Deliverable D 1.3
Application Areas

Project acronym:	RAILS
Starting date:	01/12/2019
Duration (in months):	43
Call (part) identifier:	H2020-S2R-OC-IPX-01-2019
Grant agreement no:	881782
Due date of deliverable:	Month 19
Actual submission date:	30 June 2021
Responsible/Author:	Stefano Marrone (CINI)
Dissemination level:	Public
Status:	Issued

Reviewed: no

Document history		
Revision	*Date*	*Description*
1	June 10^{th} 2021	First issue for internal review
2	June 16^{th} 2021	Second issue for Advisory Board review
3	June 30^{th} 2021	Final version for submission to the JU
4	September 1^{st} 2021	Major updates after the JU revision: • Section 4.7.1 added; • Discussion added in Section 6.1; • Structure of Section 7.2 slightly changed; • Conclusions extended.
5	September 7^{th} 2021	Final Version

Report contributors		
Name	Beneficiary Short Name	Details of contribution
Stefano Marrone	CINI	Contributor
Lorenzo De Donato	CINI	Contributor
Valeria Vittorini	CINI	Contributor
Roberto Nardone	CINI	Contributor
Ruifan Tang	LEEDS	Contributor
Nikola Bešinović	TUDELFT	Contributor
Francesco Flammini	LNU	Internal Review
Rob Goverde	TUDELFT	Internal Review
Zhiyuan Lin	LEEDS	Internal Review

Advisory Board Reviewers	
Name	*Company or Institution*
Marina Aguado	European Union Agency for Railways
Stefano Delucchi	Aitek

Funding

This project has received funding from the Shift2Rail Joint Undertaking under the European Union's Horizon 2020 research and innovation programme under grant agreement n. 881782 Rails. The JU receives support from the European Union's Horizon 2020 research and innovation program and the Shift2Rail JU members other than the Union.

Contents

Executive Summary 5

Abbreviations and acronyms 6

1. Background 7

2. Objective 8

3. Introduction 9

4. Sources of Information 10

4.1 Railway domains definitions 10

4.2 Survey 11

4.3 Advisory Board 12

4.4 AI4RAILS Workshops 13

4.5 Related Projects 14

4.6 Taxonomy and Literature Review 16

4.7 AI Policies and Regulations 18

4.7.1 Considerations about Ethical and Privacy aspects of AI in railway applications 20

5. Survey Key Findings 22

5.1 Survey Methodology and General information 22

5.2 Survey Sample 23

5.3 Findings about Challenges 25

5.3.1 Practical issues 26

5.3.2 Regulatory and methodological issues 27

5.3.3 Key milestones 27

5.3.4 Trustworthy AI 28

5.4 Findings about the State-of-Practice 30

5.4.1 Interesting rail applications for AI usage 30

5.4.2 AI techniques, models and supporting tools used in practice 31

5.4.3 Data acquisition and management 34

5.5 Concluding remarks from the survey 37

6. Artificial Intelligence meets Railways 38

6.1 Problems relevant to railways 39

6.2 Basic AI Usage Guidelines 44

7. Application Areas 49

7.1 Urgent Issues 51

7.2 High Impact Areas 54

7.3 Uncharted and promising Areas 56

8. Conclusions 57

Appendix - Questionnaire 58

Executive Summary

This report identifies current and potential application areas of AI across railway domains. With this aim the document surveys the main railway problems to which artificial intelligence techniques are currently being applied or that could benefit from AI based approaches, as they emerged from the activities carried out in WP1 (State-of-the-art of Artificial Intelligence in railway transport). The main challenges to be faced and some steps necessary to an effective take up of AI in railways are also delineated, basing on the results of the mentioned activities, which include results from a survey, the analysis of scientific literature and relevant projects, and feedback and information from the Advisory Board. The report also provides a matching between the set of relevant problems and the current AI techniques, as well as some guidelines to drive the choice of appropriate AI approaches focusing on a particular aspect of the problem under analysis.

Abbreviations and acronyms

Abbreviations / Acronyms	Description
AB	Advisory Board
ACO	Ant Colony Optimization
AI	Artificial Intelligence
ANN	Artificial Neural Networks
ATO	Automatic Train Operation
CEN	European Committee for Standardization
CENELEC	European Committee for Electrotechnical Standardization
CINI	Consorzio Interuniversitario Nazionale per l'Informatica
CLC	CENELEC (in document references)
CNN	Convolutional Neural Networks
CPU	Central Processing Unit
DBSCAN	Density-Based Spatial Clustering of Applications with Noise
DIANA	DIvisive ANAlysis
DLT	Distributed Ledger Technology
ERA	European Agency for Railways
GRU	Gated Recurrent Unit
IEC	International Electrotechnical Commission
IEEE	Institute of Electrical and Electronics Engineers
IoT	Internet of Things
ISO	International Organisation for Standardisation
ITS	Intelligent Transport Systems
JTC	Joint Technical Committee
KNN	K-Nearest Neighbour
LSTM	Long-Short Term Memory
ML	Machine Learning
NLP	Natural Language Processing
PCA	Principal Component Analysis
RAILS	Roadmaps for AI integration in the raiL Sector
RAM	Random Access Memory
S2R	Shift2Rail
SC	Subcommittee
SoP	State of Practice
SOTA	State Of The Art
SVM	Support Vector Machines
SVR	Support Vector Regression
TPU	Tensor Processing Unit
V&V	Verification and Validation
XAI	Explainable AI

1. Background

The present document constitutes the Deliverable D1.3 “Application Areas” of the S2R JU project “Roadmaps for AI integration in the Rail Sector” (RAILS). The project is in the framework of Shift2Rail’s Innovation Programme IPX. As such, RAILS does not focus on a specific domain, nor does it directly contribute to specific Technical Demonstrators but contributes to Disruptive Innovation and Exploratory Research in the field of Artificial Intelligence within the Shift2Rail Innovation Programme.

Deliverable D1.3 describes the work carried out in task 1.4 of Work Package WP1 whose objectives are:

- Define a taxonomy of AI to enable its application in railway transport
- Determine the state-of-the-art of AI techniques in railway transport
- Determine the state-of-the-art of Shift2Rail projects
- Identify application areas of AI in railways

The work package identifies specific needs, challenges and opportunities; it contributes to evaluate and select techniques and methods for picking the right AI technology able to solve open problems or improve performance in railway scenarios. To this aim, a systematic literature review is performed including the study of the available results from recent and ongoing projects. This work package clearly states a vision: it depicts a preliminary shared vision of the future railway systems among partners, it bridges the gap between AI and railway-domain experts by clearly defining the expectations of the potential of emerging technologies, and selects the most suitable AI techniques for their realisation. Finally, it defines scope and boundaries of AI-Technology against railway targets for identifying new opportunities in achieving desired objectives from the development of emerging AI-technologies, i.e. identify application areas of AI across railway domains. The main outcomes of this work package are:

i. A taxonomy of suitable AI techniques to be adopted for railways (Deliverable D1.1);
ii. A map of the current state-of-the-art in railway research from S2R and other relevant projects (Deliverable D1.2);
iii. A set of current and potential application areas (this Deliverable).

The overall objective of the RAILS research project is to investigate the potential of AI approaches in the rail sector and contribute to the definition of roadmaps for future research in next generation signalling systems, operational intelligence, and network management. RAILS addresses the training of PhD. students to support the research capacity in AI within the rail sector across Europe by involving research institutions in four different countries with a combined background in both computer science and transportation systems.

2. Objective

The main objective of this document is to identify and describe current and potential application areas for AI techniques and methods across railway domains. This objective is achieved by elaborating the outcomes of the state-of-the-art and further activities carried out in WP1, also including feedback and information from members of the RAILS Advisory Board, the results of a survey on challenges and state-of-practice of AI applications in railways, and information gained from the AI4RAILS 2020 workshop. Hence, the application areas identified in this document are not limited to issues that will be addressed in WP2, WP3 and WP4, even if a special focus is put on AI techniques that have been used or could be used in railway safety and automation, maintenance, traffic planning and management. The document also identifies some areas of intervention that although not directly tied to the application of AI techniques, should be considered in order to enable their fast take-up in the rail sector. This results in: a) the identification of the potential of AI for railways, achieved through a comprehensive and up-to-date overview of relevant state-of-the-art of AI approaches, innovation technologies and trends applicable to railways from the transport sector, b) the alignment of the research activities with available results from relevant ongoing projects and initiatives in the railway sector.

3. Introduction

The RAILS project follows the Technology Road-Mapping Methodology in order to support a fast take up of AI technology in railways. The research is structured in three main phases 1) DISCOVER, covering all the preliminary survey and analysis activities, 2) ASSESS, covering proofs of concept development and experimentation activities, 3) LEARN, covering all the follow-up and knowledge dissemination activities.

This deliverable summarises and draws conclusions of the first phase developed in WP1 - State-of-the-art of Artificial Intelligence in railway transport. The document is organised as follows.

Chapter 4 describes the main sources of information for this document and draws a summary of the railway problems which are being investigated or could be addressed by applying AI approaches, as they emerged from the different sources and activities carried out in WP1. In particular, Section 4.5 and 4.6 refer to the study of scientific literature and the analysis of relevant research reported in Deliverable 1.1 and Deliverable 1.2. This chapter just summarises the relevant railway problems, and introduces the survey conducted among stakeholders about the challenges and the state-of-practice of AI in railways. In addition, Section 4.7 is dedicated to very recent interventions relating to more general issues, such as AI regulation and initiatives for trustworthy AI.

Chapter 5 illustrates and discusses the key findings of the survey. The survey results point out some of the obstacles to be faced and important milestones to reach for effective adoption of AI in railways. Moreover, they provide indications about AI models and tools currently used and railway problems from the respondents' point of view. Chapter 4 and Chapter 5 are the input of the next two chapters.

Chapter 6 contains a first attempt to match railway problems and applicable AI techniques, as well as a preliminary definition of application guidelines, hence contributing to select AI techniques and methods able to cope with specific problems.

Chapter 7 presents a comprehensive picture of the railway problems and draws the conclusion of WP1, identifying not only possible application areas of AI across the railway domains but also providing some hints about steps that should be taken to make this application effective.

Although AI for cyber-security is an area worth mentioning, as it is essential and challenging in railways as well as in many other transport systems to fight against cyber-threats and protect their assets, this report does not include a specific analysis related to that topic, which is inherently cross-domain. Cyber-attacks from hackers, criminal organisations or intelligence services are prone to undermine the security and integrity of data coming from different sources, hence the adoption of AI-based approaches could help counteract those threats by providing intelligent information fusion for superior situation awareness [1, 2].

4. Sources of Information

A relevant effort has been spent in the first phase of the project to collect and elaborate information from all RAILS relevant target groups in order to build a comprehensive picture of the current research and application of AI in railways and delineate future trends and application areas. The target groups include railway stakeholders, the scientific and academic community, and enterprises developing AI-based products that can be used/integrated into Railway applications and systems. Among the railway stakeholders, the activities conducted in the framework of WP1 aimed at involving in particular S2R JU members, S2R past and ongoing projects, railway regulation and standardisation bodies, associations, mass-transit operators, companies, suppliers and infrastructure managers. Hence, a number of different initiatives have been carried out that provided inputs for the analysis presented in this document. The main sources of information are:

- A survey on AI challenges and state-of-practise in railway transportation (Section 4.2);
- The members of the RAILS Advisory Board;
- The ongoing research submitted to the AI4RAILS international workshop;
- A systematic review of the scientific literature;
- The publicly available information about ongoing and past S2R projects, as well as other relevant worldwide projects;
- The available AI Policies and Regulations.

The related initiatives and their contribution to the identification of railways application areas are briefly described in the next Sections. The results and conclusions we derived from the collected information about the application areas of AI in railways are summarised and discussed in Chapters 6 and 7.

4.1. Railway domains definitions

Deliverable D1.1 [3], identified the railway sub-domains pointed out by the WP1 activities to investigate existing as well as potential applications of AI to the railway sector. In this Chapter and throughout the deliverable we will refer to such sub-domains, whose definition is therefore reported below.

Maintenance and inspection Railways are made up of complex mechanical and electrical systems. Maintenance covers all preventive and corrective activities intended to keep a system or sub-system in proper operating condition. These activities are essential to avoid deterioration with possible consequences on safety because of improper maintenance.

Safety and security Safety and security are of primary concern for any transport system, as travellers expect transportation to be safe and secure. Transport safety and security refers to all activities and means reducing the risks of both unintentional and intentional causes of accidents that may directly or indirectly cause injury to persons and/or damage to physical assets.

Autonomous driving and control The International Association of Public Transport (UITP) defines five Grades of Automation (GoA) with respect to train operation: GoA0, which means no automation; GoA1, where the presence of the driver is strictly necessary also for basic operations; GoA2, that encompasses semi-automatic train operations, and the driver is responsible for many safety-related procedures; GoA3, where trains run automatically from station to station but a staff member is always in the train, with responsibility for handling of emergency situations; and GoA4, trains are capable of operating automatically and on-board staff is not required for safe operation. Autonomous driving and control deals with trains that are operated automatically without any (or with only limited) human intervention.

Traffic planning and management Traffic planning and management deals with effective and efficient capacity management, timetabling, control of railway operations as well as resource allocation and resource management. This includes traffic state prediction and traffic rescheduling, analysis of passenger and freight railway transport, estimation of traffic demand and capacity, scheduling of trains and crews, optimal use of rolling stock and energy in order to increase the efficiency and competitiveness of passengers and freight transport.

Revenue management Revenue management is the application of disciplined analytics that predict consumer behaviour at the micro-market levels and optimise product availability and price to maximise revenue growth.

Transport policy Transport policy deals with the development of a set of strategies and programmes, that are established by governments and regulatory bodies to achieve specific objectives relating to social, economic and environmental conditions, and the functioning and performance of the transport system.

Passenger mobility Passenger mobility refers to the movement of people using any kind of transportation means. In this context we refer to railway transportation and to the following mobility characteristics: Time, that is the time needed to reach the destination; Affordability and Accessibility, as the rail options need to be affordable and accessible to provide a successful transportation service; and Safety, that is the essential precondition for rail mobility.

4.2. Survey

In order to get the overall RAILS research founded on the knowledge of the current situation and opportunities, we wanted to know from the railway stakeholders the State-of-Practice regarding the application of AI techniques in the rail sector as well as their opinion about the current challenges to be faced. An online survey was created for this reason which has been distributed to the whole S2R community, to railway associations, to regulatory and standardisation bodies, and disseminated through social channels. The submitted questionnaire consists of three parts:

a) General context and background of the survey participant, providing information about the participant's working context, motivation, experience and railway domain or application of interest.

b) Challenges and Open Issues of AI in railways, asking for the participant's opinion about the obstacles, the milestone and the railway problems that could be effectively addressed by the adoption of AI techniques.
c) State of Practice, trying to depict the current scenario through the AI solutions, techniques, datasets, tools and technologies currently in use.

The next Chapter of this deliverable is entirely dedicated to the survey and its outcomes as they have not been presented in other documents yet. The questionnaire is reported in the Appendix.

4.3. Advisory Board

The main objective of the RAILS Advisory Board (AB) group is to provide valuable feedback on project results as well as suggestions about possible research directions based on the relevant expertise and point of view of its members. The AB includes representatives of ERA (the European Agency for Railways), railway operators, companies, enterprises and Industries operating in the development of Artificial Intelligence and data-driven applications. A first meeting was held during which some interesting issues about possible applications of AI in a subset of the railway domain were presented. The topics addressed in this first meeting are a subset of all relevant issues worth addressing in this field of research, but they confirm some of the general research directions emerged from the project survey and reviews, with a focus on specific railway problems, open challenges and possible approaches based on data-driven techniques. Among others:

- Maintenance and Inspection; this includes the capability of detecting the health status of rail assets, the estimation of their remaining useful life, early warning, and the automation of maintenance activities.
- Security and safety of travellers and workers; in particular accidents analysis, prediction and prevention of collisions, fire, accidents at level crossings, derailments, etc.
- Safety and automation, e.g. self-driving trains in diverse environmental and system conditions.
- Traffic planning and management, in order to provide for effective and efficient passenger transportation even in face of disruptions and emergencies.

At a higher level of abstraction, addressing those problems requires situational awareness and decision making. This includes detection (object/obstacle detection, intrusion detection, signal detection), localisation, remote inspection, tracking, passenger flow analysis in stations as well as on-train, and the capability to analyse scenarios, learn from the past, correlate events and information. These problems raise the need to cope with the regulatory framework as well as technical issues.

- Aspects related to the regulatory framework include, among others:
  - The need for certification processes of AI-based systems in railways.
  - Issues related to data privacy and ethics.
- Some of the most important technical issues are related to:
  - Dealing with uncertainty.
  - The collection, availability and analysis of data:
    - data availability, in particular data related to rare events;

* data homogeneity (e.g. coping with multi-lingual concerns);
* data interoperability;
* data models;
* training data.

The open issues listed above are complex and no gold solutions are available. Some approaches have been taken to deal with some of the above technical challenges, based on:

- Generative Adversarial Networks as one of the promising techniques to perform data augmentation in case of limited data.
- Text mining and natural language processing (NLP) techniques.
- The definition of ontologies.
- Video Content Analysis (VCA) solutions based on Computer Vision.
- The usage of technologies such as drones and satellites.

4.4. AI4RAILS Workshops

AI4RAILS is a new international workshop series stemming from RAILS, and it is the first workshop/conference series specifically addressing topics related to the adoption of Artificial Intelligence in the railway domain. The ambition of AI4RAILS is to be a reference forum for researchers, practitioners and business leaders to discuss and share new perspectives, ideas, technologies, experience and solutions for effective and dependable integration of AI techniques in rail-based transportation systems, in the general context of intelligent and smart railways.

The first 2020 edition[1] was held on September 7, 2020, co-located with the 16th European Dependable Computing Conference (EDCC 2020) and hence focused on dependability aspects. Due to the COVID-19 pandemic, the workshop was held online. The second 2021 edition[2] takes place in a hybrid format, 11-14 July 2021, and is co-located with the 31st European Conference on Operational Research (EURO2021), and focused more on operational aspects.

The two editions have received submissions from more than 10 different countries from all over the world, and more than 30% of the authors were from companies (operators, suppliers and infrastructure managers). With the 194 registered participants of the first and the 19 registered presenters of the second edition (the information about the participants is not yet available), AI4RAILS workshops offer a relevant view on the ongoing research. Moreover, the keynote speeches (2 for the 2020 edition, 1 planned for the 2021 edition) and tutorials given by charismatic people complete this view. During 2020, in fact, the first keynote speech was given by Jens Braband from Siemens Mobility GmbH, addressing the issues of AI and machine learning within railway safety assessment, which is an extremely relevant topic given the safety-criticality of several railway control and supervision functions. The second keynote speech was given by Giorgio Travaini, Head of Research & Innovation at the European Union's Shift2Rail Joint Undertaking, highlighting the strong connection between the Shift2Rail programme and the research and innovation challenges and opportunities given by AI in railways. The tutorial was provided by The MathWorks, a worldwide leading company in the fields of Data Science and Machine Learning Platforms, as recognised by

[1] https://sites.google.com/view/ai4rails
[2] https://rails-project.eu/ai4rails/

the Gartner's Magic Quadrant 2020, mainly known for their Matlab and Simulink software applications.

The four technical sessions of the 2020 edition described multiple applications of AI; the main topics covered were maintenance and inspection (54%), traffic planning and management (22%) and autonomous driving and control (22%). Among the different applications presented, obstacle detection was widely considered as well as the inspection of tracks for anomalies and irregularities. Within the traffic planning and management, the focus was on train unit shunting and UIC code recognition. In autonomous driving and control, covered topics were related to the automatic and safe recognition of railway signals and audio-events. The presented papers are published in the workshop proceedings [4].

The main topics covered within the 2021 edition are traffic planning and management (66%), autonomous driving and control (22%) and maintenance and inspection (11%). In traffic planning and management, diverse applications were presented including strategical planning (track alignment), scheduling and routing, shunting, and rescheduling and traffic predictions for yards, depots, stations and networks. Within maintenance and inspection, the focus was on obstacle detection and track deterioration modelling. Within autonomous driving and control, researchers addressed autonomous driving, calibrating engine parameters, minimising energy consumption and assessing risks of deploying computer vision. Diverse AI approaches are applied for both freight and passengers' operations, in order to simulate and optimise the railway system and its components.

4.5. Related Projects

Deliverable D1.2 [5] provides a review of relevant projects worldwide where AI was used to support and improve railway systems in different scenarios, with particular emphasis on those within the European Shift2Rail (S2R) funding programme. In order to delineate relevant application areas, we summarise here our main findings of this comprehensive review showing the tackled research areas according to the railway subdomains.

Maintenance and inspection:

- Rail tracks related issues:
  - Turnout fault diagnosis [6] and failure prediction [7];
  - Track geometry [8,9] and track deterioration [6,10,11] monitoring, as well as identification of both location and timing of unexpected changes to the track system [12];
  - Turnout weaknesses and track profile degradation prediction for maintenance activity planning oriented to reduce costs [13];
  - Tracks defect prediction through suitable customised Track Quality Indices (TQI) [14], as well as broken spikes detection [15];
  - Introduction of Smart Wayside Object Controllers (SWOC) to handle control and diagnosis data related to both SWOCs themselves and the route management system [16,17];
- Rolling stock related issues:
  - Condition-based maintenance for bogies and wagons [18] and traction and braking systems [19], as well as fault diagnosis for bogies components [20] and wheels

defect detection [21];
  - Ongoing investigation towards the integration of Digital Twins and AI for bogies condition monitoring [22].
- Infrastructures related issues:
  - Ongoing investigation towards the integration of Digital Twins and AI to predict crack pattern changes in tunnels and bridges [23];
  - Development of a Building Information Management/Modelling (BIM) platform for the integration of algorithms and gathered information collected by different kinds of sensors, especially for tunnels and bridges [8, 24, 25];
  - Infrastructure condition assessment [26], defect detection in high-speed railway infrastructures [27], health condition and optimal intervention time and type prediction [28], and detection and classification of damages within tunnel linings [29];
  - Ongoing investigations towards the usage of drones to recognise infrastructure components and discover eventual faults on the assets [30].

