with data and technology in the rail sector. The upskill of workers will ensure that data is treated correctly and that it meets the necessary standards while simultaneously making actors more aware of the benefit potential that data offers.

Conclusions

OS and its applications have been enjoying a growing attention in the last few years, extending its reach from strictly academic circles towards other areas including transport and, consequently, the rail sector. However, OS in rail is still in an initial stage. Proof of this is the fact that no other comprehensive analysis of its landscape has been performed beforehand. Despite the subject's novelty, some of its elements have gained certain momentum within the sector. So is the case for OD, OT, and OSt. With regards to the former, the irruption of data intensive practices such as MaaS, the seek for increased efficiency and service planning through the smart use of resources, and the development of new business models reliant on big data and IoT have incentivised its expansion. The overall benefits in the leverage of such data, provided it is made open, have been found to be vast. As in other fields, the use of OT is widespread in the sector. More interesting is, however, the development of OT by rail stakeholders. Despite the focus on research applications of the developed OT, recent multistakeholders initiatives emerged suggest that there is a growing interest in this area, leading to potential commercial applications of OT. Regarding OSt, the numerous initiatives identified offer an interesting example of cooperation between rail stakeholders, which may be taken as example for other OS areas. It is not casual that these 3 areas are very often interconnected.

In contrast, not as much change has taken place with regards to OA and CS, either by an already pre-existing interest or a lack of such. In this sense, and as per OA, discussions on the subject have not become a major topic in the rail sector. This can be explained by the importance of the applied research and the need of protection of innovations' intellectual property together with the reduced importance of fundamental science in the rail sector. However, the increasing number of publications in OA follow the general tendency towards openness of scientific results. As per CS, there is little evidence for any kind of initiative in these directions, despite the mentioned hackathon events organised by rail operators and other occasional actions. However, the potential of this area for the rail sector in general and for the OS in particular is worthy of consideration. Despite not being analysed in this work, other OS areas such as OER could play an important role in the future to skill up workers and attract new talent to the sector.

Despite the growing interest, OS in the rail sector is still underdeveloped. Findings point towards several issues, which would explain this situation. Firstly, the inexistence of a sector-wide OS infrastructure which ensures the governance and correct implementation of its elements. More specifically, and especially with regards to OD, the lack of a framework ensuring data transparency, usage, access, standards, value and principle discourages actors to both share and use data. Secondly, this paper concludes that the EU is largely focused in implementing OS in the research area, relegating other key sectors such as industry to a background position. This fact implies the loss of opportunities, which could greatly contribute to the sector's innovation and competitiveness.

In the light of the above shortcomings, this paper suggests 2 main policy actions designed to encourage a widespread use of OS elements in the rail sector. Firstly, the establishment of a *European Rail Open Science Policy Platform*, which would act as a sectorial platform in which to agree on a joint position on how to address and exploit OS in the sector. Secondly, the establishment of a *Joint Rail Data Action Plan*, especially focused on OD and OSt, to define a sector-wide OS governance framework. The content of the framework would be focused on regulating data usage and access, standards, value and principle, providing the necessary sense of security needed by the sector's actors to share and use OD. Finally, the paper encourages the EU, universities and research institutions to liaise in order to provide the necessary technical needed by the workforce to keep up and implement these initiatives.

Future research needs are connected with the identified issues identified and the policy recommendations presented in this work. Detect needs, challenges and (lack of) interests of the different rail stakeholders is key to identify possible conflicts between them and find satisfactory solutions. This requires an in-dept study of the stakeholders with surveys and other quantitative and qualitative tools. The results would also serve to finetune the policy recommendations issued in this work.

Funding

This work was supported by the project "European forum and oBsErvatory for OPEN science in transport" (BE OPEN). This project has received funding from the EU's Horizon 2020 research and innovation programme under the grant agreement No 824323.

The results in this paper reflect only the authors' view. Neither the *Innovation and Network Executive Agency* (INEA) nor the *European Commission* (EC) is responsible for any use that may be made of the information contained therein.

Author contributions

Celestino Sánchez Martín conceived the study, prepared the 1st draft, wrote the Introduction, Sections 1 and 2, co-wrote the Conclusions and reviewed the whole paper.

David Calonge Cases wrote Section 3, wrote the Conclusions, and reviewed the whole paper.

Miloš Milenković contributed to Section 2.

Disclosure statement

Authors of this paper declare they not have any competing financial, professional, or personal interests from other parties.

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