Safety and security:
- Rail track related issues:
  - Earth activity monitoring and active deformation areas identification [31], earthwork status change prediction [6], and landslide prediction [32–34];
  - Collision prediction at road-rail level crossings [34] and derailment risk prediction [7];
  - Track circuit false occupancy detection [6], as well as obstacle detection/intrusions on tracks [32, 35, 36];
- Railway stations and workplaces:
  - fare evasion detection as well as vandalism, unattended baggage, and so on [37];
  - increment safety and security at railway stations by crowd management analysis [38];
  - workers' safety during inspection activities [39];
- Information technology systems:
  - Anomaly detection to increment cyber-security in railway systems [40];
  - ITC systems analysis to identify technical issues and problematic patterns before they cause service interruptions [41].

Traffic planning and management:
- Train delay [7, 32, 42], dwell time and restore time [43], cancellations, and route change prediction and unexpected events prognosis [44];
- Timetable construction for long-term planning, real-time planning, and replanning during disruptions [45],
- Marshalling operations optimisation [35] and development of Intelligent Video Gate (IVG) for wagons recognition at the entrance of marshalling yards to optimise operations [18, 46];

Autonomous driving and control:
- Energy optimised driving profiles [43, 47];
- Ongoing investigation towards automated and optimised train movements [17].

Passenger mobility:

- Crowdedness prediction, travellers pattern recognition, and travellers clustering [48], passenger flow modelling and simulation to reduce congestion [49], and passengers' origin-destination estimation [50];
- Ongoing investigation towards the integration of Digital Twins to manage crowds in stations [51];
- Face recognition solutions to optimise the railway real-name entry verification system to enhance passengers travel experience [52].

In addition to these findings, we also found some uncharted areas from both the rail and AI perspectives. Particularly, some AI technologies have not been widely investigated such as "Autonomous systems & Robotics", while others have not yet been involved in any project surveyed, such as "Logic programming" and "Natural Language Processing" and "Speech Recognition". These AI technologies and applications may be potentially addressed in ongoing/future projects, as could be for NLP in TRANSLATE4RAIL [53] and "Autonomous systems & Robotics" in TAURO [54]. Concerning railway subdomains, none of the projects carried out tackled the Revenue Management challenges, while only in one case research was performed towards Transport Policy [55].

The graphic in Fig. 4.1 shows the number of AI-related projects per topics that have been covered by the review performed in WP1.

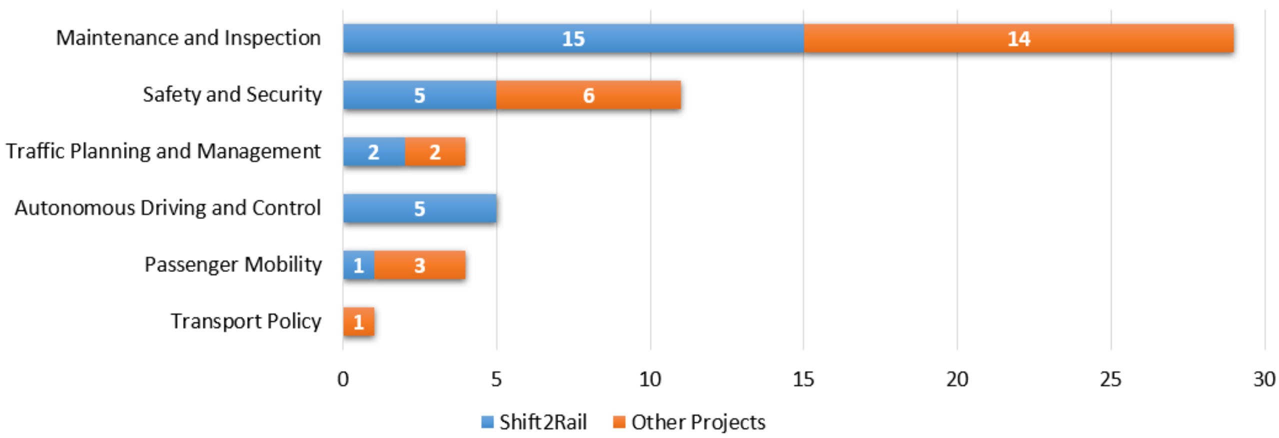

Fig. 4.1. AI-related projects covered in D1.2

For further analysis on relevant projects, please refer to RAILS deliverable D1.2 [5], Section 4.

4.6. Taxonomy and Literature Review

In our first deliverable [3], we defined a reference taxonomy of AI in railways and subdivided the rail sector into seven sub-domains, as recalled in section 4.1, that were used as a baseline for our investigations. In addition, we performed an initial high-level analysis to identify existing and potential applications of AI in the railway sector. These results were then extended through a state-of-the-art (SOTA) of the literature, performed in the

RAILS deliverable [5], which main findings, in terms of research areas, are synthetically summarised below.

Maintenance and Inspection:

- Rail Tracks related issues:
  - Track geometry defects detection and prediction, rails' surface defects detection, contact fatigue defect detection and prediction, and occurrence of broken rails prediction;
  - Fasteners defects detection and/or their classification;
  - Turnout fault diagnosis and failure prediction, track circuit fault diagnosis and failure prediction, railway point machine fault detection and diagnosis, and spatial and temporal dependencies measurement of faults in track circuits;
  - Predicting the type of maintenance intervention and whether the maintenance activity should be performed or delayed at switches;
  - Rails health conditions estimation (mostly squats defects) for data-driven maintenance planning.
- Rolling Stock related issues:
  - Angle cock and fastening bolts defect detection, as well as wheels' wear condition estimation;
  - Axle bearings fault diagnosis and remaining useful life estimation;
  - On-board equipment fault diagnosis, on-board systems failure prediction, and anomaly identification in data coming from train sensors;
  - Autonomous adaption of the cab front cleaning robot to the surface of the cab;
  - Plugs identification in trains' frames to improve maintenance activities.
- Defects identification within railway signalling requirements documents;
- Catenary defects identification;
- Diagnosis of maintenance equipment.

Safety and security:

- Risk assessment of hazardous events when shunting and accident occurrence analysis at railway depots;
- Risk assessment approaches to quantitatively reveal the severity for different hazardous events in various scenarios such as stations, rail lines, and buildings;
- Railway network route selection;
- Track circuit disruption length estimation, as well as track circuit coding reasoning and deducting process simulation in high-speed rails;
- Detection of variations in correspondence of the rail tracks through the analysis of environmental anomalies;
- Level Crossings analysis and evaluation in order to select those that need improvements from passively protected to active system-aid protected.

Traffic planning and management:

- Timetable generation and routing optimisation;

- Train delay minimisation, total travel time or waiting time reduction, and track allocation and departure/arrival time optimisation for delay minimisation;
- Delay analysis and conflict prediction, running and dwell time and train event time prediction, and arrival time prediction for freight trains;
- Analysis of weather conditions and scheduled timetables to comprehend how they affect train delays as well as delay estimation and pattern identification;
- Train rescheduling in case of disruptions to minimise total/primary/knock-on delays of trains and maximise the quality of service and passengers' satisfaction.

Autonomous driving and control:

- Energy-efficient driving optimisation;
- Energy consumption reduction whilst maintaining comfort level and punctuality.

Passenger mobility:

- Predict metro on-board passenger flow as well as entrance and exit flows;
- Unravel the influence of spatial characteristics in predicting passenger flow;
- Predict and classify passengers load categories.

Besides these findings, the state-of-the-art also showed that no AI-based solution has still been proposed for railway revenue management and transport policy.

4.7. AI Policies and Regulations

Trustworthiness, ethics, robustness and explainability are essential for AI-based systems, especially when used in critical domains such as health and transport. As discussed in Deliverable 1.1 [3], the European Commission (EC) has recently addressed some of these issues by introducing "Ethics Guidelines for Trustworthy Artificial Intelligence" [56], the "General Data Protection Regulation (GDPR)" [57], and the "Report on the safety and liability implications of Artificial Intelligence, the Internet of Things and robotics" [58]. However, very recently (i.e. Spring 2021), new concerns and proposals for regulations have arisen addressing the real applicability of AI, especially in relation to humans' fundamental rights such as non discrimination, equality between women and men, integration of persons with disabilities, and respect for private life. Focusing on the European panorama, the European Commission has issued a new "Proposal for a Regulation laying down harmonised rules on artificial intelligence (Artificial Intelligence Act)" [59] which relies on and/or extends the aforementioned documents and introduces a cross-domain, horizontal regulatory framework, oriented to preserve the fundamental human rights. Indeed, with this proposal, the EC bans those AI applications that may violate fundamental rights or could manipulate persons beyond their consciousness in order to distort their behaviour; as the main example, AI-based social scoring applications are prohibited. In addition, real-time remote biometric identification systems (i.e., AI systems oriented to recognise persons leveraging their biometric data) are banned in public spaces, with any exceptions requiring special authorisation. Beyond these prohibitions, the framework collects a set of requirements that high-risk AI systems, listed in Annex III [60], must meet in order to be marketed and operated in Europe; these include documentation, tests, risk assessment, data quality evaluation, recording of events (i.e. logging), etc. Although flexible, as it allows providers of AI systems to delineate the required procedures to meet these specifications, the framework imposes a well detailed “ex-ante” assessment of the conformity of the product and a continuous “post-market” monitoring and reporting. Regarding trustworthiness evaluation of AI-based systems, last year the AI High Level Expert Group (AI HLEG) has released “The Assessment List for Trustworthy Artificial Intelligence (ALTAI) for self assessment” [61]. It is worth mentioning that Microsoft has recently released (May 2021) a new tool, named Counterfit[3], with the aim to allow organisations to conduct AI security risk assessments to ensure robustness, reliability, and trustworthiness of their AI-based systems; this tool is open-source and available online on GitHub[4].

In the same period, the U.S. Federal Trade Commission (FTC) set out some interesting points to make AI truthful, fair, and equitable[5]. They mainly focus on datasets, which should contain useful, *unbiased*, and non-discriminatory information. For instance, as also considered by the FTC, if the dataset misses information about a particular population, it would lead to an AI system that is intrinsically discriminatory. In addition, the FTC promotes embracing transparency of data and independence of the researchers as an effective means to monitor and adjust bias factors in datasets.

Furthermore, in the current year (2021), CEN and CENELEC have launched a new technical committee[6] on Artificial Intelligence. The new CEN/CLC/JTC 21[7] aims to produce, in the near future, standardisation deliverables on AI and related data. It will also take into account the work performed within other international standards and organisations (e.g. the ISO/IEC JTC 1/SC 42[8]).

In the context of Autonomous and Intelligent Systems (AIS), it is worth underlining that the Institute of Electrical and Electronics Engineers Standards Association (IEEE SA) has proposed a “Global Initiative on Ethics of Autonomous and Intelligent Systems”[9]. Within this initiative, a landmark paper named “Ethically Aligned Design” [62] was issued, intended to provide recommendations and guidance for standards, certification, and regulation for design and use of AIS. It also includes discussions about the potential harm of AIS to privacy, discrimination, and possible negative long-term effects on societal well-being. Practically, this initiative encompasses a series of standards (IEEE P7000[10]), which are being developed, assessing transparency of autonomous systems, data-related issues and privacy, and ethically driven robotic, intelligent and autonomous systems. Regarding the assessment of safety and the trustworthiness of AIS, IEEE is also carrying out activities within “The Ethics Certification Program for Autonomous and Intelligent Systems (ECPAIS)”[11] by

[3] https://www.microsoft.com/security/blog/2021/05/03/ai-security-risk-assessment-using-counterfit/
[4] https://github.com/Azure/counterfit/
[5] https://www.ftc.gov/news-events/blogs/business-blog/2021/04/aiming-truth-fairness-equity-your-companys-use-ai
[6] https://www.cencenelec.eu/News/Brief_News/Pages/TN-2021-013.aspx
[7] https://standards.cen.eu/dyn/www/f?p=204:7:0::::FSP_ORG_ID:2916257&cs=1E73EA11303EDD288BB954271E14DE3AE
[8] https://www.iso.org/committee/6794475/x/catalogue/
[9] https://standards.ieee.org/industry-connections/ec/autonomous-systems.html
[10] https://ethicsinaction.ieee.org/p7000/
[11] https://standards.ieee.org/industry-connections/ecpais.html

establishing criteria and processes to certify transparency, accountability, and algorithmic bias in AIS.

In conclusion, the development of AI standards, regulations and guidelines addressing trustworthy autonomous systems has very recently undergone rapid development and evolution, which is still ongoing. Depending on local applicable laws and domain-specific standards, developers of intelligent transportation systems, including smart railways, would need to be compliant with multiple requirements at different levels; therefore, it would be important for the railway industry to setup structured and systematic approaches within multi-compliance frameworks, similarly to what companies have already done in fields of similar complexity and criticality, such as cyber-security compliance.

4.7.1. Considerations about Ethical and Privacy aspects of AI in railway applications

We would like to conclude this section by providing some remarks about AI applications in railways for which special care must be devoted to privacy and ethical aspects. We provide some example directions for further investigation, as each of the points addressed would require an in-depth analysis that is beyond the scope of this study. Some relevant considerations relate to the so-called "ethical dilemmas" associated with the deployment of trustworthy AI, as they are reported in the study of the European Parliament "The ethics of artificial intelligence: Issues and initiatives" [63]. With respect to the ethical and moral issues reported in this document, in the context of our study on AI application to railway systems, we mainly consider the impact on society and the impact on trust, and in particular here we refer to: labour market, privacy and human rights, fairness, transparency and accountability. Other issues could be considered by conducting specific studies. Therefore, we provide some hints about AI applications in the railway sub-domains pointed out by RAILS activities that may raise privacy and ethical concerns:

Maintenance and inspection

- Applications which have impact on work and unemployment by replacing people with AI-based machines or AI models, or create labour-market discrimination. This is a concern originated by the replacement of human labour by automation, or by the fact that new skills are required. The area of maintenance and inspection could be affected by these phenomena as autonomous maintenance is increasingly adopted.
- Applications which require the analysis of video or data that may violate the privacy of people (for example, video analytics solutions requiring cameras watching public areas such as at level crossings, or on board of trains).

Safety and security

- Trust is a main concern in safety and security. Therefore, AI techniques used to support decision making processes suffer from data uncertainty and from the lack of transparency of Machine Learning algorithms (including Deep Learning approaches). Intelligent rail obstacle detection is an example application where detection may be affected by the fine tuning of performance to find a balance between false negatives (associated with a negative safety impact) and false positives (associated with a negative availability and cost impact).
- Intelligent railway monitoring and station surveillance systems (i.e., CCTV with video analytics) are important to guarantee safety and security, nonetheless they bring up a number of privacy issues, for example with respect to the level of control over the usage

of collected data to prevent or avoid accidents, such as data coming from tracking people by recognising their biometric characteristics and behaviour.

Autonomous driving and control

- Accountability is a problem when technology spreads moral responsibility between many actors or delegates to new roles. In particular, autonomous driving poses important ethical issues that are being discussed in several domains, notably in automotive. Trains have a more constrained behaviour compared to road vehicles or aircrafts, but a high level of autonomy implies the capability and the necessity of taking decisions without human control, with explainability being of paramount importance in such a context.
- Similarly to rail surveillance applications, obstacle detection may also be affected by privacy issues, especially in case videos are recorded.

Revenue management and Passenger mobility Privacy concerns can also be risen by both Revenue management and Passenger mobility applications. Revenue management applications require to automatically collect and elaborate a high volume of personal data, and the same holds for applications addressing the evaluation of passenger satisfaction. Passenger mobility applications may require data from both people tracking using mobile devices, as well as networks of cameras and other sensors for people counting and crowd analysis.

As a final remark, it should be noted that several ethical and privacy issues are not specifically related to AI but more in general they are raised by technologies also used in more traditional systems. This is the case, for example, of all the applications that increase the level of autonomy of the systems and make use of technologies based on probabilistic and statistic models, on the usage and elaboration of sensors data. Such applications are not necessarily AI-based, but AI solutions are often depending on the same technologies and may increase their effects.

5. Survey Key Findings

This Chapter provides an overview and summary of key analytical points of the survey. The objective of the survey was to obtain a deeper understanding of the Challenges and State-of-Practice (SoP) of Artificial Intelligence in railways from the perspective of the railway stakeholders and gain information to shape future research directions and roadmaps for an effective introduction of AI techniques in the railway sector. The main goal was to collect feedback and indications from *relevant stakeholders and experts* to delineate *trends and directions*, therefore the survey did not involve the general public.

5.1. Survey Methodology and General information

The survey was conducted from 26th April to 31st May 2021. It was addressed above all to relevant railway stakeholders directly involved in railways innovation and digitalization, hence we adopted a dissemination strategy in two phases.

We circulated the questionnaire to selected stakeholders in the first 20 days, and specifically among the RAILS AB members, S2R JU members, S2R projects, railways industry, agencies and bodies, researchers and organisations conducting activities in the field of AI applied to railways, also outside Europe. In this phase the following communication channels were used:

- S2R newsletter and social channels;
- S2R website;
- RAILS project AB contacts;
- Mailing list from the AI4RAILS workshop
- Specific contacts from RAILS partners.

In the second phase, we enlarged the target group by disseminating the survey through social channels, including the RAILS website and LinkedIn profile.

The survey was submitted in the form of a questionnaire, designed by the RAILS partners. A first draft of the questionnaire was proposed by CINI, built on the basis of the results from the Taxonomy, the state-of-the-art, the presentations from AB members, AI4RAILS speakers and keynotes. The questionnaire has been then largely revised and improved alternating several steps of discussion and review with the partners. Finally, it was also revised by the AB members and further improved according to the received feedback.

The questionnaire comprised both closed and open-ended questions. Closed-ended questions included multiple choice and ranking questions. They consisted of pre-populated answers for the respondent to choose from and also allowed the respondent to add his/her own answer. Open-ended questions asked the respondent to provide his/her feedback, in some cases to explain or motivate a previous answer to a closed-ended question.

As already explained in Section 4.2 the questionnaire was structured in three parts: the first group of questions was related to the respondent's context and background; the second group was related to the SoP of AI in railways according to the respondent's experience and knowledge; the third group specifically addressed the main challenges and issues to be faced according to the respondent's point of view.

The main research questions we would like to answer using the results of the survey with respect to the SoP are:

- For which rail applications is AI currently *used*?
- Which are the AI techniques, models and supporting tools/computing resources currently used in industrial practice or research?
- How big is the problem related to data acquisition and management?

The main research questions we would like to answer using the results of the survey with respect to the challenges to be faced are:

- Which are the practical issues that have to be overcome to effectively apply AI in railway applications?
- Which are the regulatory and methodological issues that need to be addressed to make AI strategic for the rail sector?
- Which are the key milestones to be reached?

In the remainder of this chapter, we summarise the main findings to delineate an answer to these questions according to the survey respondents. An analysis of the survey sample is provided in Section 5.2.

5.2. Survey Sample

The sample was selected in two stages, as explained at the beginning of the chapter. The universe of this study consists of practitioners and experts in both railway problems and AI-related issues, therefore the boundaries of the study are well defined and the borders are not very wide. A total of 60 participants responded to the questionnaire from more than 40 diverse bodies, over 10 of those are research institutes and 30 are railway companies/organisations.

The uncertainty about the remaining 20 answers is due to the anonymity of the interviewees. In these cases, we can say if they work in research institutes or railway companies considering their answer to the specific question, but we do not know if they are from diverse bodies or if they belong to already counted organisations. Nevertheless, all the answers have been considered in the analysis. Most of the respondents are located in Europe (**81.7%**) followed by North America (**11.7%**), as shown by the pie chart on the left side of Fig. 5.1. Many of them work in companies operating in more than one country, therefore a significant number of organisations are represented in the survey, including railways companies and operators, operating all over the world (right side of Fig. 5.1). Fig.5.2 shows the distribution of the survey participants with respect to the type of the organisation in which they work: over half of them from railway settings (e.g., companies, suppliers, operators, infrastructure managers), more than one-third from universities or other research institutes, and about one-sixth work from a railway joint undertaking or railway association. The pie chart on the left side of Fig.5.2 says that the majority of the respondents work for very large organisations (**15%** have less than 100 employees, while **18.3%** have 100 to 1000 employees, and **66.7%** have more than 1000 employees).

More than 83% of the respondents said that they address AI applications to railways in their job, hence the level of competency and awareness of the sample with respect to the topics investigated by the study is very good. Fig. 5.3 provides a picture of the railway area in which the interviewees work, and what railways applications they are interested in. The

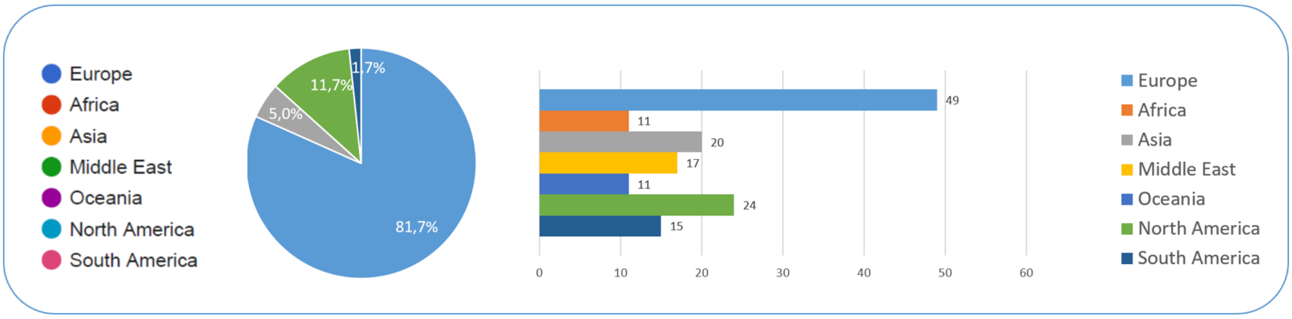

Fig. 5.1. Respondents by geographical regions (left) and areas where their organisations operate (right)

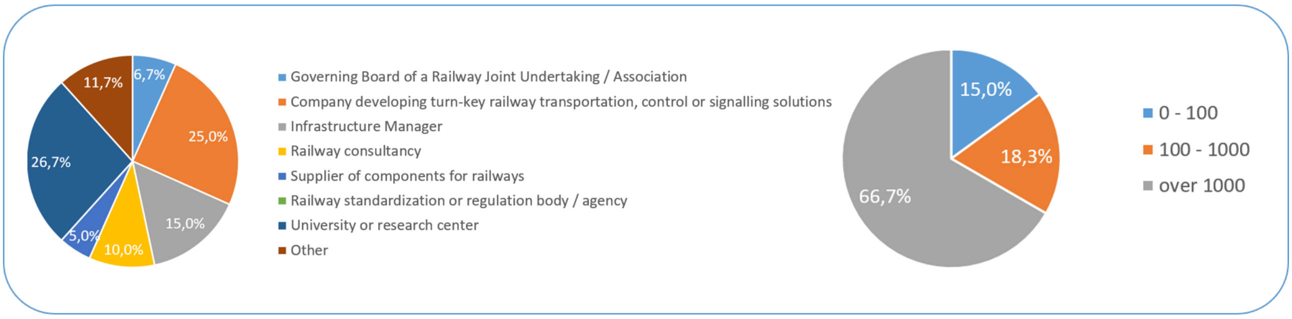

Fig. 5.2. Type of organisation (left) and number of employees (right)

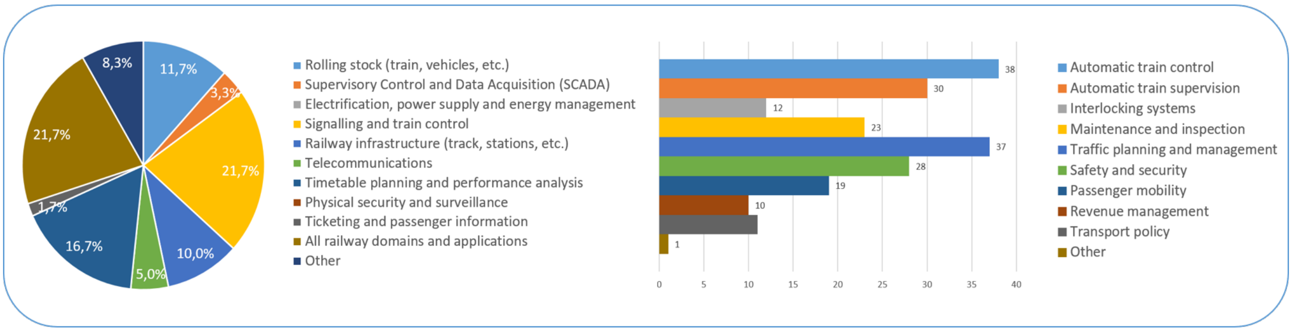

Fig. 5.3. Respondent's railway domains (left) and applications of interest (right)

latter question allowed for multiple choices (this is evident from the histogram on the right, because the sum of the collected answers is greater than 60).

The pie chart shows that most of the suggested railway areas are explicitly covered by the sample, one-third of the respondents answered their activity is cross-cutting several railway domains and applications (over half of the interviewees said to be involved in innovation and/or research); one-third of respondents are directly involved in signalling and train control, followed by timetable, planning and performance analysis (**16.7%**), rolling stock (**11.7%**) and railway infrastructure (**10%**). Two areas have not been explicitly selected by the interviewees: physical security and surveillance, and electrification, power supply and energy management.

Some indications come from the distribution of the applications of interest. The survey data reveal that currently the most *attractive* application areas are: i) autonomous train control and supervision, ii) traffic planning and management. This result is not simply a consequence of the number of responders who are involved in related railway domains, as it might seem from the data in the pie chart, in fact, more than 50% of respondents said they were interested in these two areas. A further observation is that 10 interviewees said to be interested in revenue management, which currently seems not to be among the most investigated applications of AI in railways.

5.3. Findings about Challenges

Our analysis of the survey data identifies some key points about the respondents' sentiment toward the main challenges to be faced for an effective adoption of AI techniques. The survey mainly points out *obstacles* and *milestones* in order to understand what is the perception of those who work and research in the field. The questionnaire asked the interviewees to *rank* the obstacles proposed by a multiple choice question by assigning each obstacle a score on a scale of 6 values from 0 ("the issue is not an obstacle") to 5 ("the issue is blocking"). Fig. 5.4 visualises the rankings, whereas the table in Fig. 5.5 reports detailed results and help to understand what is the weight of the various obstacles according to the respondents. The average values in the tables have been calculated by shifting the score values to be in the range [1,6]. All the tables are ordered according to the value of the average of the scores.

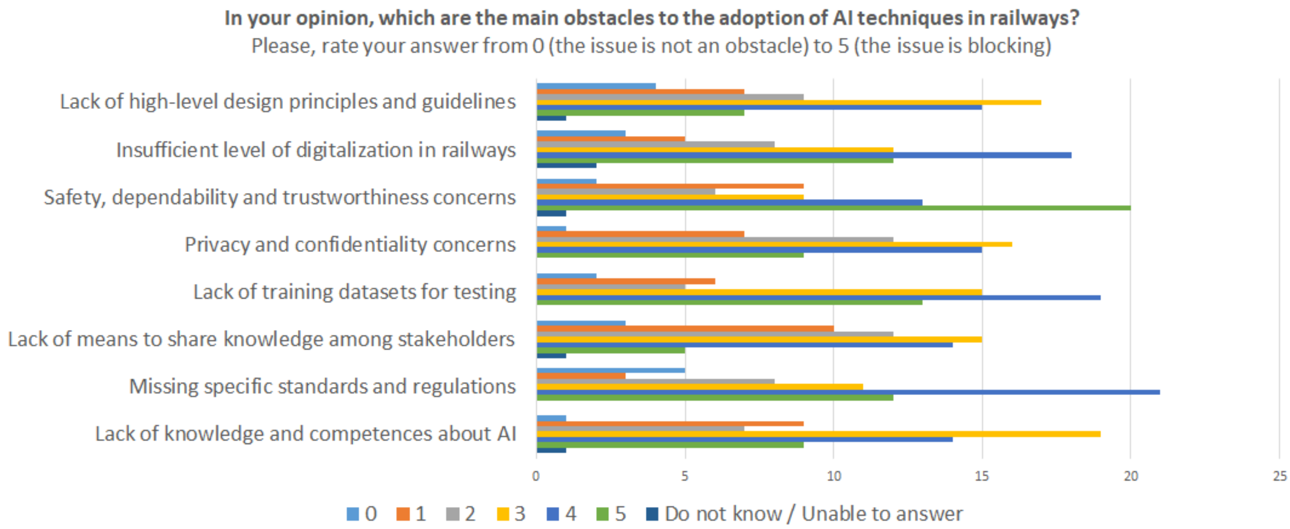

Fig. 5.4. Ranking obstacles to the adoption of AI in railways

Two facts emerge at first glance:

- **All proposed obstacles were considered relevant**, in fact, the average score value is always greater than 3 on a scale of 1 to 6;
- **Safety, dependability and trustworthiness concerns are perceived as the most blocking factor by the survey sample**, as the related item has both the highest average score (4.39) and the highest number of respondents (20) who awarded this obstacle with the maximum score.

The analysis has been conducted also dividing the sample into **two focus groups** including respondents from **research institutes** and **railway organisations**, respectively. If we compare the answers from the two groups, two different perspectives emerge (Fig. 5.6).

On average, the lack of proper datasets for training the AI models is the most important factor from the railway respondents' perspective, followed by the need for specific standards and

Obstacle	Number of selected scores from «not an obstacle» (left) to «blocking» (right)						Average of the scores
Safety, dependability and trustworthiness concerns	2	9	6	9	13	20	4,39
Lack of training datasets for testing	2	6	5	15	19	13	4,37
Missing specific standards and regulations	5	3	8	11	21	12	4,27
Insufficient level of digitalization in railways	3	5	8	12	18	12	4,26
Lack of knowledge and competences about AI	1	9	7	19	14	9	4,07
Privacy and confidentiality concerns	1	7	12	16	15	9	4,07
Lack of high-level design principles and guidelines	4	7	9	17	15	7	3,90
Lack of means to share knowledge among stakeholders	3	10	12	15	14	5	3,71

Fig. 5.5. Obstacle weights

Lack of training datasets for testing	2	5	3	12	14	8	4,25
Missing specific standards and regulations	5	2	4	8	18	7	4,20
Insufficient level of digitalization in railways	3	4	8	6	10	11	4,17
Safety, dependability and trustworthiness concerns	2	9	3	7	10	12	4,16
Lack of knowledge and competences about AI	0	8	6	11	12	6	4,05
Lack of high-level design principles and guidelines	4	4	8	11	12	5	3,86
Privacy and confidentiality concerns	1	7	10	11	10	5	3,84
Lack of means to share knowledge among stakeholders	2	9	8	12	8	4	3,63
Railway organizations							
Safety, dependability and trustworthiness concerns	0	0	3	2	3	8	5,00
Lack of training datasets for testing	0	1	2	3	5	5	4,69
Privacy and confidentiality concerns	0	0	2	5	5	4	4,69
Insufficient level of digitalization in railways	0	1	0	6	8	1	4,50
Missing specific standards and regulations	0	1	4	3	3	5	4,44
Lack of knowledge and competences about AI	1	1	1	8	2	3	4,13
Lack of high-level design principles and guidelines	0	3	1	6	3	2	4,00
Lack of means to share knowledge among stakeholders	1	1	4	3	6	1	3,94
Research Institutes							

Fig. 5.6. Comparison between the two focus groups

regulations. Nonetheless, safety, dependability and trustworthiness is still the issue which obtained the highest number of maximum score (12), hence perceived as the most urgent to be faced together with the insufficient level of digitalisation in railways.

The questionnaire also asked the respondents to give indications about further obstacles, not included in the proposed set. A discussion of results also including this feedback is provided in the next subsections, where open issues are discussed separately with respect to: i) practical and infrastructural aspects (e.g., datasets, digitalisation, knowledge), ii) regulatory and methodological aspects (e.g., standards, privacy, guidelines), and iii) main milestones.

5.3.1. Practical issues

Figure 5.7 shows the comparison between the answers of the two focus groups to the multiple choice questions restricted to the practical obstacles that are currently limiting or slowing the integration of AI-based solutions in the railway sector. Therefore, Fig. 5.7 reports an excerpt from the table in Fig. 5.6 to focus on specific aspects related to practical obstacles.

The ranking based on the average score is identical. Among the practical issues, **the lack**

of proper datasets for training the AI models is the main obstacle for both the groups, immediately followed by **an insufficient level of digitalisation** of railways. Nonetheless, *the need for digitalisation is perceived slightly more blocking by the respondents belonging to railway organisations*, seeing at the number of respondents who selected the maximum score. In addition, their point of view also appears to be more diversified with respect to the respondents from the research institutes.

Obstacle	Number of selected scores from «not an obstacle» (left) to «blocking» (right)						Average of the scores
Lack of training datasets for testing	2	5	3	12	14	8	4,25
Insufficient level of digitalization in railways	3	4	8	6	10	11	4,17
Lack of knowledge and competences about AI	0	8	6	11	12	6	4,05
Lack of means to share knowledge among stakeholders	2	9	8	12	8	4	3,63
Railway organizations							

Obstacle	Number of selected scores from «not an obstacle» (left) to «blocking» (right)						Average of the scores
Lack of training datasets for testing	0	1	2	3	5	5	4,69
Insufficient level of digitalization in railways	0	1	0	6	8	1	4,50
Lack of knowledge and competences about AI	1	1	1	8	2	3	4,13
Lack of means to share knowledge among stakeholders	1	1	4	3	6	1	3,94
Research Institutes							

Fig. 5.7. Practical issues to overcome (excerpt from the table in Fig. 5.6)

5.3.2. Regulatory and methodological issues

The two focus groups have different visions and attitudes towards the regulatory and methodological issues.

Fig. 5.8 reports an excerpt from the table in Fig. 5.6 to focus on these specific aspects: it shows that the ranking based on the average is quite different in the two cases.

On average, **the main obstacle for the respondents from the railway organisations is the lack of specific standards and regulations, but safety, dependability and trustworthiness concerns are the most blocking issue.** The need for guidelines, privacy and confidentiality concerns have almost the same importance after the first two places in this ranking.

Safety, dependability and trustworthiness concerns are instead the first issue for the respondents from the research institutes, both on average score and number of maximum score collected. The second place in this ranking goes to privacy and confidentiality concerns that instead is last in the ranking of the other focus group.

5.3.3. Key milestones

The histogram in Fig. 5.9 visualises the relevance of the milestones suggested by the related open-choice question according to the survey sample. At first glance, the most relevant milestone is an in-depth study on the development and applicability of explainable and trustworthy AI approaches, followed by the creation of cross-sector working groups on AI in critical systems to discuss, share and learn from other sectors.

The table in Fig. 5.10 reports the general ranking of the proposed milestones; here, as for all the tables in this chapter, the average values have been calculated in the range [1,6] and

Obstacle	Number of selected scores from «not an obstacle» (left) to «blocking» (right)						Average of the scores
Missing specific standards and regulations	5	2	4	8	18	7	4,20
Safety, dependability and trustworthiness concerns	2	9	3	7	10	12	4,16
Lack of high-level design principles and guidelines	4	4	8	11	12	5	3,86
Privacy and confidentiality concerns	1	7	10	11	10	5	3,84
Railway organizations							

Obstacle	Number of selected scores from «not an obstacle» (left) to «blocking» (right)						Average of the scores
Safety, dependability and trustworthiness concerns	0	0	3	2	3	8	5,00
Privacy and confidentiality concerns	0	0	2	5	5	4	4,69
Missing specific standards and regulations	0	1	4	3	3	5	4,44
Lack of high-level design principles and guidelines	0	3	1	6	3	2	4,00
Research Institutes							

Fig. 5.8. Regulatory and organisational issues to address (excerpt from the table in Fig.5.6)

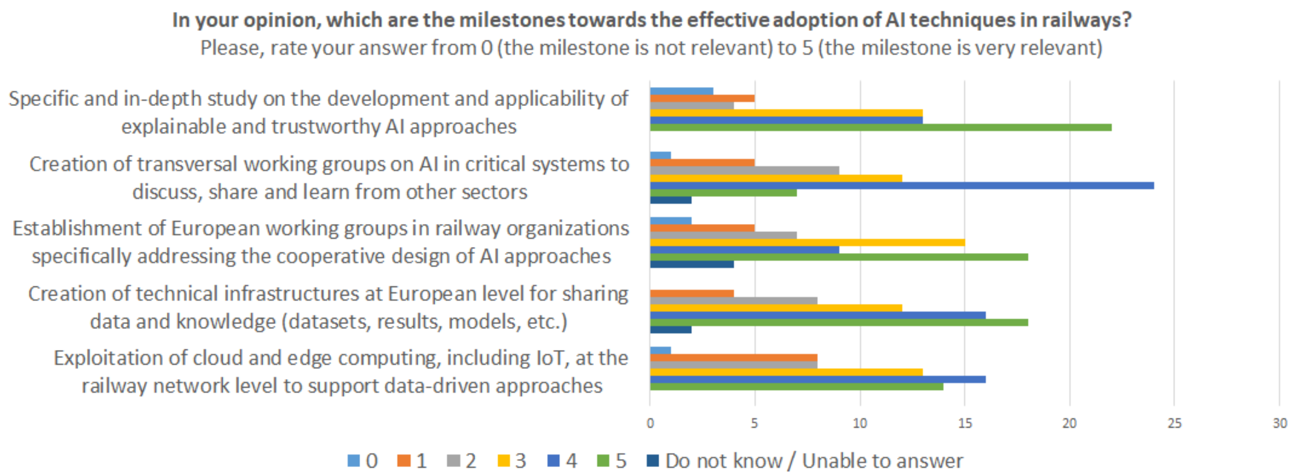

Fig. 5.9. Milestones towards AI integration

all the rows have been ordered according to these averages. The numbers show that the choice was very difficult: the values of the averages are all very close and greater than 4. From this table (Fig. 5.10), it is evident that on average **the most relevant milestone is the creation of technical infrastructures at the European level for sharing data and knowledge, followed by the study on the development and applicability of explainable and trustworthy AI approaches**.

Data reported in Fig. 5.11 and Fig. 5.12 say that this ranking is confirmed by the two focus groups separately.

5.3.4. Trustworthy AI

Only 12 people of the interviewed sample are aware of trustworthy AI. From the received answers, some of them are aware of approaches in other relevant sectors (such as Environmental Science, Energy, or customers' sector), but some others are focusing their attention on the initiatives in critical systems. As an example, the DEEL project[1] is cited in the answers since it aims at dependable, robust, explainable and certifiable artificial intelligence technological bricks applied to critical systems, involving both industrial and academic part-

[1] https://www.deel.ai/

Milestone	Number of scores from «not relevant» to «very relevant»						Average Score
Creation of technical infrastructures at European level for sharing data and knowledge (datasets, results, models, etc.)	0	4	8	12	16	18	4,62
Specific and in-depth study on the development and applicability of explainable and trustworthy AI approaches	3	5	4	13	13	22	4,57
Establishment of European working groups in railway organizations specifically addressing the cooperative design of AI approaches	2	5	7	15	9	18	4,39
Exploitation of cloud and edge computing, including IoT, at the railway network level to support data-driven approaches	1	8	8	13	16	14	4,28
Creation of transversal working groups on AI in critical systems to discuss, share and learn from other sectors	1	5	9	12	24	7	4,28

Fig. 5.10. Milestones ranking

Milestone	Number of scores from «not relevant» to «very relevant»						Average Score
Creation of technical infrastructures at European level for sharing data and knowledge (datasets, results, models, etc.)	0	4	6	9	10	14	4,56
Specific and in-depth study on the development and applicability of explainable and trustworthy AI approaches	3	3	2	12	10	14	4,48
Establishment of European working groups in railway organizations specifically addressing the cooperative design of AI approaches	2	5	5	10	6	13	4,27
Exploitation of cloud and edge computing, including IoT, at the railway network level to support data-driven approaches	1	8	3	9	13	10	4,25
Creation of transversal working groups on AI in critical systems to discuss, share and learn from other sectors	1	5	8	8	16	5	4,12

Fig. 5.11. Milestones ranking: railways focus group

Milestone	Number of scores from «not relevant» to «very relevant»						Average Score
Specific and in-depth study on the development and applicability of explainable and trustworthy AI approaches	0	2	2	1	3	8	4,81
Creation of technical infrastructures at European level for sharing data and knowledge (datasets, results, models, etc.)	0	0	2	3	6	4	4,80
Establishment of European working groups in railway organizations specifically addressing the cooperative design of AI approaches	0	0	2	5	3	5	4,73
Creation of transversal working groups on AI in critical systems to discuss, share and learn from other sectors	0	0	1	4	8	2	4,73
Exploitation of cloud and edge computing, including IoT, at the railway network level to support data-driven approaches	0	0	5	4	3	4	4,38

Fig. 5.12. Milestones ranking: research focus group

ners. Other answers cited the standard ISO/IEC JTC 1/SC 42, which has the objective of providing standardisation in the area of Artificial Intelligence, also providing a practical guide to JTC 1, IEC, and ISO committees developing Artificial Intelligence applications.

Among the tangible approaches, prescriptive maintenance, knowledge-based scheduling and dispatch systems, anonymization algorithms, online risk calculation and risk drive control represent the cited applications; Federating learning, causal models and Bayesian Network were the techniques employed.

5.4. Findings about the State-of-Practice

5.4.1. Interesting rail applications for AI usage

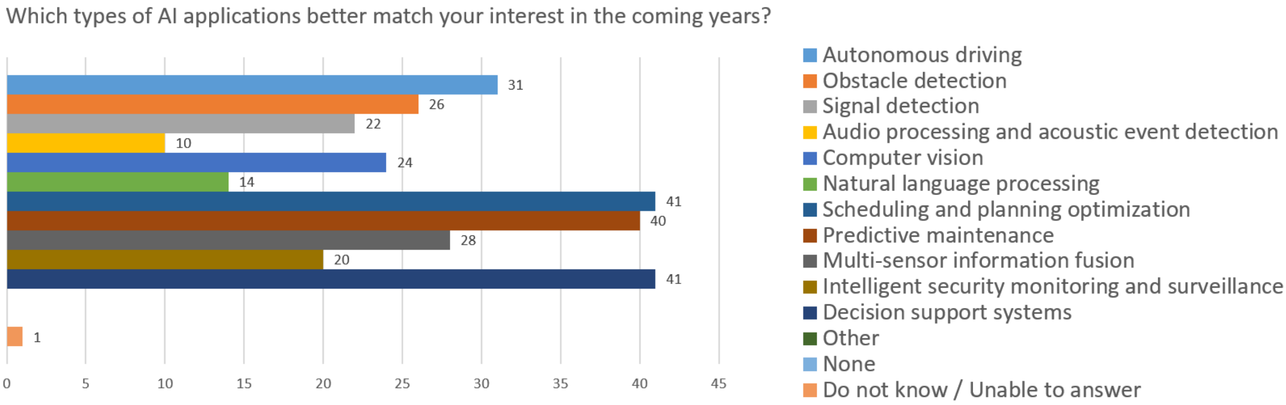

Fig. 5.13. AI application ranking

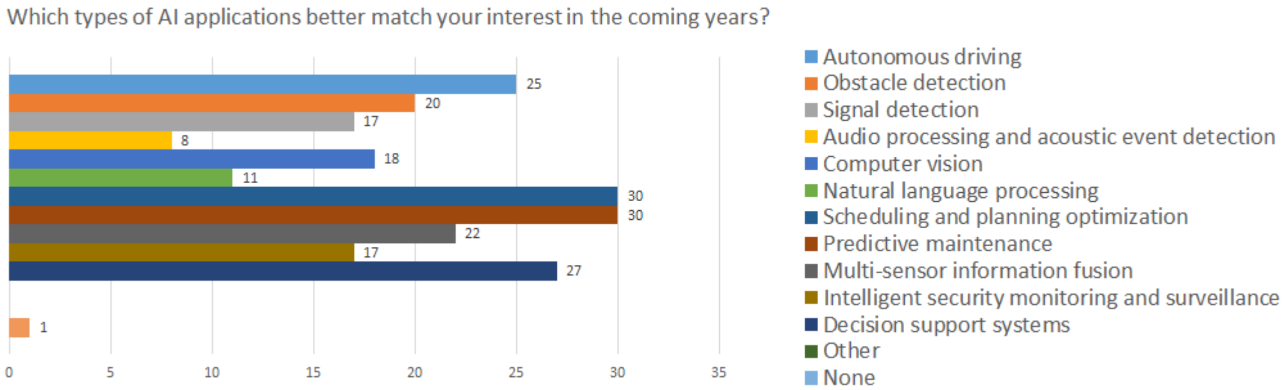

Fig. 5.14. AI application ranking: railways focus group

The histogram in Fig. 5.13 reports the interest for AI usage in rail applications. Results confirm a high interest in scheduling and planning optimisation, predictive maintenance and decision support systems, with more than 40 preferences of interviewed people. Autonomous driving also raises a strong interest, followed by multi-sensor information fusion, obstacle detection, computer vision, signal detection and intelligent security monitoring and surveillance. In the last places are positioned natural language processing and audio processing and acoustic event detection.

This trend is confirmed with the attention on the railway focus group (Fig. 5.14). By focusing on the research focus group (Fig. 5.15) the trend is slightly different. In fact, the highest interest of interviewed researchers is on decision support systems, as well as there is no difference among autonomous driving, obstacle detection, computer vision and multi-sensor information fusion. Intelligent security monitoring and surveillance, at last, collect a reduced interest.

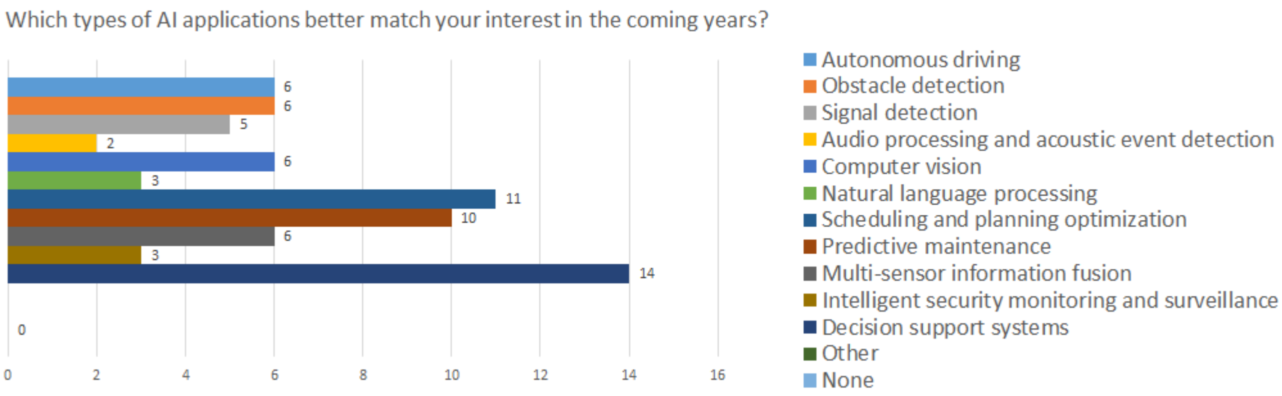

Fig. 5.15. AI application ranking: research focus group

5.4.2. AI techniques, models and supporting tools used in practice

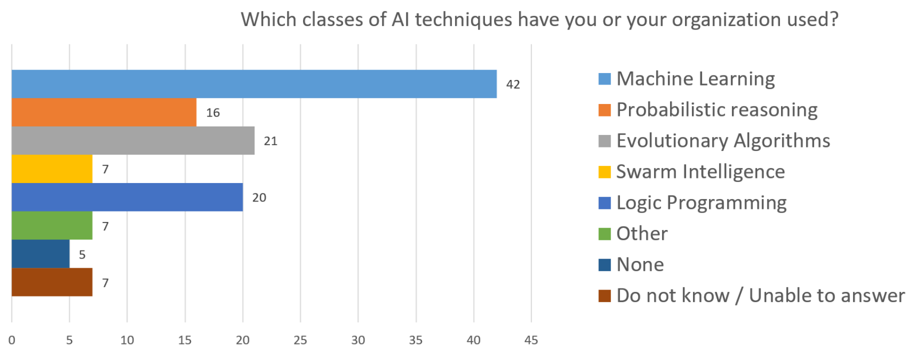

Fig. 5.16. AI techniques ranking

With respect to AI techniques currently used in practice, Fig. 5.16 depicts the related histogram. As expected, Machine Learning is the most diffused technique with more than 40 preferences. Evolutionary algorithms and Logic Programming represent also quite widespread techniques with more than 20 preferences, followed by Probabilistic Learning with 16 preferences. Swarm Intelligence received 7 preferences.

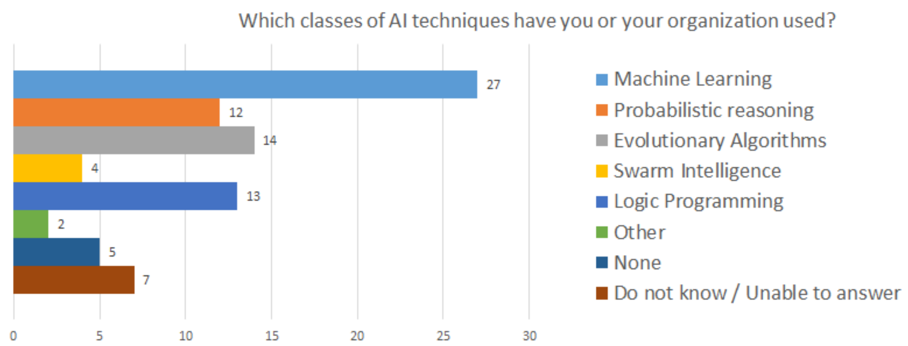

Fig. 5.17. AI techniques ranking: railway focus group

By restricting the focus both on the railway (Fig. 5.17) and on the research focus groups (Fig. 5.18), the trend is almost confirmed.

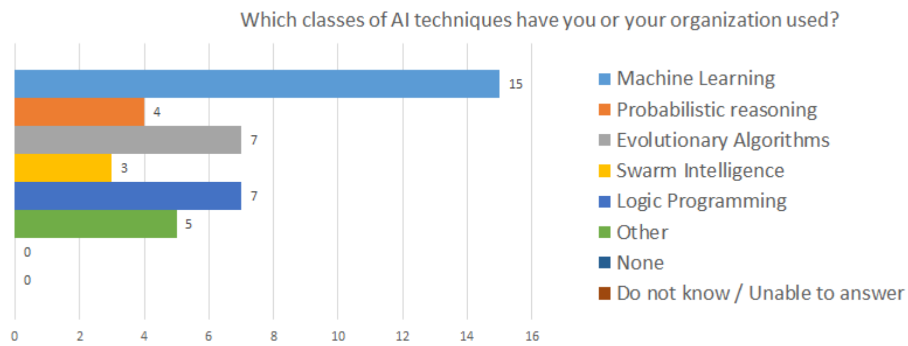

Fig. 5.18. AI techniques ranking: research focus group

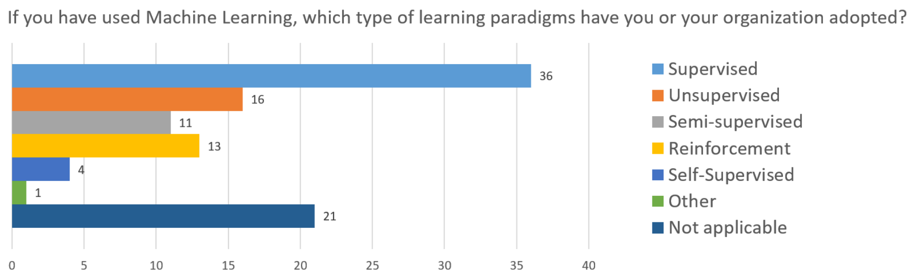

Fig. 5.19. Learning Paradigms ranking

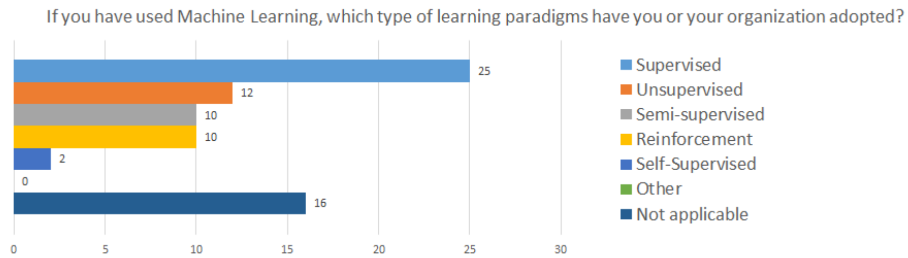

Fig. 5.20. Learning Paradigms ranking: railway focus group

With respect to the learning paradigms in Machine Learning, the histogram depicted in Fig. 5.19 highlights that the supervised paradigm is surely the most adopted, while the self-supervised is the least one. It is worth noting that for 21 responders the question is not applicable since they do not personally use Machine Learning.

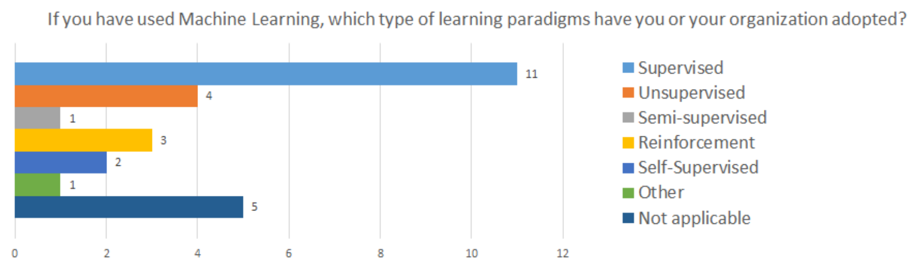

Fig. 5.21. Learning Paradigms ranking: research focus group

Also in this case, there is no substantial difference between the railway and the research focus groups, with the exception of the semi-supervised paradigm, which is not widely diffused among the interviewed researchers.

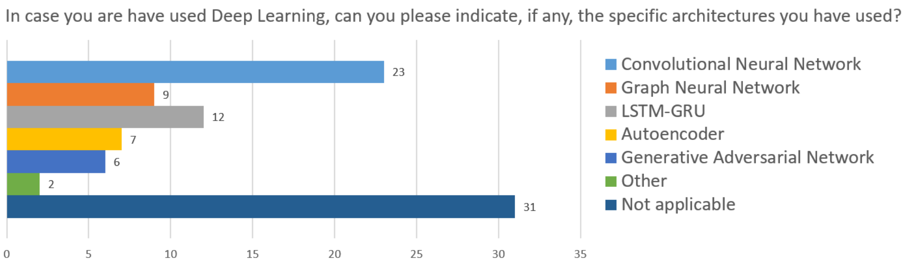

Fig. 5.22. Deep Learning specific architecture ranking

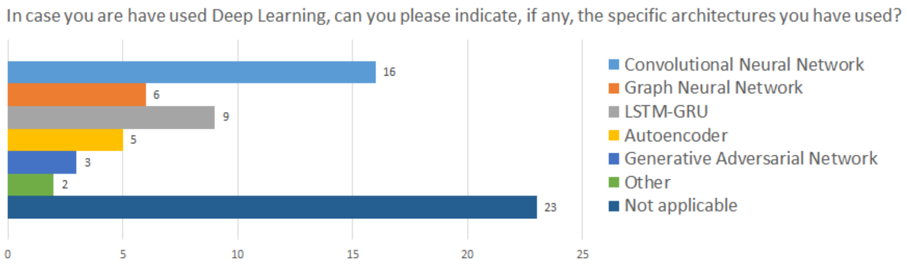

Fig. 5.23. Deep Learning specific architecture ranking: railway focus group

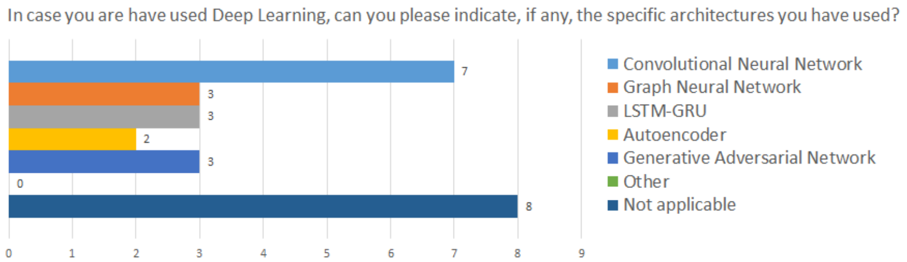

Fig. 5.24. Deep Learning specific architecture ranking: research focus group

Focusing on Deep Learning, Fig. 5.22 shows that the general preference is the usage of the Convolutional Neural Network specific architecture. The restriction to railway and research focus groups confirm this choice. Moreover, Generative Adversarial Network seems to be more used by researchers, to the detriment of LSTM-GRU. Also in this case, it is worth noting that 31 respondents considered the question not applicable since they do not personally use Deep Learning.

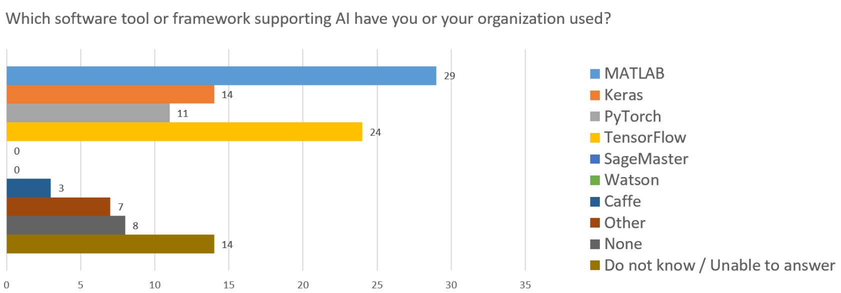

Fig. 5.25. Tools/Framework ranking

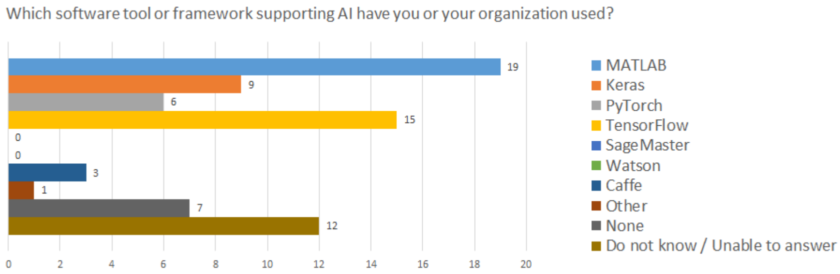

Fig. 5.26. Tools/Framework ranking: railway focus group

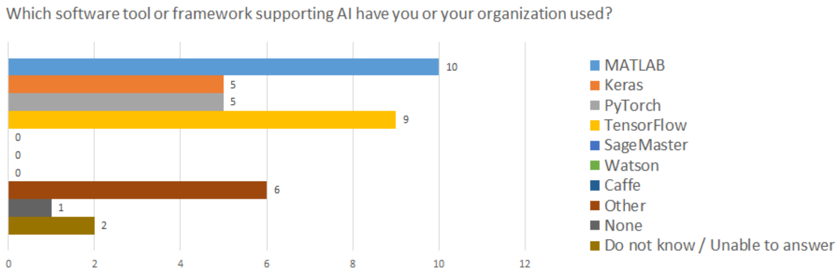

Fig. 5.27. Tools/Framework ranking: research focus group

The histogram in Fig. 5.25 demonstrates that MATLAB and TensorFlow represent the most used frameworks supporting AI applications. The result is similar restricting to the two considered focus groups (Fig. 5.26 and Fig. 5.27). With respect to the interviewed sample, Caffe is used only in the industrial setting and not by researchers.

5.4.3. Data acquisition and management

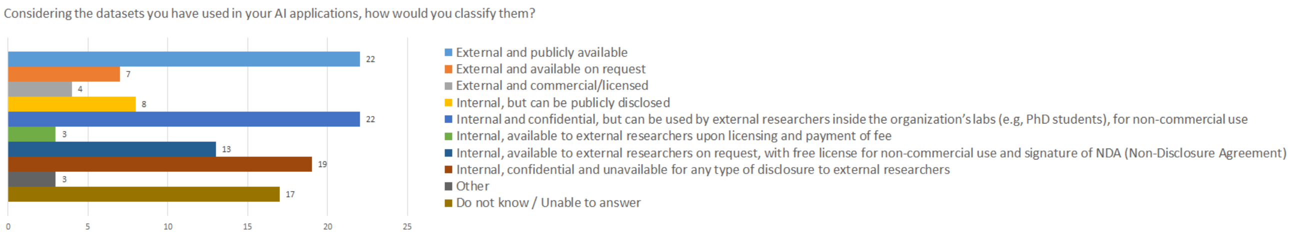

Fig. 5.28. Dataset ranking

With respect to the data acquisition step, the histogram in Fig. 5.28 highlights that both external and internal datasets are used. In fact, the most selected options are external and publicly available and internal and confidential but available on request. Moreover, also a relevant number of internal and unavailable datasets are present.

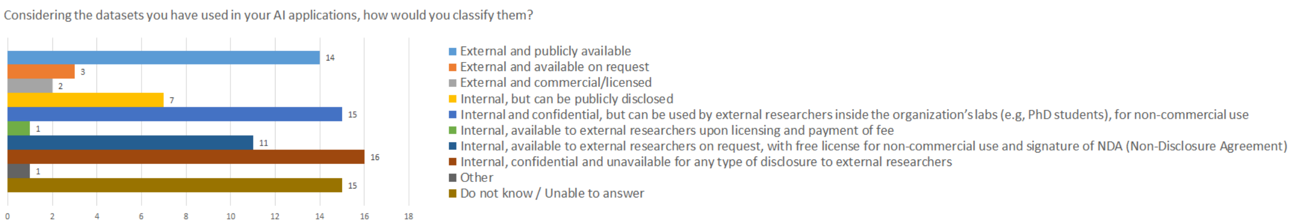

Fig. 5.29. Dataset ranking: railway focus group

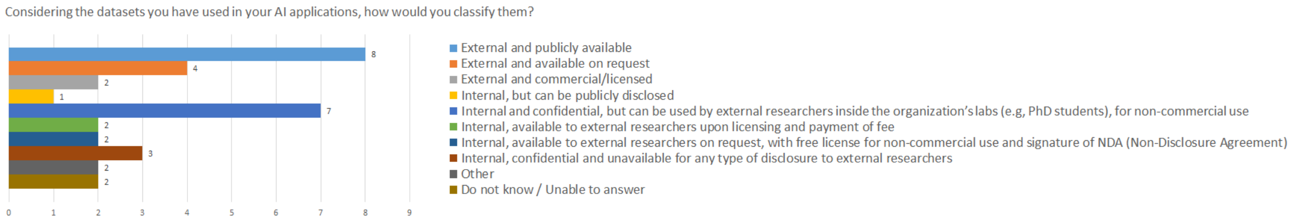

Fig. 5.30. Dataset ranking: research focus group

By restricting the analysis to railway and research focus groups, it appears a situation in which railway organisations are producing datasets, but not all of them can be shared with external researchers (Fig. 5.29). On the contrary, researchers are relying on both external and publicly available datasets, as well as on internal and confidential ones, available on request (Fig. 5.30). Even if Non-Disclosure Agreement seems to be a valid means for railway organisations, researchers are not widely using this way to obtain datasets. Finally, from the answers of the two focus groups, we can conclude that some research organisations also produce their own ("internal") datasets that are not made available for external use.

The most employed approach for data labelling is the manual one (Fig. 5.31). Comparing the ratio of the related answers from the two focus groups, automatic labelling seems to be more used in research than in industrial settings (see Fig. 5.33 and 5.32).

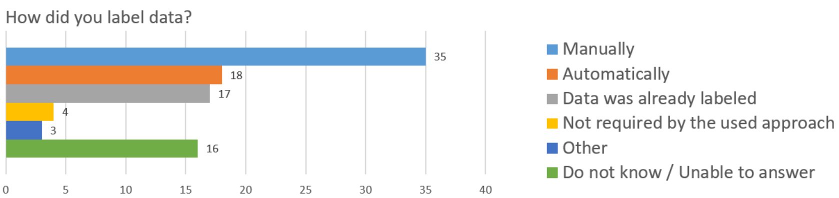

Fig. 5.31. Data labelling ranking

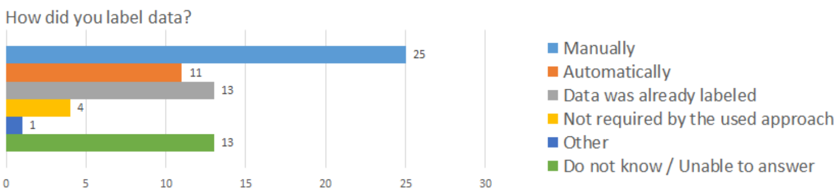

Fig. 5.32. Data labelling ranking: railway focus group

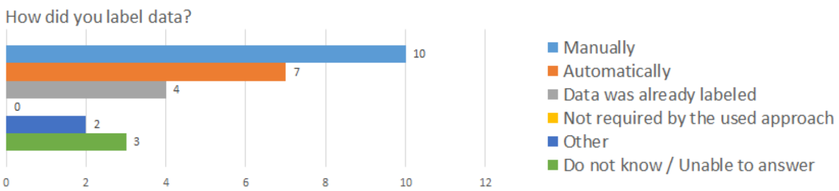

Fig. 5.33. Data labelling ranking: research focus group

At last, with respect to the effort to generate and maintain the dataset, the histograms in Fig. 5.34 confirm that the perceived effort is higher in generating than maintaining the dataset.

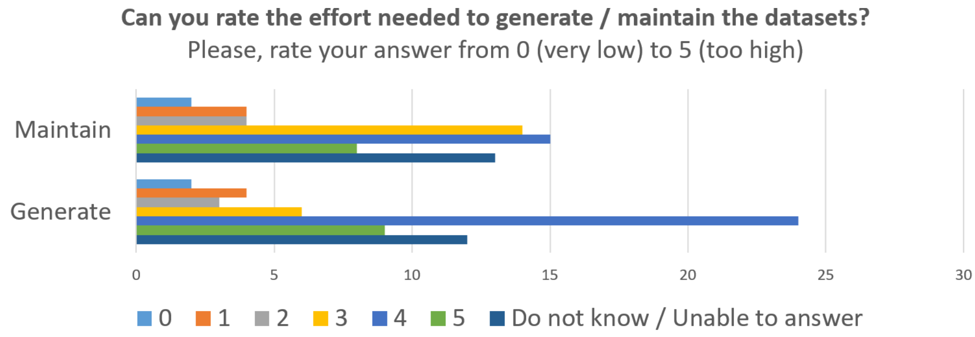

Fig. 5.34. Dataset management effort ranking

By focusing on the two considered groups, it is possible to verify that research institutes perceive the effort (in both generating and maintaining datasets) as higher than railway organisations.

Railway organizations

Effort	«very low» to «too high»						Average Score
Generate	2	3	3	5	16	6	3,37
Maintain	2	4	3	11	10	5	3,09

Research institutes

Effort	«very low» to «too high»						Average Score
Generate	0	1	0	1	8	3	4,92
Maintain	0	0	1	3	5	3	4,83

Fig. 5.35. Dataset management effort ranking: focus groups

In conclusion, the AI maturity level is considered medium. In fact, the histogram in Fig. 5.36 has a mean value related to a technical maturity between 2 and 3. Moreover, even if 5 interviewed people still consider AI as completely immature, no one considers AI techniques as fully mature and immediately applicable.

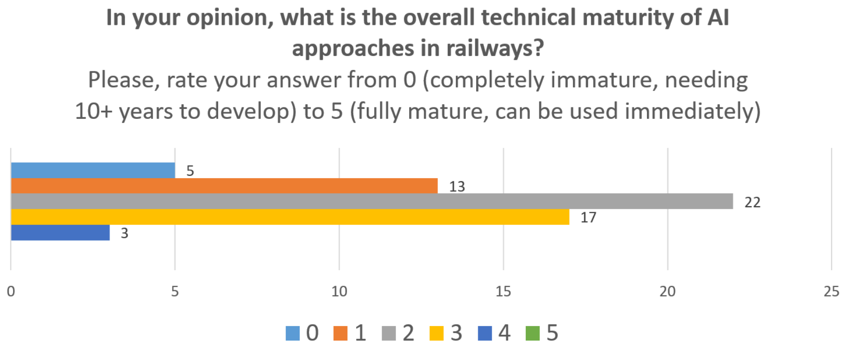

Fig. 5.36. AI maturity ranking

Restricting the attention to the two considered focus groups, it seems that railway organisations perceive AI as more mature than research institutes, which are slightly more cautious in considering AI techniques applicable in the short term. However, among railway organisations, there is a limited slice of people who consider AI techniques completely immature.

Maturity	Number of scores from «completely immature» to «fully mature»						Average Score
	5	7	14	15	3	0	3,09
Railway organizations							

Maturity	Number of scores from «completely immature» to «fully mature»						Average Score
	0	6	8	2	0	0	2,75
Research institutes							

Fig. 5.37. AI maturity ranking: focus groups

5.5. Concluding remarks from the survey

With respect to the research questions introduced in Section 5.1, we report here some concluding remarks.

AI is largely adopted in current rail applications, with a specific focus on traffic and maintenance optimisation as well as in decision-support systems. Moreover, railway organisations (more than research institutes) are experiencing AI in autonomous driving and obstacle detection systems.

Among the set of techniques, as expected, Machine Learning is widely used both in railway organisations and in research, with the adoption of the supervised learning paradigm. Among the tools and frameworks supporting AI, MATLAB and TensorFlow are those widely used both in railway organisations and in research institutes.

About the data management, both the groups agree on considering the generation as requiring a greater effort than maintaining the datasets. On the other side, the data labelling activity is conducted mainly manually. Automatic labelling is also quite employed in research institutes.

As stated before, safety, dependability and trustworthiness concerns are perceived as the most blocking factors, even if all the proposed obstacles are considered as relevant for the effective adoption of AI in railways.

Among the practical issues, the lack of appropriate datasets for training the models is perceived as the main obstacle, followed by the insufficient level of digitalisation in railways.

All the suggested key milestones are considered relevant, particularly the creation of technical infrastructures at the European level for sharing data and knowledge is requested by all the respondents.

At last, the perceived technical maturity of AI approaches in railways is reassuring: both railway organisations and research institutes consider AI not fully mature, but not so far from reaching a sufficient maturity level.

6. Artificial Intelligence meets Railways

Chapters 4 and 5 provide an overview of relevant problems in the railway domains that can (or could) be addressed (even partially) by means of AI. Fig. 6.1 briefly reports the problems collected from the analysis of the current state-of-the-art, while Fig. 6.2 shows additional problems that arose mainly from the feedback provided by the RAILS advisory board and from the received surveys.

Before going ahead and analysing the railway relevant problems for AI, let us spend few words about Revenue Management. Fig. 6.1 shows that almost no research work investigated the application of AI techniques in this railway domain. From one hand, this is not that surprising because we have found that railway Revenue Management is not very addressed in the scientific literature in general, contrary to what happens instead for airlines or for hotel industry. This has been already pointed out in past survey works (e.g., see [64]) and the situation does not appear to have changed significantly since then. Limiting the discussion to the comparison with air transport, our opinion is that the research in that field has been driven by the extreme necessity of the airline companies to remain competitive on the market and maximise their revenues. Therefore, airline companies not only need to predict how many people will travel from point A to point B in given time slots and time periods, but they also have to monetarily enhance every single seat, by introducing personalised services and customised fares. AI-based pricing and promotion can greatly help these companies to meet their goals.

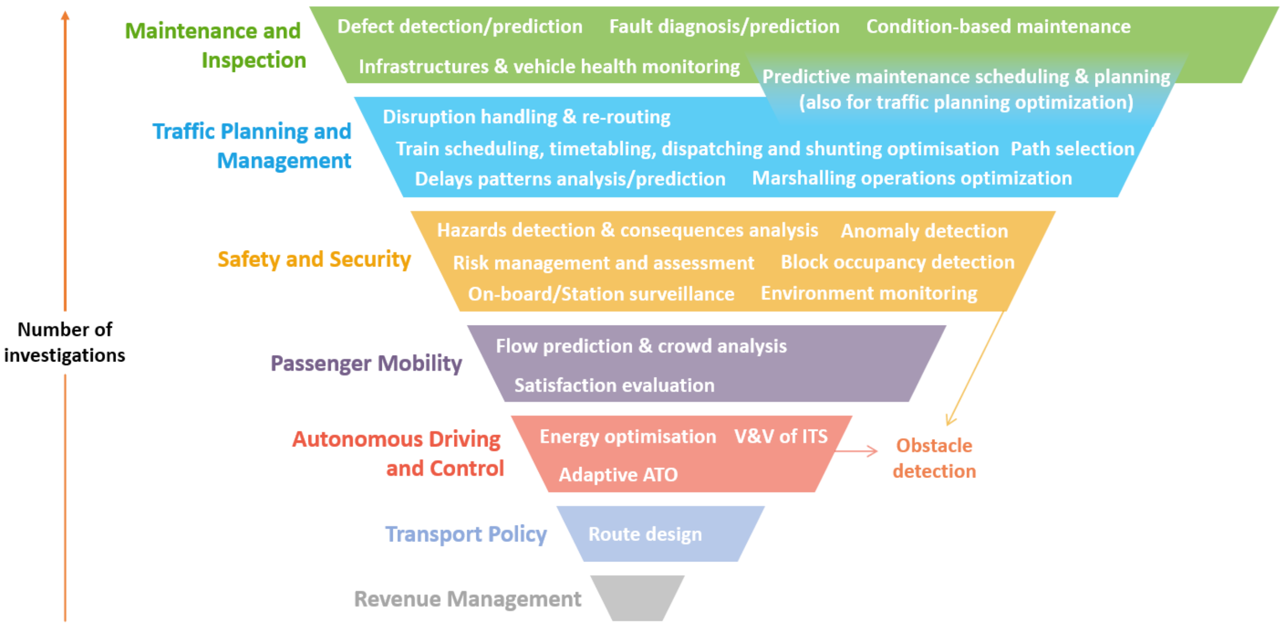

Fig. 6.1. Set of problems collected from the analysis of the current state-of-the-art sorted by the number of found papers investigating them.

As described in RAILS Deliverable D1.1, the term AI is used to identify a broad domain encompassing research fields, techniques and applications [3]. In recent years, AI has been applying to a wide set of problems and domains, including applications to industry (above all

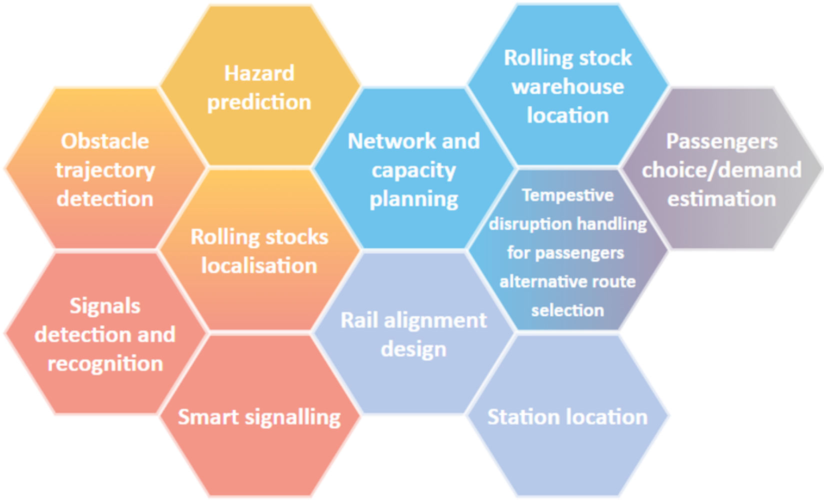

Fig. 6.2. Set of problems/needs as arose from the the feedback provided by the RAILS advisory board and from the received surveys

agri-food [65] and manufacturing [66]) and transport systems [67]. This has been possible since even very different domains usually have to deal with problems related to the same set of families. Indeed, problems to be addressed can be clustered based on the type of data, the required computational efficiency, the desired goal (e.g. detection, classification, etc.) and so on.

Thus, once railway relevant problems have been identified, it is possible to "navigate" the clusters previously defined to find the set of approaches that are worth to be explored. Despite this is expected to produce maps with elements matching more than one possibility, it can still be very useful by allowing for simpler identification of AI techniques suitable for the problem under analysis. For example, considering the problem of detecting the operational status of a level crossing barrier using videos acquired by security cameras, the aforementioned procedure could suggest the use of Convolutional Neural Networks (CNN) to process the video/images and a Long-Short Term Memory (LSTM) architecture for the audio alarm detection.

This chapter aims at providing support for this decision-making process, by i) clustering the problems declared relevant for the railway domain and then ii) by proposing a set of guidelines to help in determining a suitable set of AI techniques to be explored to solve the problem under analysis. It is important to note that this chapter is not intended to be exhaustive, nor pretends to be the definitive manual for AI applications. Instead, *it has been strongly tailored and built based on the problems marked as relevant for the railway domains*. This must always be taken into account while reading it.

6.1. Problems relevant to railways

In chapter 4 we recalled the problems deemed relevant for the railway domains, as emerged from the analysed sources, while in chapter 5 we analysed the problems marked as important as emerged from the surveys. To define a set of guidelines for the choice of the AI approach to be used (section 6.2), we will subdivide the relevant *Railway problems* according to the railway sub-domains recalled in section 4.1, before matching them to some crucial aspects as emerged from the analysis of sources. It is also important to highlight that we also include some problems not yet faced in any scientific papers, but resulted to be relevant from the survey analysis. However, in this case, we were able to consider only those problems for which enough information, such as desired goal and data used (defined below), was delivered. Moreover, problems are gathered based on their primary application although, in some cases, they could be referred to two or more sub-domains (e.g. obstacle detection on tracks involves both safety and autonomous driving aspects).

Once the railway relevant problems have been clustered, the next step toward the design of a set of AI usage guidelines is their analysis under some different aspects. To this aim, the following three tables match each of the so identified railway problems with the sub-element of the following three aspects:

- the **Desired Goal**, namely the pursued aim (e.g. classification of samples, results reporting, optimisation of limited resources, etc.);
- the **Type of Data** used in that problem (e.g. images, text, raw signals, etc.);
- the required **Responsiveness** level, intended as the time constraints the selected approach have to stick with while solving the problem. This level ranges from *Low* (i.e. there are no time constraints and the task can be performed off-line) to *High* (i.e. the task must be managed in an on-line fashion by processing data as soon as they arrive).

It is worth noting that while the following tables encompass all the problems shown in Fig. 6.1 and Fig. 6.2, a few problems have been grouped into a single row in two main cases: i) different (but strongly related) problems having the same goal, considering the same type of data and subject to the same time constraints; ii) problems were separately highlighted during the SOTA/project analysis and the surveys/hints from the advisory board, but that can be grouped under the same topic (e.g. “obstacle detection” from the SOTA and “obstacle trajectory detection” form the survey have been grouped under “obstacle detection & avoidance”). An **X** mark in the table indicates that at least one match has been found in the cited sources between the corresponding railway problem (on rows) and aspect (on columns). For example, referring to table 6.1, the **X** mark in the cell connecting fault diagnosis and classification indicates that we found at least one paper or survey pursuing (or needing to pursue in the latter case) that goal for that problem. This implies that the absence of a mark in a cell only means that none of the analysed sources addressed that particular combination (i.e. that combination may exist in other sources or domains, as well as it may be faced in the future). Moreover, in table 6.3, the considered responsiveness level is based on the analysed sources only, and not on how the responsiveness level of that problem is commonly perceived. Finally, it is worth noting that problems coming from the surveys and/or suggested by the advisory board may not be explicitly associated with the desired goal, used data or required responsiveness level. In these cases (marked with a *), the corresponding aspects have been speculated based on our experience.

The analysis of the reported tables allows to catch some interesting trends about the means and approaches adopted in the use of AI in the railway domain. Table 6.1 highlights that *classification* is the most common task, followed by *regression* and *clustering*. In particular, going at a sub-domain level, the table shows that “maintenance and inspection” problems

		Desired Goal				
Railway sub-domains	**Railway problems**	**Classification**	**Regression**	**Clustering**	**Reporting**	**Optimization**
Maintenance and Inspection	Fault diagnosis/prediction	x		x		
	Infrastructures & vehicles health monitoring	x	x	x		
	Defect detection/prediction	x				
	Preventive maintenance scheduling and planning	x	x			x
Safety and Security	Hazards prediction, detection & consequences analysis	x	x	x	x	
	On-board/Station Surveillance	x	x	x		
	Anomaly detection	x		x		
	Block occupancy detection	x				
	Environment monitoring	x	x			
	Risk management & assessment	x	x	x	x	
Autonomous Driving & Control	Energy optimisation		x			x
	Obstacle Detection & Avoidance	x				
	Signal detection and recognition	x				
	Smart signalling *	x	x	x	x	x
	Verification and Validation of ITS				x	
Traffic Planning & Management	Delay patterns analysis/prediction	x		x		
	Routing, Scheduling and Shunting optimisation					x
	Disruption handling & re-routing		x			x
	Marshalling operations optimisation	x				x
	Network and capacity planning *		x			x
	Stations & warehouses location *					x
Passenger Mobility	Flow prediction & crowd analysis	x	x	x		
	Passenger choice & demand estimation *	x		x		
	Alternative routes suggestion *					x
	Satisfaction evaluation					x

Table 6.1: Railway relevant problems matched with the desired goal.

are more classification-oriented, while “safety and security” ones are more uniform between the three main tasks. The former mostly focus on the detection of elements not properly working, but also includes regression-oriented applications (such as the estimation of the remaining useful life of a system); similarly, the latter also includes the regressive prediction of possible accidents and clustering approaches (to identify, for instance, active deformation areas, as in MOMIT [31]). As opposed to these two sub-domains, the “traffic planning and management” main goal is to optimise a given service, such as train punctuality, capacity, marshalling operations, and so on. The latter example deserve a deeper analysis, as classification-oriented computer vision applications (e.g. through Intelligent Video Gates [46]) proved to be useful to identify incoming vehicles, speeding up yards operations. Moving to “autonomous driving and control” sub-domain, beside the outlier *Verification and Validation* problem involving reporting, it is evident the predominance of classification and regressive tasks. Indeed, computer vision has been (or is planned to be) adopted to deal with obstacle detection/avoidance and signal recognition tasks in a classification-oriented fashion, as emerged from the advisory board and from some S2R projects, such as SMART I [35] and II [36], GoSAFE RAIL [32]. Nonetheless, it is also worth to note that smart signalling domain is quite broad, with applications oriented to regression, as well as to clustering, reporting and optimisation. Focusing on this latter aspect, *energy optimisation* is an hot topic aiming, among the other purposes, to optimise the vehicles’ speed profile (e.g. OPEUS [47], IN2DREAMS [43], and other research papers [68, 69]). Finally, “passenger mobility” does not really show a trend, with applications ranging from passengers flow regressive predic-

		Type of Data				
Railway sub-domains	**Railway problems**	**Tabular**	**Image/Video**	**Audio**	**Signal**	**Text**
Maintenance and Inspection	Fault diagnosis/prediction	x	x	x	x	
	Infrastructures & vehicles health monitoring		x		x	
	Defect detection/prediction	x	x	x	x	x
	Preventive maintenance scheduling and planning	x			x	
Safety and Security	Hazards prediction, detection & consequences analysis	x	x	x	x	x
	On-board/Station Surveillance		x	x		
	Anomaly detection	x	x			
	Block occupancy detection	x			x	
	Environment monitoring	x	x			
	Risk management & assessment	x				
Autonomous Driving & Control	Energy optimisation	x				
	Obstacle Detection & Avoidance		x			
	Signal detection and recognition		x			
	Smart signalling *	x	x	x	x	
	Verification and Validation of ITS					
Traffic Planning & Management	Delay patterns analysis/prediction	x				
	Routing, Scheduling and Shunting optimisation	x				
	Disruption handling & re-routing	x				
	Marshalling operations optimisation	x	x			
	Network and capacity planning *	x				
	Stations & warehouses location *	x				
Passenger Mobility	Flow prediction & crowd analysis	x	x		x	
	Passenger choice & demand estimation *	x				
	Alternative routes suggestion *	x				
	Satisfaction evaluation	x				

Table 6.2: Railway relevant problems matched with the used type of data.

tion (e.g. [70, 71]), to passengers clustering (e.g. My-TRAC [48]) and optimal alternative passengers route suggestion (as from the survey).

Focusing on Table 6.2, it is clear that *tabular* datasets (i.e. consisting of structured data, organised in features) are the most exploited within railway sub-domains. Nonetheless, there are some goals related to specific problems that benefit, or are completely based on, other kinds of data. Glaring examples are computer vision-based applications, requiring *image/video* data, as well as surveillance applications, which may also leverage *audio* data. Similarly, *signal* data may represent an added value in some maintenance or safety problems, such as track circuit or switches fault prediction/diagnosis or rail track occupancy detection. Lastly, *text* data can be useful to face very vertical problems, like those involving fault log analysis for maintenance purposes or the classification of the reports content for accidents prediction/characterisation.

Last, Table 6.3 report a conceptual classification of the identified problems based on the required level of responsiveness. Traditionally, "maintenance and inspection" activities are performed on a scheduled base (e.g. during the night), thus not requiring real-time performance (i.e. an *high* responsiveness level). On a similar line, "traffic planning and management" as well as "passenger mobility" applications do not usually require *high* respon-

		Responsiveness		
Railway sub-domains	**Railway problems**	**Low**	**Medium**	**High**
Maintenance and Inspection	Fault diagnosis/prediction		x	
	Infrastructures & vehicles health monitoring	x		
	Defect detection/prediction	x		
	Preventive maintenance scheduling and planning	x		
Safety and Security	Hazards prediction, detection & consequences analysis	x	x	x
	On-board/Station Surveillance			x
	Anomaly detection			x
	Block occupancy detection			x
	Environment monitoring	x		x
	Risk management & assessment		x	
Autonomous Driving & Control	Energy optimisation	x		
	Obstacle Detection & Avoidance			x
	Signal detection and recognition			x
	Smart signalling *			x
	Verification and Validation of ITS	x		
Traffic Planning & Management	Delay patterns analysis/prediction	x		
	Routing, Scheduling and Shunting optimisation	x		
	Disruption handling & re-routing			x
	Marshalling operations optimisation			x
	Network and capacity planning *	x		
	Stations & warehouses location *	x		
Passenger Mobility	Flow prediction & crowd analysis	x		x
	Passenger choice & demand estimation *	x		
	Alternative routes suggestion *	x		
	Satisfaction evaluation	x		

Table 6.3: Railway relevant problems matched with the task responsiveness.

siveness levels, as are commonly tasks performed long before their need. Two important exceptions are represented by “disruption handling & re-routing” and “marshalling operations”, requiring solutions that must be provided as soon as possible to avoid, or minimise, severe delays. Finally, “safety and security” and “autonomous driving and control” deserve a different analysis, as they gather sensitive problems which are commonly solved by human operators, supported by IT systems. Indeed, despite applications like *obstacle avoidance*, *signal recognition*, *hazards detection*, *surveillance*, *block occupancy detection* are becoming more and more *autonomous*, the risk associated with them is so high that (almost) always require to have the final leave from a human. Thus, given the need to provide a suited and effective support, these task are commonly required to be highly responsive, as they must be able to adapt to dynamic and fast changes in the surrounding environment.

6.2. Basic AI Usage Guidelines

Choosing the most suitable way of using AI to analyse data requires experience and expertise in both the railway and AI domains. This task is hardened by the fast-developing of researches in AI that makes it really difficult to keep up with recent solutions and proposals, even for AI experts. Thus, in this section, we report a set of guidelines intended as “cheatsheets” to be used to support non-AI experts in this decision-making process. To make them more user-friendly and fast to be queried, we release them in the form of flowcharts, each focusing on a particular aspect of the problem under analysis. In these charts, rhombus elements represent (mostly binary) choices, while rounded boxes represent the suggested approach. According to the question placed within a rhombus element, it is possible to navigate the chart moving on the line matching the desired answer until a rounded box is reached. In the case the answers to a given question are both suited for the considered problem, the flow-chart navigation can be repeated more than one time, possibly obtaining different suggestions.

As these charts are based on the tables defined in the previous section, their exploration guides the user toward very specific questions intended to highlight some crucial aspects (e.g. the required interpretability level, the inference speed, the used type of data, etc.). Their combined use should help to disentangle the problem into its underlying aspects, providing suggestions for the approaches to be used. Despite we tried to cover all the relevant aspects that emerged from our previous activities (summarised in Chapter 4), this section must be considered just as an extremely simplified view about the use of AI for data analysis proposes. Despite their intuitive structures, the realised charts may still appear puzzling because of the compressed question. Therefore, we following describe the reasoning behind some of the main considered branching points:

- the flowchart in Fig. 6.3 guides the reader towards the choice of a suitable Machine Learning approach based on the desired goal (classification, regression, clustering, reporting and optimisation). The branching questions are quite self-explanatory and regard: the level of interpretability of the models, i.e. whether, and to what extent, the decision making process adopted by the model should be intuitive for a human reader; the desired training time, i.e. whether there are any constraints on the duration of the training or not; data variability and noise; the number of clusters and their overlapping; the type of the variables in an optimisation problem, whether discrete or continuous; and so on. Some additional notes may be required for the classification and for the regression parts. In the former case, the sentence “You can potentially use any ML classification technique” is intentionally intended to be very generic, as the final choice can be made by also analysing the other diagrams (e.g. the use of CNN if the considered data allows for it). In the latter case, we focus only on the data behaviour (i.e. how it varies) and not on its sources (e.g. time-varying process) as the reported branches are general enough to cope with the problems that arose from the sources.

- the flowchart in Fig. 6.4 helps to choose a suitable algorithm based on the data type. Here, it is important to properly define the meaning of the branching questions related to the feature extraction. First, there are cases in which it is not necessary to extract features, for example when the problem under examination does not explicitly requires interpretability; in this case, models with low interpretability (e.g. deep neural networks) can be easily adopted. Second, even if features interpretability is required, and thus it is mandatory to extract comprehensible features, it is not said that these features are known apriori: therefore, the answer to the question "Do you know what feature to extract?" might also be negative. In this case, it would be mandatory to adopt models able to extract significant (or high quality) features, i.e. a group of features that can be easily evaluated and understood by the experts of the domain in which the ML model is working. Notably, domain experts might not be also AI experts, but they are able to understand whether the ML model is considering the right set of features to perform the inference; even if a model works properly, it is not said that it is considering the "right" set of features, i.e. those that are effectively significant for a given problem.

- the flowchart in Fig. 6.5 provides some hints on how to select algorithms depending on the available hardware. As a general remark, these guidelines may help to individuate a suitable solution but, it is not said that others would not work as well.

The combination of these three high-level guidelines should help in indicating the first AI models to consider. Nonetheless, they should be supported by others trial-and-error based experiments because, as widely accepted in the AI domain, it is not possible to select in advance the best solution. As for the tables defined in the previous section, these guidelines represent a first draft and synthesis based on the knowledge acquired so far within the RAILS project and will be extended and/or modified as new information, discoveries, needs and solutions arise.

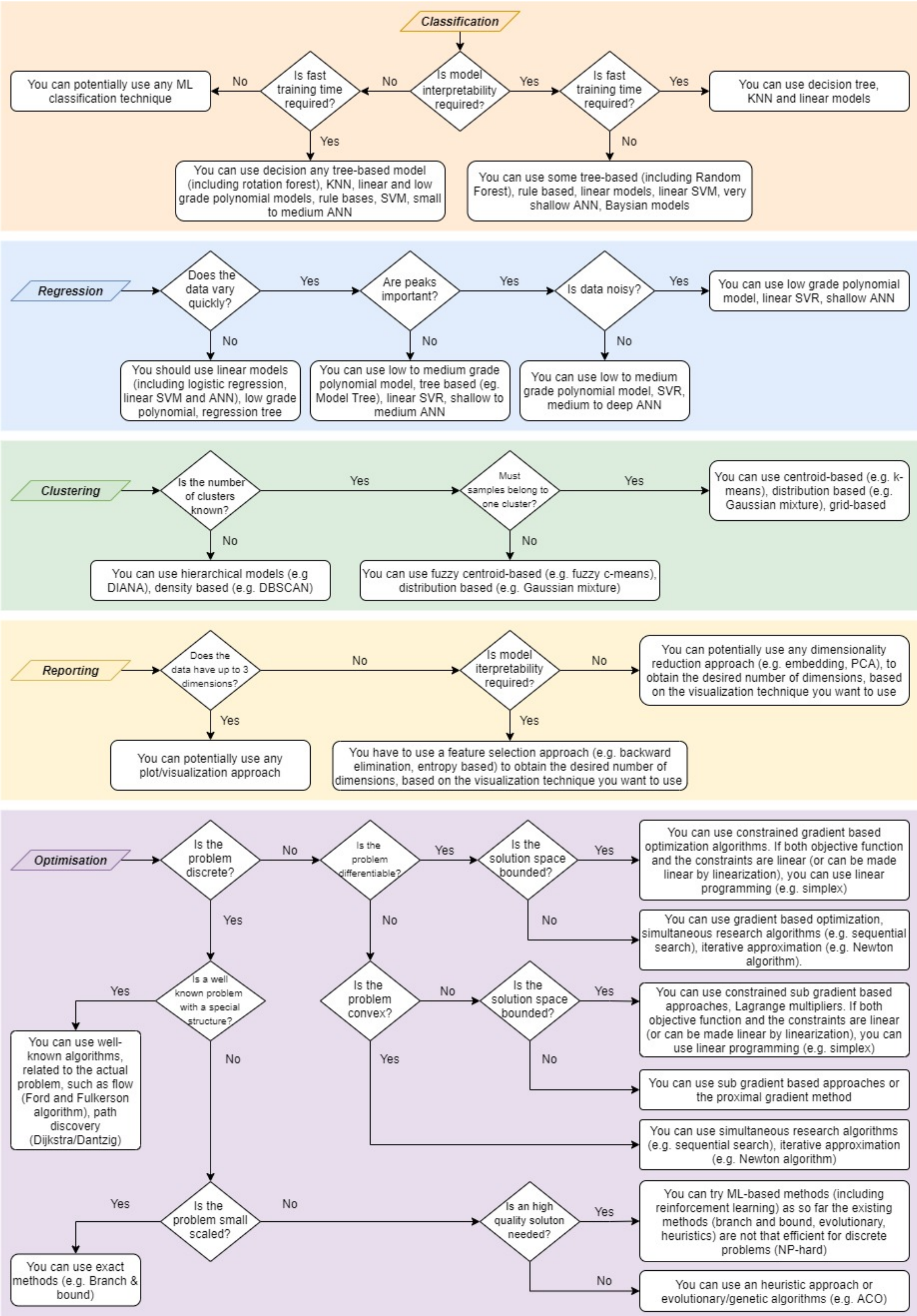

Fig. 6.3. Flow chart to support the choice of ML model based on the desired goal.

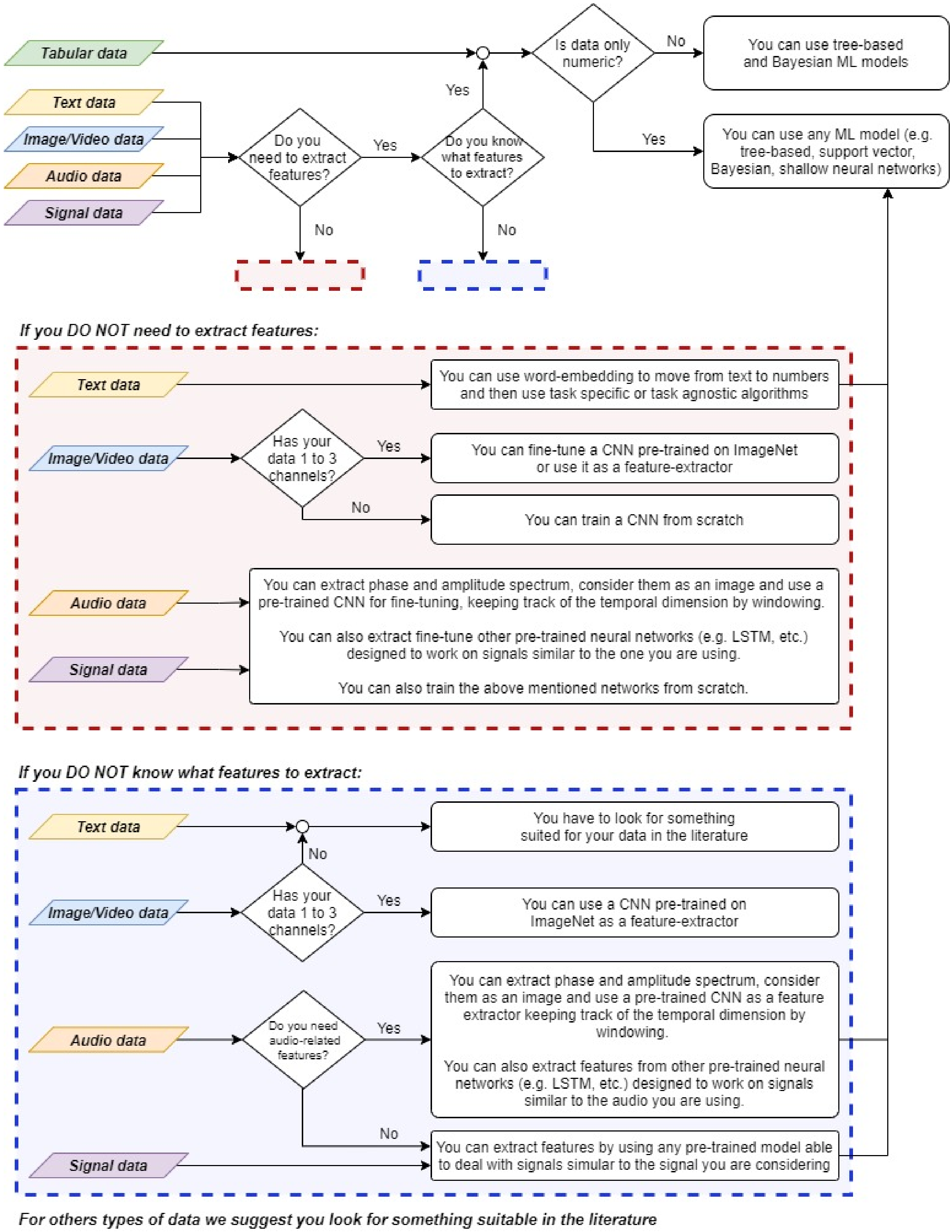

Fig. 6.4. Flow chart to support the choice of ML model based on the type of data.

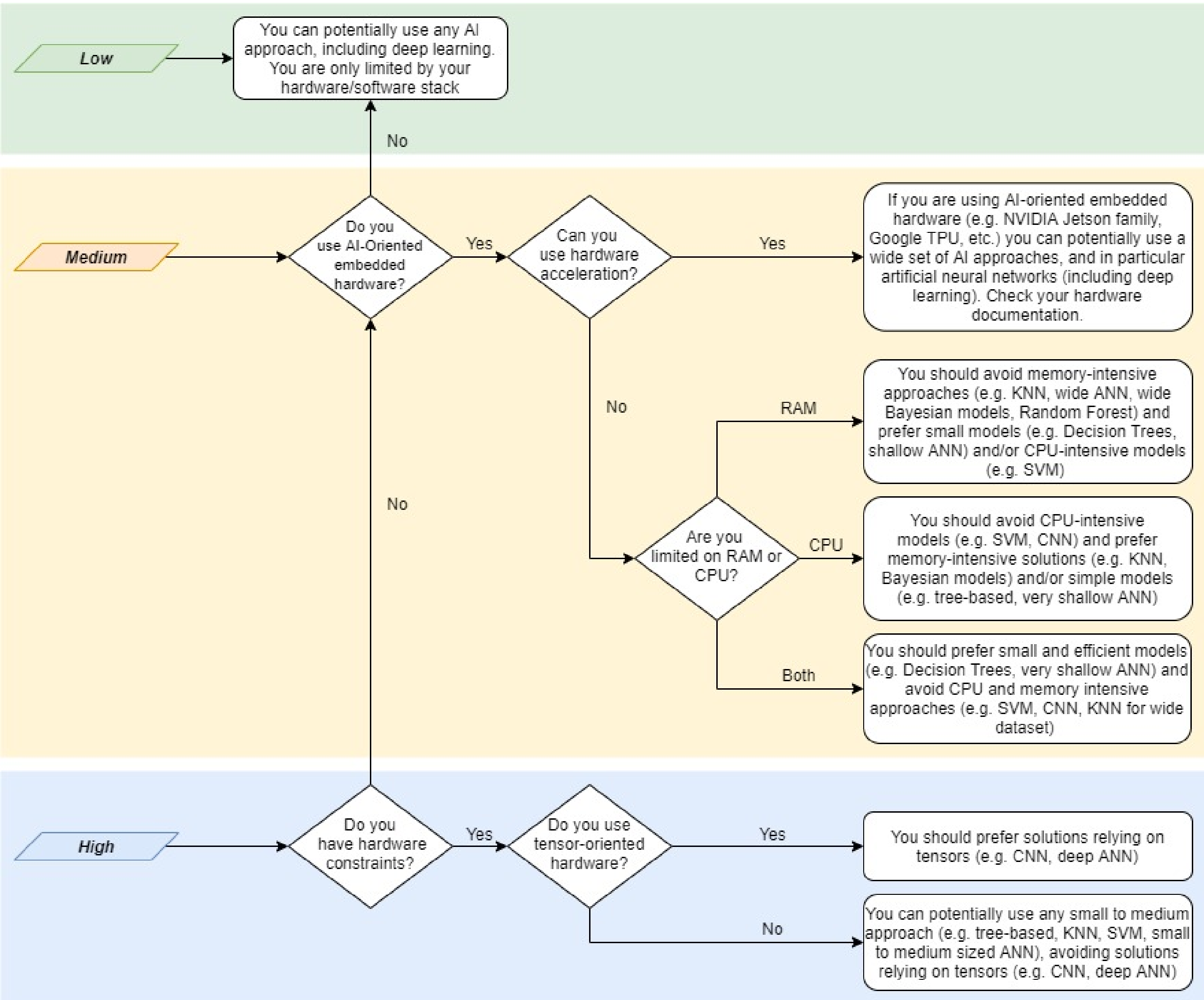

Fig. 6.5. Flow chart to support the choice of ML model based on the required responsiveness level the of problem to be addressed.

7. Application Areas

The objective of this document is to analyse the results of the activities performed in WP1 and derive the railway areas which could benefit from the application of AI techniques. Downstream of the synthesis and analysis of such results performed in the previous chapters, we have obtained a high-level view of the main railway problems that researchers and enterprises are tackling still nowadays or that they would be interested to address by AI-based solutions. Fig. 7.1 shows a comprehensive picture of such problems clustered by railway sub-domains.

Fig. 7.1. Railway Problems to investigate by AI approaches.

As mentioned in section 6.1, even though our initial perspective involved well-separated railway sub-domains, delineated by strict boundaries, some of the railway problems resulted to belong to more than one sub-domain, e.g. obstacle detection/avoidance involves both safety and security and autonomous driving aspects. These kinds of problems are characterised by a fading colour in Fig. 7.1.

Current railway problems encompass:

- Defect detection and prediction of different kinds of assets including rail tracks, infrastructures (e.g. bridges, tunnels), the pantograph and catenary system, and rolling stocks (e.g. car-bodies, bogies);
- Fault diagnosis and prediction for systems such as railway turnouts, track circuits, and wayside and on-board equipment;
- Condition-based, data-driven maintenance and health monitoring for different kinds of assets and systems as those listed above and other scenarios such as level crossings;
- Scheduling and planning of maintenance activities in a predictive manner also to optimally plan and manage the railway traffic;
- Optimised train dispatching, re-routing, scheduling, timetabling, shunting, and path selection;
- Train delays pattern analysis and prediction;
- Optimised planning for network traffic and capacity;
- Optimised marshalling yards operation scheduling;
- Disruption handling, which includes: disruption forecasting for optimised train rescheduling, and high responsiveness to provide passengers with new suitable routes;
- Passenger flow prediction and crowd analysis;
- Customers satisfaction evaluation and choice/demand estimation which may also be exploited to propose new marketing strategies;
- Risk management and assessment, accidents detection and consequence analysis, as well as hazard/accidents predictions including derailments;
- Anomaly detection both in IT systems and in the environment, monitoring the surroundings of the tracks to detect possible earth anomalies and predict land-slides;
- On-board and railway station surveillance;
- Block occupancy detection and smart/intelligent vehicles localisation on tracks, which may also be seen as an aspect of smart signalling for autonomous trains;
- Obstacle detection and trajectory estimation as well as signal detection and recognition;
- Smart Verification & Validation of Intelligent Transport Systems;
- Adaptive Automatic Train Operation (ATO), including the optimisation of driving profiles to reduce energy consumption;
- Route and rail alignment design, as well as optimised stations allocation;

The picture that emerges from the state-of-the-art carried out in WP1 shows that since 2014 there has been an exponential growth of works and research activities that address the usage of AI dealing with many of the railway problems listed above: a great effort has been made so far, in particular in the maintenance field, but there is no framework within which these research and experimental activities can be fully exploited. On the other hand, all railway stakeholders have shown great interest in adopting AI to tackle these problems, but raised different concerns about the concrete possibilities to develop AI-based solutions.

All the identified railway problems are worth investigating. In the next sections, we try to draw some general indications from this analysis focusing on: 1) issues that seem to be urgent in order to enable a fast take-up of AI in railways; 2) AI application areas that could provide great benefits due to their maturity level or their immediate impact on users and workers safety; 3) AI application areas that may open new promising directions. In this chapter, we cannot analyse all the railway problems falling in these three categories, but we'll focus on some of them, according to the results of the analysis. The next research activities of the project will focus on a sub-set of problems selected among the ones discussed in the following.

7.1. Urgent Issues

In deliverable [5], we highlighted some promising future directions taking into account the shortcomings related to both the AI and the rail sector. The whole picture has not changed so much; actually, both results from the survey and hints from the advisory board confirmed some of the points. Anyway, the lack of regulations and of standardised certification processes for AI-based system assessment and validation remains one of the most blocking issues in the railways. On the same level, data unavailability/privatisation is a cross-domain issue, that is not helping the AI evolution. However, besides these and other AI-related challenges that we have already discussed in this document and in [5], some interesting application areas came out regarding the railway scenario.
As already mentioned in the introduction of this section, we have classified the application areas according to three criteria that can be summed up in three words: urgency, impact and potential. Specifically, a topic is considered urgent if the success of the development of AI integration in the rail sector heavily depends on it, and/or if the application of those AI solutions may substantially contribute to safety (e.g., by helping to identify hazards or avoid accidents). Therefore, here we use the word ”issue” to indicate an important topic or problem for investigation. As such, the main issues that need to be urgently addressed are:

- The Data Problem;
- The need for Standards and Regulations;
- The relationship between Safety and Trustworthy AI;
- AI and Risk Assessment.

The Data Problem It is widely accepted that *data quality and availability* are among the main challenges in characterising AI models. Even though the unavailability of data has been overcome in some scenarios by introducing distributed IoT sensors and intelligent equipment, the ever-growing (real-time) volume of data they produce might not be qualitatively acceptable. Collecting brand-new and high-quality data in practical scenarios could help to improve existing models and hence to yield a better performance without any other complementary resources. Nevertheless, not all of these collected data can be perfectly compatible with a given task. As emerged from the survey, such an issue is further compacted by the variation of the data: long-term analysis should be carried out to *plan and schedule suitable data acquisition processes* and not to run into inconsistent and deceptive data over a long period of time. The data collection format may also change over time and, in addition, it is not trivial to combine data coming from different sources, especially legacy devices or different providers. In this direction, standardisation might be useful: different ontologies are actually used to describe the same scenarios, especially if hand-written reports are involved; the adaptive process to make them consistent is tricky and time-consuming. In such cases, proper data management and filtering strategies are essential to achieve acceptable results.

On the other hand, there are cases where the percentage of severe delay/abnormal events is significantly less than the normal condition samples, which has hindered the railway scholars or experts board to study sufficient knowledge from these data. There is plenty of situations where obtaining certain types of data is not easy; for example, accidents or failures of safety-critical systems, or quite impossible when it comes to *rare events*. To address this limited data issue, the most commonly used procedures include: i) **digital models or digital twins to generate synthetic data;** ii) **data augmentation methods to generate them starting from those already available (e.g. Data Augmentation Generative Adversarial Networks (DAGAN) [72])**; iii) **Transfer Learning approaches [73] to achieve good performance even on "small" datasets by reusing the knowledge acquired in other domains or tasks.**These procedures face the problem of lack of data from different perspectives: the first two approaches aim at generating new artificial data (i.e. crafted by an algorithm and not acquired by a sensor) by leveraging a digital model of the entity under analysis or by exploiting the ability of ANN to recognise patterns; the third approach uses a pre-trained model (sometimes trained on a very different task) to exploit past experience to reduce the amount of data needed to train the model.

As such approaches are quite effective when it comes to limited, it would be advisable to move towards their investigation. Lastly, other issues may be related to *confidentiality* as in some cases the privatisation of the railways has built barriers for data and knowledge sharing. **A possible solution lies in the adoption of new concepts like Federated Learning** (also known as collaborative learning) [74]: besides allowing to distribute the computational load among different systems, it could be also exploited to process data locally at each company's environment and, therefore, bypass the problem of not being allowed to divulge sensitive data and information; as an example in the railways, reference [75] investigated the combination of blockchain and federated learning for intelligent control in heavy haul railway. However, it is worth noting that such a strategy is not free from flip sides. Among all, one of the most critical is associated with the risk of a malicious user reconstructing private sensitive data, even when not directly shared with them [76].

The problem of data availability and management is so crucial that it should be answered by *structural solutions specifically tailored for the railway sector*. Such solutions should envisage i) the definition of *pilot case studies* that can be configured as challenges for the scientific and industrial communities, ii) the creation of *benchmarks* accessible to companies and researchers, iii) the development of proper *agreements* among railways stakeholders to share data, human and technological, iv) the allocation of *resources* dedicated to the development of approaches to data generation and collection, v) the creation of an *European infrastructure supporting data-driven AI projects* built on the availability of the previous mentioned elements. Different strategies could be chosen to set up such an infrastructure. A first step in this direction can exploit easy and well assessed solutions to manage and share datasets and AI models made available to the community involved in the research projects. On the basis of the matured experience cutting edge technologies such as Distributed Ledger Technologies (DLTs) could be exploited to implement more sophisticated strategies and pursue more ambitious objectives. With respect to DLTs, and in particular to Blockchain, one of the objective of the ongoing Shift2Rail project B4CM [77] is to identify and develop use cases supporting the application of Blockchain in the railway sector.

The need for Standards and Regulations As from the survey findings on the challenges (section 5.3), what concerns the most are safety, dependability, and trustworthiness aspects that AI might not guarantee at this stage. At the same level, the lack of standards and regulations also play an important role in the integration of AI. Actually, as also discussed in section 4.7, steps have been taken towards new regulations by proposing a regulatory framework for AI-based solutions [59] within the European Union very recently, and new intentions are coming out to define standards for AI in railways. These could be extremely useful also to delineate certification processes to assess, hopefully, the safety integrity level (SIL) of AI systems based, among others, on the concepts of trustworthiness, accountability, and interpretability. On the other hand, already existing regulations might have slowed the integration of AI as they put limitations on data collection due to privacy concerns.

Contributions to the advancement in this area could come from the definition of *pilot studies*, properly identified to be proposed as *challenges* to the research community and possibly strictly related to Trustworthy and Explainable AI.

The relationship between Safety and Trustworthy AI Safety, dependability, and trustworthiness concerns are seen as the most blocking issues in the rail sector. In our understanding, although some frameworks to assess trustworthiness already exist [61], the lack of regulations and standardised certification processes result in the impossibility to precisely quantify the trustworthiness of an AI-based system, and thus its safety and dependable characteristics. Not only Trustworthy AI encompasses legislative, ethical, and robustness aspects [78], it is also strictly related to safety assessment. Some AI-based systems are defined as black-boxes, i.e. their reasoning process is concealed and not evaluable; in addition, in some cases, it is difficult to predict/assess their determinism as the output of the system in response to the same input might vary when considering multiple trials under different conditions. These aspects make AI systems poorly predisposed to be assessed through "traditional" standards or procedures as not all the mechanisms are properly evaluable. To increment transparency, it would be advisable to exploit Explainable AI (XAI) approaches to make these systems more understandable, and thus analysable. Apparently, XAI has not received many practical attentions in the rail sector yet, but these approaches may help to facilitate the assessment process.

Some frameworks are being developed based on model-specific or model-agnostic techniques. The former dealing with the inner working of specific models, the latter aiming at explaining predictions of any models. Among others: SHAP[1] dealing with deep learning models for image classification and image captioning and various NLP tasks; ELI5[2], a Python package that may be used to debug machine learning classifiers and explain their predictions; WIT[3], developed by Google to understand the working of ML trained models; AIX360[4], an extensible open source toolkit developed by IBM research and SKATER[5], en-

[1] https://shap.readthedocs.io/
[2] https://eli5.readthedocs.io/
[3] https://pair-code.github.io/what-if-tool/
[4] https://aix360.mybluemix.net/
[5] https://github.com/oracle/Skater

abling Model Interpretation for all forms of models. The analysis and application of these frameworks to railway pilot case studies is an important investigation direction.

Nevertheless, it would surely be not enough; even though safety assessments come from the possibility to understand and objectively evaluate a system, well-defined procedures are required to validate and certify AI-based models. As an example, the European Union Aviation Safety Agency (EASA) and Deadalean have recently published (May 2021) a technical report on “Concepts of Design Assurance for Neural Networks (CoDANN) II” [79] to ultimate the definition of a *W-shaped developing process* to properly assess the usage of neural networks in avionics by presenting a visual traffic detection system as a case study.

Lastly, what is also important is to properly validate data. In this context, tools such as the TensorFlow Data Validation[6] could be adopted to inspect and deeply analyse data (e.g. to identify incorrect features).

AI and Risk Assessment Risk Assessment is a sub-topic of Safety and Security in our classification (see Fig. 7.1). The introduction of data-driven risk assessment is a great opportunity for railways that should be urgently investigated as AI could give a relevant contribution to safety improvement. In the context of risk analysis, it would be interesting to adopt *AI approaches to estimate the occurrence of the hazards* and *predict their consequences* within preliminary risk assessment and hazard analysis. Some findings from the state-of-the-art [5] discussed the possibility to: combine the Fine-Kinney method and fuzzy rule-based expert systems to quantitatively reveal risk clusters [80]; adopt fuzzy reasoning methods to assess hazardous events and describe frequency, severity and probability of consequences for each hazardous event [81]; and, implement Bayesian Network approaches to quantitatively assess threats in the field of cybersecurity [2]. Additionally, concerns were raised by the advisory board regarding the risk reduction at Level Crossings. Conceptually, these can be classified as safety-critical systems and, consequently, procedures aiming to detect and/or predict possible risks should be taken into consideration.

7.2. High Impact Areas

AI and maintenance. In the maintenance and inspection sub-domain, rail tracks, rolling stocks, infrastructures and catenary systems have already received much attention. Some of them were thoroughly investigated, and technologies such as drones, digital twins, and IoT sensors have been proposed (or already exploited) in conjunction with AI solutions to perform predictive/condition-based maintenance and health assets monitoring. However, beyond the “classic” defect/fault detection and prediction, interests are raising towards the estimation of the remaining useful life of systems belonging to the so-called safety-critical scenarios. As emerged, the level crossing is one of these and would be interesting to carry out researches in this direction as it also fits with the safety and security sub-domain.

AI and safety. Safety covers various topics and applications, among which particular concerns have been raised towards hazardous events prediction and consequence analysis, workers safety, safety at stations, and smart signalling and smart/adaptive Autonomous Train Operation (ATO). Being high-level impact areas for AI in railway, particular attention should be paid to these topics:

[6] https://github.com/tensorflow/data-validation

- *Hazardous events prediction and consequence analysis:* As discussed in section 7.1, there are some cases in which it is not trivial to collect data as the events of interest rarely occur; moreover, it could be challenging to uniform reports coming from different providers as they are often written considering different ontologies. The area of accidents analysis and detection includes both limitations. Also, the prediction of such kinds of hazards (e.g. derailments) is quite challenging and encompasses multiple factors that, in many cases, are not predisposed to be predicted. One of the primary stages for accident prediction/estimation is to extract useful knowledge from informative incident reports/logs. A suitable solution to uniform the different ontologies could be to apply text mining approaches (e.g. NLP), as suggested by the advisory board, to extract useful information such as frequency, distribution, and co-occurrence of the accidents from the non-tabular hand-written or automatically generated reports. In addition, word embedding techniques (e.g. GloVe [82] and Word2Vec [83]) can be utilised to explore the relationship between texts of accident reports and the actual cause of adverse events.
- *Workers safety:* What is also interesting, as resulted from the project analysis (section 4.5) is the potential application of AI and IoT devices to increment safety in workplaces, especially during maintenance inspections (e.g. [39]).
- *Safety at stations:* Similarly, some steps have already been taken towards the application of computer vision approaches to increment safety at railway stations through crowd analysis (e.g. [38]) and to detect fare evasion (e.g. [37]), or to predict fatalities through ML approaches (e.g. Decision Trees [84]).
- *Smart signalling and smart/adaptive Autonomous Train Operation (ATO):* These concepts refer also to the sub-domain of autonomous driving and control, for which we have received a lot of interesting hints from the state-of-practice. There is a growing interest in applying AI to localise train on tracks and then increment safety and automation in the context of signalling systems; similarly, energy optimised driving profiles and automatic wayside signals recognition/detection have shown to be of interest for enterprises and scholars as they may allow adaptive and smart Automatic Train Operations. Lastly, obstacle detection and their trajectory prediction also are very interesting topics to investigate further; actually, useful connections between AI and other technologies such as drones [35, 36] may represent a turning point in this direction.

AI and traffic planning and management. Considering the sub-domain of traffic planning and management, *bio-inspired and deep learning techniques* have been heavily incorporated in the process of *decision making*, such as crew scheduling and network planning, which demonstrates a huge potential in solving *railway optimisation problems* among large-scale and complex transport networks. Nevertheless, one of the inherent limitations of biologically inspired approaches (e.g. Evolutionary Algorithms) is that an optimal solution is not consequentially to be found every time. In other words, the overall outcomes of current models can not be guaranteed and normally other exact optimisation methods are useful benchmarks for measuring the algorithm's performance. A promising trend for addressing this limitation is to combine mathematical-based models with machine learning strategies in future practical scenarios [85], and so-called AI-aided optimisation approaches would receive extensive research interest from railway decision-makers. In addition, current works of conflict prediction and delay prediction mostly focus on how to dig out more potential business benefits and how to reduce the revenue loss from the perspective of train operating companies, rather than paying more attention to the impact analysis on the size and network distribution of the time allowance and delay propagation. A more comprehensive evaluation should be performed from the passenger-efficient perspective by combining passenger data under large delay situations [86].

7.3. Uncharted and promising Areas

AI and passenger mobility. Existing researches for passenger mobility heavily laid on the area of *passengers flow estimation and prediction*, no matter from a macro angle [87] or a micro perspective [88]. However, practical experience shows that more efforts should be put into the process of comprehending the characteristics for the effectiveness of a particular feature—passenger behaviour has the nature of randomness and periodicity [89], and how can the scholars essentially capture these features by employing some AI techniques (e.g., NLP and embeddings) are urgently needed to be further discussed among this sub-domain.

AI and revenue management. Revenue management could become an important topic in the railway industry and shall obtain more attention in the coming years. In addition, as already mentioned in Chapter 6, AI can be leveraged because of the newly available data. For example, the airline industry is one of the industries on which most studies have been done during the past decades, in order to analyse *revenue maximisation*. AI can be used e.g. for ticket price prediction ([90]), or seat booking control ([91]).

AI, traffic signalling and dynamic route selection. The communication between the Infrastructure Manager and Train Operating Companies is one of the core interactions in the rail sector. Self-organising systems could be a potential solution for addressing possible conflicts in this scenario. Specific Distributed AI applications might improve flexibility, capacity, and resilience of the railway system as a mobility backbone, to accomplish an efficient and demand-aware urban and interurban rail mobility growth. For example, reference [92] explored a *new paradigm for intelligent traffic signal control: "self-organising signals"*, based on dynamic coordination rules within a group of closely interacted agents and a simulation test was conducted on arterial road corridors in the US. The result shows that overall delay has been reduced significantly, therefore, it would be advisable to further *investigate the feasibility of transferring such paradigm to the railway signal system* even rescheduling problems. In addition, as also emerged from the survey, another solution for rescheduling or route selection problems could lie in the *adoption of Swarm Intelligence approaches* (e.g. PSO, ACO). In our understanding, trains would be seen as single entities communicating with each other to achieve an optimal (or near-optimal) solution in the context of optimised and dynamic route selection.

8. Conclusions

This report has identified and described current and potential application areas for AI techniques and methods across several railway sub-domains. At this level of abstraction, the analysis does not distinguish explicitly between different type of railway systems (i.e., high speed, commuter, freight, metro, etc.) because they mostly share similar basic principles and infrastructures; however, the specific type of railway system should be taken into account when dealing with some applications (e.g., intelligent obstacle detection may only work well in low-speed applications or in light controlled environments such as subways/undergrounds. Furthermore, this document has provided a synthesis of the results conducted in WP1 (“State-of-the-art of Artificial Intelligence in railway transport”) by focusing on the railway problems that are currently being addressed using AI, or that could benefit from AI. The set of railway problems identified in this report resulted from the scientific literature review and the information provided by railway stakeholders, including project Advisory Board. Moreover, this document presented the main results of a survey on the challenges and state-of-practice of AI applications in railways. As such, this report pushed a step further the discussion of possible application areas, by providing an initial match between railway problems and AI techniques, and delineating some guidelines for their applications; actions are also suggested that could be taken to cope with the challenges and obstacles to overcome for effective adoption of AI in railways.

Some preliminary recommendations can be learned from the analysis conducted so far. According to the findings of the survey, the three most blocking factors for the adoption of AI in the rail sector are:

- Safety, dependability and trustworthiness concerns;
- The lack of proper datasets for training the AI models;
- The lack of specific standards and regulations.

These results, together with the indications derived from the current railway research and the Advisory Board, suggest to:

- Appoint working groups to define pilot case studies/demonstrators to investigate the effects of AI solutions on safety-related applications, with the aim of producing the knowledge needed to drive standardisation. Challenges to the scientific and industry communities could be posed to focus on selected systems/applications and objectives (e.g., trustability, explainability, dependability, safety);
- Support specific actions for railway dataset generation and sharing, in order to feed data-driven AI approaches developed in both academic and industrial research environments. This may also include the definition of alliances/federations among relevant stakeholders, as well as funding specific actions for data collection/generation, processing and management;
- Support the development of data-driven approaches aiming at enhancing safety of passengers and workers, such as data-driven risk assessment, accident prediction, avoidance and analysis (e.g., collisions, fire, accidents at level crossings, derailments, etc.).

Appendix - Questionnaire

This Appendix reports the list of questions of the survey.

PART 1: Context and Background

In this part, questions are related to your organisation and your job.

1.1. How would you classify your organization?
  - ○ Governing Board of a Railway Joint Undertaking / Association
  - ○ Company developing turn-key railway transportation, control or signalling solutions
  - ○ Infrastructure Manager
  - ○ Railway consultancy
  - ○ Supplier of components for railways
  - ○ Railway standardization or regulation body / agency
  - ○ University or research center
  - ○ Other (please specify...)

1.2. How many employees does your organization have?
  - ○ 0 - 100
  - ○ 100 - 1000
  - ○ over 1000

1.3. Where are you located?
  - ○ Europe
  - ○ Africa
  - ○ Asia
  - ○ Middle East
  - ○ Oceania
  - ○ North America
  - ○ South America

1.4. Where does your organization operate?
  - ☐ Europe
  - ☐ Africa
  - ☐ Asia
  - ☐ Middle East
  - ☐ Oceania
  - ☐ North America
  - ☐ South America

1.5. Which of the following areas better represents the one in which you work?
  - ☐ Research & Innovation

- ☐ Engineering or product development
- ☐ Verification & Validation
- ☐ Test and Commissioning
- ☐ Operation
- ☐ Maintenance
- ☐ Infrastructure management
- ☐ Information Technology
- ☐ Physical security and surveillance
- ☐ Other (please specify...)

1.6. In which railway domain or application are you mainly involved?

- ○ Rolling stock (train, vehicles, etc.)
- ○ Supervisory Control and Data Acquisition (SCADA)
- ○ Electrification, power supply and energy management
- ○ Signalling and train control
- ○ Railway infrastructure (track, stations, etc.)
- ○ Telecommunications
- ○ Timetable planning and performance analysis
- ○ Physical security and surveillance
- ○ Ticketing and passenger information
- ○ All railway domains and applications
- ○ Other (please specify...)

1.7. Which of the following aspects are you interested in?

- ☐ Automatic train control
- ☐ Automatic train supervision
- ☐ Interlocking systems
- ☐ Maintenance and inspection
- ☐ Traffic planning and management
- ☐ Safety and security
- ☐ Passenger mobility
- ☐ Revenue management
- ☐ Transport policy
- ☐ Other (please specify...)

1.8. In your job, do you address AI applications to railways?

- ○ Yes
- ○ No
- ○ Partially

PART 2: Challenges and Open Issues of AI in Railways

In this part, questions are related to your opinion about challenges and open issues of AI in railways.

2.1. In your opinion, which are the main obstacles to the adoption of AI techniques in railways?
Please, rate your answer from 0 (the issue is not an obstacle) to 5 (the issue is blocking)

- Lack of knowledge and competences about AI
- Missing specific standards and regulations
- Lack of means to share knowledge among stakeholders
- Lack of training datasets for testing
- Privacy and confidentiality concerns
- Safety, dependability and trustworthiness concerns
- Insufficient level of digitalization in railways
- Lack of high-level design principles and guidelines

2.2. Do you think there are additional obstacles to the adoption of AI techniques in railways? If yes, please, indicate them in the following.

2.3. In your opinion, which are the milestones towards the effective adoption of AI techniques in railways?
Please, rate your answer from 0 (the milestone is not relevant) to 5 (the milestone is very relevant)

- Exploitation of cloud and edge computing, including IoT, at the railway network level to support data-driven approaches
- Creation of technical infrastructures at European level for sharing data and knowledge (datasets, results, models, etc.)
- Establishment of European working groups in railway organizations specifically addressing the cooperative design of AI approaches
- Creation of transversal working groups on AI in critical systems to discuss, share and learn from other sectors
- Specific and in-depth study on the development and applicability of explainable and trustworthy AI approaches

2.4. Do you think there are other milestones towards the effective adoption of AI techniques in railways? If yes, please, indicate them in the following.

2.5. Are you aware of any approaches to “trustworthy AI” (where “trustworthy” also includes ”safe”, ”explainable”, “ethical”, etc.) in railways or other relevant sectors?

○ Yes
○ No

2.6. If you replied ”yes” to the previous question, please list the approaches to “trustworthy AI” (where “trustworthy” also includes ”safe”, ”explainable”, “ethical”, etc.) you are aware of in railways or other relevant sectors.

2.7. Can you indicate one or more railway problems you would like to address by using AI techniques? (i.e., specific problems such as catenary maintenance, track planning, etc.)

PART 3: State of Practice

In this part, questions are related to the state of practice in your organization.

3.1. Which classes of AI techniques have you or your organization used?

- ☐ Machine Learning
- ☐ Probabilistic reasoning
- ☐ Evolutionary Algorithms
- ☐ Swarm Intelligence
- ☐ Logic Programming
- ☐ Other (please specify...)
- ☐ None
- ☐ Do not know / Unable to answer

3.2. Which specific AI models or algorithms have you used (e.g., Support Vector Machine, Random Forest, Bayesian Network, Artificial Neural Network, etc.)?

3.3. If you have used Machine Learning, which type of learning paradigms have you or your organization adopted?

- ☐ Supervised
- ☐ Unsupervised
- ☐ Semi-supervised
- ☐ Reinforcement
- ☐ Self-Supervised
- ☐ Other (please specify...)
- ☐ Not applicable

3.4. In case you are have used Deep Learning, can you please indicate, if any, the specific architectures you have used?

- ☐ Convolutional Neural Network
- ☐ Graph Neural Network
- ☐ LSTM-GRU
- ☐ Autoencoder
- ☐ Generative Adversarial Network
- ☐ Other (please specify...)
- ☐ Not applicable

3.5. Which types of AI applications better match your interest in the coming years?

- ☐ Autonomous driving

- ☐ Obstacle detection
- ☐ Signal detection
- ☐ Audio processing and acoustic event detection
- ☐ Computer vision
- ☐ Natural language processing
- ☐ Scheduling and planning optimization
- ☐ Predictive maintenance
- ☐ Multi-sensor information fusion
- ☐ Intelligent security monitoring and surveillance
- ☐ Decision support systems
- ☐ Other (please specify...)
- ☐ None
- ☐ Do not know / Unable to answer

3.6. Which software tool or framework supporting AI have you or your organization used?

- ☐ MATLAB
- ☐ Keras
- ☐ PyTorch
- ☐ TensorFlow
- ☐ SageMaster
- ☐ Watson
- ☐ Caffe
- ☐ Other (please specify...)
- ☐ None
- ☐ Do not know / Unable to answer

3.7. Considering the datasets you have used in your AI applications, how would you classify them?

- ☐ External and publicly available
- ☐ External and available on request
- ☐ External and commercial/licensed
- ☐ Internal, but can be publicly disclosed
- ☐ Internal and confidential, but can be used by external researchers inside the organization's labs (e.g, PhD students), for non-commercial use
- ☐ Internal, available to external researchers upon licensing and payment of fee
- ☐ Internal, available to external researchers on request, with free license for non-commercial use and signature of NDA (Non-Disclosure Agreement)
- ☐ Other (please specify...)
- ☐ Do not know / Unable to answer

3.8. How did you label data?

- ☐ Manually
- ☐ Automatically

- ☐ Data was already labeled
- ☐ Not required by the used approach
- ☐ Other (please specify...)
- ☐ Do not know / Unable to answer

3.9. Can you rate the effort needed to generate / maintain the datasets?
Please, rate your answer from 0 (very low) to 5 (too high)

- Generate
- Maintain

3.10. Please justify the rate expressed in the previous question

___

3.11. In your opinion, how important is it for you or your organization to get research funding on future AI applications in railways?
Please, rate your answer from 0 (not important at all) to 5 (extremely important)

3.12. Please justify the rate expressed in the previous question

___

3.13. In your opinion, what is the overall technical maturity of AI approaches in railways? Please, rate your answer from 0 (completely immature, needing 10+ years to develop) to 5 (fully mature, can be used immediately)

3.14. Please justify the rate expressed in the previous question

___

PART 4: Personal data

4.1. Please let us know how we can use your personal data and if we can contact you again.

- ☐ I give consent to share my name and the name of my organization with the authors of this questionnaire
- ☐ I am available to be contacted

4.2 If you want to share your personal data, please specify it below.

- Name

  ___

- Surname

  ___

- Organization name

  ___

- Email address

  ___

- Web Page

  ___

Bibliography

[1] Z. Zhang, H. Ning, F. Shi, F. Farha, Y. Xu, J. Xu, F. Zhang, and K.-K. R. Choo, "Artificial intelligence in cyber security: research advances, challenges, and opportunities," *Artificial Intelligence Review*, pp. 1–25, 2021.

[2] M. J. Pappaterra and F. Flammini, "A review of intelligent cybersecurity with bayesian networks," in *2019 IEEE International Conference on Systems, Man and Cybernetics (SMC)*, 2019, pp. 445–452.

[3] RAILS, "Deliverable D1.1 Definition of a reference taxonomy of AI in railways," October 2020, https://rails-project.eu/wp-content/uploads/sites/73/2020/08/RAILS_D11_v25.pdf. Revised, April 2021. DOI: 10.13140/RG.2.2.24887.75681.

[4] S. Bernardi, V. Vittorini, S. Bernardi *et al.*, *Dependable Computing-EDCC 2020 Workshops: AI4RAILS, DREAMS, DSOGRI, SERENE 2020, Munich, Germany, September 7, 2020, Proceedings*. Springer Nature, 2020.

[5] RAILS, "Deliverable D1.2 Summary of existing relevant projects and state-of-the-art of AI application in railways," April 2021, https://rails-project.eu/wp-content/uploads/sites/73/2021/05/RAILS_D12_v23.pdf. DOI:10.13140/RG.2.2.11353.03686.

[6] Intelligent Innovative Smart Maintenance of Assets by integRated Technologies (IN2SMART). [Online]. Available: https://projects.shift2rail.org/s2r_ip3_n.aspx?p=IN2SMART

[7] Innovative Intelligent Rail (IN2RAIL). [Online]. Available: http://www.in2rail.eu/

[8] Measuring, monitoring and data handling for railway assets; bridges, tunnels, tracks and safety systems (ASSET4RAIL). [Online]. Available: http://www.assets4rail.eu/

[9] Automated track geometry monitoring system. [Online]. Available: https://www.mountain-plains.org/research/details.php?id=448

[10] Research into enhanced tracks, switches and structures (IN2TRACK). [Online]. Available: https://projects.shift2rail.org/s2r_ip3_n.aspx?p=IN2TRACK

[11] Vibration-based longitudinal rail stress estimation exploiting acoustic measurement and machine learning. [Online]. Available: https://rip.trb.org/View/1627383

[12] Application of machine learning techniques toward time-based change in track condition using an onboard sensor in revenue-service rolling stock. [Online]. Available: https://rip.trb.org/View/1604536

[13] Transforming transport (tt). [Online]. Available: https://transformingtransport.eu/

[14] Principal components analysis and track quality index: A machine learning approach. [Online]. Available: https://www.unlv.edu/railteam/research/principal-components-analysis

[15] Laser-based non-destructive spike defect inspection system. [Online]. Available: https://apps.trb.org/cmsfeed/TRBNetProjectDisplay.asp?ProjectID=5065

[16] Start-up activities for Advanced Signalling and Automation Systems (X2RAIL-1). [Online]. Available: https://projects.shift2rail.org/s2r_ip2_n.aspx?p=X2RAIL-1

[17] Advanced signalling and automation system - Completion of activities for enhanced automation systems, train integrity, traffic management evolution and smart object

controllers (X2RAIL-4). [Online]. Available: https://projects.shift2rail.org/s2r_ip2_n.aspx?p=X2RAIL-4
[18] Development of Functional Requirements for Sustainable and Attractive European Rail Freight (FR8RAIL). [Online]. Available: https://projects.shift2rail.org/s2r_ip5_n.aspx?p=FR8RAIL
[19] Smart Maintenance and the Rail Traveller Experience (SMaRTE). [Online]. Available: http://www.smarte-rail.eu/
[20] Innovative RUNning gear soluTiOns for new dependable, sustainable, intelligent and comfortable RAIL vehicles (RUN2RAIL). [Online]. Available: http://www.run2rail.eu/home.aspx
[21] INNOvative monitoring and predictive maintenance solutions on lightweight WAGon (INNOWAG). [Online]. Available: http://newrail.org/innowag/
[22] Locomotive bOgie Condition mAinTEnance (LOCATE). [Online]. Available: https://projects.shift2rail.org/s2r_ip5_n.aspx?p=S2R_LOCATE
[23] Research into enhanced track and switch and crossing system 2 (IN2TRACK2). [Online]. Available: https://projects.shift2rail.org/s2r_ip3_n.aspx?p=IN2TRACK2
[24] L. Stanislav, J. Veljko, and J. Uroš, "Infrastructure monitoring data handling with a help of bim."
[25] L. Stanislav, J. Veljko, J. Uroš, and A. Andrej, "Bim based integrated road assessment management."
[26] Video-sensor data fusion for enhanced structural monitoring. [Online]. Available: https://r3utc.psu.edu/research/core-research-projects/ciam-cor-r25/
[27] Sichuan science and technology research and development project. [Online]. Available: http://gb.oversea.cnki.net/kcms/detail/detail.aspx?recid=&FileName=TLZG201911019&DbName=CJFDLAST2019&DbCode=CJFD
[28] Predictive Maintenance for railway switches. Smart sensor networks on a machine learning analytics platform (ANDROMEDA). [Online]. Available: https://www.konux.com/
[29] Safety of Transport Infrastructure on the TEN-T Network (SAFE-10-T). [Online]. Available: https://www.safe10tproject.eu/
[30] Inspection Drones for Ensuring Safety in Transport Infrastructures (Drones4Safety). [Online]. Available: https://drones4safety.eu/
[31] Multi-scale Observation and Monitoring of railway Infrastructure Threats (MOMIT). [Online]. Available: https://www.momit-project.eu/
[32] Global Safety Management Framework for RAIL Operations (GoSAFE RAIL). [Online]. Available: http://www.gosaferail.eu/
[33] Artificial intelligence for advance landslide warning along railroad tracks in pennsylvania and delaware. [Online]. Available: https://r3utc.psu.edu/research/current-research-projects/active-projects-year-2-3/warning-along-railroad-tracks/
[34] Developing a safety management system including hazardous materials for highway-rail grade crossings in region vii. [Online]. Available: https://rip.trb.org/View/1740394
[35] Smart Automation of Rail Transport (SMART). [Online]. Available: http://www.smartrail-automation-project.net/

[36] Advanced integrated obstacle and track intrusion detection system for smart automation of rail transport Danijela Ristic-durrant (SMART2). [Online]. Available: https://projects.shift2rail.org/s2r_ip5_n.aspx?p=S2R_SMART2

[37] TRAINSFARE: Smart Tool to Protect Public Transport Revenues, Assets, Passengers and Mobility. [Online]. Available: https://www.trainsfare.eu/

[38] Future Secure and Accessible Rail Stations (FAIRSTATIONS). [Online]. Available: http://www.fairstations.eu/

[39] ZIMASS: Smart Mobile awareness and safety system for workzone invasion. [Online]. Available: https://cordis.europa.eu/project/id/874184

[40] Cybersecurity in the RAILway sector (CYRAIL). [Online]. Available: https://cyrail.eu/

[41] A.I. enabled knowledge analysis automation to increase resilience, security and performance of Enterprise ICT systems (RAIKA). [Online]. Available: https://cordis.europa.eu/project/id/874184

[42] Increasing Capacity 4 Rail networks through enhanced infrastructure and optimised operations (CAPACITY4RAIL). [Online]. Available: http://www.capacity4rail.eu/

[43] INtelligent solutions 2ward the Development of Railway Energy and Asset Management Systems in Europe (IN2DREAMS). [Online]. Available: http://www.in2dreams.eu/

[44] Advanced Travel Companion and Tracking Services (ATTRAkTIVE). [Online]. Available: https://projects.shift2rail.org/s2r_ip4_n.aspx?p=ATTRACKTIVE

[45] Optimal Networks for Train Integration Management across Europe (ON-TIME). [Online]. Available: https://cordis.europa.eu/project/id/285243

[46] Real time information applications and energy efficient solutions for rail freight (FR8HUB). [Online]. Available: https://projects.shift2rail.org/s2r_ip5_n.aspx?p=FR8HUB

[47] Modelling and strategies for the assessment and OPtimisation of Energy USage aspects of rail innovation (OPEUS). [Online]. Available: http://www.opeus-project.eu/

[48] My TRAvel Companion (My-TRAC). [Online]. Available: http://www.my-trac.eu/

[49] Passenger flow modeling and simulation in transit stations. [Online]. Available: https://cait.rutgers.edu/research/passenger-flow-modeling-and-simulation-in-transit-stations/

[50] Estimation of Origin-Destination Matrix and Identification of User Activities Using Public Transit Smart Card Data. [Online]. Available: https://rip.trb.org/View/1455346

[51] Innovative Solutions in Future Stations, Energy Metering and Power Supply (IN2STEMPO). [Online]. Available: https://projects.shift2rail.org/s2r_ip3_n.aspx?p=IN2stempo

[52] China railway corporation technology research and development project. [Online]. Available: http://gb.oversea.cnki.net/kcms/detail/detail.aspx?recid=&FileName=TLJS201807013&DbName=CJFDLAST2018&DbCode=CJFD

[53] Translation for breaking language barriers in the railway field (TRANSLATE4RAIL). [Online]. Available: https://translate4rail.eu/

[54] Technologies for the AUtonomous Rail Operation (TAURO). [Online]. Available: https://projects.shift2rail.org/s2r_ipx_n.aspx?p=tauro

[55] Major scientific research fund project of china railway corporation. [Online]. Available:

http://gb.oversea.cnki.net/KCMS/detail/detail.aspx?filename=TDBS201807005&dbcode=CJF&dbname=CJFD2018

[56] AI HLEG. (2019) Ethics guidelines for trustworthy AI. [Online]. Available: https://ec.europa.eu/digital-single-market/en/news/ethics-guidelines-trustworthy-ai

[57] European Commission. (2016) Data protection: Rules for the protection of personal data inside and outside the eu. [Online]. Available: https://ec.europa.eu/info/law/law-topic/data-protection_en

[58] ——. (2020) Report on the safety and liability implications of artificial intelligence, the internet of things and robotics. [Online]. Available: https://ec.europa.eu/info/publications/commission-report-safety-and-liability-implications-ai-internet-things-and-robotics-0_en

[59] ——. (2021) Proposal for a Regulation laying down harmonised rules on artificial intelligence (Artificial Intelligence Act). [Online]. Available: https://ec.europa.eu/digital-single-market/en/news/ethics-guidelines-trustworthy-ai

[60] ——. (2021) Annex to the Proposal for a Regulation laying down harmonised rules on artificial intelligence (Artificial Intelligence Act). [Online]. Available: https://ec.europa.eu/digital-single-market/en/news/ethics-guidelines-trustworthy-ai

[61] AI HLEG, "The assessment list for trustworthy artificial intelligence (ALTAI) for self-assessment," *B-1049 Brussels*, 2020.

[62] "Ethically Aligned Design: A Vision for Prioritizing Human Well-being with Autonomous and Intelligent Systems, First Edition," 2019. [Online]. Available: https://standards.ieee.org/content/ieee-standards/en/industry-connections/ec/autonomous-systems.htm

[63] N. J. R. L. E. W. E. Bird, J. Fox-Skelly and A. Winfield, *The ethics of artificial intelligence: Issues and initiatives*. European Parliamentary Research Service, 2020.

[64] A. Armstrong, J. Meissner. (2010) Railway revenue management: overview and models. [Online]. Available: https://eprints.lancs.ac.uk/id/eprint/49017/

[65] M. Lezoche, J. E. Hernandez, M. d. M. E. A. Díaz, H. Panetto, and J. Kacprzyk, "Agri-food 4.0: a survey of the supply chains and technologies for the future agriculture," *Computers in Industry*, vol. 117, p. 103187, 2020.

[66] J. Lee, H. Davari, J. Singh, and V. Pandhare, "Industrial artificial intelligence for industry 4.0-based manufacturing systems," *Manufacturing letters*, vol. 18, pp. 20–23, 2018.

[67] R. Abduljabbar, H. Dia, S. Liyanage, and S. A. Bagloee, "Applications of artificial intelligence in transport: An overview," *Sustainability*, vol. 11, no. 1, p. 189, 2019.

[68] M. Brenna, F. Foiadelli, and M. Longo, "Application of genetic algorithms for driverless subway train energy optimization," *International Journal of Vehicular Technology*, vol. 2016, pp. 1–14, 02 2016.

[69] J. Yin, D. Chen, and L. Li, "Intelligent train operation algorithms for subway by expert system and reinforcement learning," *IEEE Transactions on Intelligent Transportation Systems*, vol. 15, no. 6, pp. 2561–2571, 2014.

[70] M. Gallo, G. De Luca, L. D'Acierno, and M. Botte, "Artificial neural networks for forecasting passenger flows on metro lines," *Sensors*, vol. 19, pp. 1–14, 08 2019.

[71] H. Zhu, X. Yang, and Y. Wang, "Prediction of daily entrance and exit passenger flow of rail transit stations by deep learning method," *Journal of Advanced Transportation*, vol. 2018, pp. 1–11, 04 2018.

[72] A. Antoniou, A. Storkey, and H. Edwards, "Data augmentation generative adversarial networks," 2018.

[73] S. J. Pan and Q. Yang, "A survey on transfer learning," *IEEE Transactions on Knowledge and Data Engineering*, vol. 22, no. 10, pp. 1345–1359, 2010.

[74] Q. Yang, Y. Liu, T. Chen, and Y. Tong, "Federated machine learning: Concept and applications," *ACM Transactions on Intelligent Systems and Technology (TIST)*, vol. 10, no. 2, pp. 1–19, 2019.

[75] G. Hua, L. Zhu, J. Wu, C. Shen, L. Zhou, and Q. Lin, "Blockchain-based federated learning for intelligent control in heavy haul railway," *IEEE Access*, vol. 8, pp. 176 830–176 839, 2020.

[76] B. Hitaj, G. Ateniese, and F. Perez-Cruz, "Deep models under the gan: information leakage from collaborative deep learning," in *Proceedings of the 2017 ACM SIGSAC Conference on Computer and Communications Security*, 2017, pp. 603–618.

[77] Blockchains as a Distributed Ledger for Attribution of RCM Data in Rail. [Online]. Available: https://www.b4cm.co.uk/

[78] AI HLEG, "Ethics guidelines for trustworthy AI," *B-1049 Brussels*, 2019.

[79] EASA and Daedalean, "Concepts of design assurance for neural networks (codann) ii," Tech. Rep., 5 2021.

[80] M. Gul and E. Celik, "Fuzzy rule-based fine–kinney risk assessment approach for rail transportation systems," *Human and Ecological Risk Assessment: An International Journal*, vol. 24, no. 7, pp. 1786–1812, 2018.

[81] M. An, Y. Chen, and C. J. Baker, "A fuzzy reasoning and fuzzy-analytical hierarchy process based approach to the process of railway risk information: A railway risk management system," *Information Sciences*, vol. 181, no. 18, pp. 3946–3966, 2011.

[82] J. Pennington, R. Socher, and C. D. Manning, "Glove: Global vectors for word representation," in *Proceedings of the 2014 conference on empirical methods in natural language processing (EMNLP)*, 2014, pp. 1532–1543.

[83] M. Heidarysafa, K. Kowsari, L. Barnes, and D. Brown, "Analysis of railway accidents' narratives using deep learning," in *2018 17th IEEE International Conference on Machine Learning and Applications (ICMLA)*. IEEE, 2018, pp. 1446–1453.

[84] H. Alawad, S. Kaewunruen, and M. An, "Learning from accidents: Machine learning for safety at railway stations," *IEEE Access*, vol. 8, pp. 633–648, 2020.

[85] Y. Bengio, A. Lodi, and A. Prouvost, "Machine learning for combinatorial optimization: a methodological tour d'horizon," *European Journal of Operational Research*, 2020.

[86] H. Zhuang, L. Feng, C. Wen, Q. Peng, and Q. Tang, "High-speed railway train timetable conflict prediction based on fuzzy temporal knowledge reasoning," *Engineering*, vol. 2, no. 3, pp. 366 – 373, 2016.

[87] L. Heydenrijk-Ottens, V. Degeler, D. Luo, N. V. Oort, and J. V. Lint, "Supervised learning : Predicting passenger load in public transport," 2018.

[88] M. Gallo, G. De Luca, L. D'Acierno, and M. Botte, "Artificial neural networks for forecasting passenger flows on metro lines," *Sensors*, vol. 19, pp. 1–14, 08 2019.

[89] Y. Liu, Z. Liu, and R. Jia, "DeepPF: A deep learning based architecture for metro pas-

senger flow prediction," *Transportation Research Part C: Emerging Technologies*, vol. 101, pp. 18 – 34, 2019.

[90] T. Wang, S. Pouyanfar, H. Tian, Y. Tao, M. Alonso, S. Luis, and S.-C. Chen, "A framework for airfare price prediction: A machine learning approach," in *2019 IEEE 20th International Conference on Information Reuse and Integration for Data Science (IRI)*. IEEE, 2019, pp. 200–207.

[91] S. A. M. Shihab, C. Logemann, D.-G. Thomas, and P. Wei, "Towards the next generation airline revenue management: A deep reinforcement learning approach to seat inventory control and overbooking," *arXiv preprint arXiv:1902.06824*, 2019.

[92] B. Cesme and P. G. Furth, "Self-organizing traffic signals using secondary extension and dynamic coordination," *Transportation Research Part C: Emerging Technologies*, vol. 48, pp. 1–15, 2014. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S0968090X14002228